Forging the Future of Space Science: The Next 50 Years

National Research Council

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FORGING THE FUTURE OF SPACE SCIENCE

THE NEXT **50 YEARS**

An International Public Seminar Series Organized by the Space Studies Board: Selected Lectures

Space Studies Board
and
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences

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Preface

Certain events in human history warrant commemorative celebrations. One of these is the International Geophysical Year (IGY) of 1957–1958 during which scientists from 66 countries coordinated their studies of the Earth, including the first measurements from artificial Earth satellites. With the launch of these first satellites, the Space Age began.

The Space Studies Board (SSB) was created on June 26, 1958, by the National Academy of Sciences as a result of the IGY and the launch of the first U.S. satellites. The SSB's mandate is to provide advice to the government on priorities in space science research and related issues. It seems fitting then that the SSB should celebrate the 50th anniversary of the IGY, and recognize and marvel in all of the science that has been accomplished during the past 50 years and look forward to the discoveries that await us in the next 50 years. Hence, the SSB conducted, from September 2007 to June 2008, an international public seminar series, with each monthly talk highlighting a different topic in space and Earth science. The principal lectures from the series are compiled in this book. The series culminated in June 2008 with a celebration of the 50th anniversary of the Space Studies Board itself.

The seminar series involved eight half-day events held in various locations around the United States and one in Paris (home of the international Committee on Space Research), and two all-day colloquia held at the National Academies' Beckman Center in Irvine, California, and at the National Academy of Sciences in Washington, D.C. The half-day events began with panel discussions by local scientists who spoke on the research they have underway and the promise it holds. These events then concluded with a public lecture by an internationally prominent scientist. The all-day colloquia consisted of lectures and panel discussions by international scientists and space officials. The topics of these events covered the full spectrum of space and Earth science research, from global climate change, to the cosmic origins of life, to the exploration of the Moon and Mars, to the scientific research required to support human spaceflight. All of these lectures and panel discussions were Web-cast and were available on the SSB Web site.

The seminar and colloquia series culminated on June 26, 2008, with an evening reception at the Smithsonian Institution's National Air and Space Museum to celebrate the 50th anniversary of the SSB. At this event, Frank B. McDonald delivered the first Space Studies Board James A. Van Allen Lecture, entitled "Explorer 1: Gateway to the Never Ending Wonders of Space Science."

The SSB is very grateful to the many sponsors who made this outstanding series of events possible, beginning with the presidents of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. NASA was a major sponsor of the series, and we also are grateful to the Aerospace Corporation, ATK, Ball Aerospace, Boeing, Lockheed Martin, Northrop Grumman, and Orbital for their financial support. We are especially grateful to the Richard Lounsbery Foundation for its sponsorship of the Space Studies Board James A. Van Allen Lecture.

The prevailing messages throughout the seminar series as demonstrated by the lectures in this book are how much we have accomplished over the past 50 years, how profound are our discoveries, how much contributions from the space program affect our daily lives, and yet how much remains to be done. The age of discovery in space and Earth science is just beginning. Opportunities abound that will forever alter our destiny.

L.A. Fisk
Chair, Space Studies Board (2003–2008)

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FORGING THE FUTURE OF **SPACE SCIENCE**

THE NEXT **50 YEARS**

An International Public Seminar Series Organized by the Space Studies Board: Selected Lectures

JOHN C. MATHER is a senior astrophysicist in the Observational Cosmology Laboratory at NASA's Goddard Space Flight Center (GSFC). His research centers on infrared astronomy and cosmology. As a National Research Council postdoctoral fellow at the Goddard Institute for Space Studies (New York), he led the proposal efforts for the Cosmic Background Explorer (COBE) (1974–1976) and came to GSFC to be the study scientist (1976–1988), project scientist (1988–1998), and the principal investigator for the Far Infrared Absolute Spectrophotometer (FIRAS) on COBE. He and his team showed that the cosmic microwave background radiation has a blackbody spectrum within 50 parts per million, confirming the Big Bang theory to extraordinary accuracy. As senior project scientist (1995–present) for the James Webb Space Telescope, he leads the science team and represents scientific interests within the project management. He is the recipient of many awards, including the Nobel Prize in Physics (2006) with George Smoot for the COBE work.

From the Big Bang to the Nobel Prize and on to the James Webb Space Telescope

John C. Mather
Observational Cosmology Laboratory
NASA Goddard Space Flight Center

The Big Bang 13.7 billion years ago started the expansion of our piece of the universe, and portions of it stopped expanding and made stars, galaxies, planets, and people. I summarize the history of the universe and explain how humans have learned about its size, expansion, and constituents. The COBE (Cosmic Background Explorer) mission measured the remnant heat radiation from the Big Bang, showed that its color (spectrum) matches the predictions perfectly, and discovered hot and cold spots in the radiation that reveal the primordial density variations that enabled us to exist. My current project, the James Webb Space Telescope (JWST), is the planned successor to the Hubble Space Telescope (HST) and will extend its scientific discoveries to ever greater distances and ever closer to the Big Bang itself. Its infrared capabilities enable it to see inside dust clouds to study the formation of stars and planets, and it may reveal the atmospheric properties of planets around other stars. Planned for launch in 2013, it is an international project led by NASA along with the European and Canadian space agencies.

INTRODUCTION

From the beginning of time to the end of time, with a few details in between, is the story of cosmology. The journey to the Nobel Prize began long ago and far away, on a small planet around an ordinary star in an ordinary galaxy. And now, humans have the temerity to push beyond, to seek to understand the origins of everything—from the primordial explosion, to the formation of objects (stars?) from the initial material, to the formation of galaxies, stars with planets, and even life. Such is the quest of modern astrophysics, and remarkable steps have been taken while enormous mysteries abound.

My personal career began with childhood on a scientific research station, the Dairy Research Station of Rutgers University, located perhaps 75 miles northwest of New York City as the crow flies but immensely distant for a child. My dad was a professor investigating the breeding and feeding of dairy cattle, a subject at one time of immense commercial importance to the state of New Jersey. The chemistry laboratory was located next to the barn where 20 bulls lived, and there were tanks

FIGURE 1.1 Lusscroft Farm, Sussex County, New Jersey, where I lived. SOURCE: Courtesy of the Heritage and Agriculture Association, Wantage Township, N.J.

of liquid nitrogen as well as Geiger counters for civil defense against the possibility of nuclear attack from the Soviet Union.

But somehow, the cows were not as fascinating to me as the mysteries of the sky. When I was around 8, my parents took me and my sister to the American Museum of Natural History in New York City, and we saw the planetarium show and the dinosaur and fish bones. My parents also read aloud to me and my sister from biographies of Darwin and Galileo. Quite an introduction to science, which looked very important and a bit dangerous!

Jumping ahead many decades, astronomers now have a coherent story to tell about the origin of today's universe. We say there was a Big Bang 13.7 billion years ago that started everything, we have a lot of mathematics to describe how it worked, and we have elaborate computer simulations of how the primordial material would grow into the things we see today. But until recently, when the COBE satellite flew, we did not know the details of the starting point, so we did not know what computer simulations to run. The scientific impact of the COBE was to provide that starting point.

Surprise! Explosions in the Bathroom Mirror

One of the great challenges of modern science has been to work out the origins of the chemical elements. When you look in the mirror in the morning, thinking of hair and whiskers and the day ahead, you are looking at the remains of exploded stars. The Big Bang gave us only hydrogen and helium and tiny traces of lithium, and everything else has been made since then by nuclear reactions inside stars. The basic idea was explained by Fred Hoyle in 1946, and developed in great detail over the years. However, much is still unknown about this, since the details seem related to the nuclear reactions that take place during the final explosions of supernovas. Those are very difficult to calculate because the three-dimensional structure of the explosion is highly turbulent.

Looking Back in Time

Astronomers look back in time in a way that is not open to anybody else. We see things as they were when they emitted light, and that can be a long time ago if we are looking at things very far away. The speed of light, immense though it is from a human perspective, is still finite. We see the nearest star as it was 4 years ago, the center of our galaxy as it was 25,000 years ago, and if we look almost to the edge of the visible universe, we look back almost 13.7 billion years. Geologists look at old rocks, historians look at old documents, but astronomers really travel back in time with their telescopes.

Measuring Distances

Astronomers naturally need to know how far away things are, and we have two basic methods (see Figure 1.3). First, we draw triangles, just as the ancient Egyptians did. Given one side and two angles of a triangle, we can compute the other parts. The ancient Greeks, at least some of them, knew how to apply this to get the size of Earth and a rough distance to the Moon, but everything else was too far away for them to calculate. The other basic method astronomers use is the standard candle method: if two objects are known to have the same intrinsic brightness, then the fainter one is farther away, in accordance with the inverse square law. (In the expanding universe, this law has to be modified a bit.)

Measuring Velocities

Of course, we also need to know how fast things are moving. The Sun, the Moon, and the planets move

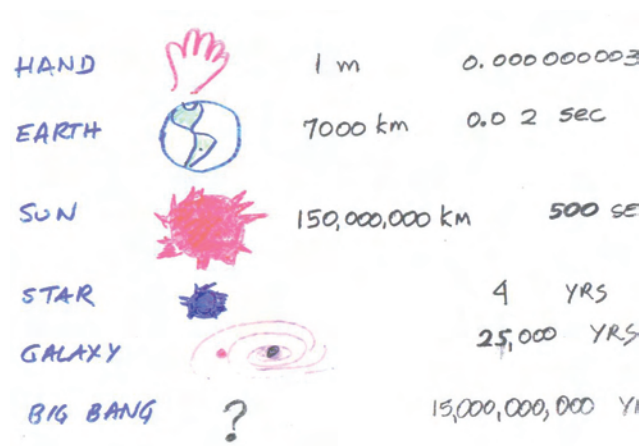

FIGURE 1.2 Looking back in time by looking at things far away.

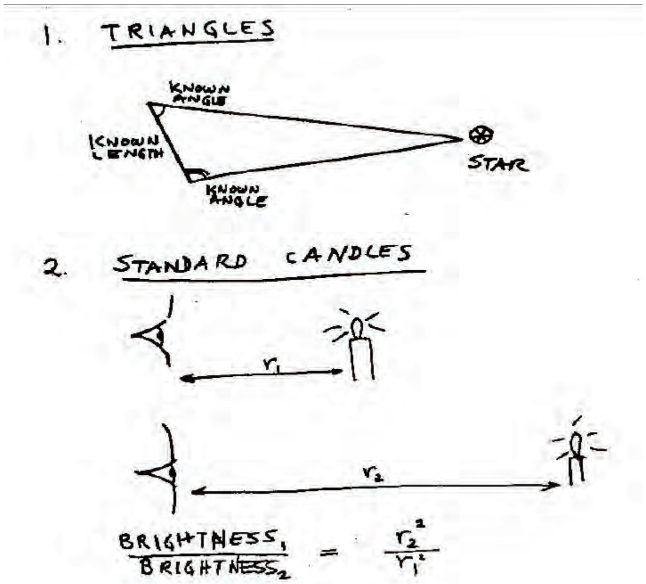

FIGURE 1.3 Measuring distances with triangles, and with standard candles.

pretty fast across the sky, and we know how far away they are, so we can get their velocities very accurately. Some stars also move quickly enough to measure. But most do not move fast across the sky, but we can still spread their light out with a spectrometer. As it happens, stars like the Sun emit a wide range of wavelengths of light, but at certain wavelengths the light is a lot brighter or fainter than one might expect. These special wavelengths are the result of the interactions of chemical elements and molecules, which absorb or emit in very characteristic patterns. That means that we can determine the chemistry and physical properties of distant stars by analyzing their spectra. It also means that we can use the Doppler effect to measure their velocities. If a star is coming toward us, the light we receive is at shorter wavelengths than if the star is not moving, and conversely, if it's going away, the light is at longer wavelengths, i.e., it is redder. Since the chemical elements have very characteristic patterns, we can determine the apparent velocity (towards or away from us) very precisely.

The Big Surprise: The Expanding Universe!

Back in 1929, Edwin Hubble was using the biggest telescope in the world, the 100-inch Hooker telescope on Mount Wilson, to study distant galaxies. He had recently discovered that there are pulsating stars in the galaxy M31, the great nebula in Andromeda. Since he knew about pulsating stars close to home, and he saw similar patterns in these distant stars, he could estimate the distance to the Andromeda Nebula, and then with much more work, even more distant nebulae. The distances were immense, far greater than those within the Milky Way galaxy. And even more surprising, the distant galaxies were almost all going away from us at high speeds. Remarkably, there was a pattern to all this: the galaxies fit close to a straight line on the velocity-distance plot (see Figure 1.4). So it appeared that all of them were together a few billion years ago! Hubble had discovered the expanding universe in the same year that the worldwide economy collapsed. Needless to say, Hubble's discovery was front-page news around the world.

Why the Surprise, Dr. Einstein?

Back in 1905, Albert Einstein shocked the physics world, and then the world at large, by proposing that space and time are inevitably mixed together, and neither one has absolute meaning. He was driven to this by "thought experiments" about synchronizing clocks using light signals, then a hot topic in the engineering world. Working in the Swiss Patent Office, he saw many patent applications about this, so it turned out to be a good thing for him that he was not a professor. As it happens, this Special Theory of Relativity also explains why the Michelson Morley experiment could not detect the "luminiferous ether" that was supposed to be the medium in which light waves would oscillate. The famous $E = mc^2$ came from this work. Then, in 1915 and 1916, he developed the General Theory of Relativity, shocking the world further with the assertion that gravitation works by curving space and time. It did not take long for his predictions to be confirmed by Eddington's observation of the bending of light by the Sun, during a solar eclipse. Einstein applied his equations to the universe as a whole, and (assuming that the universe must be static) added a constant of integration to the equations to keep the (theoretical) universe from expanding or contracting. Why did Einstein assume that the universe had to be static? It was a fair guess, there was no evidence against it, and it seemed simple.

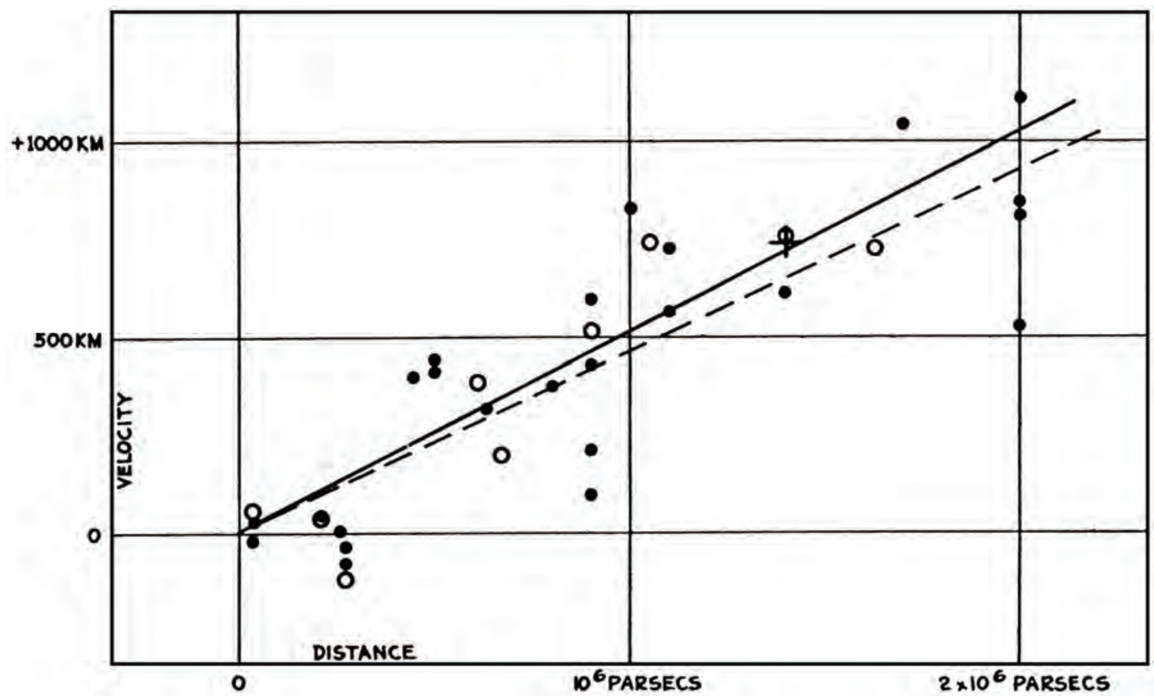

FIGURE 1.4 Edwin Hubble's plot of speed of galaxies versus distance. SOURCE: Hubble Box 24(1), "Velocity-Distance Relation among Extra-Galactic Nebulae," Papers of Edwin Powell Hubble, 1900–1989, The Huntington Library, San Marino, California.

But it was wrong. In 1922, Alexander Friedmann, a young mathematician in the Soviet Union, applied Einstein's equations without assuming the universe would be static, and showed that the mathematics allowed for an expansion. Einstein heard about it and said that was wrong. Three years later, Friedmann died. But in 1927, Georges Lemaître, a Belgian priest and mathematician, came to similar conclusions and was similarly rejected by Einstein, who admitted that the math was OK, but that the physics was terrible. Lemaître named his initial state the Primeval Atom and described in clear terms that the universe was expanding from this extraordinary event. It was only 2 more years before Hubble found by measurement that Friedmann and Lemaître were right, and Einstein had to apologize for what he termed his greatest blunder.

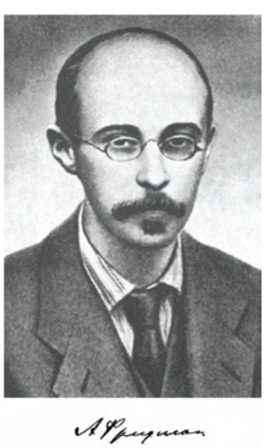

FIGURE 1.5 Alexander Friedmann, first to recognize in 1922 that Einstein's General Relativity suggests that there was an initial compressed state of the universe. SOURCE: Courtesy of the Russian Federation.

No Center, No Edge!

Curiously enough, the pattern of motion that Hubble found says that there is no center and no edge of the observable universe. We can calculate what an astronomer in another galaxy would observe, and he or she would also see distant galaxies receding, with the same shape of diagram found by Hubble. So, we all think we're in the middle. Therefore, there can not be a middle. As it happens, this also simplifies the mathematics of general relativity immensely, so it's very convenient to think that this means the universe is really infinite and almost uniform throughout. But in truth, we've only measured a little piece, the part we can see in the 13.7 billion years that light has been traveling. Quite possibly, the part we can not see is pretty different.

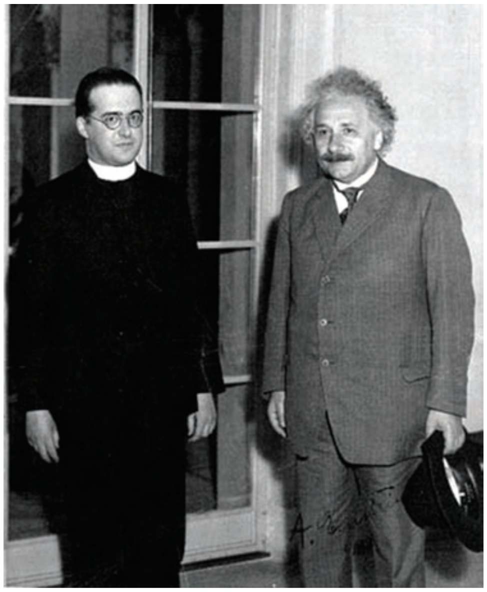

FIGURE 1.6 Georges Lemaître (left) and Albert Einstein (right). In 1927 Lemaître rediscovered Friedmann's equations and named the Primeval Atom. SOURCE: New York Times Magazine, February 19, 1933.

The Power of Thought

Jumping ahead to the end of World War II, scientists came back to science and started applying the knowledge gained in battle. George Gamow (originally from Kiev) came to Washington and started thinking about the Big Bang (it was not called that yet). He had a young postdoc, Robert Herman, and a young graduate student, Ralph Alpher, and set them to work. This

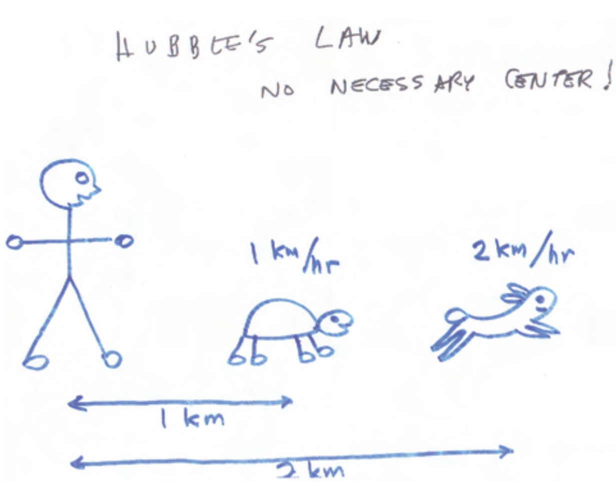

FIGURE 1.7 Three astronomers independently obtain the same Hubble constant from different locations. None can claim to be at the center, so there is no center.

FIGURE 1.8 George Gamow, extraordinarily creative physicist, initiated work on Big Bang physics in 1948. SOURCE: Courtesy of Professor William C. Parke, The George Washington University.

team considered first whether the Big Bang could have made the chemical elements in the abundances that we find them today. The answer was tantalizing: neutrons captured by atomic nuclei would make bigger nuclei, with an abundance pattern like what we see. But, there is a bottleneck: there is no way to make a carbon nucleus by attaching neutrons to smaller nuclei, so the Big Bang can not make all the chemical elements. But the other big question was, what happened to the heat in that Big Bang? Alpher and Gamow computed that it should still exist, and should have an equivalent temperature of about 5 Kelvin (K), not far from the current measured value of 2.7 K. Gamow decided it would be fun to have Hans Bethe's name on the paper, so it was the Alpher, Bethe, Gamow paper, but it was mostly Alpher's work. Alpher eventually got the National Medal of Science, shortly before his death in 2007. So there was a prediction that the universe should be filled with this heat radiation, but in 1948 it was either impossible or extremely difficult to measure it. Perhaps in hindsight we would say it could have been done given the motivation of a Nobel Prize, but serious scientists at that time gave up and did not try.

It was not until 1965 that another team was motivated to try. Robert Dicke at Princeton University was thinking about that Big Bang and the possibility of an eternally oscillating universe that would fill the universe with heat radiation. He thought it might be possible to measure the heat radiation, so he set the Gravity Group at Princeton going to do the measurement. Meanwhile, a few miles away, a pair of scientist-engineers (Arno Penzias and Robert Wilson) at Bell Laboratories were checking out their antenna and found a persistent excess temperature in it. When the two groups were put in contact it was immediately clear what the Bell Labs group had found: the predicted whisper of the Big

FIGURE 1.9 Robert Herman (left) and Ralph Alpher (right) at the launch of the COBE satellite. They worked out the Big Bang physics under Gamow. SOURCE: Courtesy of NASA.

Bang. The companion paper by Dicke, Peebles, Roll, and Wilkinson gave the interpretation of the Penzias and Wilson discovery. A few months later the Princeton group confirmed the measurement at a different wavelength. Then the race was on to learn all about the cosmic microwave background radiation, or CMB, as it came to be called.

Inflation, and How Did That Little Ball Make the Whole Universe?

There were a lot of mysteries about the Big Bang, and one of them was How could the universe become so completely uniform (as it appears today) if there has not been time for the different parts to communicate with each other? So, scientists were looking for a way to make the whole universe erupt from some primordial material that was pretty uniform. In 1980, Alan Guth found such a theory, now known as Cosmic Inflation. Guth found a way to apply the theory of elementary particles to imagine a new kind of cosmic energy that could take a small volume of space, say 10 centimeters (cm) across, and make it grow exponentially, doubling in size around a hundred times in the tiniest fraction of a second. So if that is what happened, then the 10-cm ball of primordial material could grow big enough to kick off the expanding universe we see today.

Needless to say, the conditions in such a little ball were extreme, but nevertheless, it seems possible to calculate many things about it. This is now the favored picture of the origin of the universe: a 10-cm blob of primordial material, probably surrounded by other stuff that is a bit different, that has a quantum fluctuation and starts to expand exponentially, stretching out space and time and filling them with the stuff of physics: particles, antiparticles, quarks, gluons, leptons, photons, gravitational waves, and so on, and so on.

Then, skipping many details that have been calculated and might even be true, the universe expanded and cooled. When it was a few minutes old, some of the neutrons attached themselves to the protons and made helium nuclei, and traces of lithium. And that is it as far as nuclear reactions went, until the formation of stars.

When the universe was about 380,000 years old, it reached a temperature of about 3,000 K, and that was cool enough that the electrons could stick to the atomic nuclei and make neutral gas. That's an important day for us, because when that happened, the gas became transparent, and the heat radiation became free to move across the universe. This event is called the Decoupling, because the radiation and the matter were no longer coupled together. Moreover, the radiation was then free to come to us, human observers, almost unchanged. The expansion of the universe stretched out the wavelengths, reducing the temperature of the radiation accordingly, but the brightness pattern we see today was mostly imprinted on the radiation when the universe was 380,000 years old.

Then, the universe entered a kind of "Dark Ages," when nothing much happened except expansion and cooling. But during this quiet time, gravitation was working, pulling on the denser parts of the universe and reversing their expansion. According to calculations, if the early universe had been completely uniform, we could not ourselves exist, because no part of the universe would have stopped expanding. So this is a very interesting question: How did the material begin to move to make stars and galaxies?

We calculate that the first stars and galaxies could have formed when the universe was a few hundred million years old and maybe 1/10 or 1/20 as large as it is today. The first objects might have been very massive stars, maybe a few hundred times as massive as the Sun, and they would have burned very hot (maybe 100,000 K) for about 3 million years. Then, they would end their lives in supernova explosions, possibly producing black holes, as well as liberating the heavier chemical elements that make up places like Earth. If stars and planets had formed from this enriched material, it is conceivable that life might have formed soon after, in the first hundreds of millions of years after the Big Bang.

Then, somehow, ordinary galaxies of ordinary stars were formed. This process is a great mystery, though numerical calculations are giving us a hint. It seems likely that galaxies evolve by colliding with and absorbing their neighbors, and indeed the Milky Way still has two small satellite galaxies (the Magellanic Clouds) that are still falling in. Then, quite recently on a cosmic scale, only 4.5 billion years ago, the Sun formed with the planets, apparently rather abruptly from the isotopic evidence in various residual bits of the early solar system. So our solar system is very young, only 1/3 of the age of the universe.

Very Recent History

We have evidence that life appeared on Earth shortly after it became cool and wet enough to support life as we now it, but that is a topic for another science. And shortly after a small asteroid made a crater in the Yucatan about 65 million years ago, mammals replaced dinosaurs as the dominant large land animals. Only a million years ago or so, the large mammals of today came into their present forms: lions, elephants, and humans (or their ancestors). And in 1609, Galileo pointed his newly improved telescope at the heavens and discovered satellites of Jupiter, craters and mountains on the Moon, and spots on the Sun. Copernicus was right, the Protestant Reformation was in full swing, and science was politicized. But Galileo was buried in honor in Santa Croce in Florence, Italy, across the hall from Michelangelo, and now the Church has admitted to a terrible misunderstanding. Moreover, the Vatican maintains its own observatory and sponsors conferences on cosmology.

In 1905, Einstein had his Miracle Year of major discoveries; we celebrated the International Year of Physics in 2005; and in 2009, we will celebrate Galileo's discoveries with the International Year of Astronomy.

Just 50 years ago, on October 4, 1957, the Sputnik launched a new era of the space race. Started as a scientific research project, it had huge effects on the world. NASA was founded a year later, on October 1, 1958.

The Future

Perhaps in another 50 years, we will find signs of life on other planets. But certainly, in a billion years or so, the Sun will be so bright that there will be no place on Earth capable of supporting life. And in about 5 billion years, it is predicted that the great Andromeda Nebula will collide with the Milky Way, changing its shape beyond recognition. Possibly the Sun will end up orbiting around the Andromeda nebula. And then, about 7.6 billion years from now, the Sun will expand so much that Earth will orbit inside its surface. Shortly after, the Sun will go out. Then, over billions of years, the remaining hydrogen and helium gas will form new stars, those stars will themselves burn out, and the universe will become mostly dark. If present trends continue, most of the distant galaxies will continue to recede from us, and the universe will seem small and isolated. But, since we do not know why the universe is expanding now, we do not know if it will continue. Perhaps there will be the Big Crunch, a.k.a. the Gib Gnab.

THE STORY OF COBE, THE COSMIC BACKGROUND EXPLORER

In 1970, I was looking for a thesis project at the University of California, Berkeley, just 5 years after the discovery of the CMB. At the time there had been some really wrong measurements of the CMB at short wavelengths, around a millimeter, so it was a time to try a thesis project. Mine involved a ground-based measurement at White Mountain with Mike Werner and Paul Richards, and then a balloon payload with David Woody and Paul Richards and Norm Nishioka. It was tough work, and the balloon payload did not work right on the first flight. I left Berkeley thinking I would try something easier as a postdoc in radio astronomy with Pat Thaddeus at the Goddard Institute for Space Studies in New York City. But in 1974, a few months after I arrived in New York, NASA announced an opportunity to propose new scientific satellites, and it seemed obvious that a better version of my thesis work had to be proposed. My advisor, Pat Thaddeus, gave me some names, we called them up and made a team, and we submitted our proposal. In 1976, NASA chose to make a new team, composed of members of our team and two other teams, to define the new mission. So I moved to Goddard Space Flight Center in Greenbelt, Maryland, to work on it. The new team named it the Cosmic Background Explorer, or COBE.

The hair-raising details of this project are well told in the book *The Very First Light*, a popular account by

John Mather and John Boslough. The project suffered many perils, and had to be re-designed after the loss of the space shuttle *Challenger*. But it was finally launched on November 18, 1989, and almost immediately began returning data.

Proving the Big Bang

You cannot prove the Big Bang. But you can test the predictions of the theory, and you can compare them with other theories. There were two major predictions: First, the spectrum of the CMB should match that of a perfect black radiator at a temperature of about 2.7 K. Second, the CMB should be slightly non-uniform (anisotropic, in Greek), so that some parts of the universe would have enough gravitation to stop expanding and turn into galaxies, stars, and people.

The first experiment to report scientific results was the FIRAS, the Far Infrared Absolute Spectrophotometer. This was my thesis project, grown larger and made to work very well by professional engineers. When I presented the first results to the American Astronomical Society in January of 1990, I showed them a graph that had the measurements as little boxes and the theoretical curve as a solid line (Figure 1.11). All the boxes were right on the line. The result was a standing ovation from the audience of about 2,000 astronomers. I was completely unprepared for this response, since I had always thought I knew the right answer: the CMB must have the predicted form. But the audience knew that there had been repeated measurements that showed that the spectrum did not match the blackbody predictions. And there were many papers showing that it required very implausible theories to explain these deviations. So it was a huge relief for the crowd that (a) the Big Bang was now safe, and (b) none of these exotic theories were required.

Prior to the discovery of the CMB, the dominant alternate theory about the universe was the Steady State theory, which held that the universe has existed for an infinite amount of time and that, although it seems to be expanding, it is continually being refilled by the creation of new matter. This theory does allow for the existence of a cosmic background radiation, produced by stars through the infinite history of the universe, but it does not predict that the spectrum should match the perfect black radiator. So, in 1965 the Steady State theory was already dying because of the discovery of the

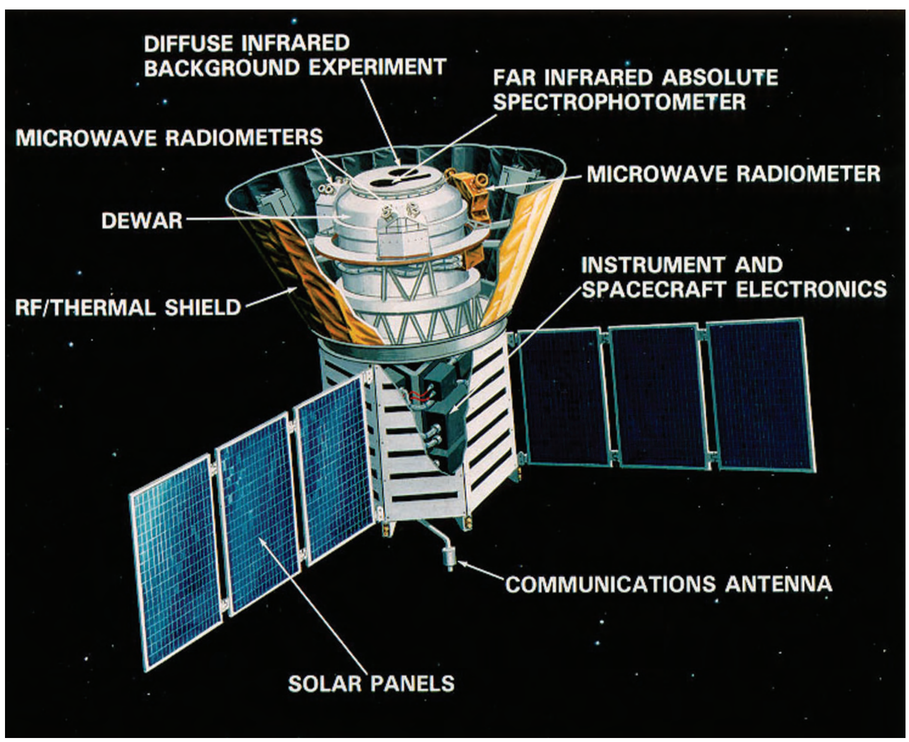

FIGURE 1.10 The COBE satellite in orbit 900 km above Earth. The instrument package is protected by conical shield. The Sun is to the side, and Earth below. SOURCE: Courtesy of NASA.

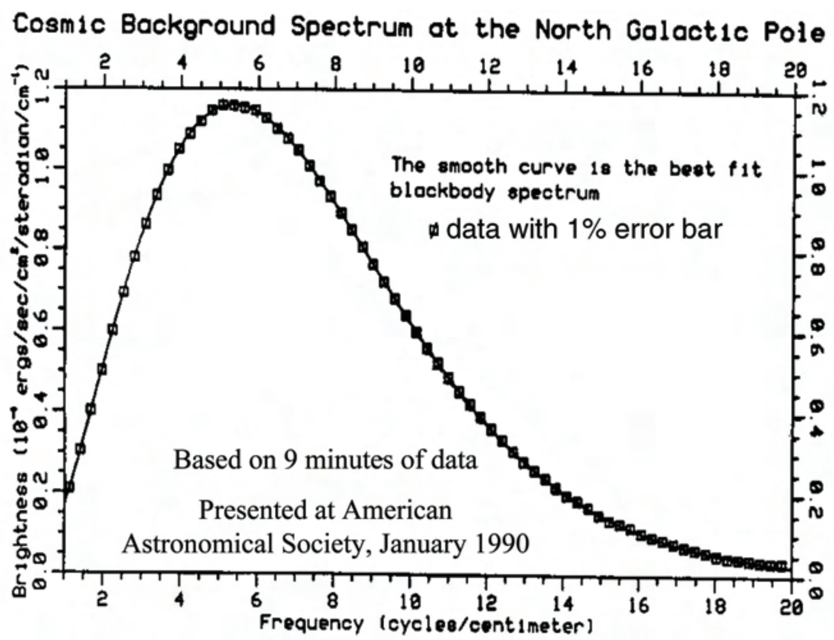

FIGURE 1.11 First public spectrum of the CMB from the COBE FIRAS instrument, shown at AAS meeting in January 1990, received a standing ovation. SOURCE: Courtesy of NASA and the COBE Science Working Group.

CMB, and in 1990 it became very difficult to make the Steady State match the CMB spectrum.

In the end, we reduced the error bars to about 50 parts per million. The CMB has a spectrum that is as close to the theoretical prediction as we can measure.

Why Are We Here? The Pink and Blue Blobs

The second major result from the COBE was announced in April 1992. The Differential Microwave Radiometer (DMR) instrument was designed to map the brightness of the CMB and to look for tiny differences in brightness from one place to another. Considering that the differences we found are very, very faint, only 30 micro-K, and that the instrument operates at a temperature of 140 K or 300 K depending on the channel, this is an extraordinary accomplishment, pulling tiny signals out of mountains of noise. It depended on making hundreds of millions of measurements and fitting them to a map of the sky using a “least squares fit” on a computer.

We found the map in three scientific stages (see Figure 1.12). First, we made the map of the sky, represented as an oval, with the center of the galaxy in the middle. This map shows a small difference between one part of the sky and the other: half of the sky is pink, and half is blue. This is the expected result if Earth is moving relative to the rest of the universe, with a speed of about 300 km/s toward the constellation of Leo. It’s

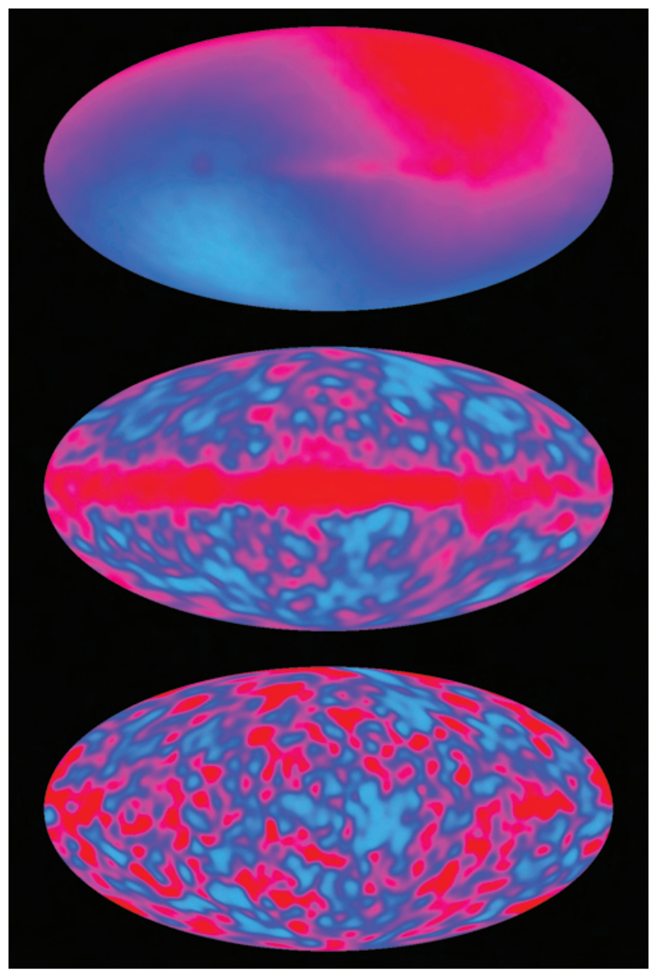

FIGURE 1.12 The first published all-sky maps of the CMB fluctuations. SOURCE: Courtesy of NASA and the COBE Science Working Group.

not of cosmic significance, but eventually we'd like to know why we have that speed. Second, we subtracted off that effect, and we got a map that has a lot of pink and blue blobs and a strong reddish band across the middle. That's the Milky Way galaxy, emitting microwave radiation because there are electrons spiraling around magnetic fields and bumping into protons. We were expecting that effect too, and we mapped the sky at three different wavelengths so we could tell what part of the map came from the electrons and what part came from the Big Bang. So the third map is all pink and blue blobs, and except for measurement errors, they all come from the Big Bang.

When Steven Hawking saw these maps, he said it was the discovery of the century, if not of all time. At first I thought he was being too generous, but now I would like to point out that if it were not for these blobs, we could not exist. These blobs map out the density differences in the early universe, and as it happens the cool (blue) blobs come from dense regions. And if there were no spots that were dense enough to stop the expansion, we would not be here to measure them.

The Nobel Prize

On October 3, 2006, I was awakened by a phone call from Sweden, wanting to know if I were the real John Mather who worked on the COBE satellite. People had been telling us for years that we had done Nobel-worthy work, and now it was happening! The next months were a whirlwind of preparations for 10 days of parties and speeches in Stockholm. The big challenge was to arrange for as many as possible of the COBE team members to go to the big event. George Smoot, my co-winner, and I each had a quota of 16 invitations. I would like to specifically mention that Ned Wright, the data team leader on COBE, was the first to compute the maps of the pink and blue blobs, and that Chuck Bennett, deputy principal investigator for the DMR instrument, was crucial for the success of the measurement. Bennett is also the principal investigator for the WMAP, the Wilkinson Microwave Anisotropy Probe, which made a tremendous improvement on the DMR measurements, and showed as well that the DMR maps were correct. Without that confirmation, perhaps the Nobel Prize would not have been given to us.

What's Next with the CMB?

The CMB has been astonishingly informative, considering how difficult it was to measure it. The DMR map had 6,144 pixels, and there may already be more than 6,000 scientific papers citing the DMR work. The WMAP already made far more detailed maps, with far sharper images and far better sensitivity. Its maps have revealed some huge surprises and confirmed others. First, the universe is filled with dark matter and dark energy—that are both far more abundant than ordinary matter. According to WMAP and other measures, the universe is composed of about 4 percent ordinary matter, 23 percent dark matter, and 73 percent dark energy. The dark matter has been suspected for a long time, going back to Fritz Zwicky in 1933, but now it is clear: the pattern of speckles on the microwave map can not be explained by ordinary matter. Dark matter is not coupled to the radiation field and is free to move under the influence of gravity, long before the decoupling event at 380,000 years, so the pattern has a different shape than it would have with ordinary matter alone.

As it happens, it was also discovered (in 1998) that distant supernovas are too faint, quite a lot too faint—about 20 percent or so—way too much to be explained by experimental error. The interpretation was that the universe is larger than it seems from the velocity of expansion, and that would be so if the universe has been accelerating. This was pretty shocking when it was discovered by the High Z team and later confirmed by the Supernova Cosmology Project, but their discovery has stood the test of time. In particular, the acceleration changes the pattern of speckles on the WMAP image of the sky in just the way that would be expected if the acceleration determined from the supernovas is really there. The big questions now for astronomy are What is that dark matter doing? How does it relate to ordinary matter? and What is causing the acceleration? We call that acceleration force "dark energy" to be able to talk about something, but in truth it was not expected by many theorists, and we see no obvious reason why it should exist.

The CMB also may harbor traces of something even more exotic: gravitational waves in the primordial material. If these waves existed, with the amplitude predicted by many theories of inflation, then they would produce an imprint of a certain pattern of polarization of the CMB. The hunt for this polarization has already started, with some preliminary results, but the final answer may require an even more sensitive satellite mission.

"MY" NEW PROJECT: THE JAMES WEBB SPACE TELESCOPE

In 1995, the COBE mission was done, and I was writing a book about it with John Boslough. The HST was up and working beautifully after its repair, but it had been very difficult and costly. I thought NASA might never again do something as exciting and challenging as the COBE or the HST, but one day in October, I received a phone call from Ed Weiler, the new head of the Origins Theme at NASA Headquarters and the long-term guiding light for the HST. Weiler knew that we needed to plan for the successor project after the HST and had already started a committee going to define what it ought to do. The committee, chaired by Alan Dressler, wrote a beautiful report called *HST and Beyond*, which outlined two objectives. First, NASA should build a new space telescope that is optimized for near infrared wavelengths (1 to 5 micrometers) as large as possible, at least 4 meters in aperture. Second, NASA should start planning for missions to observe Earth-like planets around other stars. In 1995, Michel Mayor and Didier Queloz announced that the nearby star 51 Pegasi has a big planet orbiting close in; not exactly Earth-like, but tantalizing. Obviously, NASA (and other space agencies) would have to follow up on this discovery. Now, we know of over 300 exoplanets of many different types, mostly found by this radial velocity technique.

So Ed sent a little money to Goddard Space Flight Center and we got started on a study, working with the Space Telescope Science Institute in Baltimore, with industrial partners, and gradually with international partners, the European and Canadian space agencies. Under the leadership of Dan Goldin, NASA was trying to reach out far beyond the realm of the currently possible, and an extremely ambitious telescope was just the thing. The initial studies said that a telescope 8 meters across could be built at an affordable price, even though it would have to fold up like an origami bird to fit into the rocket. New technologies were needed, but the plan was to develop them all to a high level before they were really needed. By 2007, we had a list of 10 new technologies that would be needed, and all of them were ready, which means that representative designs had been tested in the relevant space-like environment.

The JWST Team

The JWST project is led by project manager Phil Sabelhaus at NASA Goddard Space Flight Center and includes major contributions from other parts of NASA at Marshall Space Flight Center, the Jet Propulsion Laboratory, and Johnson Space Center. The observatory will be operated by the Space Telescope Science Institute in Baltimore, Maryland.

NASA held many competitions to choose the team members for the telescope. In the end, the prime contract was awarded to TRW. The part of TRW doing the telescope was then bought by Northrop Grumman and became Northrop Grumman Space Technologies, located near Los Angeles Airport. Their major subcontractors include Ball Aerospace, ITT (formerly Kodak), and ATK.

The JWST Concept

This new telescope does not look much like any telescope you've ever seen (Figure 1.13). First, it has to fold up, and second, it has to get cold. So it will fly to deep space, a million miles from Earth, and orbit around the Sun–Earth Lagrange point L2 (Figure 1.14). It will have a folding sunshield, with five plastic layers to achieve a Sun Protection Factor of a million, to let the telescope cool itself down to 40 K. It will not have a protective tube: if it did, it would not be able to radiate away its heat to outer space. So it ends up looking more like a solar energy concentrator than like the HST. But it will be far more powerful, with a mirror collecting area more than 6 times that of the HST, with infrared instruments that the HST can not use because it is too warm, and with advanced camera chips far beyond anything known before.

Naming the Telescope

Originally called the Next Generation Space Telescope (a lot of our colleagues were *Star Trek* fans), the new machine was finally named after the second

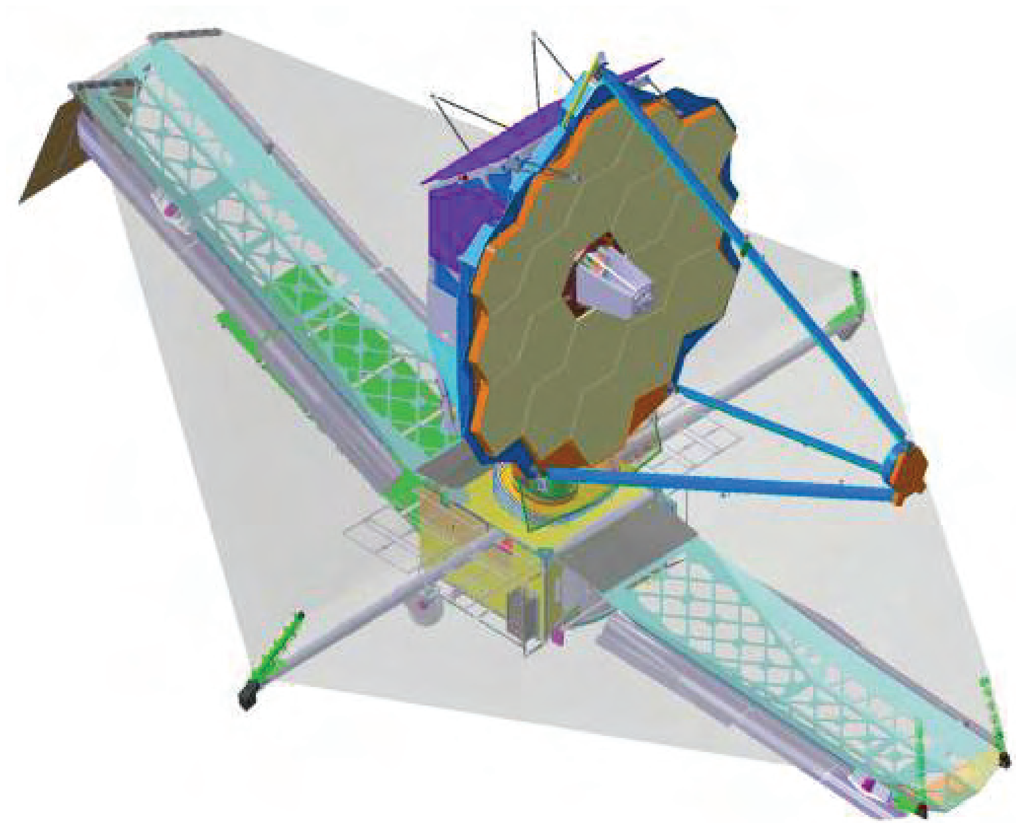

FIGURE 1.13 James Webb Space Telescope, planned for launch in 2013 as successor for the Hubble Space Telescope. SOURCE: Courtesy of NASA Goddard Space Flight Center.

administrator of NASA. Scientists rebelled: Should not every observatory be named for a great scientist? But James E. Webb, the man who built NASA to go to the Moon, did more for science than most people know. He personally persuaded John Kennedy that the science done with the Apollo program would outlast the political statement and have lasting value for the USA. As a result, Webb initiated the creation of space science laboratories at universities around the country. Science owes a lot to James Webb. For more details, consult the fine biography *Powering Apollo* by Henry Lambright.

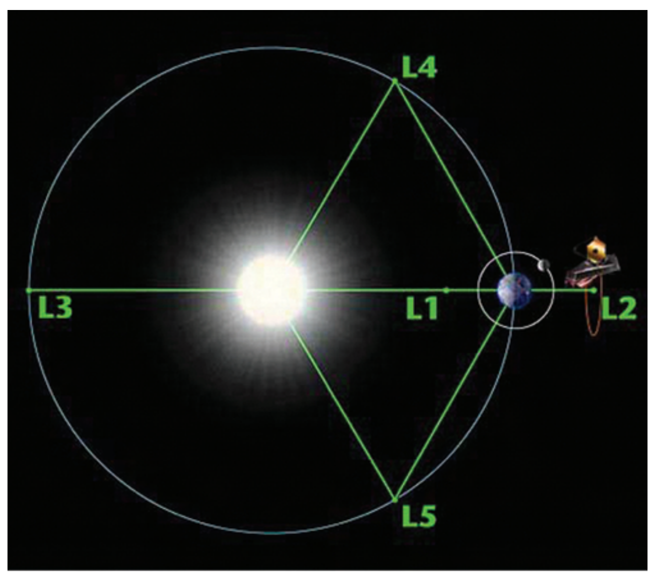

FIGURE 1.14 The 5 Lagrange equilibrium points of the Sun–Earth system, discovered in 1772. JWST orbits the L2 point, a million miles from Earth, and is overhead at midnight. SOURCE: Courtesy of NASA.

Folding Mirror!

The most obviously difficult part was the giant primary mirror. It would have to be built in segments and deployed after launch. Then it would have to be adjusted to the right shape, using the mathematics that we learned when we had to fix the HST. It would all have to happen by remote control, long after the last human could touch it. We held competitions for the mirror technology, with about a dozen contracts to famous optics companies. In the end, there was a shoot-out between two leading designs. One used a sandwich of ULE® glass sheets bonded to a glass honeycomb for light weight. The other used pure beryllium metal machined to remove 95 percent of the material and polished very carefully. In the end we chose beryllium, because the glass sandwich did not hold its shape when it was cooled down to the low temperatures we needed, around 40 K. But the beryllium is a tough material to use: it's very strong, very stiff, very light, and very hard, but it can change its shape a little if a rather modest pressure is applied, and powdered beryllium can be quite toxic.

Now, we are polishing the mirrors for the flight telescope. It takes about 4 years to get from powdered beryllium to polished hexagons, and we're about half done with the process.

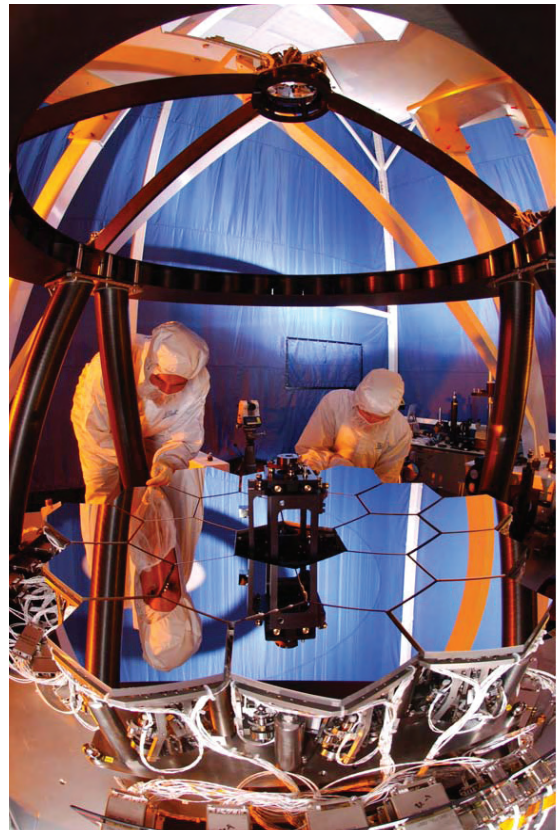

FIGURE 1.15 The JWST mirror rack. SOURCE: Courtesy of Ball Aerospace Corporation.

Adjusting the Mirror

After the HST experience, people are a little touchy about telescope mirrors in space, so we have built a testbed telescope, 1/6 scale, to learn everything about adjusting the real one. Our current plan requires 11 different adjustment methods to get from the initial deployment to a nearly-perfect mirror, so all 11 have been tried out on the testbed. It takes a computer a day or so to adjust the testbed, but we expect the real space telescope to take weeks. (Figure 1.15)

Testing the Real Telescope

One of the lessons from the HST was that conservative engineers are right: test as you fly, fly as you test. It was believed that a full test of the HST optics was too expensive. But if you do not have time to do it right, when will you have time to do it over? That's the title of an inspirational book on time management. So the test plan for the new telescope is very carefully designed to catch every possible kind of error that our engineering teams can imagine and to be ready to catch the unimagined errors as well. The big test will be held at Johnson Space Center in the same vacuum tank used by the Apollo astronauts to get ready for the Moon (Figure 1.16). It's so old, it's on the Historic Register.

In the big tank, the telescope will be at the bottom looking up. At the top will be test equipment located at the center of curvature of the primary mirror, as well as 3 autocollimating flat mirrors that will reflect light back into the telescope. A tiny light at the focal point of the telescope will radiate outwards to the flat mirrors, and their beams will return through the telescope to detectors to create an end-to-end test. The telescope will be cold and in vacuum, but of course not in zero gravity.

Scientific Objectives and Instruments

The JWST will collect light from distant stars and galaxies, and instruments will spread it out into images and spectra for transmission back to the ground. There are four main scientific topics that will certainly be investigated by users of the telescope, along with many others that will be proposed by observers:

1. The end of the Dark Ages: first light and reionization of the universe,
2. The assembly of galaxies,
3. The birth of stars and protoplanetary systems, and
4. Planetary systems and the origin of life.

To enable these investigations, the JWST will carry four instruments:

1. The Near Infrared Camera (NIRCam), being produced by the University of Arizona with its major contract to Lockheed Martin;
2. The Near Infrared Spectrograph (NIRSpec), being produced by the European Space Agency (ESA) with its major contract to Astrium;
3. The Mid Infrared Instrument (MIRI), produced by a European Consortium led by the United Kingdom Advanced Technology Center (UKIRT), in partnership with the Jet Propulsion Laboratory; and
4. The Fine Guidance Sensor (FGS), including the Tunable Filter Imager (TFI), produced by the Canadian Space Agency, with their major contractor COMDEV.

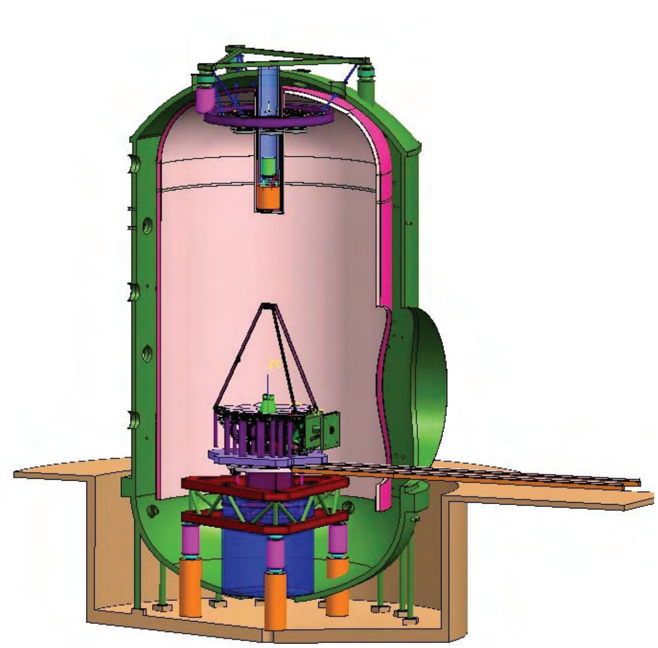

FIGURE 1.16 JWST optical system in test chamber at Johnson Space Center, looking up to test apparatus at top of chamber. The end-to-end test! SOURCE: Courtesy of NASA.

The near infrared instruments (NIRCam, NIRSpec, FGS, and TFI) cover the wavelength range from red (0.6 microns) to 5 microns, and the MIRI covers the range from 5 to 28 microns. The near-infrared detectors are all made with mercury-cadmium-telluride (HgCdTe) sensing layers and are produced by Teledyne (formerly Rockwell), and the mid-infrared detectors are arsenic-doped silicon produced by Raytheon.

The End of the Dark Ages

The prime objective in this area is to discover and measure the earliest possible objects that formed after the Big Bang. As described above, theoretical predictions suggest that these were extremely massive stars, hundreds of times the mass of the Sun, that would be extremely hot and bright, burning out in a few million years with some kind of spectacular supernova explosions. If so, individual supernovas could be detectable from a time when the universe was only a few hundred million years old. To find them, the JWST would survey the sky, returning repeatedly to the same areas to search for objects that have changed in brightness. Close to home, supernovas rise rapidly to maximum brightness in a few days and then slowly decay over a period of months. The most distant ones will show time dilation, with days stretching into months and months stretching into years.

We also imagine that the first objects may have been clustered together because of the way in which the primordial density variations combine to enable gravity to slow and stop the expansion of the original material. If so, we might find proto-galaxies containing thousands of massive stars burning near each other.

We would recognize the first objects in several ways. First, they would be extremely hot, as expected from the lack of heavy chemical elements in them. Second, they would be embedded in the primordial hydrogen, so their ultraviolet radiation at rest wavelengths less than 0.1216 microns would be cut off by absorption by that intergalactic hydrogen. We would use the NIRCam to search for the objects and to determine whether they show the predicted lack of ultraviolet radiation due to the hydrogen. Third, they might be clustered together, with a group all at the same redshift. We would use the TFI to hunt for this effect, since it can be set to search for objects emitting hydrogen Lyman-alpha spectra at a specific redshift. Fourth, their spectra would show no signs of elements heavier than the primeval hydrogen and helium. Unfortunately, this last step is very difficult, because it requires not only discovering the first objects, but also obtaining their spectra. We would carry out this step with the NIRSpec, which has been optimized for just this purpose. The NIRSpec is capable of observing 100 candidate objects at the same time, using a remarkable new technology of microshutter arrays.

According to predictions, these first objects are outside the range of ground-based telescopes and even the HST, because the expansion of the universe has stretched the original ultraviolet light out into the infrared by the time we see it. So, we need a giant space telescope capable of observing the infrared.

The Assembly of Galaxies

We would very much like to know how our own home galaxy, the Milky Way, was formed. We now have two small satellite galaxies, as do many other galaxies. We imagine that the Milky Way has grown by absorbing many such small galaxies, and we can check this theory by observing other galaxies like ours. With the JWST, we will look back in time to see how different the early galaxies were in shape, rotational characteristics, color, brightness, chemical composition, and temperature. In addition, we would pursue one of the great current mysteries: Why is there a giant black hole in the middle of almost every galaxy? Did the galaxy make the black hole, or did the black hole make the galaxy? Was there just one black hole made per galaxy, or were there many of them, merging together later to make bigger ones?

We currently see that most galaxies are either spiral in shape, like the Milky Way, or elliptical. We already know that at earlier times, many more galaxies were irregular in shape, as though their internal motions had not settled down. We also know that at early times, galaxies collided frequently with one another. It appears that the universe became a much more peaceful place around the time that the Sun was formed about 4.5 billion years ago. Curiously enough, that is also when the expansion started to accelerate.

In any case, this whole story has to be checked by measurement. Thousands of galaxies will be observed; cataloged; classified by shape, redshift, color, spectra, and brightness; and then compared with simulated galaxies based on theories about how this process is supposed to have worked.

The Formation of Stars and Planetary Systems

Understanding the history of the solar system has always been one of the fascinating challenges of astronomy. Early astronomers had no idea that the solar system was very old, and, indeed, before the discovery of nuclear energy and the conversion of mass into energy it seemed the Sun had to be very young. But now, we see stars forming before our very eyes in nurseries like the Orion Nebula (the fuzzy spot in Orion's sword). Some stars are hot and bright and must be very young, only a few million years old, otherwise they'd already be burned out. But the process is largely hidden from us now, because the nebulae where birth occurs are dusty. The dust itself is a part of the process, because it shields the gas clouds from external heat and enables the gas to cool and condense into massive knots that then become stars. Using visible light, the HST gave us the famous pictures of the Eagle Nebula, also called "the Pillars of Creation," where bright new stars have just been born (Figure 1.17). Using infrared light, the Very Large Telescope in Chile has shown us that we can see inside the dust clouds. However, most infrared wavelengths do not reach ground-based telescopes, because the atmosphere is opaque, so we need an infrared telescope in space to see better. The JWST MIRI will be especially important for this task because it observes wavelengths that pass through the dust clouds very well and that are emitted by objects far too cool to emit visible light. The MIRI includes both cameras and spectrographs to detect candidate young stars and stellar nurseries and to analyze their temperatures, structures, and compositions.

Planetary Systems and the Origin of Life

Since the first planets around other stars were discovered in 1995, the tantalizing possibility that some might harbor life has driven intense efforts to learn more about them. There are several major topics to investigate.

First, we have small residual pieces from the formation of our own solar system that are orbiting the

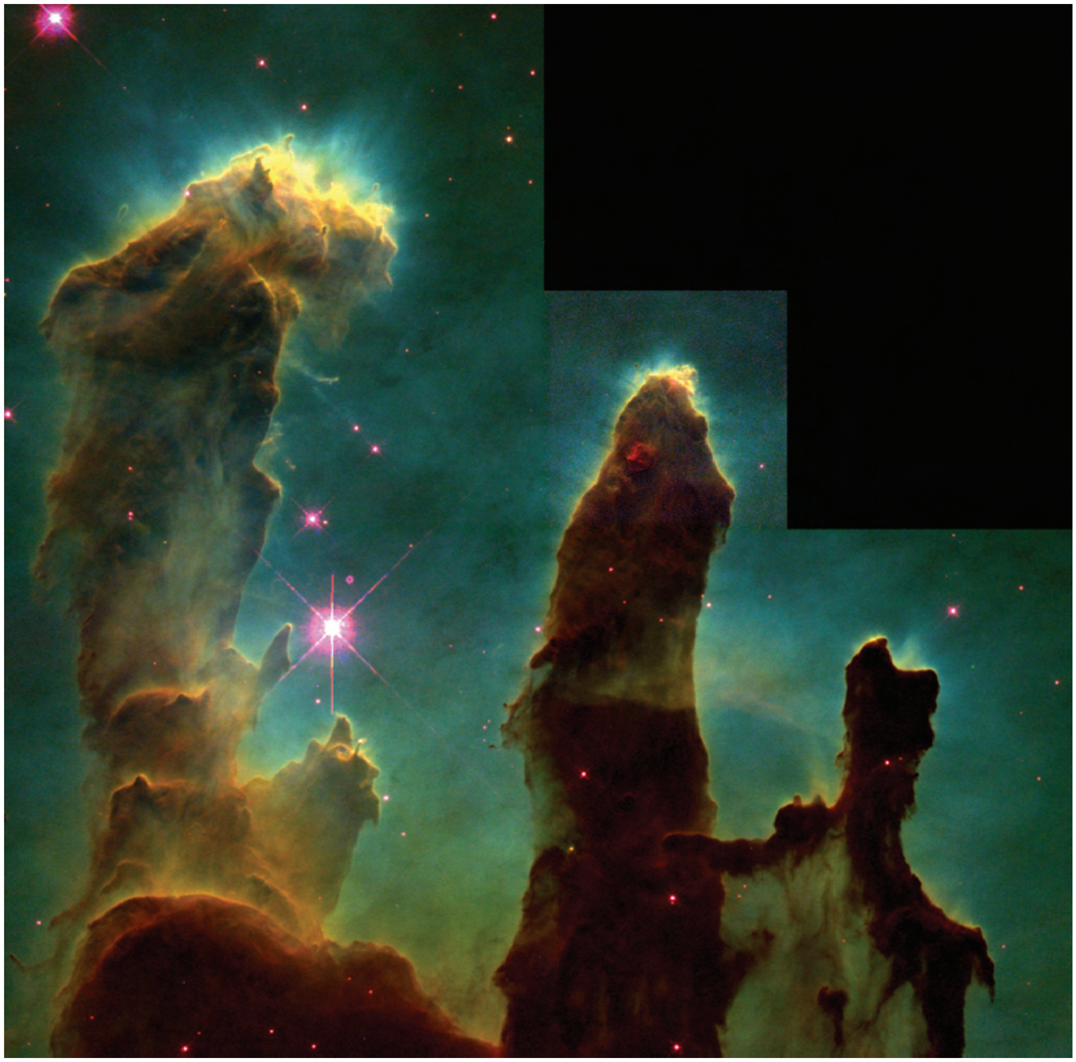

FIGURE 1.17 The Eagle Nebula, the "Pillars of Creation," where stars have been formed in the last few million years. Dust obscures the birth sites, but JWST can see through the dust. SOURCE: Courtesy of NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University).

Sun but far from here—in the outer reaches beyond Neptune and in the asteroid belt between Mars and Jupiter. Understanding how these pieces relate to our own existence is a great challenge for solar system exploration, either by robot, in person, or by remote observation with telescopes. JWST will use all its instruments to find and study the small bits, along with the well-known planets.

Second, we know of dozens of transiting planets—objects that pass between ourselves and their host stars, blocking starlight. The Hubble and Spitzer space telescopes have already been used to determine the orbit, temperature, and even the atmospheric composition of a few exoplanets. NASA plans to launch the Kepler observatory in 2009[1] to find many more transiting exoplanets, including a predicted handful of Earth-like planets around Sun-like stars. Needless to say, the JWST will be devoted to following up these observations as well as possible.

Third, we know of locations where dust clouds orbit distant stars in a way that suggests the presence of planets. The shapes of the dust clouds sometimes tell us that a planet must exist and sometimes where it ought to be and how big. The star Fomalhaut has a dust ring around it, offset a bit, and a good explanation is that there is a large planet at a particular spot, fairly far

[1]The Kepler Spacecraft was launched on March 6, 2009.

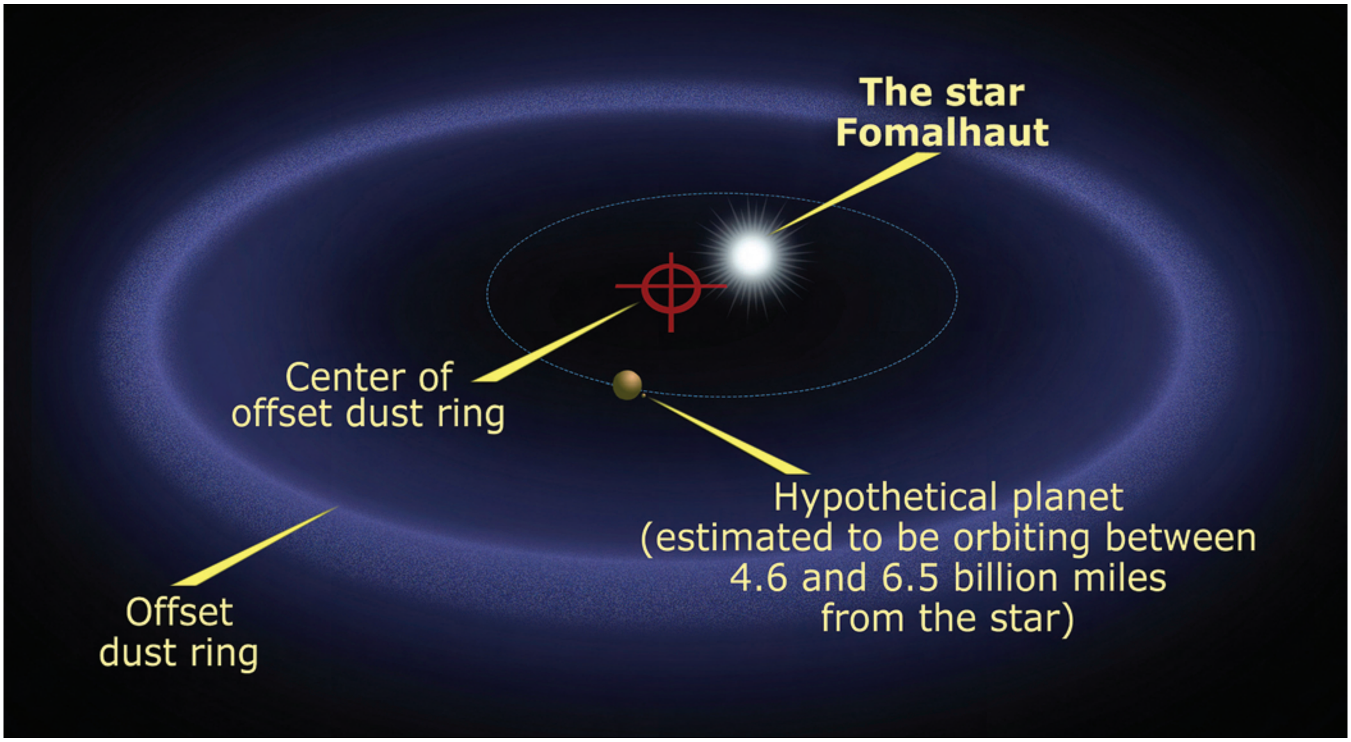

FIGURE 1.18 Drawing of dust ring around Fomalhaut, pulled off center by hypothetical planet that could be observed by JWST. SOURCE: Courtesy of NASA, ESA, and A. Feild (STScI).

from the star. (See Figure 1.18.) Moreover, this system appears to be young, so the planet might be hot enough to measure directly with the JWST. Three of the four JWST instruments will have coronagraphs, devices that block the bright glare of a star to enable us to hunt for faint planets nearby.

After JWST, The Search for Life Elsewhere

The same committee report that recommended the JWST also recommended that telescopes should search for planets around other stars. NASA and ESA have studied three main types of such telescopes. First, an extremely well-made telescope with extremely good coronagraphs could see planets directly. For a long time, I thought that this would be the easiest method, since the telescope is relatively small and could fit into a single rocket payload, like the JWST. However, perfection is difficult to achieve, and this technology is not quite ready yet. The second method would use a group of infrared telescopes flying in formation in space, relaying light beams to a combining station.. This is called an interferometer, which can be used to direct the starlight away from the image of the planet. But this is also difficult and requires formation flying technology with extremely good accuracy, which we do not have yet either. The third technology is a remote blocking device flying in formation tens of thousands of kilometers away from a general-purpose telescope in space. Such a device was proposed for the JWST but was not ready yet. Recent progress on blocking devices (called occulters) has been rapid, and both Northrop Grumman and Lockheed are working with scientific teams to develop this method. The technology is still difficult, but it does not require perfect optics, and the shifts the demands to spacecraft engineering.

What would be signs of life on a planet around another stars? Earth seen at a great distance would be recognizably alive, because of photosynthesis, which has filled our atmosphere with oxygen (Figure 1.19). Oxygen is so reactive that it would quickly disappear if it were not continually regenerated by algae and land plants. So, if we could find signs of oxygen in the atmosphere of an exoplanet, along with other signs like carbon dioxide and water, we could argue we had found another Earth. And on Earth, chlorophyll has a

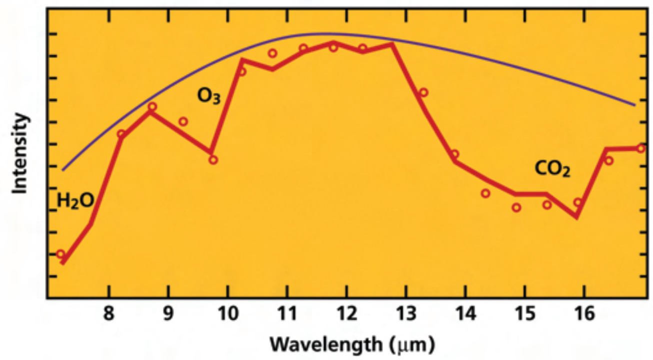

FIGURE 1.19 Spectrum of Earth from a distance, showing features of water, ozone, and carbon dioxide. The combination would not occur on Earth without photosynthetic life. SOURCE: The TPF Science Working Group, *The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets*, JPL Publication 99-003, C.A. Beichman, N.J. Woolf, and C.A. Lindensmith, eds., May 1999. Courtesy of NASA Jet Propulsion Laboratory.

distinctive color. We might also be able to tell if there are continents and oceans, even without making maps of other planets, because the color and brightness of Earth changes as it spins.

And what of life that is based on some different chemical system? Biologists are taking this question seriously and there is even a professional journal about it: *Origins of Life and Evolution of Biospheres*, a journal of the International Astrobiology Society. So if there are other chemical systems that support life, at least we might think of them and recognize their signs.

Some argue that the function of carbon-based life is to create artificial life, maybe based on silicon electronics that can travel through the universe. If it exists already, either here or elsewhere, we have not noticed yet. But maybe it's not impossible—have a look at Ray Kurzweil's book *The Singularity is Near*.

Big Questions, Open Now

To conclude, let me say that there are many questions that are way too difficult to answer today, but that may become answerable in the near or distant future. These include: What happened before the Big Bang? What's at the center of a black hole? How did we get here? Are we alone? What is our cosmic destiny? What are space and time?

Perhaps you who are in the audience or reading this later will be the ones to find these answers.

ACKNOWLEDGMENTS

Beginning with elementary school, my work has always been supported by the U.S. taxpayers. Thomas Jefferson and Ben Franklin would be proud that their country has produced scientific and technological knowledge that they could never have imagined. More specifically, my parents Martha and Bob, my wife Jane, my scientific mentors Paul Richards, Mike Hauser, Pat Thaddeus, and Nancy Boggess, my project managers, especially Roger Mattson, Dennis McCarthy, Bernie Seery, and Phil Sabelhaus, and at NASA Headquarters, especially Ed Weiler, have all made enormous changes to my life. Without them, nothing would be the same. And without my co-author John Boslough, you would not have our book *The Very First Light* to read about this series of fortunate events.

RALPH J. CICERONE, president of the National Academy of Sciences, is an atmospheric scientist whose research in atmospheric chemistry and climate change has involved him in shaping science and environmental policy at the highest levels nationally and internationally. His research was recognized on the citation for the 1995 Nobel Prize in chemistry awarded to University of California, Irvine, colleague F. Sherwood Rowland. The Franklin Institute recognized his fundamental contributions to the understanding of greenhouse gases and ozone depletion by selecting Dr. Cicerone as the 1999 laureate for the Bower Award and Prize for Achievement in Science. One of the most prestigious American awards in science, the Bower also recognized his public policy leadership in protecting the global environment. The American Geophysical Union awarded him its 2002 Roger Revelle Medal for outstanding research contributions to the understanding of Earth's atmospheric processes, biogeochemical cycles, or other key elements of the climate system. Dr. Cicerone is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society. He has served as president of the American Geophysical Union, the world's largest society of Earth scientists, and he received its James B. Macelwane Award in 1979 for outstanding contributions to geophysics. He has published about 100 refereed papers and 200 conference papers and has presented invited testimony to the U.S. Senate and House of Representatives on a number of occasions.

Global Climate Change and Human Causes

Ralph J. Cicerone
National Academy of Sciences

INTRODUCTION

Global climate change is a much discussed topic at the present time. This paper starts with a brief discussion about Earth's climate and its energy budget from a planetary perspective. It then addresses the greenhouse effect caused by certain greenhouse gases. Current data on recent climate change are summarized, and the subject of carbon dioxide from fossil-fuel burning is discussed. Human causes, what we need to do about the situation, and first steps towards solutions are then considered. Throughout, the contributions of the space program to the study of global climate change and the mitigation of its effects will be addressed.

Earth's Climate and Energy Budget

Figure 2.1 depicts the Sun shining down on Earth. The number 342 indicates the amount of power the planet receives—342 watts per square meter averaged over the planetary surface day and night and annually. About one third of this power is directly reflected back to space from white surfaces such as the tops of clouds and the snow surfaces at the poles. (Black surfaces and dark surfaces absorb, light surfaces reflect.) On balance then, 237 of the 342 watts per square meter are being absorbed in the form of visible sunlight (plus a tiny amount of ultraviolet sunlight and a little bit of infrared).

On a short time scale, say one year, the planet is not heating up, nor is it getting very cold. We are roughly in an energy balance, a fact that has been borne out by measurements from space platforms.

The problem is we are "roughly" in balance, not exactly in balance. We are warming up due to certain gases in the atmosphere that interfere with the balancing that would be caused by planetary radiation. The lower layers of Earth's atmosphere are heating up, while the amount that continues to escape is almost in balance with what is coming in.

The Greenhouse Effect

Is the greenhouse effect real or merely an unproven idea? There is a lot of evidence to show that it is real and is operating.

For example, we are able to calculate the temperature of the surface of Mars. We could calculate it before it was actually measured by spacecraft. It is about 30°C below zero, varying a little during the day and night cycle. We could calculate the number correctly because there is no greenhouse effect on Mars. The atmosphere is too thin. The way we do such a calculation is to multiply the incoming sunlight (which at Earth-orbit distance is 342 watts per square meter as mentioned earlier) by 1 minus the reflectivity of the planet. If the planet were reflecting 100 percent of the incoming light, that would be zero; however, Mars only reflects about 30 percent. If you assume that nothing is changing with time, this is the equation you have to solve,

NOTE: Transcribed from a lecture presented at the University of New Hampshire, October 19, 2007.

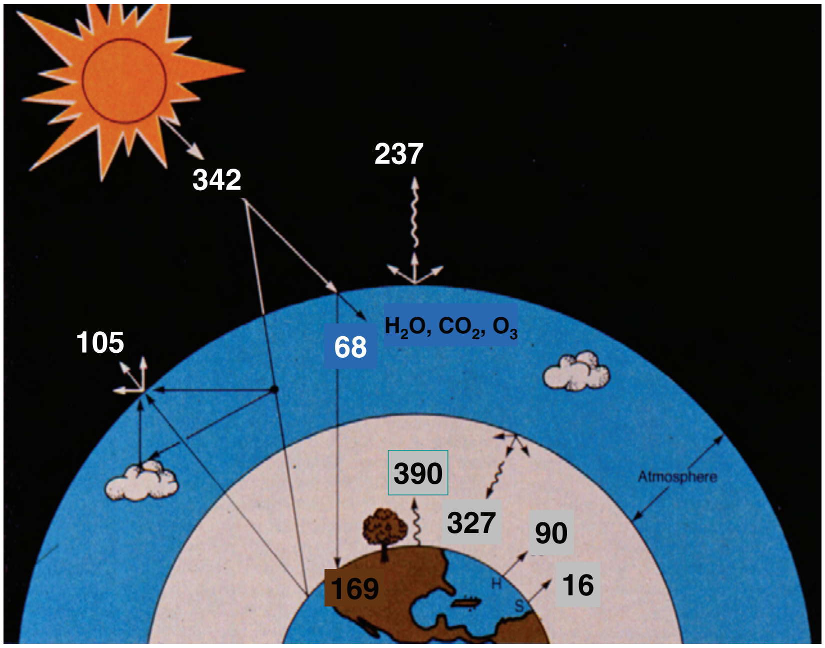

FIGURE 2.1 Earth's energy balance. SOURCE: Reprinted with permission from V. Ramanathan, B.R. Barkstrom, and E.F. Harrison, Climate and the Earth's radiation budget, *Physics Today* 42(5):22–33, 1989, with modifications. Copyright 1989, American Institute of Physics.

which should provide the effective temperature of the planet. We get the right number for Mars.

However, if we try the same calculation for Earth, it does not work. We would calculate that Earth's surface is a subfreezing 18°C below zero on average and should be frozen into a solid block of ice. As far as we know, that has never been true throughout geologic history, let alone being correct now. The reason it is wrong is that we have neglected the ability of the gases—notably water vapor, carbon dioxide, ozone, and a few others—to assist in heating the surface of the planet. There is a level in our atmosphere at which the temperature is exactly –18°C, but not at the surface. That is because of the greenhouse effect.

If we do the same calculation for Venus, we get a really incorrect answer. We underestimate the temperature of Venus by several hundred degrees. That is because the Venus atmosphere, as we have learned from the space program, is very thick, very heavy, has a much higher pressure than Earth's, and is composed largely of carbon dioxide. Some people attribute the Venus situation as being due to a runaway greenhouse effect. Venus is not that different in distance from the Sun than Earth, but its temperature is grossly different, around 540°C.

This is powerful evidence that the greenhouse effect is natural, real, and was operating before humans were even here.

Beginning in the fall of 1957, David Keeling started measuring carbon dioxide in the air on the flanks of the Mauna Loa volcano on the big island of Hawaii roughly once an hour, and he averaged the data every month. Keeling died about 3 years ago, but this recording (Figure 2.2) is being carried on by hundreds of other people around the world. Each one of the black dots in Figure 2.2 is the average of a month's data.

The average carbon dioxide amount started out around 312 parts per million (ppm), and by 2005 it was about 380 ppm. The most important thing that the graph shows is that carbon dioxide in the atmosphere continues to increase rather smoothly. Superimposed on the long-term trend are the annual cycles, almost like a sine wave.

In either hemisphere, in the spring or summer the carbon dioxide amounts are lower. In the fall and winter, they go up. The next spring and summer they come down a little bit, and again in the fall and winter, they go up. In the spring and summer photosynthesis is drawing carbon dioxide out of the air, and in the fall and winter the decay of annual plants, the decay of organic matter in soils, and root respiration exude carbon dioxide back into the atmosphere. In fact, the peak-to-peak amplitude of the depth of this oscillation tells us something about the total amount of photosynthetic activity on the planet. This is where our oxygen comes from. There is a lot of geochemical and bio-geochemical information contained in this graph. Many other scientists have been making such measurements for many years, using many different techniques. The numbers are right. They have been tested many times before.

Carbon dioxide is a strong greenhouse gas. In fact, we think it and water vapor are responsible for keeping Earth's temperature above the subfreezing temperature mentioned above.

For the last 20 years, scientists have been extracting ice cores in Antarctica and Greenland, and by counting layers and by other identifying information, they have created an historical record extending back 600,000 years.

The particular record in Figure 2.3 goes back more than 400,000 years. Today is time zero, and time goes back to the left. The lower curve is an approximation of what the temperature was like in the region where the snow and ice formed, obtained from isotopes of water, hydrogen, and oxygen.

Glaciated periods can be seen in the past. The most recent glacial period, when there was a great deal of ice over the northern hemisphere, was about 20,000 years ago. The previous one was about 140,000 or 150,000 years ago. The temperature was low. In between those glaciated periods, there are periods of interglacial warming. We are in such a period now.

On the upper curve is a carbon dioxide record. The ice cores that have been dated can be interrogated as to what the gases are inside, either by crushing the ice and extracting the gas under vacuum, or by melting it, which does not work quite as well if the gas is water-soluble. When the temperature was low in the previous ice age, carbon dioxide amounts were very low: on this scale, about 180 ppm.

From Dave Keeling's curve (Figure 2.2) we are now around 380 ppm. In the long ice-core record going back over four planetary ice ages, we see that carbon dioxide was around 180 ppm during each of the cold times, and during the warm times over the last four glacial cycles it was 280 ppm, 260 ppm, and 280 ppm—never 380 ppm.

Whatever is happening, Earth is now being pushed into a regime where it has not been before at any time

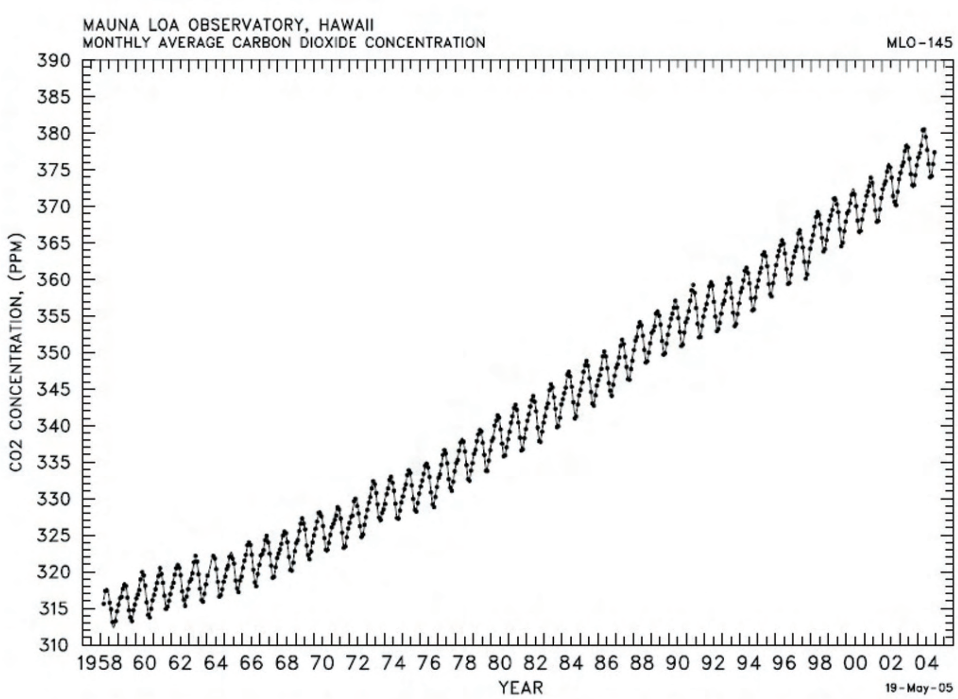

FIGURE 2.2 Atmospheric CO_2 concentrations (ppmv), 1958–2004, derived from in situ air samples collected at Mauna Loa Observatory, Hawaii. SOURCE: Courtesy of C.D. Keeling, T.P. Whorf, and the Carbon Dioxide Research Group at the Scripps Institution of Oceanography, University of California, La Jolla.

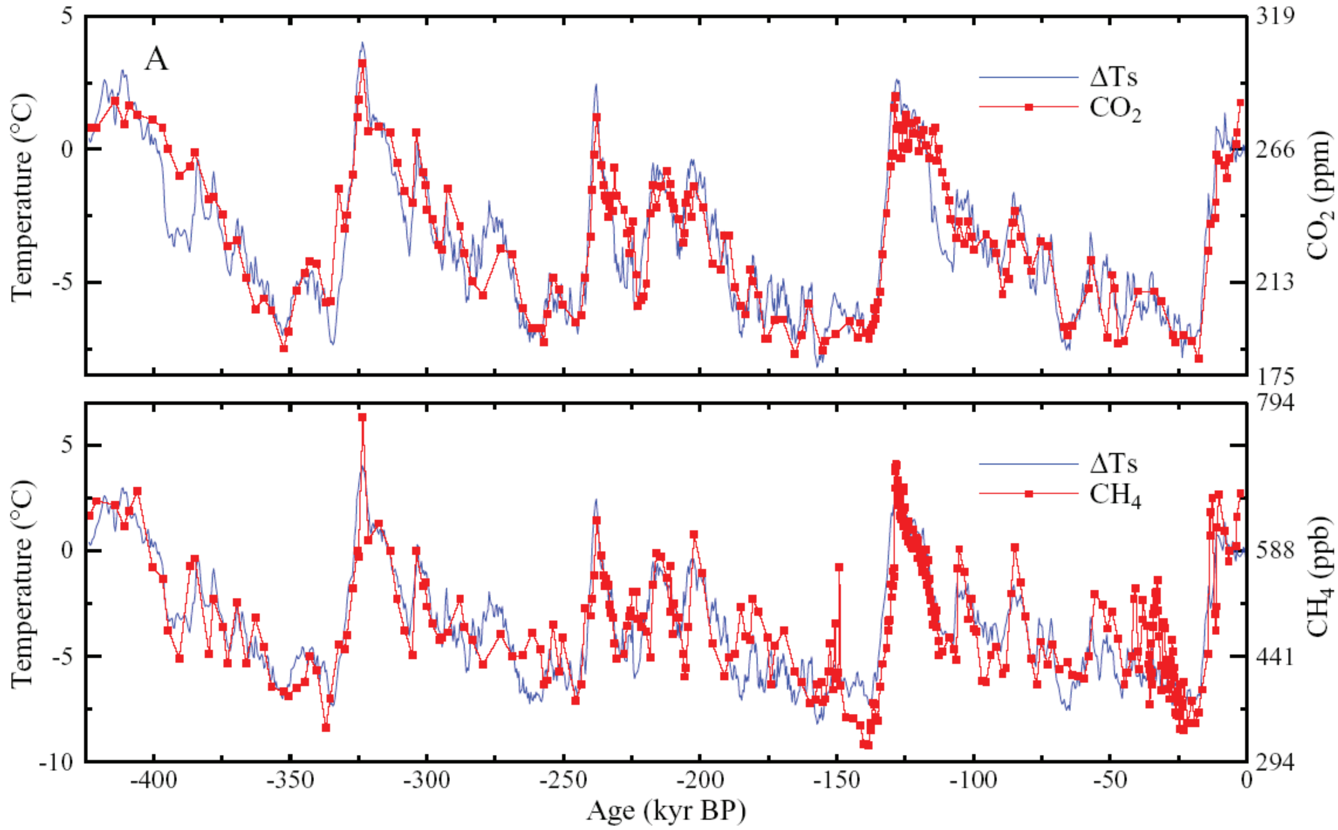

FIGURE 2.3 Antarctic ice core records. Temperature CO_2 (upper) and CH_4 (lower) time series (thousands of years before present) from the Vostok Antarctic ice core. SOURCE: J. Hansen and M. Sato, Greenhouse gas growth rates. *Proceedings of the National Academy of Sciences* 101(46):16109–16114, 2004. Copyright 2004 National Academy of Sciences, U.S.A. Original data from J.R. Petit, J. Jouzel, D. Raynald, N.I. Barkov, V.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davisk, G. Delaygue, M. Delmotte, et al., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* 399: 429 436, 1999.

where we have direct measurements. There is certainly evidence that hundreds of millions of years ago Earth was warmer, and we infer that there was a lot of carbon dioxide. There is really no direct evidence of this, although some people think there is indirect evidence.

In the case of methane, which is another very important greenhouse gas, partly natural, it is the same story. When the temperature was low in the ice ages, methane was at one-third parts per million. When it was warm, methane was at two-thirds parts per million. One third, two thirds, one third, two thirds, and so forth. Methane amounts are now five times higher than they were in low times, or about two and a half times higher than they were in the highest times geologically. There is real evidence that these greenhouse gases have now entered into a realm of concentration where they have not been for the last half million years.

Figure 2.4 shows the same modern record (Keeling curve) shown in Figure 2.2 superimposed on the geologic history. On the time scale shown, that is the way carbon dioxide is behaving.

So where is the carbon dioxide coming from? Can we really be sure that the increase of carbon dioxide in the global atmosphere is due to fossil fuel burning? We can, but we have to look at a lot of evidence, for example, the actual amounts.

If you look in Figure 2.5 at the amount of carbon dioxide that is being discharged by fossil-fuel burning, plus a little bit generated during cement production, you can see that it has been growing very rapidly, such that 100 years ago we were only discharging about 120th as much carbon dioxide, because we were not really using as much oil, petroleum, and so forth. Figure 2.5 shows the current amount of carbon dioxide lost into the air from fossil-fuel burning to be about 7 billion (7,000 million) metric tons (as carbon, including

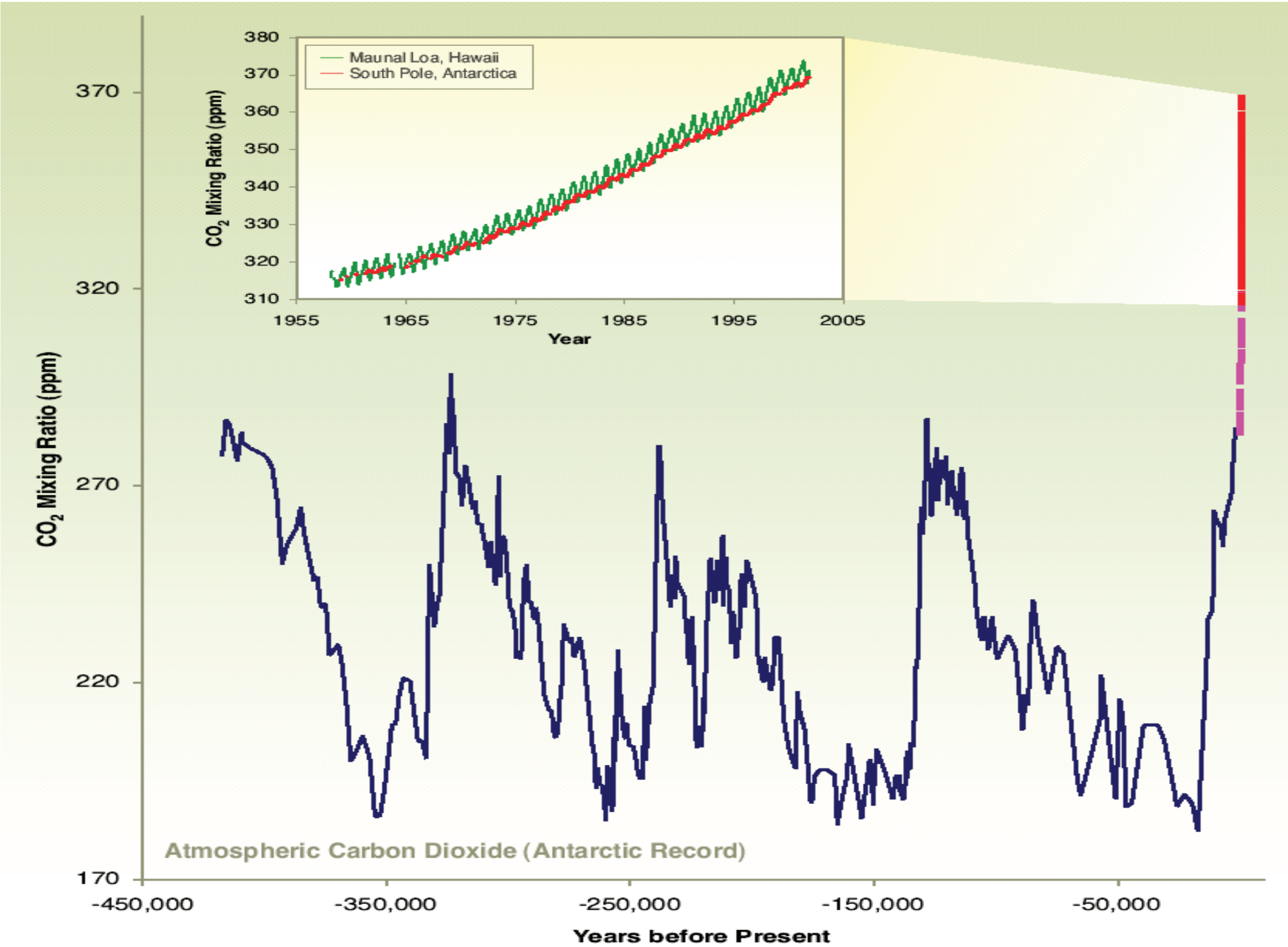

FIGURE 2.4 Atmospheric CO_2 concentrations (Keeling curve) superimposed on the geologic history. Atmospheric Carbon Dioxide (Antarctic Record) Years before Present. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: *Nature* (J.R. Petit, J. Jouzel, D. Raynaud, N. I. Barkov, J. M. Barnola, I. Basile, M. Bender, J. Chappelaz, M. Davis, G. Delaygue, M Delmootte, V. M. Kotlyakov, M. Legrand, V. Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman, and M. Stievenard, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* 399, 429–436, 1999) Copyright 1999). Inset from C.D. Keeling and T.P. Whorf, Atmospheric carbon dioxide record from Mauna Loa (1957–2004), 2005, available at http://cdiac.ornl.gov/trends/co2/graphics/ mlo145e_thrudc04.pdf, and earlier Keeling and Whorf CDIAC data sets.

that due to the flaring of natural gas; the red curve). Some of it is due to the direct burning of natural gas, some of it is due to the burning of petroleum, and some of it is due to the burning of coal and wood.

These numbers add up. In fact the amount of carbon dioxide that we measure increasing in the air every year is about 60 percent of this amount, rather than 100 percent. Several other things are going on. Carbon dioxide is being taken up by oceans and by plant growth. Also, there is some carbon dioxide entering the air due to the decay of the biological material in an imbalanced way, the tropical deforestation, for example. It is not just the burning of the plant material and wood that releases carbon dioxide—it is the loss of soil or organic matter when those tropical soils are exposed and are no longer controlled by the roots.

Figure 2.6 shows carbon dioxide emissions from energy consumption in the United States, broken down by source. The United States alone releases 6 to 7 billion tons of carbon dioxide a year. About 2.6 billion tons comes from the burning of petroleum, about 1.2 billion tons from the burning of natural gas, and a little over 2 billion tons from the burning of coal. On this scale, if you look at the contributions to carbon dioxide emission from other sources like hydroelectric plants, biomass, geothermal plants, and so on, they are virtu-

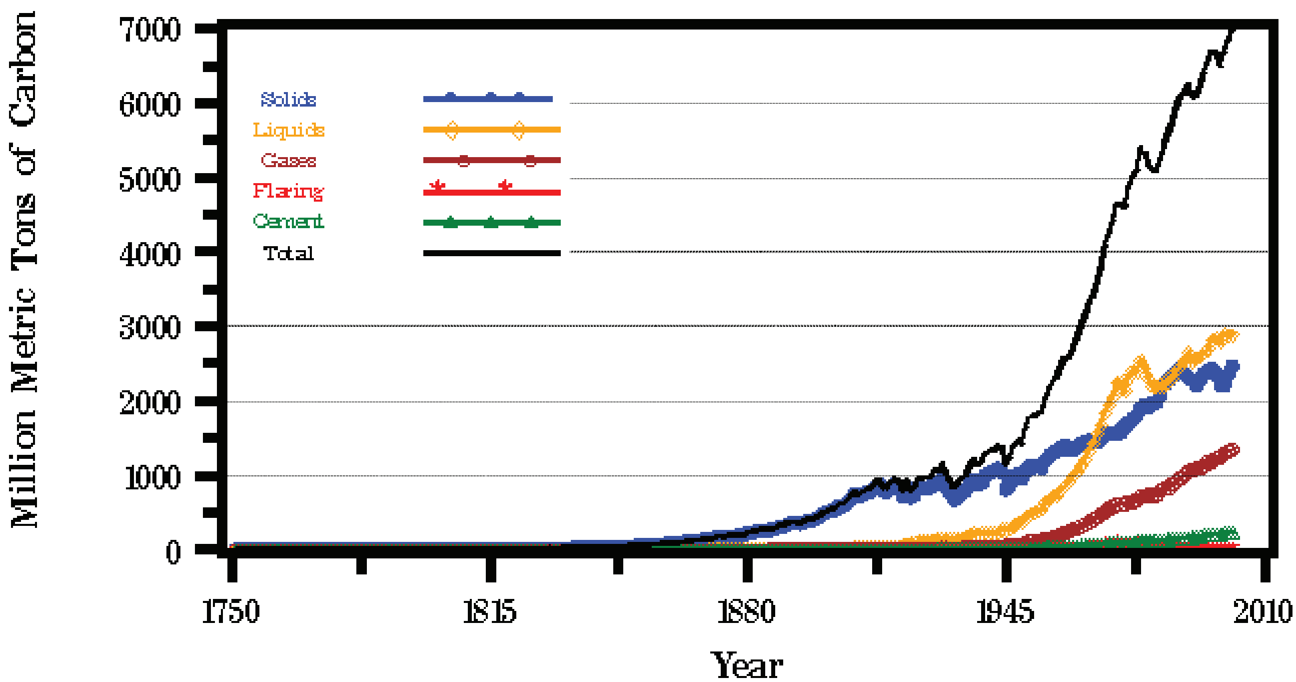

FIGURE 2.5 Global CO_2 emissions from fossil fuel burning, cement production, and gas flaring for 1751–2002. SOURCE: Data from the Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory.

ally zero. It is primarily the fossil fuels that release the carbon dioxide in the very active burning from which we derive the energy, due to exothermic chemical reactions. It is inherent in the process of extracting energy. Figure 2.7 shows U.S. carbon dioxide emissions from energy consumption by usage instead of source.

When you go through all the numbers, compare atmospheric measurements, and use other lines of evidence like the isotopic content of the carbon and fossil fuels compared to the isotopic content of the carbon dioxide, the spatial patterns, the geographical patterns, the seasonal behavior, and so forth, you have very compelling evidence that the carbon dioxide increase that we are seeing is caused by humans.

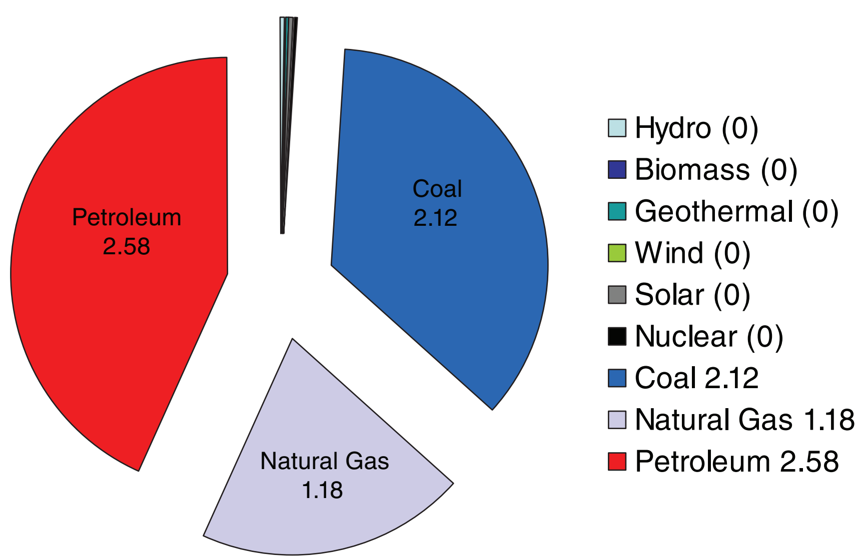

FIGURE 2.6 U.S. carbon dioxide emissions from energy consumption by source (in billion metric tons CO_2). SOURCE: Data courtesy of the University of California, Lawrence Livermore National Laboratory and the Department of Energy.

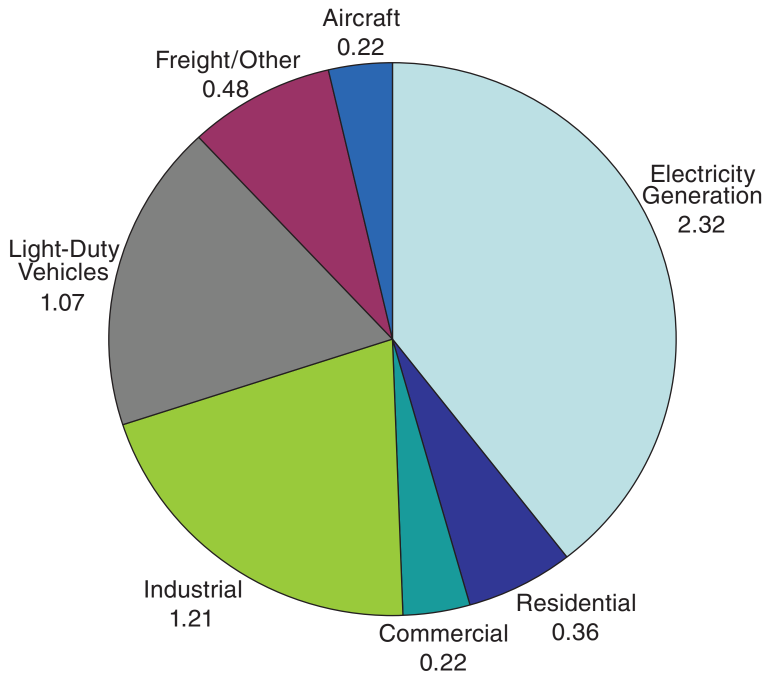

FIGURE 2.7 U.S. carbon dioxide emissions from energy consumption by usage (in billion metric tons CO_2) SOURCE: Data courtesy of the University of California, Lawrence Livermore National Laboratory and the Department of Energy.

Similarly with methane. In Figure 2.8 the red part of the pie chart represents annual methane release rates that are due to human activities. Some of them are under human control, some of them are inadvertent. The yellow part of the pie chart shows natural sources of methane.

There are some new entries here, but frankly the changes have not made much of a difference. The best known number here is rather euphemistically called "enteric fermentation." That is basically belching and flatulence of cows. You might think that this is a wild guess, but in fact it is the most well-known number on the chart because a typical cow loses about 10 percent of its daily caloric intake every day due to methane loss.

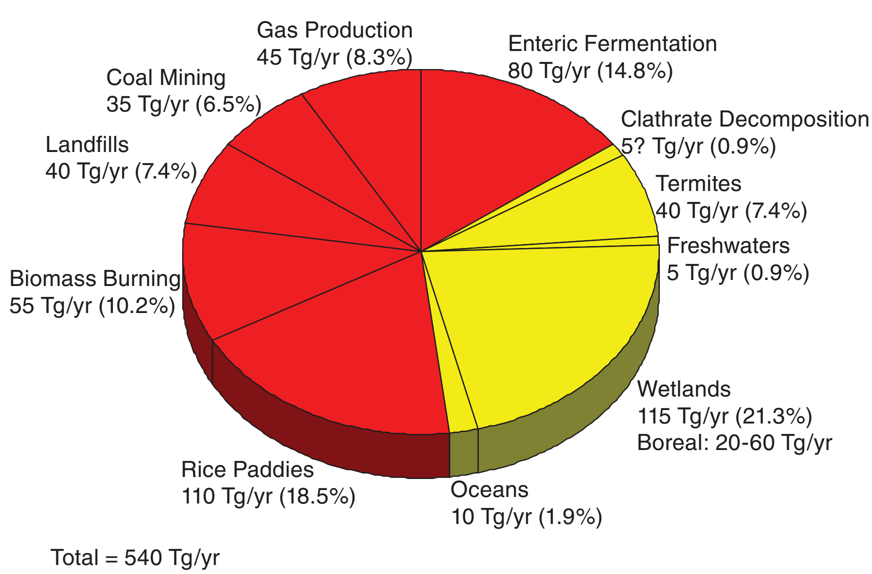

FIGURE 2.8 Global methane release rates. SOURCE: R. Cicerone and R.S. Oremland, Biogeochemical aspects of atmospheric methane, *Global Biogeochemical Cycles* 2:299–328, 1988. Copyright 1988 American Geophysical Union.

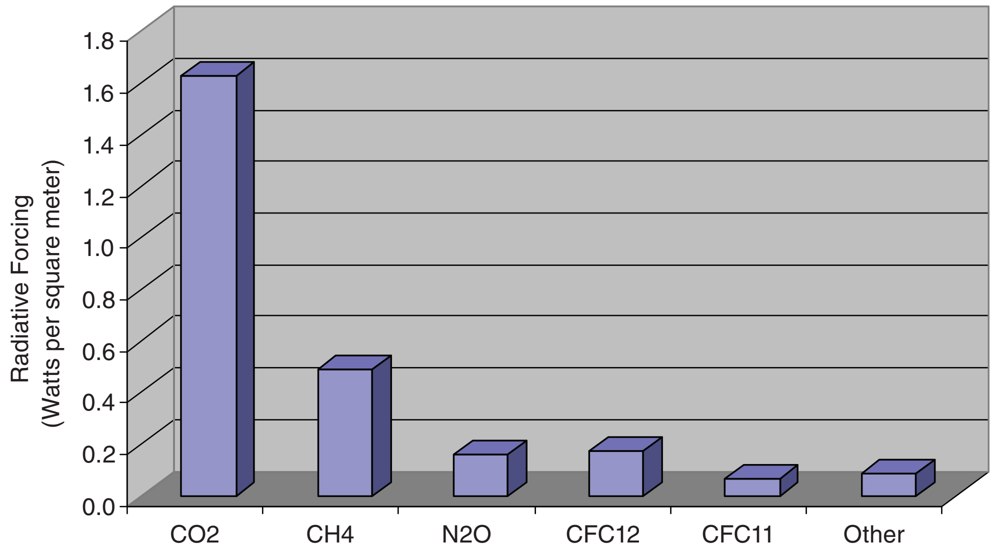

FIGURE 2.9 Radiative forcing from well-mixed greenhouse gases, 2004. SOURCE: Data from NOAA ESRL Global Monitoring Division.

People have known this for 100 to 125 years, and they have tried to stop it by changing the cow's diet. It turns out that the poorer the diet is, the higher the loss as methane. Sheep are similar.

So what does it all mean? As noted, we receive a net of 237 watts per square meter of sunlight. What is the effect of greenhouse gases in trapping energy near Earth's surface? It turns out to be one percent.

As shown in Figure 2.9, the added carbon dioxide measured in the last 60 to 80 years is contributing about 1.6 watts per square meter of extra energy trapped in Earth's planetary boundary layer down at aircraft altitudes and below. Methane contributes about 0.5 and nitrous oxide and a whole slew of other greenhouse gases add up to a little bit more than one percent of the solar constant. The output of a star like our Sun does change over its lifetime, but not as much as one percent per century. There is no theory or observations that suggest that the output of the Sun could change one percent in a hundred years. There are people who wish it were so, and 10 or 15 years ago we thought that maybe the climate changes we were beginning to see could be blamed on the Sun, but there is evidence that refutes this assumption.

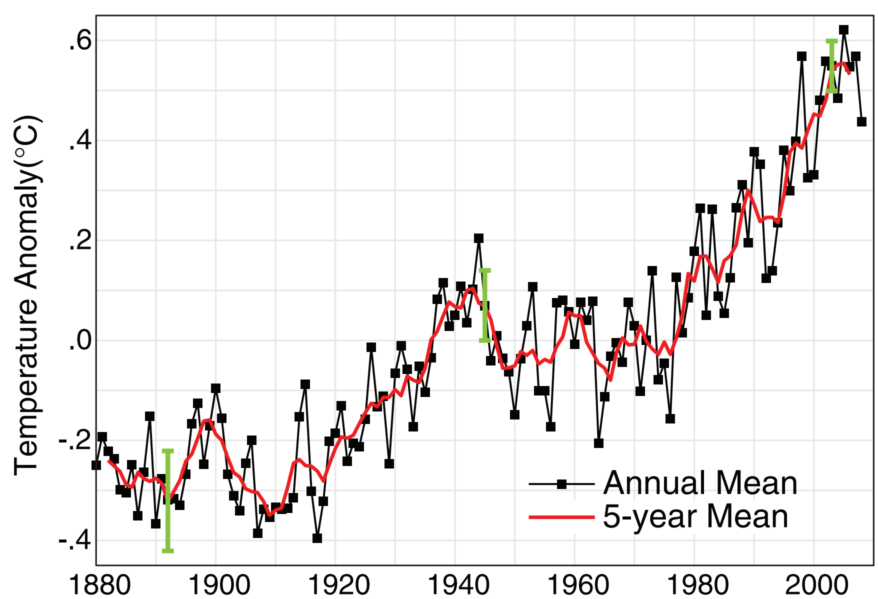

FIGURE 2.10 Global temperature: Land-ocean index from NASA Goddard Institute for Space Studies. SOURCE: Updated from J. Hansen, Mki. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, Global temperature change, *Proceedings of the National Academy of Sciences* 103:14288–14293, doi:10.1073/pnas.0606291103, 2006. Copyright 2006 National Academy of Sciences, U.S.A.

The Warming of the Planet

So what is happening now? Since 1980, NASA has been gathering temperature measurements (several hundred million) from around the world going back to 1880.

In Figure 2.10 from the NASA Goddard Institute for Space Studies, zero is not zero degrees, it is a reference point—the average temperature all over the world from 1951 to 1980. Compared to that average, the period of 70 years before 1951 was mostly colder, except around 1940, and everything since has been warmer.

In Figure 2.11 temperatures are measured over land and sea, averaged according to the size of the latitude belt, and presented as a global average. The urban-heat-island effect is removed. Many of the places where we have been measuring temperatures have been surrounded by cities as time has developed. Blacktop and human energy usage is making our cities hotter than the surrounding regions. What is interesting is that now the temperature increase is seen almost everywhere, although it is not uniform. In Figure 2.11 the lower boundary is the South Pole and the upper boundary the North Pole.

Note that you can see the outlines of continents in the heat pattern. The warming on this false-color scale is largest in the high-latitude continental regions like upper Siberia and the Arctic region. The warming there is really pronounced compared to everywhere else, except down in the high southern latitudes. Over some of the open ocean regions, there is a very small, or zero, temperature increase because of the heat capacity of water. What suggests that this phenomena is not natural is that warming is taking place everywhere at the same time.

Historically, when we have temperature records such as the Medieval warm period, or a mini ice age, we have records from different places on Earth that are contradictory, or nonexistent, because when it is cold in one place, it is hot in another. In fact that is even true today in the United States on a single day. What is happening now, though, is that the warming is taking place everywhere at once.

The Rise in Sea Level

Another noted phenomenon is the rise in sea level. For about 100 years, people have been measuring sea level rise carefully, but in a very primitive way—basically, pounding stakes into the shoreline and recording mean sea level at many locations around the world. Figure 2.12 has been constructed over the last 100 years and shows sea level rise averaged over the ocean basins of about 1.5 millimeters a year, which is about 15 centimeters, or 6 inches, a century.

Not all the ocean basins have behaved the same way, because there is geological heaving and rising going on at the same time that has nothing to do with water-related sea level rise. The right-hand part of Figure 2.12 shows a red curve which is a new set of data

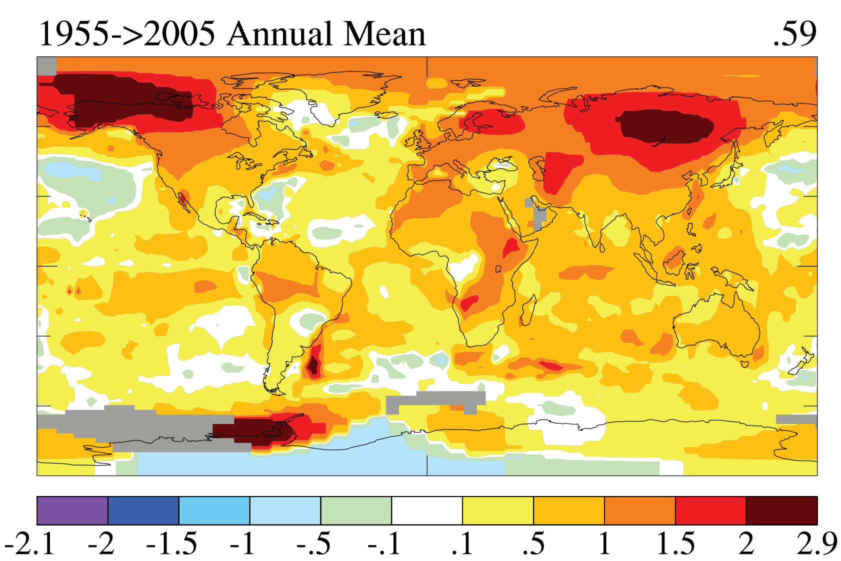

FIGURE 2.11 Last 50 years surface temperature change based on linear trends (degree C) SOURCE: J. Hansen, R. Ruedy, M. Sato, and K. Lo, NASA Goddard Institute for Space Studies, and Columbia University Earth Institute, New York, N.Y.

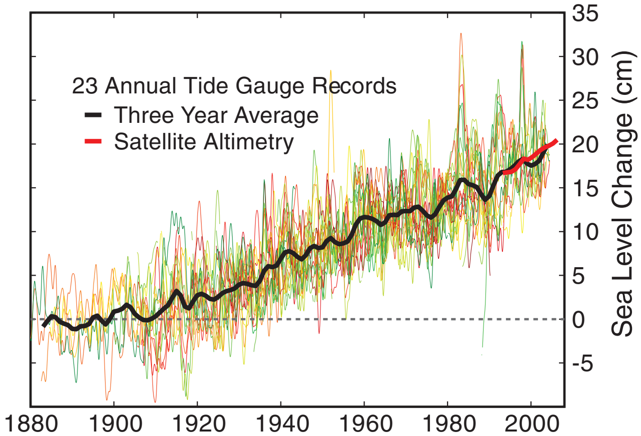

FIGURE 2.12 Recent sea level rise (1882–2005) based on Permanent Service for Mean Sea Level (PSMSL) tide gauge data from 23 sites selected by Douglas (1997). SOURCE: Created by Robert A. Rohde, University of California, Berkeley. Courtesy of Global Warming Art, available at http://www.globalwarmingart.com/wiki/File:Recent_Sea_Level_Rise_png.

collected by satellite-born altimeters on two spacecraft, TOPEX and Jason, looking down at Earth. Figure 2.13 is the detailed record of what the satellite data show.

Satellite measurements are probably more accurate and are global, with proper averaging over all the ocean basins. They show a rate of sea level rise double that which had been measured earlier—3 millimeters per year rather than 1.5. No one is sure yet whether this represents an acceleration of the rise of sea level over the last 15 years, or whether it is just a more accurate determination of a trend that was underway. Sea level is rising globally—that is for sure.

Ice Cover

Figure 2.14 is a visual representation of the change in Northern Hemisphere sea ice between 1979 and 2003. It is evident that the ice cover in the Arctic region has been reduced. Such measurements are now being made from space.

One example of such a space-based data collection activity is the Gravity Recovery and Climate Experiment (GRACE) mission (Figure 2.15) involving two satellites that very accurately measure the distance between each other using a K-band interferometry, as shown in Figure 2.15. They also make use of Global Positioning System signals for accurate position location. If there is any minor perturbation to Earth's gravitational field due to a "mass anomaly," such as a large mountain or a big piece of ice, the leading satellite feels the gravitational anomaly sooner and starts to separate in distance a little bit from the trailing one. By carefully measuring the variations in distance between the two satellites and when they occur, over a period of months it is possible to infer changes in the mass of the ice. In the case of Greenland, after taking measurements for several years, it was possible to put together Figure 2.16 showing the ice mass loss.

These results in Figure 2.16 compare very well

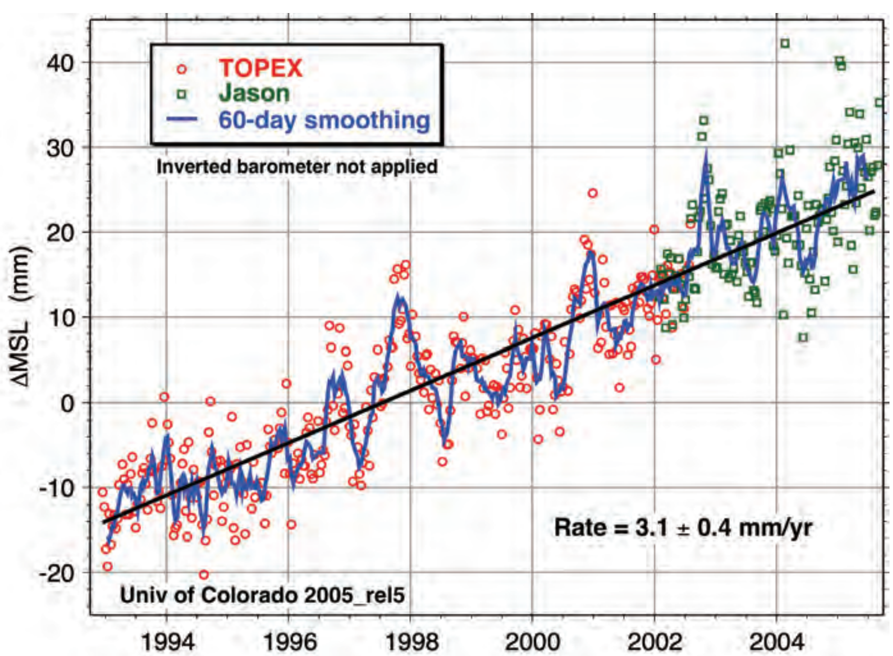

FIGURE 2.13 1992–2006 sea level rise observed by satellite altimetry SOURCE: Eric Leuliette, University of Colorado, Boulder available at http://sealevel.colorado.edu; updated from Leuliette, E. W, R.S. Nerem, and G. T. Mitchum, 2004, Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change, *Marine Geodesy* 27(1-2):79–94.

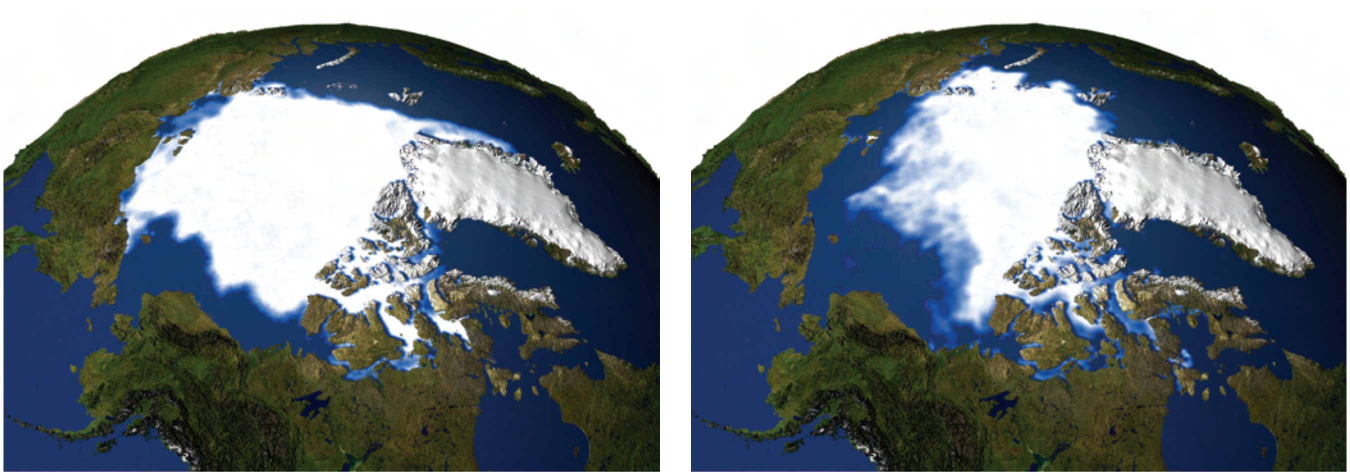

FIGURE 2.14 Northern Hemisphere sea ice extent (1979 versus 2003) *Left:* Sea ice minimum extent for 1979. *Right:* Sea ice minimum extent for 2003. SOURCE: NASA Goddard Space Flight Center Scientific Visualization Studio.

with those generated by other satellite missions using different measurement techniques. One such technique involves a radar altimeter looking down at the ice, which enables the mapping of the height of the ice. By mapping the height of the ice and the way it is shrinking in height, you can calculate how much ice mass has been lost. When compared to what is measured by the GRACE mission, you get roughly the same number. A big ice-mass loss is taking place. Unfortunately the satellite record is only 3 or 4 years long at this point. Similar results have been noted over Antarctica, but not in all parts.

Throughout the Cold War, the United States and Russia (the former Soviet Union) were operat-

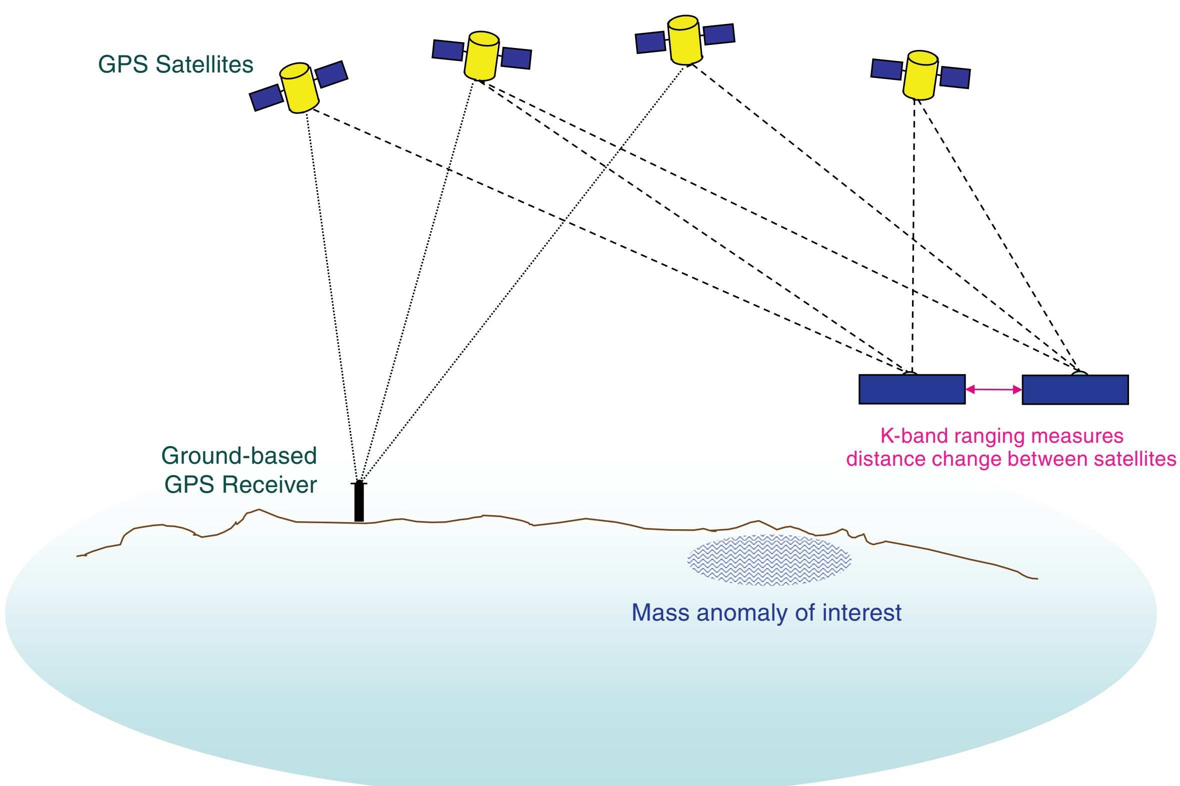

FIGURE 2.15 GRACE mission concept. SOURCE: Courtesy of NASA.

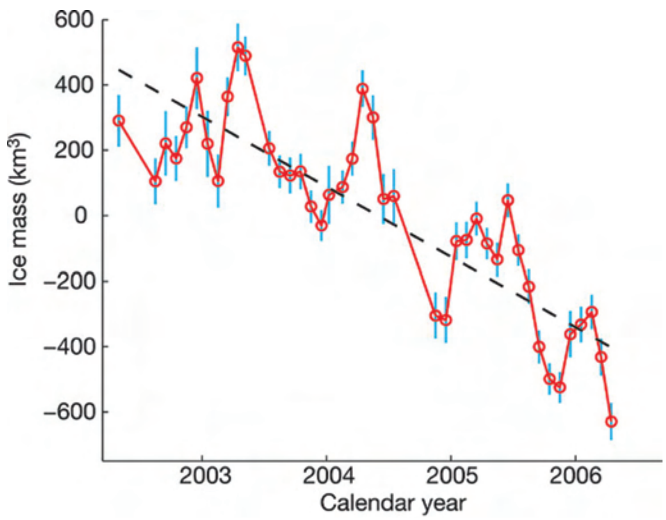

FIGURE 2.16 Greenland Grace monthly mass solutions. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: *Nature* (I. Velicogna and J. Wahr, Acceleration of Greenland ice mass loss in spring 2004, *Nature* 443:329–331), Copyright 2006.

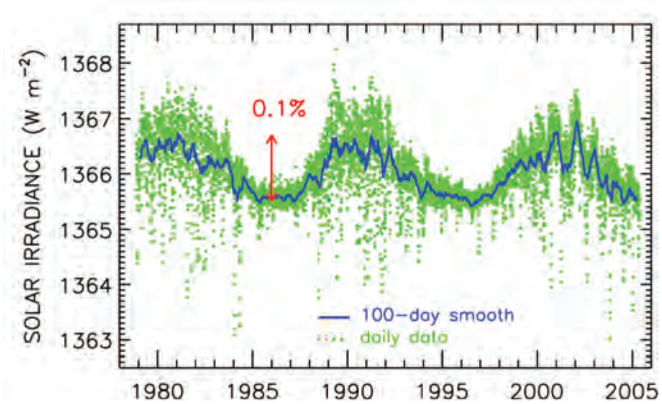

FIGURE 2.17 Recent analyses of satellite measurements do not indicate a long-term trend in solar irradiance (the amount of energy received by the Sun). SOURCE: Courtesy of Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center (http://www.pmodwrc.ch), updated from C. Fröhlich, Solar irradiance variability since 1978: Revision of the PMOD composite during solar cycle 21, *Space Science Reviews* 125(1-4):53–65, 2006.

ing nuclear-powered submarines under the ice caps throughout the Arctic. It was very much in their interest to measure how thick the ice was above their heads if they ever had to surface. A lot of these data have now been declassified. They show that the thickness of the sea ice over the Arctic has decreased roughly 40 percent in the last 40 years.

Referring now to Figure 2.10, there is something unusual about the last 30 years. The warming is now being observed everywhere. It is really difficult to find any temperature station in the last 30 years that is showing anything other than warming. Furthermore, the rate of change is faster than anything that has been measured before. It is also beyond the rate of variability that can be generated in a first principles fluid dynamical model of Earth's oceans and atmosphere.

Another distinction about the last 30 years is that it is the first period in human history in which it has been possible to measure the output of the Sun with enough precision to be able to say whether the Sun is getting warmer, giving us more heat or less.

Figure 2.17 is a graph by Claus Frohlich and Judith Lean. They have merged measurements of the output of the Sun made by three different satellites over a 22-year period. The output is changing, up and down, by a tenth of a percent, roughly like a solar cycle. It is not trending upward.

It was not that many years ago that people were theorizing that climatic changes that we were seeing were due to the Sun. It is not possible to do that anymore. We now have measurements that show that is not the case. The evidence is very strong that what we are seeing is a human effect.

Figure 2.18 displays the result of a set of cal-

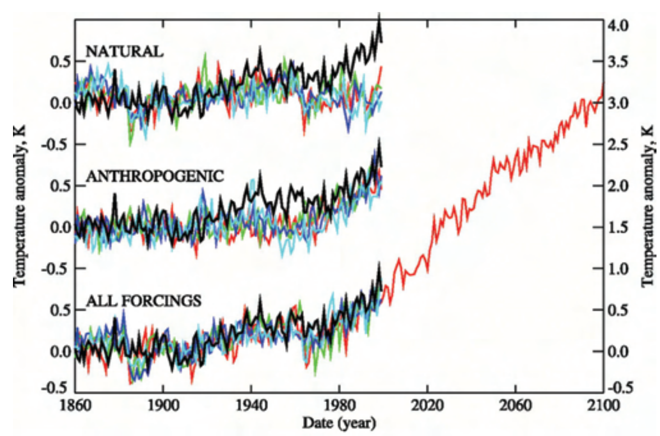

FIGURE 2.18 Computed and observed temperatures. SOURCE: P.A. Stott, S.F.B. Tett, G.S. Jones, M.R. Allen, J.F.B. Mitchell, and G.J. Jenkins, External control of 20th century temperature by natural and anthropogenic forcings, *Science* 290(5499):2133–2137, doi:10.1126/science.290.5499.2133, 2000. Reprinted with permission from AAAS.

culations done 5 or 6 years ago by Peter Stott and colleagues, where they tried to assimilate data into a global average temperature record. Globally averaged temperature is not the most important indicator of climate variability, but it is the easiest to measure and understand and the easiest to calculate.

If you look at either natural or human activity ("anthropogenic") separately, the calculations do not represent what actually has been happening, but if you look at the two together ("all forcings") you get a pretty good simulation of what has been measured. As the calculations in Figure 2.18 project into the future, based mostly on fossil-fuel energy usage, they indicate a continued global warming. This is why people are getting seriously concerned about the melting and breaking of ice formations over Antarctica and Greenland. When ice formations on land melt, the water goes into the ocean, adding to sea level rise.

One other kind of evidence of ice changes has to do with seismic activity and cracks inside the ice, which is being recorded by seismic instruments. The level of that activity has multiplied in the last 5 years.

What Do We Do? Where Is It All Coming From? What Is Going to Happen?

Figure 2.19 comes from the Energy Information Agency, which has compiled data of total world-marketed energy consumption, by types of economy

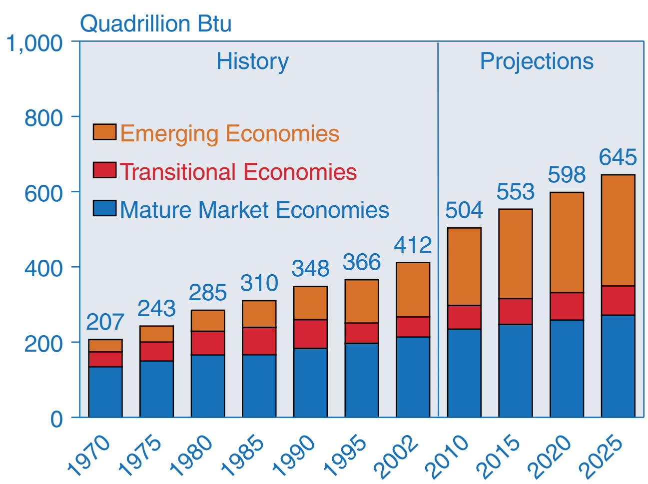

FIGURE 2.19 World marketed energy consumption by region, 1970–2025. SOURCE: Courtesy of Energy Information Administration, U.S. Department of Energy.

from 1970 to today, and then projected into the future. Currently we are at about 412 quadrillion Btu. That number has virtually doubled in 35 years—from 207 to 412 Btu (35 years at a 2 percent per year growth rate). Projecting ahead to the next 20 years, there is another 50-percent increase. This is thought to be a rather conservative projection. (Probably 80 or 85 percent of the carbon dioxide build up in the atmosphere is due to fossil fuel usage. Fifteen to twenty percent is due to tropical deforestation and loss of organic matter from soil.)

Another interesting feature, aside from raw growth in demand, is where the growth is occurring. The dark blue part of the histogram in Figure 2.19 is from mature market economies like the United States, Western Europe, and Japan. The red part is from so called "transition economies." These are a little bit harder to define. The brown part accounts for emerging economies like China and India and a few other places in Asia. This is where the significant growth has come from in the last 10 years.

It can be seen immediately that if we are going to try to solve this problem, either with technology or moderating demand and improving efficiency, we have a double challenge on our hands. We have to deal with what is happening currently and also with aspirations for economic development, which is strongly linked to energy use in the emerging economies. This is one of the reasons why it has been difficult to obtain an international agreement on what to do.

What do we need to do? Most people would say we need a dual strategy. We have to maximize energy efficiency and minimize energy use. We have to develop new sources of clean energy—where "clean" means not just lower carbon dioxide emission, but lower emissions of mercury, sulfur, and black carbon and soot (the things that are making cities in developing countries so unhealthy). This is the challenge.

There is some good news; in fact, there is a lot of good news. Figure 2.20 shows the electricity consumption per person in the United States and in California.

California's electricity use per person has flattened out over the last 30 years, while in the rest of the United States it has continued to go up. This has happened for several reasons. First, California instituted statewide regulations on insulation in appliances and homes

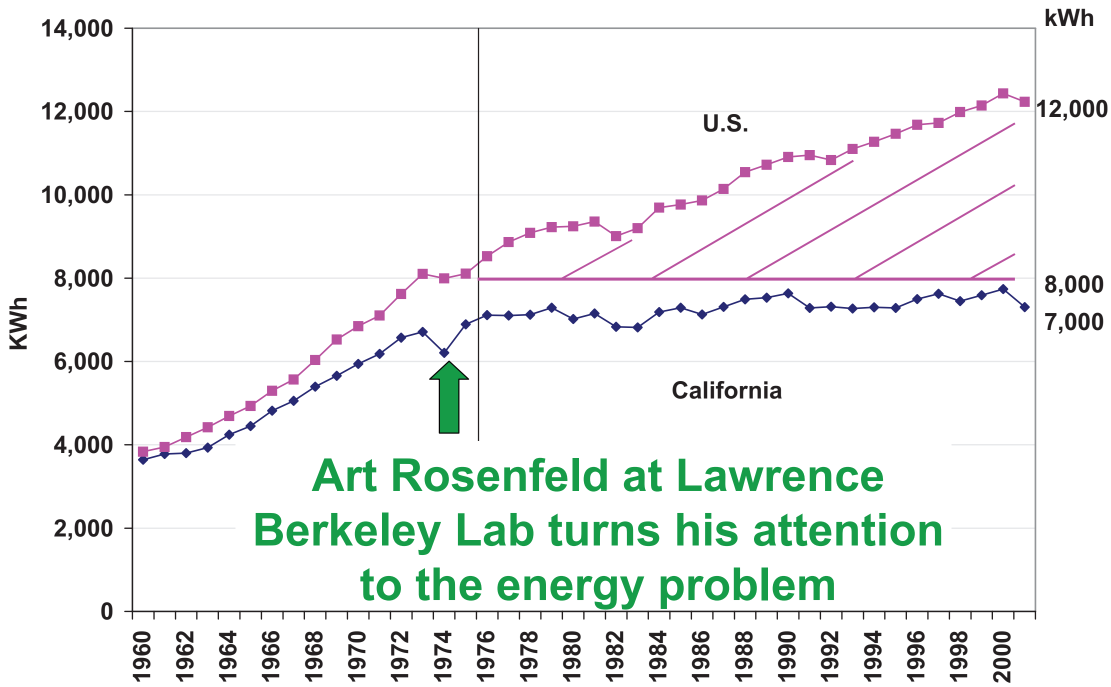

FIGURE 2.20 Electricity consumption/person in the U.S. and California. SOURCE: Adapted from Commissioner Art Rosenfeld, "Sustainable Development, Step 1: Reduce Worldwide Energy Intensity by 2% Per Year," presentation at the Global Energy International Prize Presentation and Symposium, University of California at Berkeley, November 19, 2003. Courtesy California Energy Commission.

and made it easier to buy energy-efficient appliances. Second, California adopted a pricing strategy whereby you pay more for electricity if it is used at peak demand hours and less if you use it during off-peak hours. That saved a lot of money in terms of transmission lines—power plants that did not have to be built, and so on. California also de-coupled the profits of utilities from the amount they were selling. Some of this was done through legal intervention and some through regulation.

During a congressional hearing last year where this author testified, the question was asked, "What's the big deal about 2 degrees temperature change?" Another witness said, "I can not even feel it. I can not tell the difference between 72 degrees and 74." By way of response, it is worth referring to Figure 2.21, which is based on data from the California Energy Commission for the summer of 2004. If the data are broken down into the number of days in the summer when the temperature was 75˚F, 80˚F, 85˚F, and so on, and the total electricity use for each temperature is plotted, the result is a straight line. Every 2 degrees increase in summer daytime temperature costs 1.2 Gigawatts of electricity! Carrying out the same exercise in other states, you get basically the same graph with more scatter.

No matter how you look at it, these changes are already happening, and in the future are going to be significant. One way to rate the changes in importance is whether or not they are reversible.

Back in the 1950s, 1960s, and 1970s, the biggest use of electricity in the home was the refrigerator. If you assume that there was basically one refrigerator in every house, Figure 2.22 shows the way household refrigerator electricity consumption was going. In that period refrigerators were getting bigger. Then California instituted some standards on efficiency of appliances and forced the manufacturers to start building better refrigerators, and the refrigerator electricity consumption in California started going down. At the same time, the refrigerators were still getting bigger. In fact, what limits the size of a household refrigerator today is the width of the kitchen door!

But there is a mysterious "vampire" that has come into the situation. The lower curve in Figure 2.22 shows the typical usage in a California household of "vampire electricity"—the electricity needed to operate

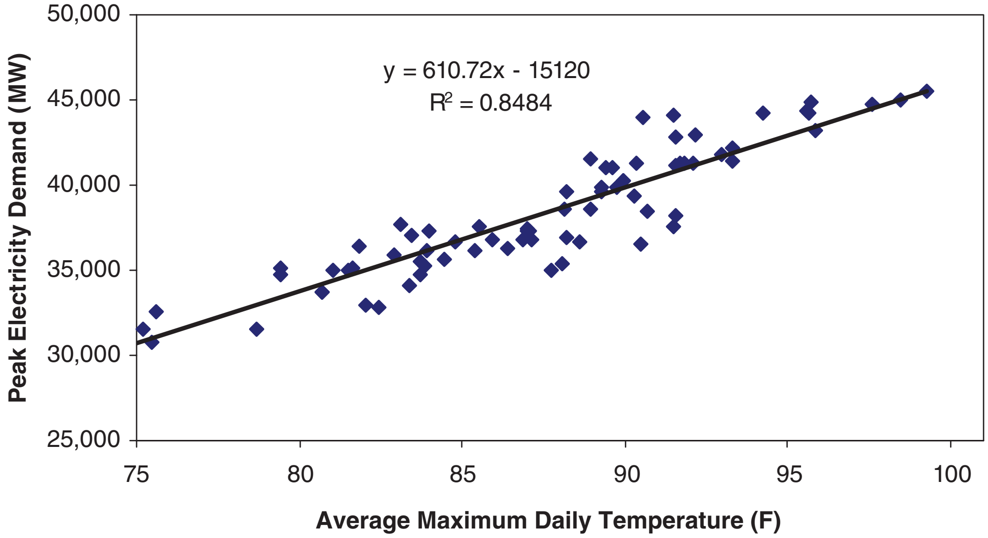

FIGURE 2.21 Peak electricity demand in the CallSO area as a function of maximum daily temperature: June–September 2004. NOTE: CallSO = California Independent System Operator, a not-for-profit public-benefit corporation charged with operating the majority of California's high voltage power grid. SOURCE: California Climate Change Center, *Climate Change and Electricity Demand in California*, White Paper CEC-500-2005-201-SF, February 2006. Courtesy California Energy Commission.

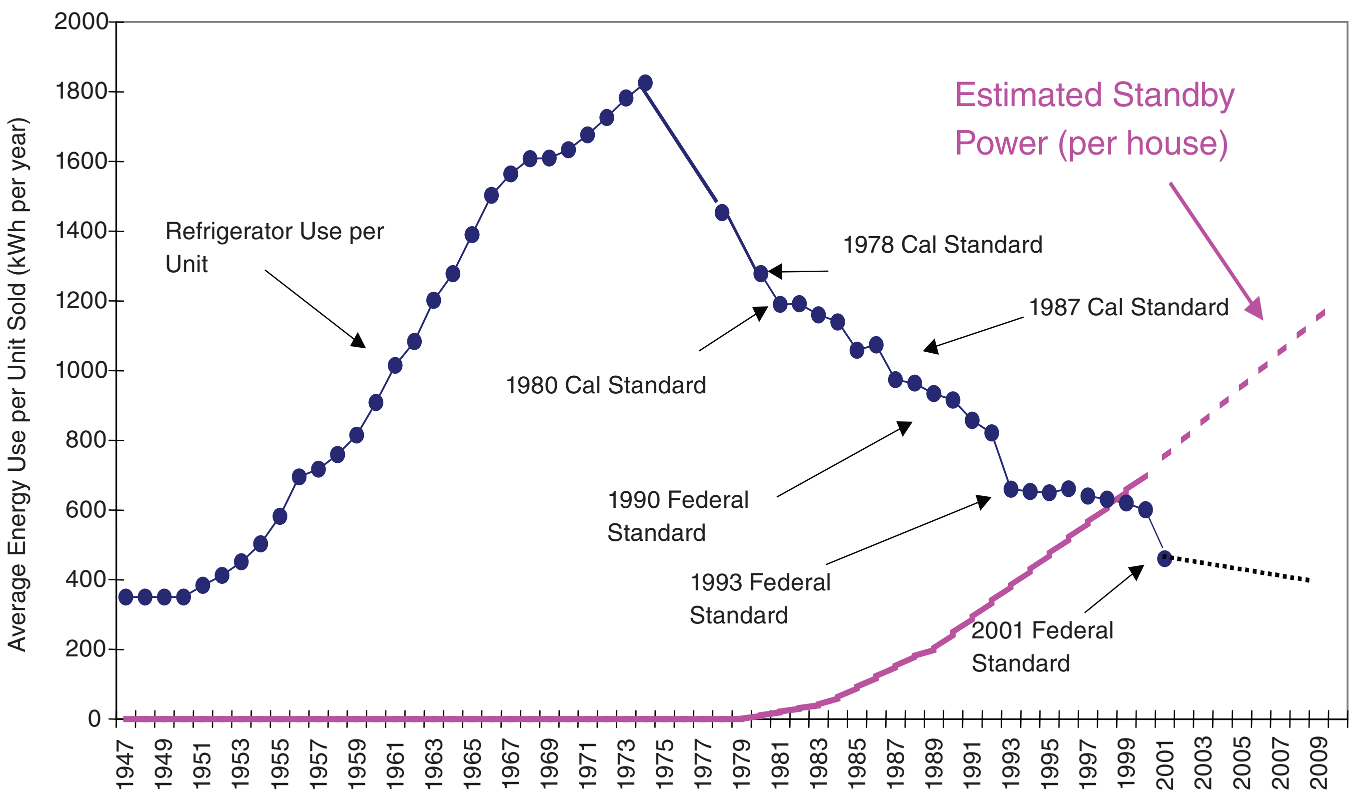

FIGURE 2.22 United States refrigerator use (actual) and estimated household standby use v. time. SOURCE: Commissioner Art Rosenfeld, "Sustainable Development, Step 1: Reduce Worldwide Energy Intensity by 2% Per Year," presentation at the Global Energy International Prize Presentation and Symposium, University of California at Berkeley, November 19, 2003. Courtesy California Energy Commission.

appliances (TVs, computers, video recorders, and so on) in the stand-by mode. We have got to do something about the way many of these electronic appliances are designed, because they have now surpassed what used to be the biggest consumer of electricity in a typical household! We can do this. It is not that difficult.

What else can we do? Energy efficiency has to be the first step. Even if you do not think that climate change is serious, or you did not want to bet that climate change is going to be serious, you would still have good reasons to do this because of all the things that energy efficiency would do.

First of all, it could decrease U.S. dependency on foreign oil. Just driving our cars and trucks in the United States today, we are using 6 million barrels of oil per day more than we are producing. At $50 a barrel, this accounts for about $200 billion of our trade deficit. This trade deficit means that we are dependent for the operation of our country's entire economy on parts of the world that do not particularly like us. We should clearly decrease our dependency and thus improve our national security. We could decrease local air pollution and increase our national competitiveness. (On average, manufacturing in Germany and Japan currently uses about 60 percent as much energy per unit produced as we do. At times of high-energy prices, that cost of manufacturing is a significant part of the cost of unit production.) We could encourage the development of new products for global markets.

Americans are supposed to be the innovators. We are supposed to know how to create whole new industries. We could be grabbing these markets and helping the world at the same time, if we would only get serious about energy efficiency and create a whole new generation of energy-efficient products. All this, while also slowing down the increases of carbon dioxide and methane in the atmosphere. Energy efficiency seems to be a no-brainer.

There are lots of other things we can be doing. However, it is going to take a combination of citizen action, governmental action, and business leadership.

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Science Goes to the Moon and Planets: Celebrating 50 years since the IGY

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Carnegie Institution of Washington

INTRODUCTION

This year marks the fiftieth anniversary of the International Geophysical Year (IGY). The IGY was organized by an international council of scientists in 1955 and set to begin on July 1, 1957. It was the largest international scientific endeavor ever undertaken, and it actually went on for about 5 years. The significance of the IGY to the space age is that both the United States and the Union of Soviet Socialist Republics (USSR) proposed to orbit satellites of Earth as part of the IGY. Both succeeded and opened the door to space. The scientific exploration of space began as an element of the IGY.

After the launch of Sputnik on October 4, 1957, and the first U.S. satellite, Explorer, almost 4 months later, the United States established its civilian space agency, NASA, on October 1, 1958. The U.S. National Academy of Sciences had already established its Space Science Board, now named the Space Studies Board, in June 1958 to advise federal agencies on research in space. In commemoration of the IGY, the opening of a new age of space science, and the establishment of NASA and the Space Studies Board, it seems very appropriate now to reflect back on these past 50 years, how far we have come, and where we want to go.

A LITTLE HISTORY

A little more than 50 years ago we had no space program at all. But we did have a vision. Americans had been treated to a dream of space travel authored by Werner Von Braun in magazine articles and on television programs. In 1952, *Collier's* magazine began a series of articles about Von Braun and his vision for putting a space station in orbit around Earth and using it as an assembly point to send spaceships first to the Moon and then to Mars. The articles were filled with fabulous paintings by Chesley Bonestell illustrating how all of this would be done (Figure 3.1). It was science fiction brought to reality. The articles were thrilling. And shortly afterwards Walt Disney, who had an immensely popular weekly show on television, made animated movies based on the *Collier's* articles that brought it all to life for American audiences.

The first *Collier's* article outlined in technical detail and in brilliant illustrations how man would conquer space with new rockets and space stations—written by experts with considerable respect. The second issue showed how we would get to the Moon. It all seemed fantastic but at the same time credible, and a fair amount of it actually came true. We even dreamed in the mid-1950s of going to Mars—the planet foremost and most mysterious in the mind of man—and the third article in *Collier's* in 1954 showed how we could do it.

It was not just a U.S. dream either. The Russians also had dreams to go to the Moon and Mars—visions contemplated by Sergei Korolev, the hidden rival in the Soviet Union to Von Braun in the United States. The USSR built its own version of the Saturn V, the N1, but could not make it succeed. After realizing in 1969 that they had lost the race to the Moon, the Russians countered with robotic rovers and sample return mis-

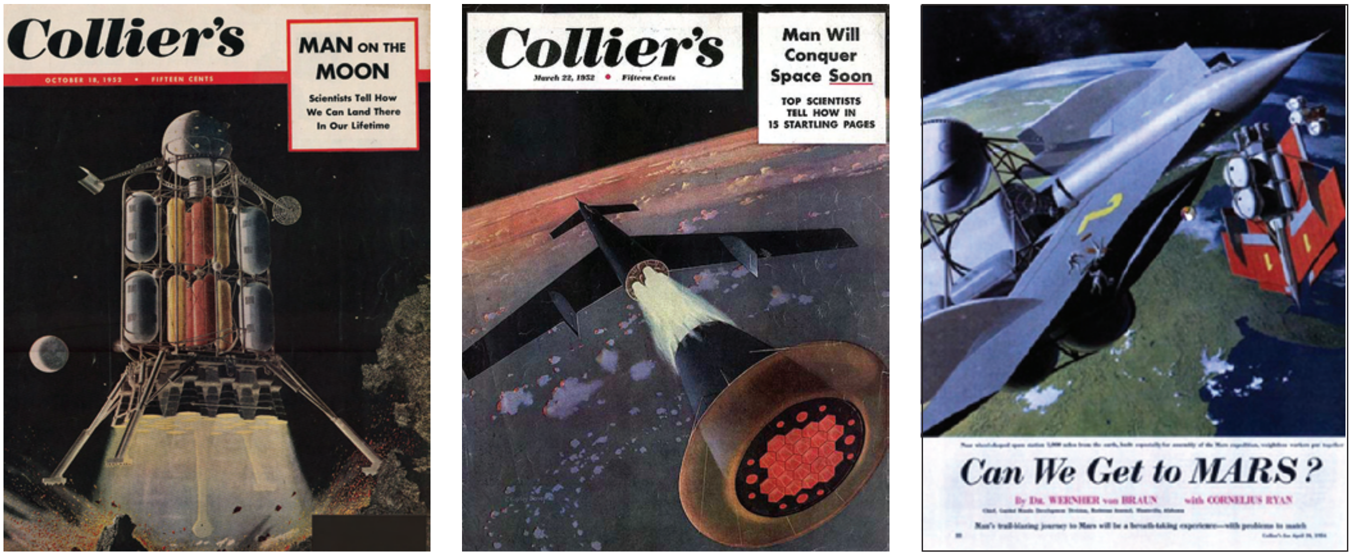

FIGURE 3.1 American dreams—*Collier's* magazine covers in 1952 and 1954 illustrating Werner von Braun's dreams of spaceflight. SOURCE: Reproduced with permission of Bonestell Space Art.

sions to the lunar surface—perhaps not as dramatic as astronautics walking on the surface, but certainly just as scientifically valuable, demonstrating the utility and excitement of robots traveling beyond Earth and exploring the surface of new worlds under control of humans on Earth.

We did set foot on the Moon almost exactly as Von Braun had originally envisioned, but not on Mars.

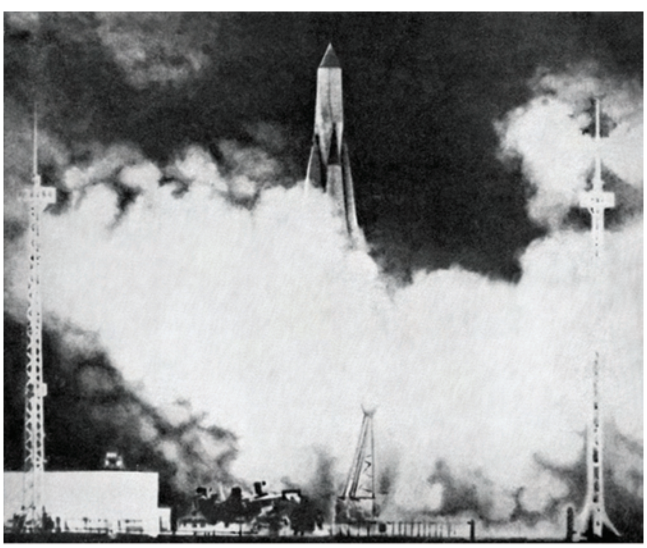

FIGURE 3.2 Beginning of the Space Age—the launch of Sputnik on October 4, 1957. SOURCE: Courtesy of RKK Energia.

After Apollo, the political will in the United States evaporated. In 1972 the United States abandoned the Apollo program and the future promise of lunar bases and human flights to Mars. The human space exploration enterprise retreated to Earth and was resigned to remain in Earth orbit.

While human space exploration languished after 1972, robotic exploration flourished (see Figures 3.3, 3.4, 3.5, and 3.6), and that has kept our dreams alive. Humans may not have exploded out into the solar system, but our robots certainly have. We have leapt off the surface of our home planet and sent robotic extensions of our eyes, ears, noses, arms, and legs to the far reaches of the solar system. Our robotic explorers go where we cannot go because of the limitations of our bodies, and they go where we cannot yet go because of the limitations of our own vision and will.

Since the abandonment of human exploration of space beyond Earth, robotic spacecraft have surveyed the solar system from Mercury to beyond Pluto; orbited Venus, Mars, Jupiter and Saturn; and landed on the Moon, Venus, Mars, and Titan to show us the bizarre surfaces of exotic new worlds. In 1957 these places could only be imagined, and traveling to them was in the realm of science fiction. Today, the solar system has become our backyard.

FIGURE 3.3 The Moon (USA/Apollo 15). SOURCE: Courtesy of NASA.

WHY DO WE EXPLORE SPACE?

Why do we find spaceflight so compelling? Because exploration is part of what we are as human beings. We have cultural, scientific, political, and economic incentives to explore space.

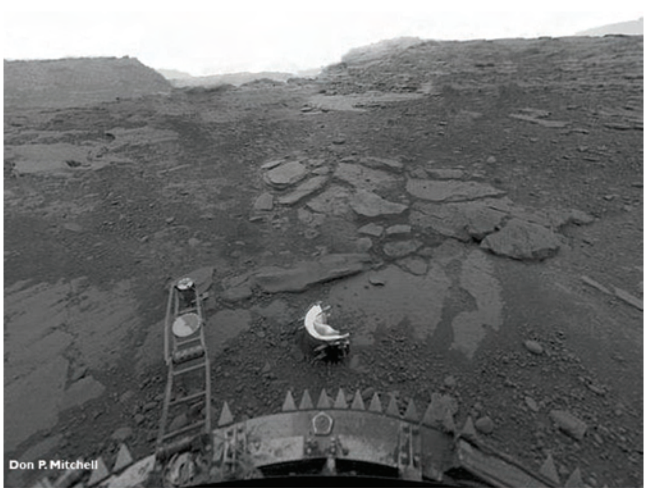

FIGURE 3.4 Venus (USSR/Venera 13). SOURCE: Courtesy of Don P. Mitchell of Redmond, Washington.

Humans have an inborn imperative to explore and to understand. Exploration and the drive to make new discoveries and to learn about what we do not understand are qualities that have allowed humans to survive on Earth. Human beings strive to know and to understand what surrounds them. By exploring the unknown, humans gain security and dispel fear of the unknown, of what is beyond. This survival mechanism is encoded in our genes.

We use the challenge of exploration to advance and to learn, to improve our scientific and technological skills for survival, to sustain our human experience, and to progress. We also exploit the adventure of exploration to provide hope for the future. This is particularly important for our youth, who need to be given a positive vision for their future and inspiration toward achievement.

The development of powered flight and global air transportation in the 20th century created new economic opportunities and ultimately connected societies all over the planet. So too will the exploration of space create new economic opportunities in the 21st cen-

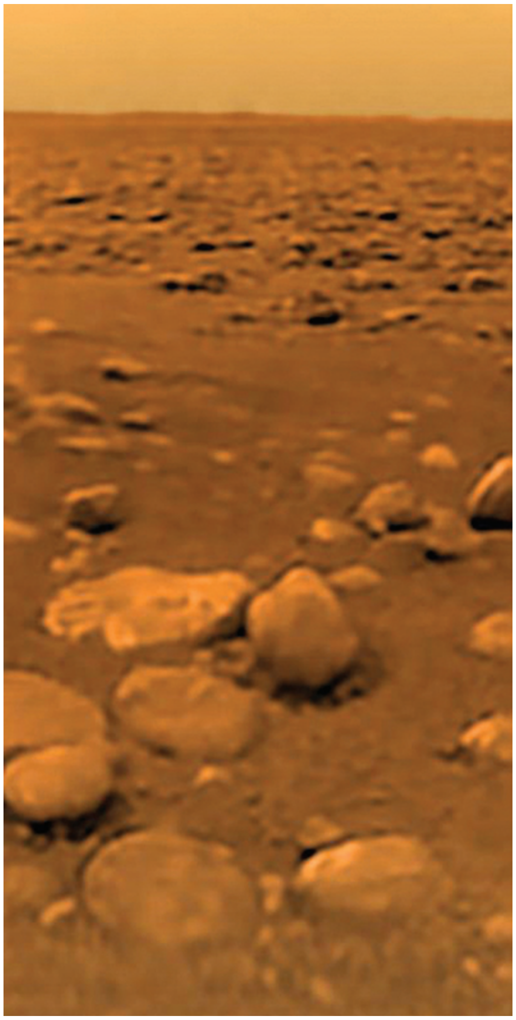

FIGURE 3.5 Titan (ESA/Huygens). SOURCE: Courtesy of ESA/NASA/JPL/University of Arizona.

tury in ways that we cannot anticipate today. Spurred by the advent of the space age in the late 1950s, the investment in science and technology by the United States, a relatively young country, drove a half-century of unprecedented wealth and prosperity. Science and technology are the greatest engines of economic growth in America, and this has become obvious to the rest of world as new nations open up their own roads to the Moon and beyond.

In our complex world of national interests and barriers, the exploration of space can and should be a global enterprise. Space exploration is an adventure of and for humankind, not for any nation in particular. It is the perfect place for nations to cooperate, because space is new, unbounded, and open. Achievements in space can be accomplished by nations working together, and thereby each gains security by cooperating in a challenging enterprise where there are no risks to national sovereignty. Space is a place to be utilized by Earth, by the humans of Earth, not by any one nation.

SCIENTIFIC EXPLORATION: WE ARE COMPELLED

The exploration of space is a noble human enterprise with roots in the exploration of our own planet in the 20th century. At the beginning of the 20th century we were exploring the unknown polar regions of our own planet with ships and men. At the end of the 20th century we were exploring the Moon and beyond with spacecraft, robots, and men. Science has been a partner in all of this. We have now stepped upon the Moon and sent robotic spacecraft on flights past every planet in the solar system. We have conducted orbital reconnaissance of four planets and two asteroids (soon to be five planets and four asteroids); landed on two planets, an asteroid, and a moon of Saturn; and we have conducted roving expeditions on both the Moon and Mars.

We are compelled to explore the Moon and the solar system because it is there that we will find answers to fundamental questions humans have been asking themselves as long as we can remember—questions about our own origins and destiny. Questions such as How did we come to be? and What will happen to us in the future? and Are we alone in the universe? The progress we have made in space science over these past 50 years has brought us to the point where we dare voice these big questions, because we believe now that they can be answered through the scientific exploration of space. These human questions can be recast as scientific challenges—goals to be achieved in the course of exploring space. And from these scientific goals, plans can be formulated for both robotic and human explorers, including the destinations and the exploration objectives for each.

How did we come to be? This is a question that approaches the contemplation of existence. Even so, astronomers can address the question by determining how the universe began and evolved; learning how galaxies, stars, and planets formed; and searching for Earth-like planets around other stars. And when we find Earth-like planets, are they habitable or even

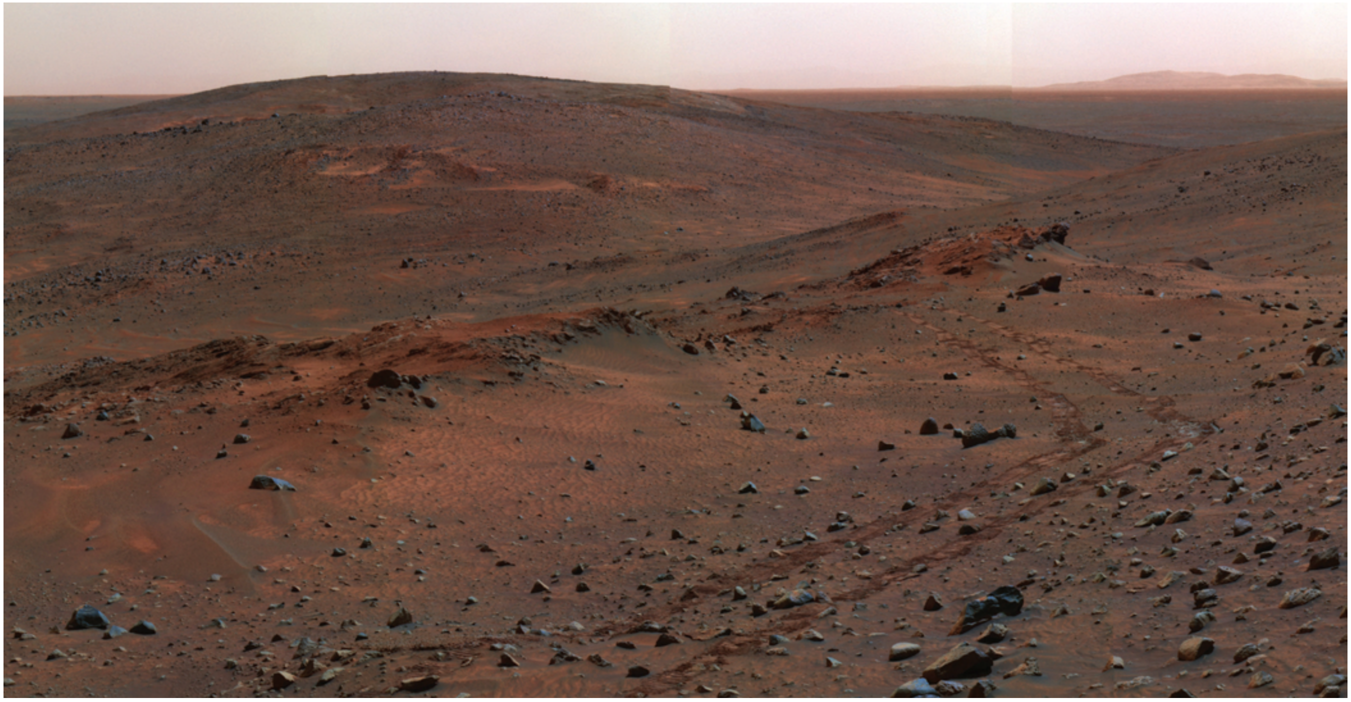

FIGURE 3.6 Mars (USA/Spirit Rover). SOURCE: Courtesy of NASA/JPL.

inhabited? The answers require large and complex space telescope systems made possible by human construction and servicing in space. We need to find out how Earth developed its biosphere and whether these same processes ever occurred on other planets in our solar system. This requires research on life here on Earth and extensive exploration of other planets in our solar system where there may have been another chance for life, such as Mars and Europa.

What will happen to us in the future? Every human wonders about the future. One form of this question asks if there is any threat to us from space, especially from Earth-crossing asteroids. The answer will come from surveys of the Earth-crossing asteroid population in space and space missions that determine their composition and structure. Another form of this question asks what future humans have in traveling to and living on other planets. Is our species destined to populate space? Ultimately I believe the answer is yes, and it will happen through exploring space and utilizing the resources we find in the most promising places out there.

Are we alone in the universe? Every human being wants to know the answer to this question. We are compelled to find its answer. Some find comfort in the notion that we should be alone; others are fearful of the potential for other life "out there." Most scientists see the possibilities and are overwhelmed by the notion that the universe might be teeming with life, at least microbial life and perhaps even intelligent forms. We will find the answer by searching for life in the most

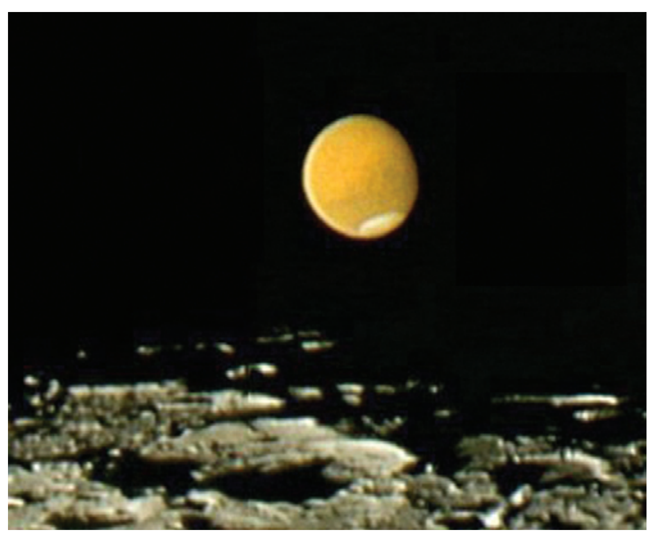

FIGURE 3.7 The Moon and Mars beyond—the two most exciting places for human and robotic exploration. SOURCE: Courtesy of Donald Parker and Jeff Beish.

promising places in the solar system, such as Mars and Europa, and by looking for signs of life on planets outside the solar system with space telescopes.

So how do we go about all this? Where do we go in the solar system, and what do we do there to try and answer these questions? Let's start with the Moon. It's not the only place we need to go, but it's close, it's right there in our sky and a convenient trip of only a few days.

WHAT GOOD IS THE MOON?

We probably would not have a space program if it was not for the Moon.

> If God wanted man to be become a space-faring species, He would have given [us] a Moon.
>
> —Krafft Ehricke, Saturn V rocket engineer

A bit facetious perhaps, but well crafted and on the mark. The Moon has been dominant in our sky since before the dawn of man. It is another planet large in our sky, demanding attention, drawing our eye and curiosity. And without it, man may never have looked so questioningly at the sky and generated the interest in going to the Moon and beyond.

The Moon is a destination for scientific exploration. There is much we still do not know about the Moon, even after Apollo. It is an archeological site for understanding solar system history, especially the earliest phases where the evidence has been wiped out on Earth. It is also a close-by platform for conducting science, a natural scientific outpost from which to observe the rest of the solar system, the Sun, Earth, and the universe.

The Moon is the first step into deep space for any nation's space enterprise. It is a nearby planetary destination for flexing the technological muscles of any country's young space enterprise. It is also a way station to exploring deep space. It can become the new Antarctica, a place for nations to cooperate in peaceful exploration and to develop the trust needed to proceed together in international deep space exploration.

The Moon is potentially a commercial destination. The possibilities have been raised for developing resources, including materials and energy to use locally on the Moon, to support further space exploration, or perhaps even for export to Earth. The Moon will at some point in the next 50 years become a travel destination, first a virtual one through robotic missions and the internet, and ultimately for humans a permanent exploration outpost and then a tourist destination.

Science On and About the Moon

The Moon is a solar system history book, a "Rosetta stone," providing a template for deciphering and understanding the history and evolutionary processes of the terrestrial planets. Due to its lack of atmospheric weathering and geological activity, the surface of the Moon is a repository of information from the earliest epochs of solar system history. Impact-generated samples of the early Earth, Venus, Mars, and asteroids may lie on the surface, and samples of lunar mantle material may also be exposed as a result of large impacts. The ancient rocks on the Moon may represent our best hope of directly sampling the material from which the Earth–Moon system formed. We can also determine the impact flux of asteroids and comets on Earth over time using the cratering record preserved on the Moon. Material from the solar wind trapped and buried in the lunar surface can also elucidate the history of the Sun.

Comet impacts over the eons may have resulted in an accumulation of water ice in permanently shaded regions at the poles. Some studies have suggested that there may be as much as 10 billion tons of water in the polar regions, potentially a valuable source of oxygen and rocket propellant for future human outposts on the Moon. Finally, the Moon may represent a potential resource for commercial exploitation. There have been proposals to export lunar resources for use on Earth, as well as proposals to use lunar-generated energy and to use the Moon for education, entertainment, or space tourism.

The Moon has also been proposed as a platform for astronomical telescopes. The most compelling of these is a low-frequency radio telescope on the far side where interference from the overwhelming background of commercial radio broadcast traffic is eliminated.

Origin of the Earth–Moon System

The Moon contains a 4.5 billion year old record of the origin of the Earth–Moon system. Apollo and other lunar missions have only scratched the surface of what the Moon can tell us about the history of the inner solar

FIGURE 3.8 The Earth–Moon pair is unique. It is the only major twin planet in the solar system, and Earth is the only planet with a surface ocean and life. SOURCE: Courtesy of NASA/JPL.

system. There remain some key elements and isotopes that have not been measured and that are necessary for fully understanding the Moon's thermal and volcanic history and for making an accurate assessment of the resource potential of the Moon. We need to explore and sample more of the diverse regions of the Moon we have not yet visited. We need samples from the lunar mantle that may await us in the deep basins on the Moon. We need to determine the interior structure and composition of the Moon in greater detail than we know today. This can be accomplished with an in situ network of seismic stations and heat flow measurements distributed around the surface. And the determination of absolute ages of lunar minerals is a requirement for understanding the history of the Moon and its relationship to Earth. These measurements now require analysis by ultra-sensitive, highly complex, and massive instruments in Earth laboratories with extensive sample preparation by human laboratory technicians. While sample return can be done robotically, sample selection and characterization on the lunar surface is a critical function, and there remains a trade-off on the capabilities of lunar robots with human operators on Earth versus human lunar field geologists.

Impact History of the Earth–Moon System

The Moon has recorded the history of impact bombardment since its solidification shortly after the formation of the solar system (Figure 3.9). It is a "witness plate" that can provide the statistics on impacts that must have occurred on Earth, but whose evidence has been erased by Earth's turbulent tectonic activity. This lunar impact record extends to time periods earlier than the origin of life on Earth, so that the chaotic disruptions caused by impacts on Earth can be used to understand the life forming process on early Earth.

There are meteorites from the Moon found on Earth, and there is every reason to suspect that the inverse is also true. It is possible that material blasted from Earth in its early years rests now on the lunar surface—stones containing secrets to the first billion years of Earth's history just waiting to be picked up. We have evidence from the oldest rocks available on Earth that life had already arisen more than 3.5 billion years ago at the end of the Hadean eon and the beginning of the Archean eon. Perhaps the clues we need to this early age are waiting to be identified and retrieved on

FIGURE 3.9 The Moon has a unique ability to record history. The lunar surface may harbor meteorites from Earth's first billion years, transported to the Moon by large impacts. The lunar soil contains embedded solar wind particles; the ancient stratigraphic record exposed on the Moon may reveal a history of the luminosity and state of the Sun over time. SOURCE: Courtesy of NASA.

the Moon. Samples of Earth ranging back into the late Hadean could tell us a lot about the early atmosphere, ocean, surface, and climate when life was first evolving on the planet.

In addition to assessing the effects of bombardment on Earth's environment in the Hadean, the post-mare cratering record on the Moon can yield information on other critical phases of the evolution of life on Earth. There is evidence that Earth periodically receives large impacts, and these have been linked to mass extinctions. This hypothesis cannot be tested on Earth, but it can be tested on the Moon by a careful examination of its cratering record.

Finally, the Moon preserves a record of the most recent impact history of the Earth–Moon system. There has been an increased awareness of the potential for future large impacts by Earth-approaching asteroids and comets. The time scale for such impacts is a strong function of size, and current statistics are not as accurate as the potential threat dictates they should be. There is a growing program for the identification, orbit determination, and monitoring of Earth-approaching objects in order to provide advance warning of any threat to the planet, but more accurate statistics are required to complement the observational techniques. These statistics could be determined by deciphering the late cratering history of the Moon from samples of a large number of post-mare craters.

A Record of the Ancient Sun

The Sun propels enormous amounts of material into space in the form of hot tenuous plasma known as the solar wind. The solar wind is a sample of the composition of the surface of the Sun. As the Sun burns hydrogen in its interior over time, it produces new elements and isotopes that migrate to the surface and are expelled in the solar wind. The solar wind impacts the Moon and is trapped in regolith material, which is well preserved on the Moon. Age dating of lunar stratigraphy with atomic and isotopic analysis of the implanted solar wind in these layers can be used to determine the past history of solar luminosity as well as to predict its future evolution. This information will help us understand the past climate of Earth over the entire time that life has existed on our planet.

A Platform for Observatories

The far side of the Moon, in permanent shadow from Earth, is the perfect location for a radio telescope. It would be possible to emplace very simple and extremely long, narrow antennas on the far side of the Moon that would have unparalleled spatial resolution on the sky with extreme sensitivity. Antennas that are kilometers in length and deployed from very small roll-up packages are easy to envision. They could be operated remotely and serviced by humans. They could be used to examine solar radio emissions and emissions from the planets, map emissions from Milky Way objects, and look back into time just after the Big Bang when stars had yet to form.

There are also notions to place optical telescopes on the Moon. The advantages are that there is no atmosphere to distort images and filter out large portions of the electromagnetic spectrum, and there is a cold, dark sky for 14 days (except at the poles where permanent night can exist). However, there are significant challenges to emplacing large telescopes on the Moon, including mitigation of lunar dust, the local atmosphere near a human-occupied base, large thermal excursions between lunar day and night, and the large propulsion requirement for the repeated trips into and out of the lunar gravity well that will be needed for construction and servicing.

Resources: Materials and Energy for Space and Earth

The Moon's regolith contains resources that might be useful for processing into materials and consumables for supporting human explorers on the Moon or for sustaining exploration of space beyond the Moon, or perhaps even for export to Earth. These prospects have been buoyed recently by the discovery that there may be water ice in permanently shadowed regions at the lunar poles. The distribution, form, and amount of any such ice in the polar regolith must be understood before the potential for supporting human exploration can be fully evaluated. This assessment can be accomplished first from lunar orbit followed by in situ measurements on the surface and at depth to characterize these potential deposits in detail. In addition to assessing the value of these deposits for oxygen and fuel production, they have scientific value in their potential to unravel the history of volatiles in the inner solar system.

In addition to the possibility of usable quantities of water ice at the poles, there may be other useful volatiles implanted in lunar dust grains, such as hydrogen from the solar wind. It may be possible to extract oxygen and metals from lunar rocks and regolith to use for life support, propulsion, and construction.

Solar energy is another resource that could be harvested on the Moon. While storage batteries would be required to survive the long lunar night, solar power plants could be placed in polar locations where there is permanent sunlight. The problem then becomes transmission of that power to other regions where it is needed. This energy could also potentially be exported to cis-lunar space or even back to Earth.

Exploration: Becoming a Space-faring Species

In addition to its intrinsic science value and its potential importance as an observational platform and a resource node, the Moon is a stepping stone into the solar system. The Moon is a natural space station, already in Earth orbit, providing a benign environment with one-sixth gravity for human utilization and exploration. The proximity of the Moon suggests its potential as a training ground for human exploration of space. The Moon is a place to learn the skills we need to live off-planet, to explore planetary surfaces, to learn the respective roles of robots and humans, to develop the means to live as much as possible with local resources, and to confront the societal and psychological impacts of confined living in a hostile, alien environment far from Earth and home.

While the Moon may seem to be a "been there, done that" destination for the American public, the rest of the world has a "go there, do that" attitude, and many nations with emerging space programs have the Moon in their sights. There will be a renaissance in lunar scientific exploration in the next several decades that the United States will not want to miss. The pull of the Moon to emerging space programs around the world can be a catalyst for a new era in space exploration—one of international cooperation instead of the rocket-rattling days of the Cold War and national breast-beating in the days since.

FIGURE 3.10 Astronaut Eugene Cernan drilling a core sample on the Moon. SOURCE: Courtesy of NASA.

Beyond the Moon

In the long run, the Moon is but one of many exciting places to visit in the solar system. Our robotic spacecraft have free reign of the entire solar system, while humans will be limited to Earth's vicinity, including the Moon, in the immediate future. The ultimate goal for human spaceflight should be to visit Mars in the next 50 years, but there are two other places for humans and their accompanying robots to visit between the Moon and Mars: one in near-Earth space just beyond the Moon, the Sun–Earth Libration Point L2 (SEL2), and the other just beyond Earth space, a near-Earth asteroid.

SUN-EARTH LIBRATION POINT L2: A PLACE THAT IS NOT A PLACE

In 1772, the French mathematician Joseph L. Lagrange showed that there are five positions of gravitational equilibrium in a rotating two-body gravity field. Three of these Lagrange points—also called "libration points"—are situated on a line joining the two attracting bodies, and the other two form equilateral triangles with these bodies. Figure 3.11 shows a total of seven libration points located in Earth's neighborhood, five

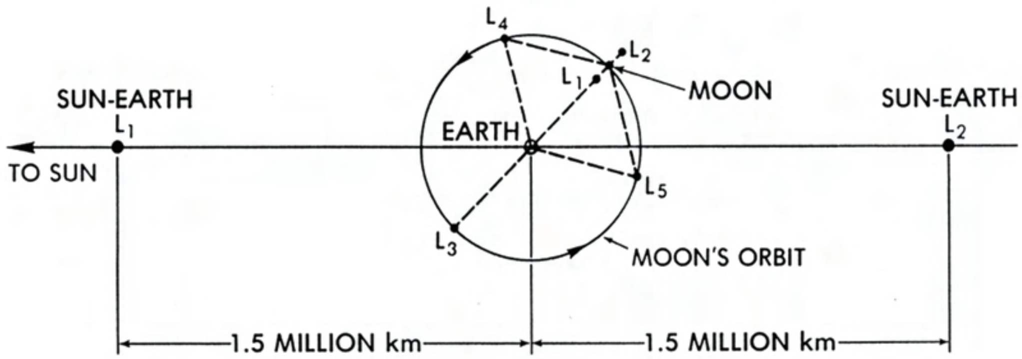

FIGURE 3.11 Libration points in the vicinity of Earth. SOURCE: Courtesy of NASA.

of which derive from the Earth–Moon gravitational system and two which derive from the Sun–Earth system. Although the collinear points are unstable, very little propulsion is needed to keep a spacecraft at or near one of these points for an extended period of time. This unique gravitational balance and consistent geometry makes the libration points very important locations in space-exploration architecture. In particular, the Sun–Earth L2 point is the ideal location for space telescopes, and it is an excellent stepping-stone to more distant destinations. Sun–Earth L1 is an excellent vantage point for solar telescopes and for viewing the entire sunlit hemisphere of Earth.

The Sun–Earth Libration Points L1 and L2 (SEL1 and SEL2) are located at the very edge of Earth's gravitational influence in the solar system. From there, you would literally fall off Earth's gravitational field into the solar system beyond. For this reason it would make an excellent staging point for astronauts traveling beyond Earth–Moon space into the rest of the solar system. The disadvantage relative to Earth–Moon libration points is that the Sun–Earth libration points are farther away and would take more travel time to reach. That extra time may be worth it, however, since SEL1 and SEL2 are energetically inexpensive points to reach in space, taking much less energy than getting into lunar orbit or reaching the Earth–Moon libration points where the Moon's gravitational field must be countered.

SEL2 is an ideal vantage point for space telescopes (Figure 3.12). It is a thermally benign environment. There are no temperature changes caused by day–night cycles like those on Earth or the Moon. Viewing constraints are minimized because the Sun, Earth, and Moon all lie in the same general direction and are far away. There is no obscuration from a local platform. The entire sky is accessible all the time. There is no dust to contaminate mirrors and clog mechanisms. There is a continuous source of solar power for uninterrupted observations. Because of these advantages, the next generation of space telescopes is targeted for SEL2 beginning with the James Webb Space Telescope.

It is conceivable to construct extremely-large-aperture telescopes at SEL2 because there is no gravity to distort mirrors or impede pointing operations. It is also possible to fly multiple telescopes in formation, their mirrors optically linked by laser metrology, to provide unfilled dispersed apertures with sizes of kilometers or more. Such large sizes can provide spectacular, unprecedented resolution on the sky. With such multiple telescope systems it will be possible to survey the universe across the entire spectrum and look back at the universe to the beginning of time. It will be possible to observe the process of planetary system formation around young stars and to search for terrestrial planets around more mature stars. We can search for evidence of life in the spectra of the extra-solar planets we find, and multiple aperture systems may ultimately be capable of imaging Earth-like planets around other stars. Imagine a time when humanity will be treated to the first image of an Earth-like planet around another star. That image will have an even larger effect on the human consciousness than did the first global image of Earth taken from space by Apollo 8 in 1968.

Such large, complex systems would probably be most cost effective if constructed and serviced by astronauts at SEL2 or at a servicing waypoint in one of the Earth–Moon libration points closer to Earth. SEL2 is

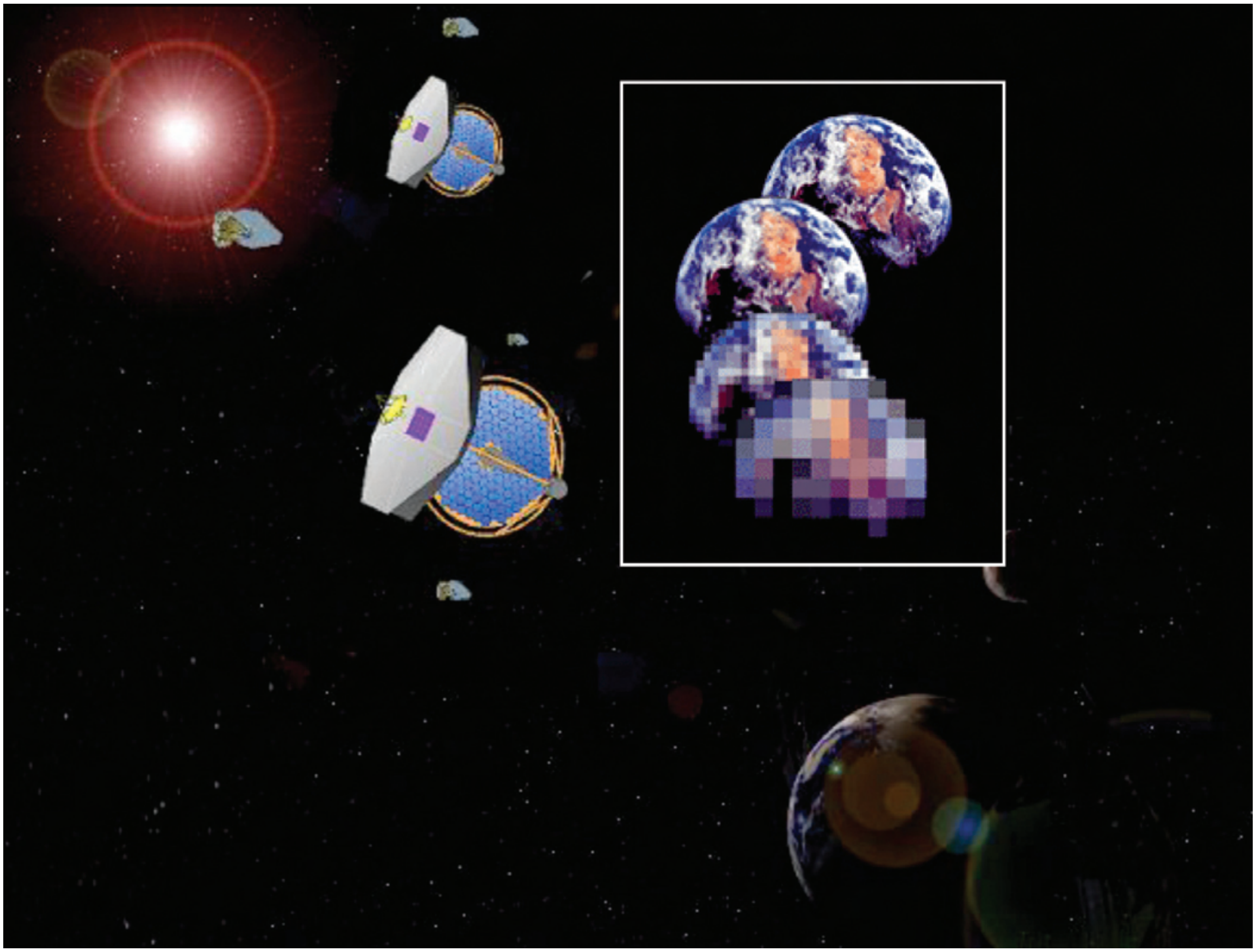

FIGURE 3.12 Multiple space telescopes flying in formation, positioned at SEL2, and coherently linked optically through laser metrics, may someday be able to resolve and image Earth-like planets around nearby stars. SOURCE: Courtesy of NASA.

a relatively benign and low-risk destination for human spaceflight. Its unique location at the edge of Earth's gravitational influence makes it an energy-efficient starting point for missions to deep space. Having developed the capability to travel to SEL2 for telescope construction and servicing, astronauts could use SEL2 to construct and service spacecraft to be staged from here for journeys to more distant destinations.

SPACE ROCKS

Near-Earth objects (NEOs), also known as near-Earth asteroids, are nearby remnants of planetary formation and represent valuable storehouses of information on the origin of the solar system. Their structure and composition may hold clues to important scientific

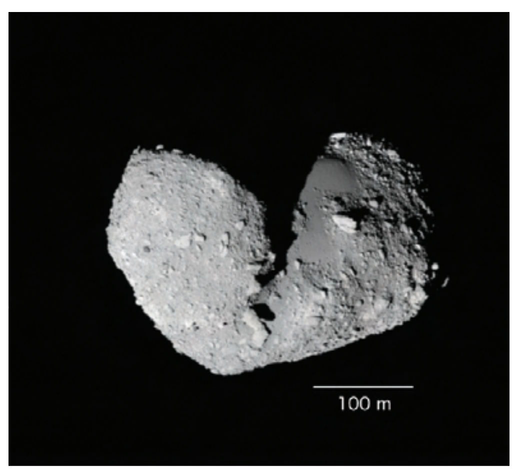

FIGURE 3.13 Itokawa, a near-Earth asteroid several city blocks long, visited and sampled by the Japanese Hayabusa spacecraft now returning its cargo to Earth. SOURCE: Courtesy of JAXA.

questions about the history of the solar system. In addition, since they pose by far the most significant impact threat to Earth, an understanding of their diversity and their physical characteristics could someday be vital to averting a potential global disaster. These objects impact Earth regularly, with mean times between collisions dependent on size—larger objects fall much less often simply because there are fewer of them. There are recent and dramatic impact scars on Earth, including the 50,000-year-old crater near Winslow, Arizona, and the massive blow down scar of the 1908 Tunguska event (probably a comet impact) in Siberia.

The primary properties of composition and bulk density must be determined in order to understand NEO structure, the nature and severity of possible impact threats, and the efficacy of various mitigation strategies. NEOs also represent substantial mineral resources in space relatively near Earth. Because NEOs have very low gravity, transportation of these resources to other locations can be done relatively inexpensively. These resources could be used for in-space operations or may have commercial potential for export to Earth.

While most of the scientific exploration of NEOs can be done robotically, NEOs are ideally situated to provide an important stepping-stone for human missions to Mars. A mission to an NEO provides an opportunity to exercise many of the required human transportation elements for Mars in a relatively low-risk manner. NEOs are relatively easy to reach, with lower energy requirements than achieving lunar orbit in many cases, but require longer flight times on the order of 6 months to a year. Their locations and physical characteristics will stretch the capabilities of human exploration just enough to greatly reduce the risk of the Mars missions to come. In addition, development of the capability for human operation on and near NEOs, in advance of the discovery of any specific impact threat, could turn out to be a wise investment.

MARS IS FOR ROBOTS AND HUMANS

Virtually ever since it was discovered, the planet Mars has been special to humankind. For centuries it has been a centerpiece for much of our scientific speculation and imagination, and it has been explored in the space age more intensively than any other body in the solar system except Earth.

Mars is the most Earth-like planet in the solar system and almost certainly had a warmer and wetter environment early in its history, with flowing and standing water on its surface. Mars may have developed life, and while its surface appears lifeless today, an early biosphere may have survived at depth where liquid water might still exist. Mars is the most accessible place in the solar system where we can search for evidence of an independent origin of life. From Mars we can learn about the origin and history of an Earth-like planet that has taken a different path in planetary evolution. By comparing the geological and climatological histories of Earth and Mars, we will gain clues to what it takes to construct a habitable planet and how that habitability may be sustained or lost over time. All of these objectives share a common thread—water. When in the planet's history did liquid water exist? Where was it and where is it now? In what form (rain, rivers, lakes, and oceans)? How much?

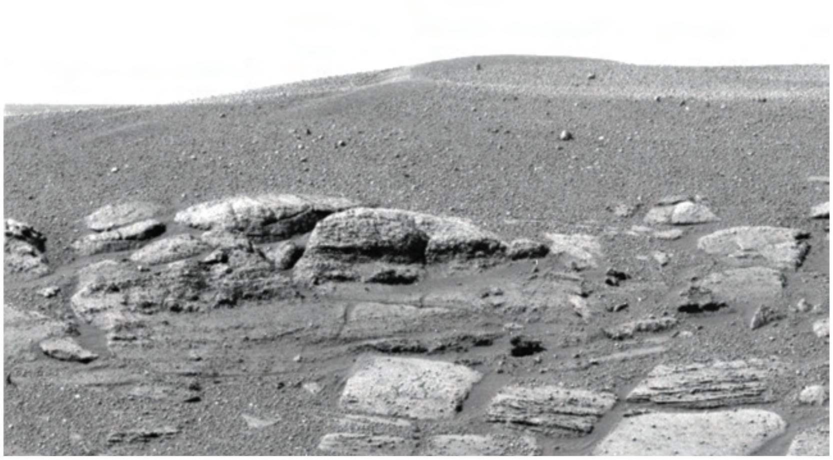

FIGURE 3.14 Mars has a history. The history of Mars can be read in sedimentary layers like these at the Opportunity rover landing site. SOURCE: Courtesy of NASA/JPL/Cornell.

There is evidence that Mars had more habitable climates in its past and has undergone climatological cycles, linked to orbital and obliquity changes, that episodically may have produced a warmer and wetter surface environment. There is every reason to believe that 4 billion years ago the surface environments of the two young planets, Earth and Mars, were very similar when life first arose on Earth. So by extension, there is a fair possibility that life may have arisen on Mars at that time. If there was life on the young Mars, there may be fossil indications of that life to be found. If life has survived and still exists today, then it is hidden below the surface of Mars where liquid water and sources of chemical energy may still be found.

By exploring the geological and climatological history of Mars, we are examining the evolution of another Earth-like planet. The knowledge to be gained will help us to understand how terrestrial planets are built and how they evolve, how a habitable environment can be established and maintained, how that environment can evolve to become biological, and what the prospects may be for other habitable planets in planetary systems around other stars.

Where Is the Water?

The key to exploring Mars is to "follow the water." Scientific results from robotic missions show that the history of martian water and the distribution of its repositories are strongly coupled to the geological and climatological histories of the planet. Water has been a major erosional force on the planet in the past; its features are written all over Mars. Water has also been a major climatological force during the history of the planet. There is enough water locked up in the seasonal polar caps today to cover the surface of Mars to a depth of 20 to 30 meters. Water is a major element in present day martian weather. While present in only trace amounts, the atmosphere is quite often fully saturated with water. There are hidden reservoirs of ice, and perhaps water, in the subsurface, evidenced by seepage channels in cliffs and crater walls and the strong near-surface signals of ice seen by orbiting neutron detectors and radar sounders. The layered polar deposits probably contain as much as 20 to 50 percent water ice.

Liquid water in extensive aquifers could exist below the surface, and there is evidence of catastrophic outbreaks of such aquifers in the past. Global remote sensing and sounding can identify potential aquifers where there might be subsurface ice or water that can be reached with in situ exploration using additional sounding and drilling. A source of liquid water would be a key resource for establishing a human outpost on Mars.

Was There or Is There Life on Mars?

On Earth, wherever there is liquid water there is life, and the same may be true of Mars. Mars may have developed an independent origin of life early in its history when it was warmer and wetter, and that life might have survived at depth where liquid water may remain. Mars is therefore a most compelling place to answer the question, Did life ever arise elsewhere in the solar system?

Life requires a source of liquid water (only a dab will do), a source of energy, and a source of chemical materials. Life is not particular about what it "eats" and seems able to adapt to whatever chemical energy source is available. Life on Earth can exist on hydrogen, carbon dioxide, hydrogen sulfide, iron, manganese, and host of other energy sources, so that martian life could do the same on mineral deposits and gases escaping from the interior. But liquid water is an absolute requirement. The search for extant life should therefore focus on areas where surface mineralogy and subsurface sounding indicates a concentration of ice, and perhaps water, at accessible depths below the surface. Sites where volatiles are escaping, particularly with some reduced components such as hydrogen and methane, would be particularly exciting.

Likewise, the search for past rather than extant martian life is the search for locations of past liquid water on the planet. Tectonic activity on the planet will likely have left samples on the surface with some fossil evidence of past biological processes. This fossil evidence could be in the form of characteristic elemental distributions, isotope ratios, organic residue and perhaps even microfossil morphologies in carefully selected rock samples. Finding such evidence can be accomplished with an orderly procedure starting with a search from orbit for a set of promising sites, followed by an in situ examination of the identified sites to certify which is most suitable, and finally concluding with in-depth study at one more particularly promising site to include very detailed local geochemical examination, drill samples, and perhaps even sample return to Earth, depending on in situ measurement capability at that time.

For its scientific value as well as for its enduring place in human consciousness, Mars is the ultimate destination for humans in the next 50 years. Until that time, robotic missions will play an important role in defining the activities of human explorers, characterizing the martian environment, searching for potential resources, and emplacing assets on the surface.

The ongoing U.S. Mars Exploration program has maintained a continuing presence at Mars since 1997. U.S. and European spacecraft operating in orbit and the Mars rovers Spirit and Opportunity operating on the surface are still making discoveries, one after another, that add to the impression of a once-wet Mars and a place ever more interesting for further exploration.

Mars beckons. There will be a day when humans will join our robots on the surface of the fourth planet from the Sun. The first stop may be the Moon, with a layover at an asteroid, and perhaps a stop at one of the moons Phobos or Deimos. But on the 100th anniversary of the space age, 50 years from now, humans will have walked on Mars.

BEYOND MARS

Beyond Mars lies the outer solar system, land of the giant planets Jupiter, Saturn, Uranus, and Neptune. And fencing off the outer solar system from the inner lays the asteroid belt, with Mars at its inner boundary and Jupiter beyond its outer boundary. These regions beyond Mars are out of reach for human exploration in the next 50 years, but they have been and continue to be regions explored by our robotic spacecraft. Fifty years ago at the onset of the IGY, and even after the launch of Sputnik, it might have seemed that the Moon and the nearest planets, Mars and Venus, might be attainable, but we have explored well beyond them. We have ventured throughout the entire solar system with our spacecraft, and the adventure continues. At this writing, a U.S. spacecraft is on its way to the innermost planet, Mercury. Europe has spacecraft in orbit about Venus and Mars, Japan and China have spacecraft orbiting the Moon, with India and the U.S. to follow. Japan has a spacecraft returning from a near-Earth asteroid, and

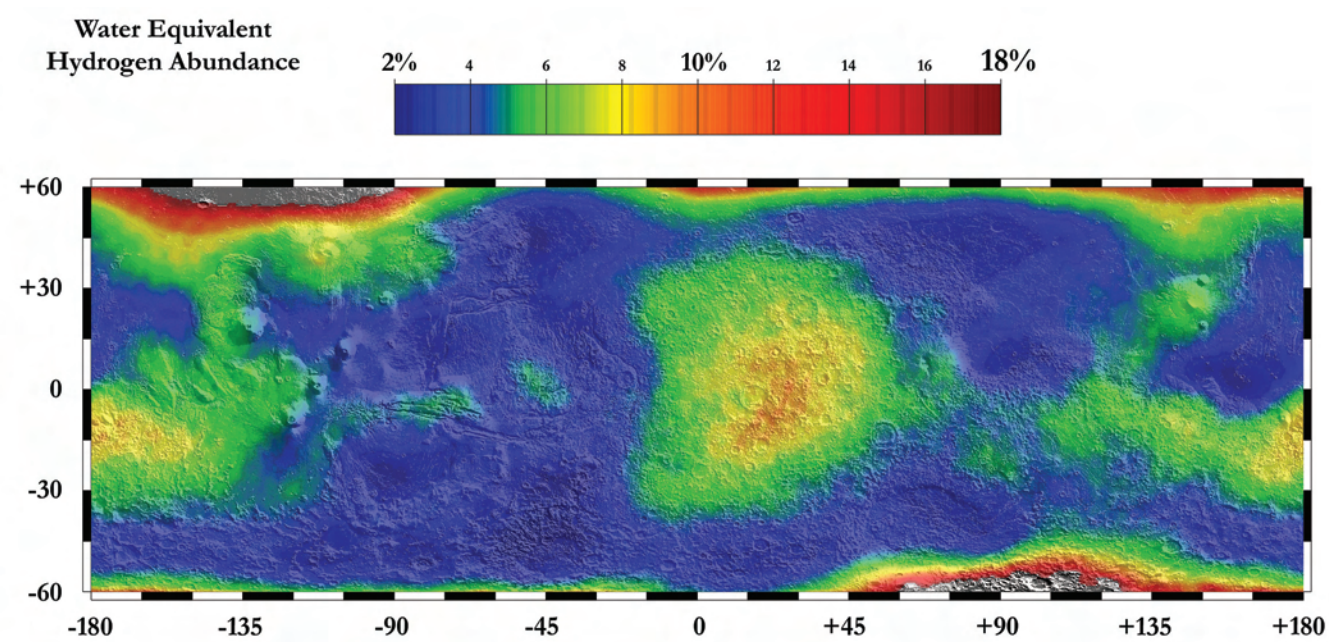

FIGURE 3.15 Is Mars a place for humans? Map of near-surface ice from the Mars Odyssey mission. To understand the potential for past or present life and the future habitability of Mars, we must determine the history of water and its form, amount, and distribution on the planet. SOURCE: Courtesy of Los Alamos National Laboratory.

the United States has a spacecraft on the way to two main belt asteroids. The United States has two orbiters and two rovers at Mars, with another lander on the way, the U.S./European Cassini spacecraft continues to orbit Saturn, and the U.S. New Horizons spacecraft is on its way to Pluto-Charon and the Kuiper Belt.

Asteroids

Japan's Hayabusa spacecraft approached the surface of Itokawa to within a few feet and activated its sampling system. It is returning from its trip and hopefully will land a sample of the asteroid on Earth in 2010. The U.S. Dawn spacecraft is on its way to two of the largest main belt asteroids, Vesta and Ceres, where it will orbit each in turn to carry out the first ever comprehensive investigation of such bodies.

Jupiter and the Galilean Moons

Beyond the main asteroid belt lies massive Jupiter with its large Galilean moons. There seems little doubt after the Galileo orbiter mission that Callisto, Ganymede, and Europa harbor subsurface oceans, but their fluidity, depth, and extent are unknown. The most intriguing is ice-covered Europa with surface manifestations of a more mobile fluid underneath (Figure 3.19). If there is an ocean beneath this ice, then it is sustained by heat flow from the interior of Europa, quite likely by

FIGURE 3.16 Mars: What might we find? Not these. SOURCE: H.G. Wells, The things that live on Mars, *Cosmopolitan*, March 1908. Illustration by William R. Leigh.

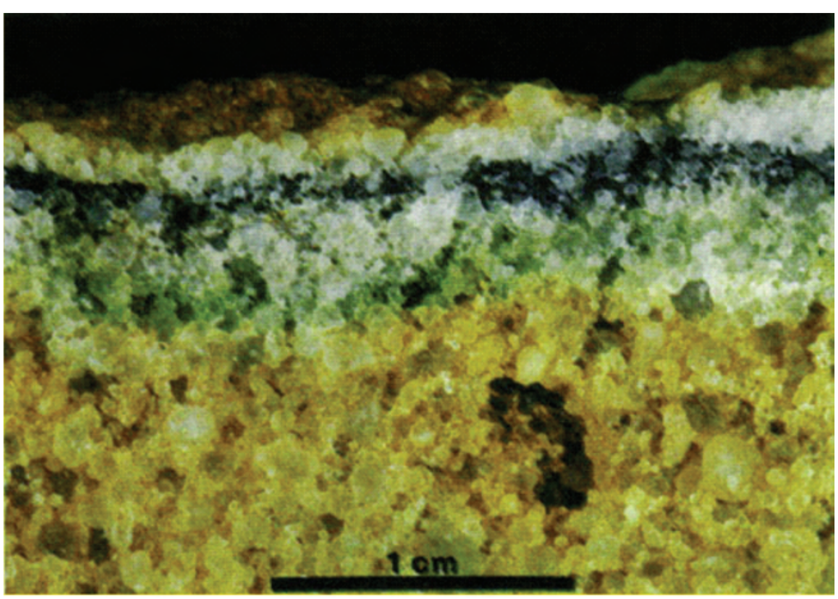

FIGURE 3.17 Microbes living in rocks deep within Earth. SOURCE: Courtesy of NASA.

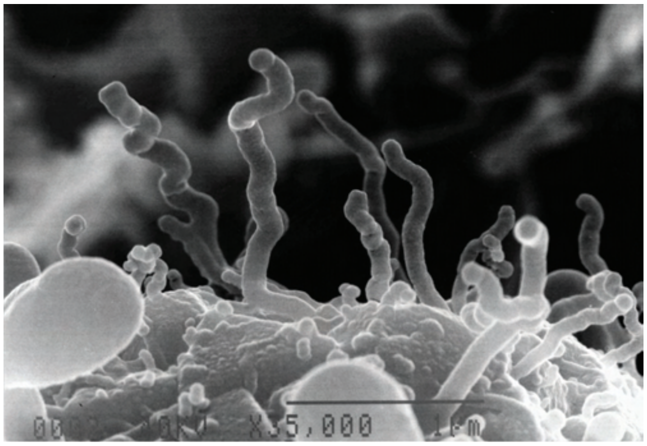

FIGURE 3.18 Microbes living on ice in Antarctica. SOURCE: Courtesy of Philippa Uwins, the Discovery Team, and the Queensland University of Australia Centre for Microscopy and Microanalysis.

tectonic processes that might also bring mineralogical nutrients into the ocean. On Earth, this is a recipe for life. There are plans in the United States and Europe for sending a robotic spacecraft to investigate the Galilean satellites in more detail and in particular to orbit Europa and investigate the depth and extent of its subsurface ocean.

Saturn and Titan

Beyond Jupiter lies perhaps the most magnificent and spectacular planet in the solar system, ringed Saturn. The Cassini spacecraft now orbits Saturn—investigating the planet, its atmosphere, magnetosphere, rings, and retinue of moons. While Jupiter has four large Galilean moons, Saturn has seven somewhat

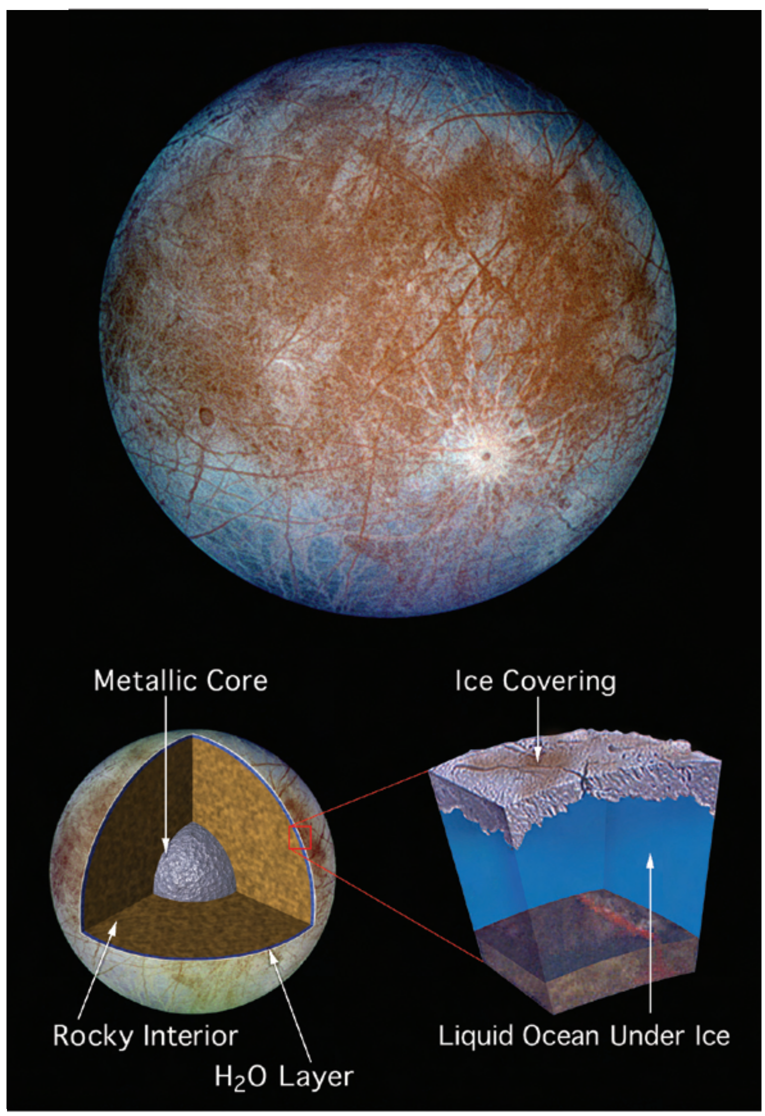

FIGURE 3.19 Europa and its subsurface ocean. SOURCE: *Top:* Courtesy of NASA/JPL/DLR. *Bottom:* Courtesy of NASA/JPL.

smaller icy moons and one giant moon, Titan, which is larger than the planet Mercury. Titan is the only moon in the solar system with a thick atmosphere. Shortly after it arrived at Saturn, the Cassini spacecraft dispatched the European Huygens spacecraft to Titan, where it entered the atmosphere, floated down on a parachute, and landed on Titan's surface. Cassini continues to make close passes at Titan, examining it with its cameras, spectrometers, and imaging radar.

Titan's surface and atmosphere show strong analogies to Earth, although it is much colder—near 93 K at the surface where methane plays a similar role on Titan that water does on Earth. Photolysis of methane leads to an atmosphere loaded with organic aerosols and hydrocarbon clouds. There are clear signs of hydrocarbon rain and mist near the surface with coastal deltas very similar to Earth's that open onto dark flat plains resembling oceans in appearance. These plains appear episodically to become covered with liquid hydrocarbon. Huygens landed on such a plain, and its instruments indicated that the surface seems to have the consistency of a mud wet with methane and other hydrocarbons. The Cassini radar has returned images of large lakes of hydrocarbon fluid in the polar regions of Titan (see Figure 3.21). Titan has indeed turned out to be a fascinating place and may hold clues to the earliest chemistry on Earth that enabled the origin of biology on our planet.

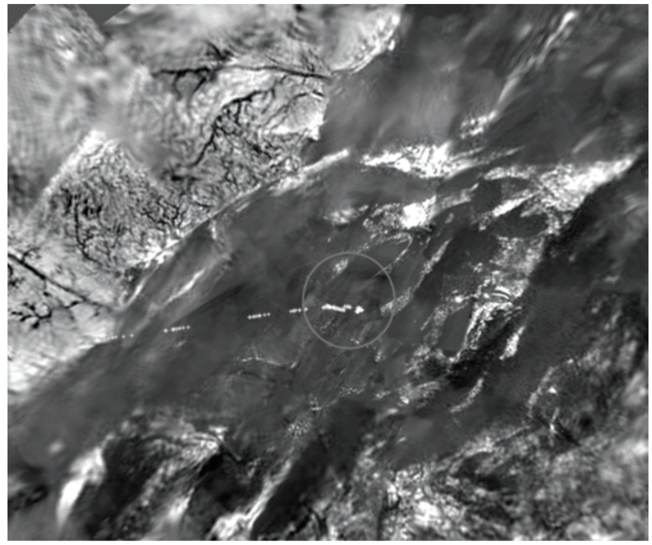

FIGURE 3.20 Huygens image of Titan's surface from 8 km altitude showing coastal-like deltas flowing into dark plains. SOURCE: Courtesy of ESA/NASA/JPL/University of Arizona.

Pluto-Charon, the Kuiper Belt, and Comets

Launched in January 2006, the New Horizons spacecraft will arrive in the vicinity of the dwarf double planet Pluto-Charon in July 2015, returning data and high-resolution images of one of the largest members of the Kuiper Belt of icy dwarf objects at the fringe of our solar system. It will proceed onward to visit at least one other yet unidentified member of the Kuiper Belt.

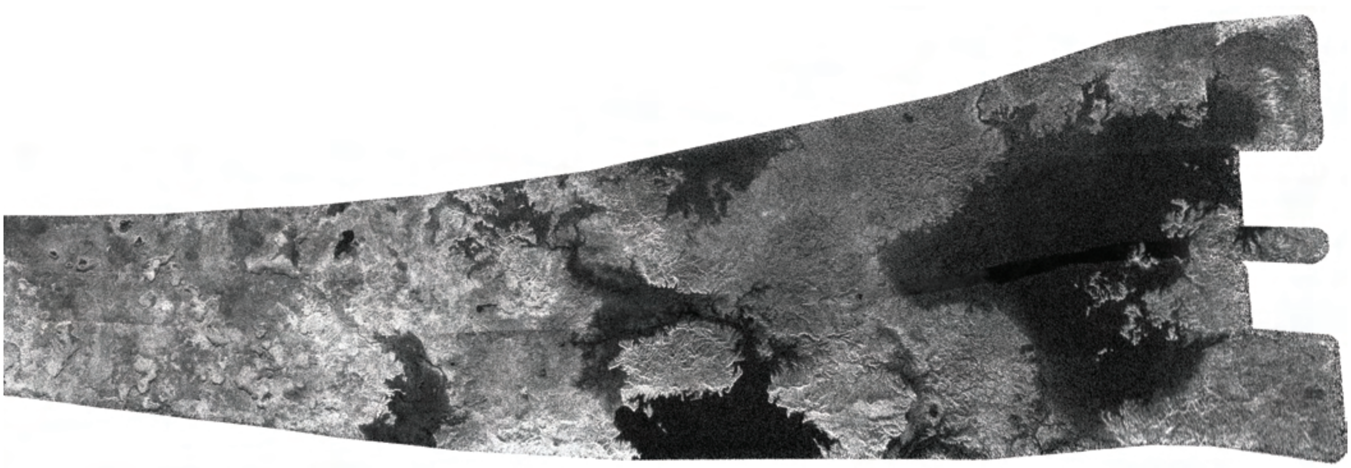

FIGURE 3.21 Cassini orbiter radar image of Titan at a northern latitude showing dark hydrocarbon lakes. SOURCE: Courtesy of NASA/JPL.

The Kuiper Belt is the storehouse of comets that occasionally get perturbed through close encounters and are thrown inward towards the Sun where they make their spectacular appearance with large halos of gas, dust, and ionized curved tails. We have even sent our spacecraft to intercept these objects, returning data and images on flybys, one returning samples after flying through the coma of Wild 2, and another impacting Tempel I to examine the resulting plume for clues to its composition and structure.

Beyond Our Own Solar System

Beyond our solar system, one day we will find another Earth-like planet in the sights of our space telescopes, a blue dot circling another star, with oceans, continents, and signs of life. This will be one of the most enduring products from space exploration in the 21st century, just as that first image of our own planet from Apollo 8 is one of the most enduring products of the 20th century. It is the Moon that first intrigued us and drew us into space, next is Mars, and finally it is the notion that we are not alone, that somewhere out there is a planet like our own, a planet with life on it, and perhaps a civilization—galactic neighbors with whom we can share the glory of the universe.

WE'VE COME A LONG WAY IN THE LAST 50 YEARS

It is amazing how far we have come since we began this adventure 50 years ago, from confinement on Earth to spacecraft on their way to the very extreme boundaries of the solar system and beyond. We have walked on the Moon and will again. We will eventually walk on Mars. And in the meantime we will continue to explore and make new discoveries with our robotic spacecraft, extensions of our human senses, that can go where no human can ever go and where we have not yet seen fit to send them.

CARL E. WALZ is a Colonel in the U.S. Air Force (USAF; retired) and a former NASA astronaut. From 1979 to 1982, he was responsible for analysis of radioactive samples from the Atomic Energy Detection System at McClellan Air Force Base, California. The subsequent year was spent in study as a Flight Test Engineer at the USAF Test Pilot School, Edwards Air Force Base, California. Col. Walz later served as a flight test engineer to the F-16 Combined Test Force at Edwards Air Force Base, where he worked on a variety of F-16C airframe avionics and armament development program and as a flight test manager at Detachment 3, Air Force Flight Test Center. He is a veteran of four space flights and one International Space Station expedition and has logged a total of 231 days in space. In addition to his flights, he served in a variety of technical and management positions within the Astronaut Office at Johnson Space Center. Dr. Walz most recently served as director for the Advanced Capabilities Division in the Exploration Systems Mission Directorate at NASA Headquarters. In the division, he played a key role in developing technologies that will lead to greater capabilities in robotic and human exploration of the solar system. He oversaw work in many fields, including nuclear power and propulsion, human adaptation to spaceflight, and lunar exploration. Many of these programs will help humans return to the moon and develop a sustained presence there. He retired from NASA in 2008 to pursue interests in the private sector. He has received numerous awards and honors, including four NASA Space Flight Medals, a NASA Distinguished Service Medal, and the NASA Exceptional Service Medal.

Leaving the Planet: Science and Technology Results on the International Space Station

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INTRODUCTION

This paper will discuss the significance of the International Space Station (ISS) for science, but also its role in the evolution of our activities toward longer duration spaceflights. The "leaving the planet" title was selected in the belief that as a species we are destined to explore and to visit new worlds, and, perhaps, expand our civilization there. Starting with a brief overview of space stations in general, from an historical perspective, the paper will then focus on the ISS in terms of its assembly, operations, and overall research themes and results. The final portion of the paper will be a discussion about the future.

Chesley Bonestell's picture of Werner Von Braun's concept for a space station (Figure 4.1) appeared in *Collier's* magazine in 1952. It's fascinating to think that Von Braun had this vision back in 1946 when World War II had just ended. So even back then, before the International Geophysical Year, people were thinking about what it would be like for humans to leave the planet and what the possibilities might be.

The toroidal design actually incorporated artificial gravity, so that people could walk around the inside at 1 G (the acceleration that Earth imparts to objects on or near its surface).

THE FIRST SPACE STATIONS

The United States did not build that kind of space station and neither did the Russians. However, the Russians, in a similar vein to us, had an idea that a space station capability should be developed, so they created a series of space stations called Salyut. Part of these stations were civilian-research oriented, and part of them were dedicated to military research.

FIGURE 4.1 Von Braun's Space Station as imagined by Chester Bonestell. Reproduced with permission of Bonestell Space Art. SOURCE: Reproduced with permission of Bonestell Space Art.

FIGURE 4.2 Salyut Series—USSR's foothold in space. SOURCE: Courtesy of NASA/JPL-Caltech.

Salyut first flew April 19, 1971. Two crews visited Salyut 1, but one visiting crew could not actually dock. The first crew experienced problems with the docking system, and so they ended up coming home early without actually staying on the station. The second crew successfully docked and stayed for approximately 23 days. However, due to a failure of the Soyuz capsule when they re-entered the atmosphere, all the crewmembers died. These experiences show that leaving Earth and going to space has tremendous risks. The Russians developed several more Salyut and Almaz space stations. The next three after Salyut-1 were failures. Either the Proton rocket they used blew up on the pad, or the station simply did not achieve orbit. So it was not until Salyut-4 that they were finally able to reestablish an orbiting station and carry out a succession of successful missions. Salyuts 4, 5, 6, and 7 were very successful, having a number of crewmembers visit and demonstrating a lot of space capabilities.

In the United States we had a military Manned Orbiting Laboratory (MOL) program that was planned but eventually did not get funded and did not fly. Although the United States decided not to carry out the MOL program, we did decide to do the civilian NASA Skylab program. Skylab was our first U.S. space station. It was a 75-ton laboratory built from a Saturn IVB stage, the upper stage of the Saturn V rocket. Skylab was launched into space on May 14, 1973, and was occupied by three crews, Skylab 2, 3, and 4. The crews stayed for periods of 28, 59, and then 84 days, respectively, during 1973 and 1974. From Figure 4.3 you can see that Skylab is asymmetric. During launch, aerodynamic forces caused one of the solar arrays to be ripped off. Fortunately this problem did not damage the pressurized module. The aerodynamic forces also ripped off some of the thermal protection system. So one of the first orders of business with Skylab was to actually do an in-flight repair and deploy a new sunshade during a spacewalk. That spacewalk was performed by the first crew and allowed the Skylab to function very well for the three missions.

The Skylab crews performed a number of microgravity physical science experiments and a number of physiological experiments, looking at how microgravity affected the human body, and also operated a solar observator (Figure 4.4).

Skylab stayed in space until 1979. After the Apollo program ended in 1975, there was a plan that called for the space shuttle to fly to Skylab and re-boost it, giving it extra time on orbit. Unfortunately the first flight of the shuttle was delayed until 1981. Skylab's orbit decayed, and it re-entered Earth's atmosphere and mostly burned up. However, some charred hardware landed in Australia.

FIGURE 4.3 Skylab—America's first experimental space station launched in 1973. SOURCE: Courtesy of NASA.

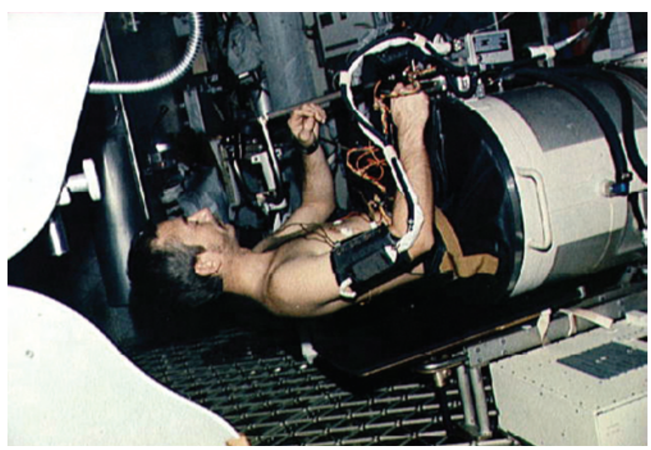

FIGURE 4.4 Skylab astronaut Owen Garriott lies in a lower body negative pressure device—a big vacuum cleaner that simulates the effects of gravity on the lower body. NASA Photo ID: SL3-108-1278. SOURCE: Courtesy of NASA.

MIR AND SHUTTLE-MIR

In parallel with the U.S. Skylab activities the Russians were building and flying their Salyut stations. Then the Russians decided that they wanted to do something a little bit different and more advanced, and they launched a very successful modular space station, the Mir (Figure 4.5).

The word "Mir" means "World" or "Peace." The first element of the space complex was launched on February 19, 1986. Mir incorporated an autonomous rendezvous and docking system, the Kurs system, which allowed these large modules to be able to find each other and to autonomously dock. This was highly sophisticated technology for its time. When crews were on board the Mir they had a backup capability where the crew could dock additional modules as well. They also had a very short but very capable robotic arm that could move the modules around from the docking configuration to their final configuration. Mir consisted of a number of modules. It started out with a base block that really had its heritage from the Salyut series and provided vital crew life support and habitability functions. In addition, other modules included Kristall, Priroda, and Spektr. These modules reflected some of the science that would be done in space.

Seven U.S. astronauts flew on Mir during the Shuttle–Mir cooperative program, the first being Norman Thagard. From the Shuttle–Mir experience, the U.S. learned a great deal about what was involved in flying long-duration missions. Our NASA long-duration spaceflight experience up until that time, excluding the Skylab missions, involved Spacelab-Shuttle flights of about 2 weeks duration. Jumping to durations of several months was a completely different story. The chance for the United States to participate in the Shuttle-Mir gave us opportunities for a close look at what kinds of challenges existed for the flight crews, design and sustaining engineers, and flight controllers in mission control for long-duration flights. Figure 4.6 shows Shannon Lucid with Sasha Kaleri. Lucid was the second American to make a long stay on Mir. She was aboard Mir for 186 days.

We learned quite a bit from the Shuttle-Mir program, including having a chance to look at some of the Russian technology. Typically the Russians could bring things up to their space stations, but they could not bring them back down. So they would use them up, and then they would just throw them away. The shuttle, however, provided a capability to bring back large items of equipment, thus giving the United States an opportunity to see what worked, what did not work, and help advance technology.

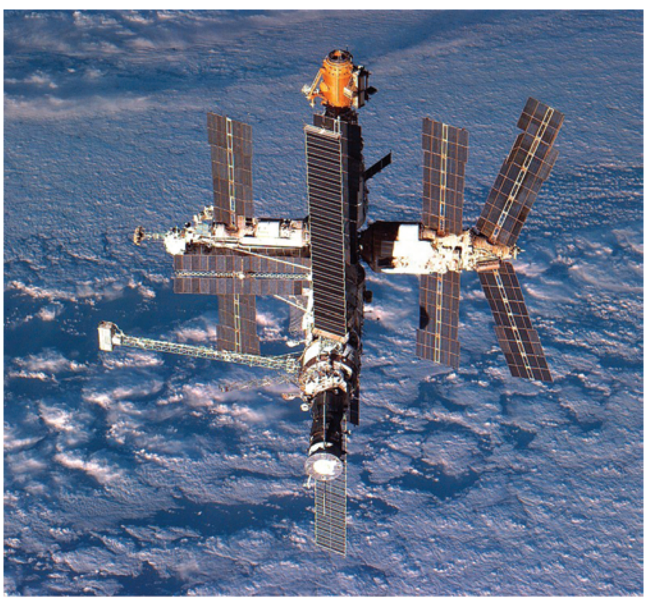

FIGURE 4.5 Mir—Russia's long-duration spaceflight testbed. SOURCE: Courtesy of NASA.

FIGURE 4.6 Shuttle-Mir: Beginning of U.S.-Russian collaboration for the long-duration spaceflight. Astronaut Shannon Lucid floats with her Russian pressure suit in the Mir space station central node. She is joined by Mir-22 flight engineer Alexander Kaleri. SOURCE: Courtesy of NASA.

THE INTERNATIONAL SPACE STATION

Now let's move on from the Mir program to a historical perspective of the ISS. The ISS involves a consortium of nations—the United States, Russia, Canada, the European Space Agency, and Japan—working together on its development and operation. The first launch of ISS was a Russian element, the Functional Cargo Block, or FGB, on November 20, 1998. It was launched on a Proton rocket from Baikonur, thus initiating a new era of human spaceflight.

Shortly thereafter, on December 4, 1998, we launched our first U.S. element, Node-1, during the STS-88 mission. Node-1 and the FGB were attached using the shuttle's robotic arm.

Once those missions had taken place there was a fairly large time gap before construction continued. The next module to go up was the Russian Service Module, launched on July 12, 2000, which is basically the living compartment for the ISS, providing the early life support system for the station. It was behind schedule, so there was a hiatus of about a year and a half in assembly flights, which enabled us to do a lot of testing of our ISS elements on the ground to verify their proper functionality. The launch of the service module broke a logjam and initiated the launch of a

FIGURE 4.7 International Space Station functional cargo block—first element. ISS Zarya module as seen from STS-88. SOURCE: Courtesy of NASA.

FIGURE 4.8 International Space Station: U.S. element and Russian element joined in space. NASA Photo ID: STS088-703-032. SOURCE: Courtesy of NASA.

number of shuttle flights which added, among other things, the Z1 Truss, which provided the control moment gyros and the first U.S. solar arrays that provide power for the station. The first crew launched to the ISS on October 31, 2001, from Baikonur, and then in February 2001, we brought up the Destiny Laboratory, which is the U.S. laboratory. At this point we were ready to begin scientific research onboard the space station, although construction of the ISS still was not complete. We continued on with a number of assembly flights—adding an airlock, a robotic arm (provided by Canada), and starting to build out the truss elements, but the assembly was halted due to the Columbia accident, which occurred on February 1, 2003. It took us until July 2005 to get the shuttle flying again. The STS-114 mission was the first post-accident shuttle flight, and it was mostly a resupply mission. Another year passed before we actually started bringing up more the elements, starting with a build-out of the solar trusses. The October 2007 configuration of the space station is pictured in Figure 4.9.

The completed ISS consists of hardware components developed by the five program partners. The following components are included:

- Zarya (Functional Cargo Block)
- Unity Node 1
- Zvezda Service Module
- Z1 Truss
- P6 Truss with a Solar Array
- Destiny Laboratory
- External Stowage Platform
- Canadarm2 Robotic Arm
- Quest Joint Airlock
- Pirs Docking Compartment & Airlock
- S0 Truss
- Mobile Base System for Canadarm
- S1 Truss
- P1 Truss
- ESP 2

FIGURE 4.9 International Space Station, October 2007. SOURCE: Courtesy of NASA.

- P3/P4 Truss with Solar Array
- P5 Truss
- S3/S4 Truss with Solar Array
- S5 Truss
- External Stowage Platform 3
- Harmony Node 2

The next flight is on the launch pad right now (January 2008). We are hoping to launch in the early February time frame.[1] That flight will bring up Europe's Columbus laboratory module. Future components to bring the ISS to its assembly complete configuration include:

- Japanese Logistics Module
- Special Purpose Dexterous Manipulator
- Japanese Pressurized Module
- JEM Robotic Arm
- S6 Truss with Solar Array
- Japanese Exposed Facility
- Docking Cargo Module
- Node 3 and Cupola
- EXPRESS Logistics Carriers 5, 1

The year 2008 should also see the first flight of ESA's Autonomous Transfer Vehicle (ATV) which will dock to the Russian Service Module and be used for station re-supply and orbit re-boost. The Japanese also plan to contribute the HII Transfer Vehicle (HTV) for station re-supply. If all goes well we will increase the crew size from three to six in 2009.

All in all, the ISS is going to be quite a vehicle when fully assembled, and we have made tremendous strides since we've recovered from the Columbia accident. All the ISS partners are looking forward to the completion of the construction in the next couple of years.

ISS Operational Results

The ISS, as you can imagine, is a very complex platform as regards engineering integration and scientific research. One fact worthy of note is that we did not put all the hardware together on the ground before launching it into orbit. We put almost all the U.S. elements together on the ground, but Russian elements were in Russia and the U.S. elements were in the United States. They had similar data buses, but they were not identical. Therefore we had to do testing using surrogate systems and hope those surrogate systems really did reflect how the actual space systems work. What we found when we put the two surrogate systems together for the first time, Russian and U.S., was they did not play together. There was a slight difference in the timing between the two data busses. We discovered this shortly before we were set to launch the Russian Service Module where, in orbit, U.S. and Russian data buses would have to communicate together. Fortunately, our engineers were able to scramble and resolve that timing issue, and their speedy work allowed us to launch the service module and then unleash the ISS construction flood gates.

And that was only one issue. There are numerous other issues that had to do with various systems, such as propellants and the control of the solar arrays, when different spacecraft come to dock. We are continuously learning how to operate this very large, complex vehicle. We are also gaining experience in crew operations, systems operations, and crew-system interface options.

As regards crew operations and training; this is the first large-scale human spaceflight effort to have a highly integrated international crew. Again, with a consortium of nations that are working together, we have to figure out ways to build teamwork in crews with varied backgrounds so that they can work together effectively. This applies both to the flight and ground crews. The ISS partners have worked very hard to do that.

The ISS will also serve as a test-bed to develop skills that will be needed for going to the Moon, and, at some time in the future, for going to Mars. Imagine if you were going to Mars, for example. Most probably, your training would not be complete when you left Earth. It would be completed on the 6- to 9-month trip out to Mars. On the ISS we are trying to develop protocols and procedures to use in-flight training capabilities; for example, ways to do refresher training. We will also be studying how we can train more for broad skills rather than doing very specific task training, When you get to Mars, or even on the station, you cannot anticipate everything that your crew might have to do. You make sure that your crews have the basic toolbox of skills and that they can adapt, do some rehearsals in space, and

[1]STS-122 was successfully launched on February 7, 2008.

FIGURE 4.10 Image of International Space Station at assembly complete. Backdropped by a blue and white Earth, the International Space Station is seen from Space Shuttle Discovery as the two spacecraft begin their relative separation. Earlier the STS-119 and Expedition, 18 crews concluded 9 days, 20 hours, and 10 minutes of cooperative work onboard the shuttle and station. Undocking of the two spacecraft occurred on March 25, 2009. NASA Photo ID: S119-E-009662. SOURCE: Courtesy of NASA.

then execute successful operations, such as spacewalks, for example. There will also be a need for advanced habitation and life support systems. When we go to the Moon, and even more so when we go to Mars, we have to cut the supply cord. It's going to be very difficult, if not impossible, to re-supply missions to Mars. Therefore closed-loop life support systems are very important, as well as evolved medical care and counter measures. These kinds of capabilities may be needed for the Moon, but will definitely be needed for Mars.

With the ISS, we can refine some of these capabilities. We have launched our oxygen generation system already, and we hope by the end of the year to launch the rest of our environmental life support system suite to more completely close the environmental loop on the station, so we can take urine, for example, and reprocess, purify, and drink it or make oxygen from it. The oxygen generation system, for example, uses water, so we could use reprocessed urine to make oxygen to breathe! Also, we're looking at some of the needs for healthcare and how we can develop better health maintenance systems and exercise protocols for our crew members.

Another area covers automation, robotics and human–machine interface. We will have two robotic arms onboard the ISS. How can we best use these arms and the crew interfaces necessary to operate them, not only by the crew but by the ground? These are capabilities that are going to be needed for the Moon. We are already involved in work sponsored by the Advanced Capabilities Division at NASA Headquarters looking at robotic agents to help crew members on the lunar surface. For going to Mars, we're going to need a big spacecraft. We will probably need automated assembly capabilities to put such a spacecraft together, as it will be launched in pieces on heavy-lift launch vehicles. Also, as we go farther away from Earth, we will need better autonomous systems. So our ISS experience can help us to validate our robotic designs, concepts, tools, and some of our operational scenarios and test what works and what does not for in-space assembly.

ISS Research Themes and Results

ISS research themes can be grouped into five areas as:

- Assuring the survival of humans traveling far from Earth,
- Expanding our understanding of the laws of nature and enriching our lives on Earth,
- Creating technology to enable future explorers to venture beyond low Earth orbit,
- Observing Earth, and
- Educating and inspiring the next generation to take the journey.

The website http://www.nasa.gov/mission_pages/station/science/experiments is a really useful resource because you can see all the various investigations that we have done or will be doing onboard the ISS. Results, when appropriate, are listed there as well, making it a great resource.

Now for a few science statistics. Through Expedition 15, we have initiated 125 investigations, 94 of which have been completed. On Expedition 15, we conducted 38 investigations. Interestingly, the initial prognosis for Expedition 16 was that we would be lucky if we got any science done at all because the crew would be so busy with robotics and space walks. Well, it turns out that although they are busy with those things, we have 60 investigations underway on the ISS right now, and the crew, Dan Tani, Peggy Whitson, and Yuri Malenchenko are doing a great job of completing these experiments. So given the limitations of small crews and ongoing assembly, we are doing really well in accomplishing science on the ISS. In fact, not the next shuttle, but the shuttle after that has some additional space available and we were able to get six shuttle middeck lockers assigned to bring up additional science investigations to conduct on the station.

Currently we have nine dedicated U.S. science racks on orbit. By the end of the year we'll have two more—the Combustion Integrated Rack (CIR) and another express rack that is scheduled to launch by the end of the year. Shortly after that, we will have a number of other research racks available, including the Fluids Integrated Rack, the Material Science Research Rack, the Window Observation Research Facility, and the Muscle Atrophy Research and Exercise System. Furthermore, because we are in a partnership with the international community, we also have opportunities to utilize facilities in their laboratories; the ESA Columbus Module and JAXA's Kibo pressurized laboratory module.

Let's now address the issue of assuring the survival of humans traveling far from Earth. By way of example let's consider three ongoing or recently completed investigations.

One of the issues that we have during long-duration space travel is that our bones de-mineralize. The freed-up calcium then has to go someplace. It goes through the bloodstream to the kidneys and it can, under certain conditions, form renal stones. While we have not had people in the U.S. program get renal stones, it has happened on the Russian side. We therefore carried out an experiment utilizing potassium citrate to help reduce the risk of renal stones. Researchers found that the potassium citrate was very effective, and it will now transition from an experimental stage to medical practice. This represents a big success from ISS research.

Exercise during long-duration spaceflight is very important. If we were leaving the planet and never coming back to Earth, exercise would not be a big deal, because if we were just going to stay in microgravity our bodies could change and would adapt to space, and we would be fine. But the fact that we have to return to a gravity field means that we have to stay in shape while we are in microgravity. So on the ISS we have the treadmill, which you see in Figure 4.11.

We also have two exercise bikes, one Russian, one U.S., and also a resistive exercise device. We typically have 2½ hours a day where we are allowed to exercise. In the FOOT experiment, we actually had sensors located on the pants that Expedition 6 commander Ken Bowersox is wearing in Figure 4.11. These pants measure bending angles of the knee during exercise. There was also a sensor in his running shoe to record the force of his heel and toe strikes when he was running on the treadmill. In the picture you can see the bungees attached to Ken. These bungees hold us to the treadmill and provide a force that we thought was equal to about what our weight was on Earth when we would exercise. It turned out from data collected during the FOOT experiment that the force, the reaction force that we were getting while running, was less than what we had expected. That was distressing because we thought we were getting a good stimulus to our bones; but we were only getting about 80 percent. The FOOT experiment was the first to measure that. As it turns out, we have subsequently set up this FOOT experiment on the ground and in bed-rest studies, and we've seen that same effect. One of the things that we found was that because the treadmill has a vibration isolation system, designed to preserve the microgravity environment on the station, when we step on to that treadmill, the treadmill actually moves away from us and so it reduces the amount of force that we get. This was an interesting result and it will change the way we do future mountings for the next

FIGURE 4.11 Astronaut Kenneth D. Bowersox, Expedition Six mission commander, wearing the Lower Extremity Monitoring Suit, participates in the Foot/Ground Reaction Forces During Spaceflight experiment. NASA Photo ID: ISS006-E-11016 (24 December 2002). SOURCE: Courtesy of NASA.

treadmill, the T2 as it's called, that will be located in the Node-3.

In the area of nutrition, one of the things we're trying to understand is, what is space normal? How do peoples' bodies change while they're up there in space? So we have established the Nutrition experiment involving the taking of blood and urine samples regularly, processing them in a centrifuge, and storing them in a minus 80 degree freezer to await return to Earth for analysis. We are trying to do a very comprehensive study to track nutritional markers such as vitamins and minerals using these in-flight blood and urine samples to understand the trends for long-duration astronauts.

Going hand-in-hand with nutrition is another experiment called Stability. It is possible that the food we bring up to the ISS actually degrades in space and that could affect astronaut nutrition. So we are trying to understand what happens to the food that is up there for up to a year before it is used. Furthermore, it has been reported that some of our pharmaceuticals, when we have brought them back from space, are shown to be ineffective. So, what happens to those pharmaceuticals in space? We think it might be radiation, but we're going to try to find out definitively.

So these are just some of the examples of things that we are doing on the ISS to try to assure the survival of humans traveling away from Earth.

We are also trying to expand our understanding of the laws of nature. The opportunity to conduct experiments in microgravity is unique. On Earth when we do experiments, the gravity (G) factor is always present. We take it for granted. But we hope to try to understand some forces that do not have the kind of impact that gravity does, but, nonetheless, affect how things occur in the physical world. Going into space allows us to better understand these fundamental phenomena. By way of example let's look at three experiments. The first one is called the BCAT, the Binary Colloidal Alloy Test, which is trying to get fundamental information on the rate of phase separation especially near the critical point for certain alloys. Colloids[2] occur everywhere in nature and in industrial processes. So getting a better fundamental understanding of how colloids behave is very important to these industrial processes. In fact, J. Hunter Waite, Jr., Space Research Laboratory, University of Michigan, who is the principal investigator of colloids, has been approached by a detergent manufacturer to try to understand better some of the forces involved there. So the word is getting out that what we develop or understand from space can have implications on Earth.

Another exciting thing we are doing is trying to understand capillary flow. In a gravity field the capillary flow can be overcome by the forces of gravity. However, in space it is very easy to observe and investigate capillary flow, in this particular case using a sample in a jar-like container. In conducting the experiment, we measure and photograph how the liquid behaves and

[2]A colloid is a type of mechanical mixture where the particles of one substance are dispersed evenly, but not dissolved, throughout another.

how it wets the container along the edges. We then compare it to computer simulations of what the behavior is expected be theoretically. In one experiment one example behaved per the theory to within one percent, while another one under different conditions behaved completely differently, compared to what was expected theoretically. This is an example of where you get one question answered and another question pops up. This experiment has been very useful in helping us to understand capillary flow and will be very important in helping us to control fluids in space. In space, fluids are important for everything from propellant systems to life support systems. So the better we understand how fluids behave and how we can influence them, the more successful we will be in building new spacecraft.

The last experiment we will discuss here is a material science experiment, called C-SLAM, the coarsening in solid liquid mixtures. Basically we are looking at the kinetics of metallic particle growth not affected by buoyancy or other gravitational forces. You have small particles in the mixture, and they tend to get smaller, while the big particles tend to get bigger. We're trying to understand the mechanics and rates of this coarsening process. This has a wide variety of applications, from the manufacture of turbine blades to how dental fillings behave when they're installed in your mouth.

All three experiments are still active onboard the station. In the case of two of them (BCAT and Capillary Flow), you can shake them up and re-do the tests. They actually have a lot of capability. The CSLAM employs equipment set up in a microgravity science glove box, because it is a tin-lead mixture. There is a chance that the lead could get out into the station environment, so we actually have a glove box there where we can do these experiments and protect that onboard environment.

Now let's consider some examples of the technologies that we're developing to enable our crews to go beyond low Earth orbit. We have developed a "lab on a chip" portable test system to do microbial monitoring. One of the things we have to do during a long mission is make sure that we do not have microbes growing onboard the space vehicle, which could be bad for peoples' health. They can also be bad for the machinery, especially some of the liquid systems. Microbes, basically slime colonies, can grow and cause problems in pumps and in tubing. So we try to keep track of that. During flights, our standard way of doing microbial monitoring was to use gels and a Petri dish, making observations over several days. The LOCAD portable test system shown in Figure 4.12, that Suni Williams is demonstrating, allows us to get a near-immediate microbial assay, thus saving a lot of time and giving us more accurate results. So if we do have a problem with microbes we can take action more quickly.

The next experiment is called smoke and aerosols

FIGURE 4.12 Astronaut Sunita L. Williams, Expedition 14 flight engineer, works with the Lab-on-a-Chip Application Development-Portable Test System (LOCAD-PTS) experiment in the Destiny laboratory of the International Space Station. SOURCE: Courtesy of NASA.

in microgravity (SAME). SAME is operated in the glove box because it generates smoke. What we're looking at is the how smoke forms, what form the smoke particles takes, and how it affects some prototype fire detectors. One of the bad things that could happen on a space station is a fire like the one on Mir in 1997. We are trying to make sure that our fire detectors are (1) responsive when there is a fire and (2) do not give us any false alarms. So this experiment will allow us to better understand the characteristics of smoke from materials on space stations, and then allow us to develop better smoke detectors.

Another technology shown here is an electronic nose (E-nose) Air Event Monitor (Figure 4.13). Again, it gives us a quicker understanding of the kinds of events that might happen in the environment where we would have to take action either by turning on atmospheric scrubbers or putting on gas masks.

Viewing Earth from Space

From the ISS we also have the opportunity to observe Earth from space. One of the cool things about the ISS is that we get a chance to fly over some areas quite frequently, and we can get great views of some physical processes on the planet as they are occurring. Figure 4.14 is a excellent image taken from the ISS of an erupting volcano.

One of the things the ISS gives us a chance to do is to look at Earth over extended time periods. For example, on the ISS mission in December 2001 one of the first things that was done was to photograph this big, circular object, the Manicougan impact crater

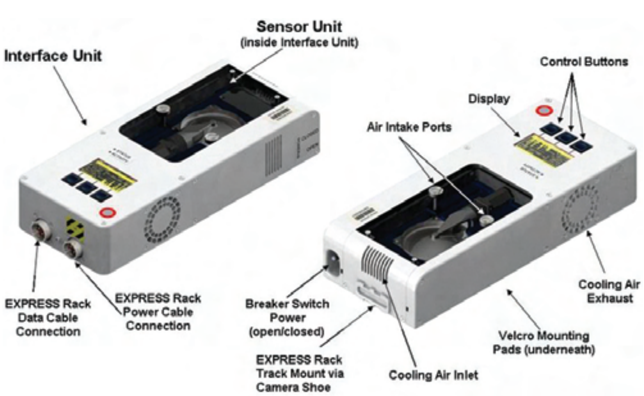

FIGURE 4.13 E-Nose, an air event monitor. SOURCE: Courtesy of NASA.

FIGURE 4.14 Eruption of Cleveland Volcano, Aleutian Islands. Alaska is featured in this image photographed by an Expedition 13 crewmember on the International Space Station. This eruption was first reported to the Alaska Volcano Observatory by astronaut Jeffrey N. Williams, NASA space station science officer and flight engineer. NASA Photo ID: ISS013-E-24184 (23 May 2006). SOURCE: Courtesy of NASA.

(Figure 4.15). A second picture of that same crater was then taken in the springtime, without the snow (Figure 4.16). It gives you a completely different perspective on Earth and its features.

We are very fortunate that we now have a record

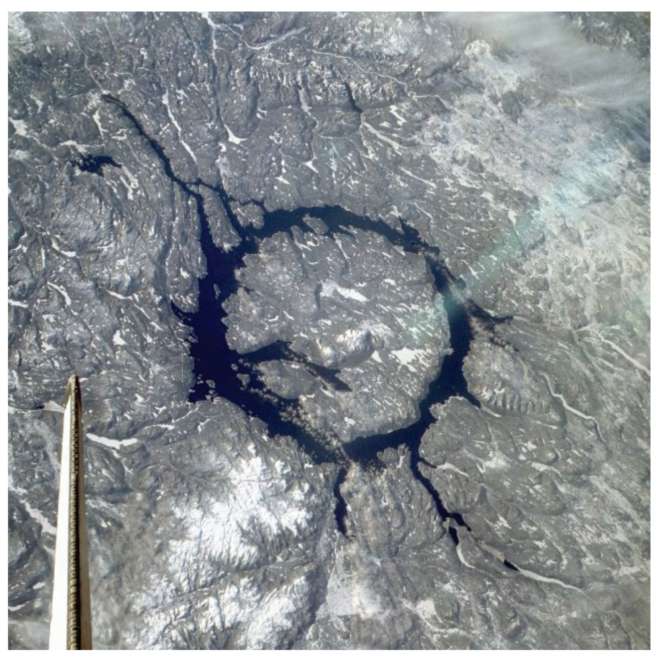

FIGURE 4.15 Manicouagan impact crater in winter. NASA Photo ID: ISS004-E-10763. SOURCE: Courtesy of the Image Science and Analysis Laboratory, NASA Johnson Space Center. Available at http://eol.jsc.nasa.gov.

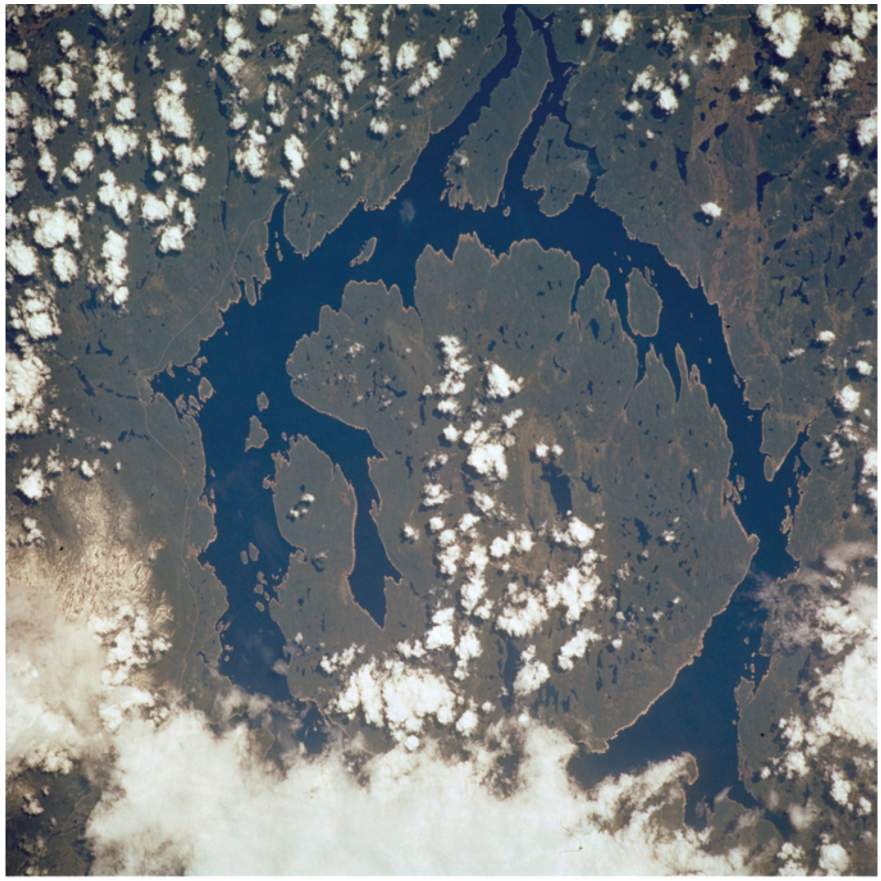

FIGURE 4.16 Manicouagan impact crater in the spring. Manicouagan Reservoir, Quebec, Canada, photographed by the STS-111 crewmembers aboard the Space Shuttle Endeavour. NASA Photo ID: STS111-719-061 (5-19 June 2002). SOURCE: Courtesy of NASA.

of Earth observations dating back to the first human spaceflights. So we can compare observations over some 40 plus years of spaceflight and see how certain areas have changed over time. It is a very powerful tool. This imagery is available on the "Gateway to Astronaut Photography of the Earth" Web site.[3]

We are also working to help encourage the next generation to take the journey; to try to inspire students to study science, technology, engineering, and math.

One example of such activities is EarthKAM, where students remotely control a camera mounted on the ISS to photograph sites of scientific interest on Earth. A worldwide educational community can command this camera. The EarthKAM is attached to the Earth-facing window of the service module and is attached to a computer. The coordinates and times for the pictures are sent up from the ground to the computer. The computer tells the camera to take the pictures, the pictures are automatically downloaded to the computer, and then further downloaded to Earth. In this way the students can get feedback on the pictures that they wanted to take.

Challenges for the Future

In closing let's address the future of the ISS. Now, challenges certainly remain. Just completing the station is a great undertaking. You are sure to have seen the news concerning the problems that we had with the shuttle that led to a delay in the December flight, rescheduled for February 2008. This followed the launching of a number of very successful on-time flights. However, every once in a while we end up with a problem, and it just takes a while for us to work through it. So completing the station is a massive undertaking.

Post-shuttle, transportation and station re-supply is going to be a very important element. We will have up-mass requirements pretty well covered with Russian

[3]Available at http://eol.jsc.nasa.gov/.

FIGURE 4.17 Seventh-graders Emily and Jessica from Westbrook Middle School in Friendswood, Texas, use a map and the Internet to determine the latitude and longitude of their next picture during the February 2006 EarthKAM session. NASA Image: JSC2006E03491. SOURCE: Courtesy of NASA Johnson Space Center. Available at http://www.nasa.gov/mission_pages/station/science/experiments/EarthKAM.html.

FIGURE 4.18 Students from Westbrook Intermediate School in Friendswood, Texas, participating in NASA Johnson Space Center's EarthKAM: Earth from Space program. SOURCE: Courtesy of NASA Johnson Space Center.

Progresses, the ATV from ESA, and the HTV from JAXA. However, the down-mass, which was a problem for the early Russians stations, could be an issue for us. So we are working through that issue right now to try to develop down-mass capability. One potential approach is the Commercial Orbital Transportation System (COTS) program run by NASA's Commercial Crew and Cargo Program Office. Within the COTS program there is one company, SpaceX, which is developing a system that will both bring cargo up and down on a commercial basis. They, of course, have to demonstrate their capabilities. NASA is "incentivizing" these private companies by partially funding their activities.[4] Other avenues are also being explored.

So those are a couple of the future challenges that we have. What we have seen is that the ISS is coming together, and we believe it will increase its scientific production in the future, with additional crew members, additional partner laboratories to provide new opportunities for science and for our investigators, and the Autonomous Transfer Vehicle, a maturation of international partner re-supply capabilities.

So the vision of ISS, a laboratory in space supporting multidisciplinary research, is being achieved. It represents a continuation of humanity's desire to explore and become "extraterrestrial," if you will. We are getting important scientific, technical, operational, and inspirational results from the station and will continue to do so, and the trend for future research opportunities on ISS looks very positive.

[4]On December 22, 2008, NASA stated they would discuss the contract selection to provide commercial cargo re-supply services for the International Space Station. The following day they announced the awarding of contracts to both SpaceX and Orbital Sciences Corporation. NASA will depend on commercial re-supply for reliable, safe and cost effective cargo delivery services to the station.

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The Possibility of Life Elsewhere in the Universe

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One characteristic of the scientific investigations undertaken for the International Geophysical Year (IGY) in 1957–1958 was an emphasis on global measurements. Studies of Earth's ionosphere, for example—crucial for the theory of short-wave radio communication—required data from all over the globe. Coordinated international studies certainly long predated the IGY, but the use of globalized data collection to support improvements in a world-spanning communications technology was a harbinger of today's "globalization," a term that is now, 50 years later, nearly a cliché.

But the IGY required an even larger context. Upper atmospheric studies also needed an understanding of the interaction of Earth with the Sun. Understanding Earth required placing Earth in its solar system context. In this sense the IGY can also be seen as a harbinger of what is now called "astrobiology." Writing in 1974, shortly after the Moon landings, Carl Sagan asserted that we could, for the first time, try to understand life on Earth in its cosmic context. Space travel revealed that this was not just a metaphor, but literally true: we could only hope to understand the origin and evolution of life on Earth by placing Earth in the context of its solar system and galactic environments. Moreover, our understanding of the prospects for life elsewhere is in turn strongly shaped by our expanding knowledge of life on Earth.

THE LIFE WE KNOW

A discussion of life elsewhere therefore naturally begins with a review of some key aspects of the biosphere here on Earth. On Earth's surface, there is something like a thousand trillion kilograms of carbon locked up in the living things that we see easily with our naked eye—plants, animals, and fungi. Most of this "biomass" is in trees. But in the past couple of decades, we've also learned that there seems to be a similar biomass of microscopic organisms living in the oceans, and another comparable biomass—this learned from deep-Earth drilling projects—of microscopic organisms living underground, down to depths of at least several kilometers. It appears that at least a small fraction of this subsurface biosphere is independent of surface conditions—that is, there are microorganisms living underground today that would likely continue to thrive even if the Sun were to go out, and photosynthesis shut down, tomorrow. This is not true for a great deal of subsurface life, much of which directly or indirectly depends on the energy harvested from sunlight at Earth's surface—e.g., because it depends on the organic molecules produced by photosynthesis, or depends on the oxidized molecules resulting from the oxygen liberated by photosynthesis. But it appears that some microorganisms—such as those that make their living by combining hydrogen (produced from subsurface water weathering rocks) with carbon dioxide dissolved—might really represent ecosystems that are independent of the surface. As long as liquid water would persist in Earth's interior—and this will be the case as long as there is enough internal geothermal heating to sustain some layer in Earth's rocks where liquid water exists—it seems likely that there will be a subsurface biosphere.

The elucidation of Earth's subsurface biosphere changes the way we think about the prospects for life elsewhere. If deep biospheres are possible, even in the face of harsh surface conditions, then the prospects for subsurface life on Mars, Europa, or elsewhere seem greater. But we must remember that the requirements for habitability are not necessarily the same as the requirements for the origin of life. On Mars, it is at least possible that life originated at the surface, where it could take advantage of the tremendous available energy from the Sun, and then migrated to the subsurface as the surface became a freeze-dried desert. In the case of Jupiter's moon Europa, which likely harbors a subsurface ocean of liquid water, it seems unlikely that there were hospitable surface conditions for more than a fleeting moment, if that, early in solar system history. For there to be life in Europa's ocean, it would likely have to have originated in the subsurface. We do not understand the origin of life well enough to assess the plausibility of this scenario.

In both of these cases—Mars and Europa—life seems at least possible because of the likelihood of the presence of subsurface liquid water. It is fair to ask: must life depend on liquid water? How many of the apparently universal characteristics of life on Earth are requirements for life everywhere? Life on Earth is carbon-based; is this a general requirement or simply one of many possible alternatives?

Of course, we can not answer this question with confidence until we know more and have explored farther. But we are already getting some hints to the answer. Consider alternatives to carbon. Speculation has often focused on silicon-based life as an alternative to the carbon-based life we know. The theoretical reason for this can be seen by glancing at the periodic table of elements; silicon sits directly beneath carbon in this table, which is a short-hand way of saying that its chemical properties are similar. Since silicon, like carbon, is also an abundant element in the universe, it might seem to provide a good alternative. But in fact, silicon's chemistry is more limited; except under extraordinary laboratory conditions, silicon atoms will not form double bonds with themselves, as carbon atoms do, so silicon chemistry is substantially more restricted than carbon chemistry. This is a consequence of the fact that the silicon atoms are simply bigger than carbon atoms, making double bonds much more difficult.

On top of this theoretical caution, there is an empirical discovery that comes from radio-wavelength investigations of the space between the stars, the so-called interstellar medium (ISM). Probing the ISM at radio frequencies reveals that there is a rich carbon chemistry throughout our galaxy; to date there are nearly a hundred carbon-based molecules observed in the ISM. There is no comparable suite of silicon-based molecules seen. Now, the ISM was not investigated primarily to test the hypothesis of silicon-based life. Rather, scientists simply wanted to learn what was out there—this was largely exploratory science, not hypothesis-testing science. But as a result of exploration, it seems more likely that carbon will be the basis for chemical life elsewhere in the universe, should any exist. Of course, this is at most an implication, not a strong conclusion.

WHAT IS LIFE?

All life we know on Earth is carbon-based, but it shares many more commonalities as well. Its basic biochem-

FIGURE 5.1 The Andromeda Galaxy, M31. SOURCE: Image from Robert Gendler. Copyright 2005 Robert Gendler, www.robgendlerastropics.com.

istry is also the same: life on Earth stores its genetic information as deoxyribonucleic acid, DNA, and uses proteins to do most of the business of metabolizing, motility, and other tasks. A molecule closely related to DNA, called ribonucleic acid, or RNA, is used to mediate between the genetic information in DNA and the construction of proteins according to the genetic plans (Figure 5.2). There are certain viruses that store their genetic information in RNA, but to reproduce, this RNA must be converted to DNA within a host cell, and the DNA-protein reproductive machinery of that cell must be brought to bear. It is possible—though there is so far no good evidence for this—that there are single-celled organisms on Earth that are unlike the DNA-protein life that we know and that remain undetected. Certainly such life would be invisible to DNA probes. But in the absence of any evidence, it's difficult to speculate much further along these lines. So far, the life we know on Earth is DNA-protein life.

Life on Earth builds its proteins by stringing together, like boxcars on a train, different sequences of amino acids among 20 that are coded for in the genetic sequence of DNA. A small number of other amino acids are also occasionally used. But from a large list of possible amino acids that could exist—some 70 different types have been found, for example, in certain meteorites—life on Earth uses only a small subset.

Most impressive is that DNA similarities can be used to construct a "phylogenetic tree"—a tree of evolutionary relationships—for all known life on Earth (Figure 5.3). These trees make it clear that all known life on Earth is related and, in fact, can be traced back to a "last common ancestor." The exact nature of this last common ancestor is debated, but the relatedness of Earth life is not. There is only one known form of life on Earth, with a common origin.

Some laboratories are getting close to making forms of life (by some definitions of "life") other than DNA-protein life, and of course it is possible that altogether

FIGURE 5.2 Ribonucleic acid (RNA) mediates between deoxyribonucleic acid (DNA) and proteins.

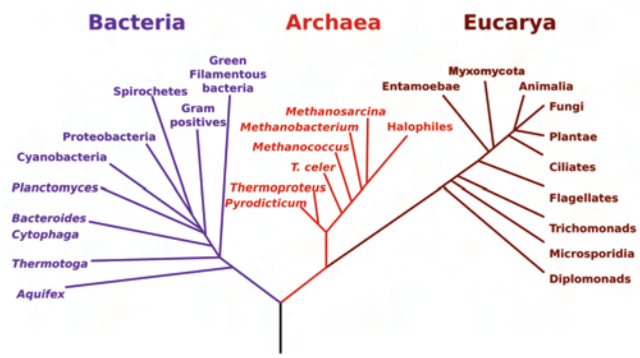

FIGURE 5.3 The phylogenetic tree of life based on comparative ssrRNA sequencing. SOURCE: Courtesy of NASA Astrobiology Institute.

different forms of life might be discovered elsewhere in the solar system or beyond. One might imagine that it would be convenient to have a general definition of what life is, apart from any particular details of life on Earth. At least since Aristotle, there have been efforts to define what life is, or to provide lists of its essential characteristics. Many definitions have been proposed. Their one common characteristic is that they all fail.

For example, there have been *metabolic definitions*, which try to define life as something that takes in energy, uses it to perform work, and then excretes wastes. But fire—which most would not want to call "alive"—also seems to do these things. In fact, the chemical reaction that powers fire is essentially the same as the one that we ourselves use. *Thermodynamic definitions* claim that life is characterized by a use of energy to create local order, but mineral crystals do the same, and most scientists would not want them to count crystals as "life." This is a common problem: proposed definitions either include things that do not seem to be alive, or exclude things that we do consider living. Even the popular *genetic* or *Darwinian* definitions for life seem to exclude certain entities that are unambiguously alive, but that are not capable of Darwinian evolution.

The philosopher Carol Cleland and I have argued that this general problem should not surprise us. We have analogized the current situation to that facing Leonardo da Vinci when, five centuries ago, he grappled with what "water" is. There is a page in his Arundel Codex on which he lists the contradictory characteristics of water—he considers only liquid water—noting that sometimes it's yellow, sometimes green, sometimes muddy; sometimes bitter, sometimes sweet, and so on. It's just very hard for Leonardo to say what the fundamental nature of water is. In retrospect, this should not surprise us. Leonardo was trying to understand "water" at a time before there was any theory of atoms and molecules. Once such a theory exists, it is easy to say what water is—water is H_2O—full stop, end of story. This clarity comes not from a "definition" of water, but rather a theoretical identity statement. In the context of molecular theory, water can be precisely identified, and there is no ambiguity. Water is H_2O, and that tells us what we mean, even if there are impurities that make a liquid solution sweet, or green, and even if the water is frozen as a solid or boiled into a vapor. But this precision is only possible in the context of an appropriate theory.

But currently, we have nothing analogous to molecular theory in our efforts to understand life. We do not even know if such a general theory of life is possible. In its absence, it's hard to see how a *definition* of life will answer any scientific questions for us. Definitions do not answer scientific questions about the world. On the other hand, it may be impossible to devise a general theory without the perspective that will come from discovering other forms of life—should other forms, in fact, exist, and should we be able to recognize them.

THE STUDY OF LIFE IN THE UNIVERSE

The study of life beyond that we know on Earth was famously given the name "exobiology" in a groundbreaking paper published in *Science* in 1960, titled "Exobiology: Approaches to Life Beyond Earth," written by the Nobel prize-winning biologist Joshua Lederberg. In 1964, another biologist, George Gaylord Simpson, published something of a reply paper in *Science* titled "The Nonprevalence of Humanoids," in which he famously scorned exobiology as a science whose subject matter may not exist. This is rhetorically powerful at first glance, but in fact puzzling from the point of view of an astrophysicist: in fact, much cutting-edge work in astrophysics, in physics, and even in fields such as materials science concerns entities or phenomena that may not exist. The Higgs boson, higher dimensions of spacetime, room-temperature superconductors—all could turn out not to exist. It is a strange view of science that this means that their investigation is somehow risible.

Since Lederberg's landmark paper, other words meant to encompass the field have been proposed. "Cosmobiology"—the biology of the cosmos—is one that particularly appeals to me, but is seldom used. "Bioastronomy" is also used, but the most prevalent term now in the United States is "astrobiology," defined to mean the study of life in the universe. With this definition, there is no artificial—and scientifically unwise—division between the study of life on Earth and the study of possible life elsewhere.

ASTROBIOLOGY IN THE SOLAR SYSTEM

The past half-century of solar system exploration has reinforced the lesson that no arbitrary division should be placed between life on Earth and astrobiology. Consider what has been learned about Earth's Moon. It may be true that the primary drivers for lunar exploration were political rather than scientific, but the scientific payoff of lunar samples returned to Earth—primarily by the *Apollo* missions but also by Soviet robotic *Luna* missions—has been huge. Much of what we now understand about early solar system history, and therefore early Earth history, begins with the Moon missions. This is because the surface of Earth is young, even though Earth is not. Earth is 4.6 billion years old,

FIGURE 5.4 The Moon. SOURCE: Courtesy of P.-M. Heden of Vallentuna, Sweden.

but there are nearly no rocks left on its surface—due to destruction by plate tectonics and erosion—to tell the tale of early conditions on our own planet. Yet the ancient sedimentary rocks we do have hint that life was established very early on, probably by 3.5 billions years ago, and possibly by 3.8 billion years ago. The Moon, however, died geologically billions of years ago, so preserves much of its record from these early dates. This history, built upon the dating of lunar samples correlated with crater counts on the lunar surface, reveals that the Moon was once subject to an intense bombardment of comets and asteroids—a bombardment exponentially higher prior to 3.8 billion years ago than is the case today. Comparison of the lunar cratering record to that of Mercury and ancient Mars suggests that the entire inner solar system was subject to this same bombardment. Therefore the origin of life on Earth must have taken place in the midst of this bombardment, with important implications both for destruction and delivery of carbon-bearing (so-called organic) molecules of use for the origin of life. To learn this about the conditions for early life on Earth, we had to visit the Moon and planets.

Casting our view farther out from the Sun, the planet Mars is one of the most intriguing possible venues for ancient or even extant life in the solar system. Among such venues, it is also most easily accessible from Earth, with spacecraft travel times that are less than one year. Spacecraft flybys, orbiters, landers and rovers have made it clear than ancient Mars once had abundant liquid water at its surface, and there is strong evidence that, in specific locations at specific times today or in the geologically very recent past, liquid water still reaches and flows at the surface (Figure 5.5). The surface itself is now a freeze-dried desert where liquid water must either freeze or evaporate. But given what we've learned about the deep biosphere on Earth, the possibility that life on Mars exists in subsurface liquid water environments—environments that may occasionally reach the surface—must be taken seriously. Because of their proximity, Mars and Earth may exchange meteorites that are created as ejecta from large impacts, and it is not out of the question that whichever planet first originated life could than have inoculated the other. Only discovering and examining possible martian life could answer this question with certainty.

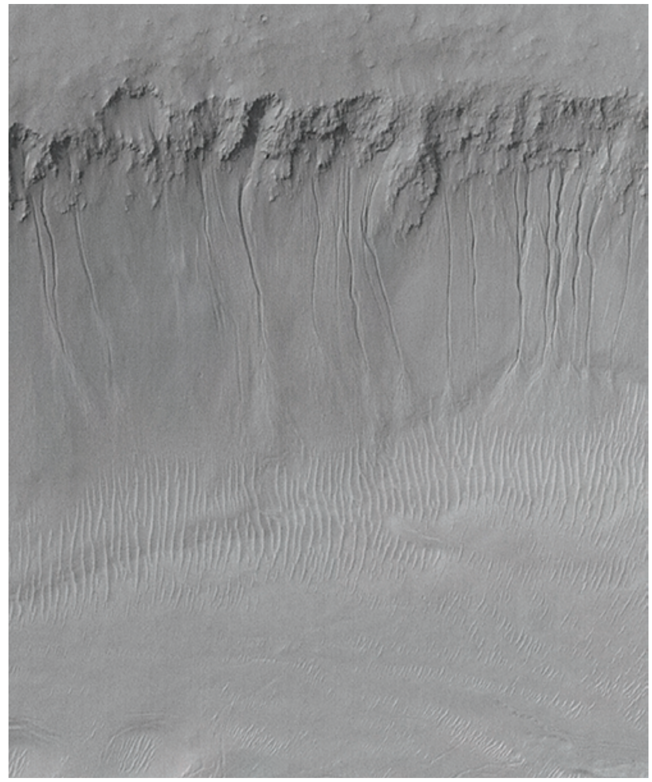

FIGURE 5.5 Evidence for recent liquid water on Mars—the south-facing walls of Nirgal Vallis. SOURCE: NASA/JPL/Malin Space Science Systems. MGS MOC Release No. MOC2-240.

Beyond Mars, in orbit around the planet Jupiter, lies the moon Europa, just a bit smaller in size than Earth's Moon. There is now strong evidence that Europa harbors an ocean of liquid water beneath its extremely cold outermost layer of ice (Figure 5.6). The volume of this ocean is about twice that of Earth's oceans. At the floor of Europa's ocean, as on Earth, liquid water is in contact with rock, raising the possibility of important water-mineral interactions in the presence of hydrothermal energy. Data from the magnetometer on the *Galileo* spacecraft not only supports the existence of the ocean, but suggests that it is very salty and that the overlying ice may be only 10 kilometers thick, or even thinner. Could there be life in this ocean? Speculative studies suggest that the energy sources needed to support life should be present. But whether the origin of life could have occurred in an ocean that was beneath kilometers of ice—so likely cutoff from sunlight—is an open question. It is much harder for Earth and Europa to successfully exchange microorganisms via meteorites than is the case for Earth and Mars, so if there is life on Europa, it is likely due to a separate origin from life on

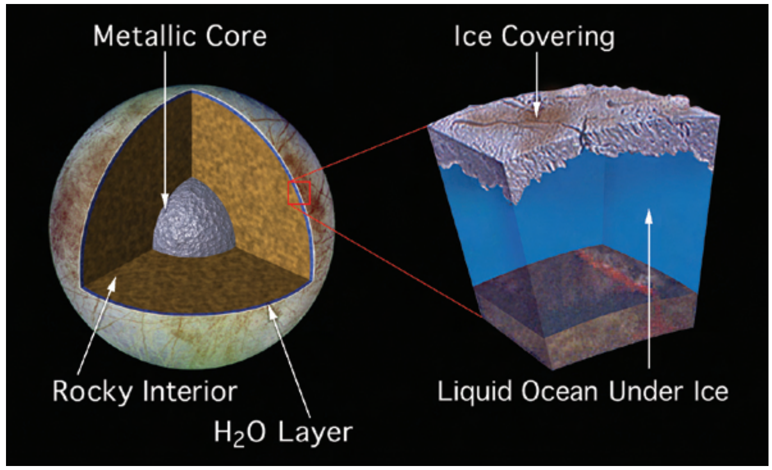

FIGURE 5.6 Cross-sectional diagram of Europa's 80–150 km thick H_2O layer assuming a metal core surrounded by rock mantle: An intermediate subsurface slush also remains a possibility. SOURCE: Courtesy of NASA/JPL. Available at http://photojournal.jpl.nasa.gov/catalog/PIA01669.

Earth. But because of the liquid water ocean, Europa may be the most intriguing site for extraterrestrial life in our solar system. It appears that Jupiter's Mercury-sized moons, Ganymede and Callisto, harbor deeper subsurface liquid water oceans as well.

Still farther out from the Sun, the planet Saturn hosts at least two intriguing worlds. The *Cassini* spacecraft has revealed that tiny Enceladus has active geysers of ice crystals that may originate in a subsurface sea of liquid water, though the exact mechanism for the geysers and whether there is enough energy to sustain liquid water in Enceladus' subsurface remains to be convincingly argued. Farther out from Saturn lies the Mercury-sized world Titan, with its dense atmosphere of nitrogen and methane. There is some evidence that Titan, too, may harbor a subsurface liquid water ocean. All of these worlds need much more exploration and should receive it later this century. Missions to the outer solar system take time (the travel time to Jupiter is 3 years from Earth) and are expensive. But a balanced program of solar system exploration, especially one emphasizing astrobiology, must systematically explore the Jovian and Saturnian systems as well as Mars.

PLANETARY PROTECTION

An important issue in planetary exploration is planetary protection. It was Lederberg who, during the IGY in 1957, wrote to the president of the National Academy of Sciences to raise this as an issue, and the Academy worked with the International Council of Scientific Unions to create an international study group on this question. The Outer Space Treaty, which entered into force in 1967 and is best known for forbidding the placement of "weapons of mass destruction" in outer space, requires space-faring nations to avoid the "harmful contamination" of other celestial bodies. Within a decade, then, Lederberg's personal concern had given way to an international treaty requirement.

The concern is scientifically well founded. Investigations with NASA's Long-Duration Exposure Facility (LDEF) and European Retrievable Carrier (EURECA) experiments reveal that certain micro-organisms survive 6 years in space at the 1 percent level—i.e., one out of a hundred *Bacillus subtilis* spores survive for this long—whereas 25 percent survive a year in space. In both cases, survival requires that the organisms are shielded from the Sun's ultraviolet light, but any organism inside a spacecraft would be. The organisms freeze-dry, or lyophilize, in the cold vacuum, but when introduced to liquid water they revive. Most NASA Mars mission spacecraft are constructed in class-100,000 clean rooms, which means they have thousands of viable sporulating bacteria present per square meter of spacecraft surface, and probably ten or more times as many other types of bacteria. Since it takes less than a year to get to Mars, this means that Mars spacecraft carry a viable bioload of microorganisms with them to the Red Planet. The first question becomes, then, whether any of these organisms could find their way from the martian surface into habitable niches with liquid water in the subsurface, and if so, whether they could grow in that new environment. The odds are long, but not impossible. The second

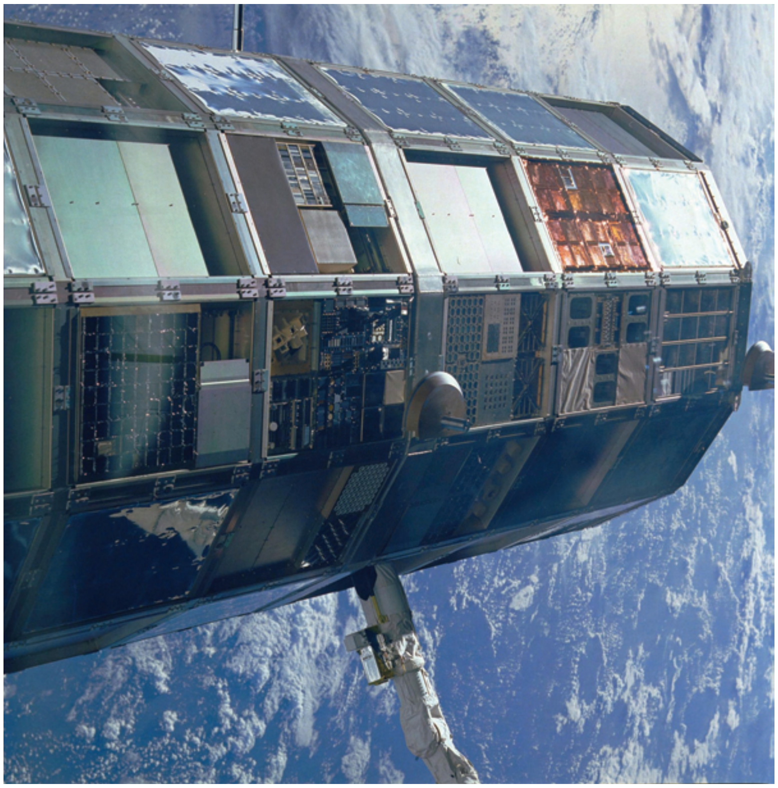

FIGURE 5.7 An overall side view of the Long Duration Exposure Facility grappled by remote manipulator system during STS-32 retrieval. SOURCE: NASA Langley Research Center. Image # EL-1994-00078.

question is what level of additional measures to reduce the bioload of Mars spacecraft should be taken during spacecraft construction. A recent report that I chaired for the National Research Council (NRC), *Preventing the Forward Contamination of Mars*, looked at these questions and concluded that NASA needs to better understand the numbers and types of microorganisms that currently fly on its spacecraft and take more stringent steps to reduce spacecraft bioload.

The current international interpretation of the Outer Space Treaty requirement is that microorganisms carried to other planets must not be allowed to take hold on that world in a way that would render it difficult or impossible to determine if a truly alien biosphere might be present. That is, planetary protection as it stands is really about "protecting the science" from contamination, not about protecting any possible alien biosphere from potential ecological assault. Our NRC report urged that it was time for an international meeting to reconsider whether planetary protection should be reinterpreted to be about "protecting the planet," and not just "protecting the science."

FOUR WAYS TO LOOK FOR LIFE

So far we have discussed in situ investigation of the solar system, in which spacecraft land on other bodies and conduct experiments at the surface to look for life. Closely related is the biological examination, in terrestrial laboratories, of samples from other worlds. These samples could arrive on Earth in an uncontrolled way, via meteorites that originated as debris blown off another world by a big impact, or in a controlled way, as samples brought back by a dedicated spacecraft. But both cases involve hands-on investigations for the presence of life in the solar system.

A third way to search for life is to examine the light coming from the atmospheres of other worlds—i.e., spectroscopy—to determine the chemical composition of those worlds' atmospheres in the hope of finding the chemical signatures of another biosphere. This has been done for Mars and other planets in our solar system for decades and has just become possible for certain giant exoplanets—planets in orbit around a star other than our Sun.

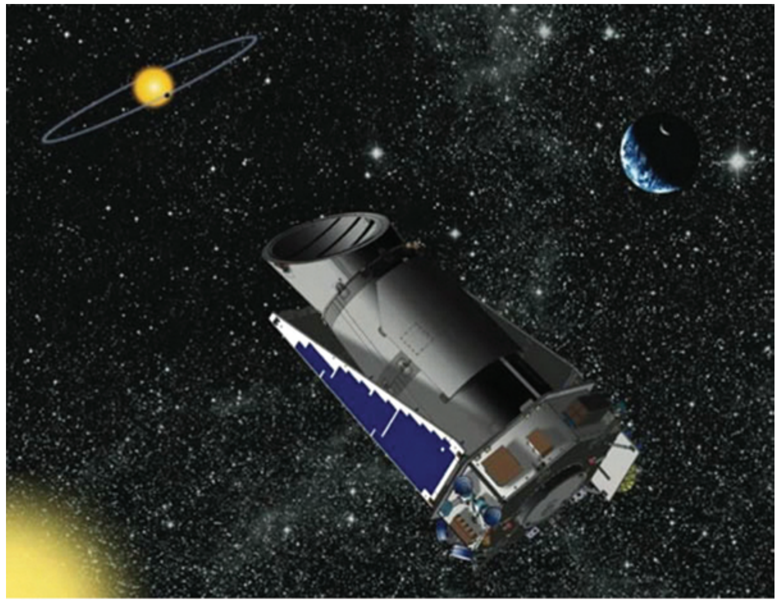

FIGURE 5.9 NASA's first mission capable of finding Earth-size and smaller planets. SOURCE: Courtesy of NASA.

With the Kepler mission that will launch in the next few years, we should soon know the statistics of the presence of Earth-sized planets around other stars. [Figure 5.9] Kepler will allow us to determine the orbits of these planets (assuming that there are any) and therefore their distances from their stars. With knowledge of the stars, we will know which, if any, of these worlds lie in the right range of distances for liquid water oceans to be possible on their surfaces. In a few years' time, we will go from almost no knowledge of whether other Earth-like planets exist to knowing their statistics and potential surface habitability. This is an extraordinary moment. Humans have speculated for millennia about whether other planets like ours could exist—for example, Aristotle asked (and answered, on theoretical grounds) this question in his book *On the Heavens*. In a few years we will no longer have to speculate. We should not let human civilization sleepwalk through this remarkable transition in our knowledge about our place in the universe.

Some decades further on we will be able to observe these planets from dedicated satellites in space, and determine the composition of their atmospheres. The hope is that we might detect some combination of gases in some atmospheres that equilibrium chemistry would seem to forbid, but which biology might just generate. This could imply that there are biospheres on these worlds.

Or maybe not. The evidence would be circumstantial, and as soon as such data were reported, scientists would rightly, and conservatively, search for non-biological explanations. Indeed, we have seen this already at Mars: it is now clear that the martian atmosphere, a highly oxidizing atmosphere flooded with ultraviolet light that should not permit organics to exist for long, contains patches of the simple organic molecule methane—at about the 10 parts per billion level. The methane must be produced by localized sources at the surface; it is well out of equilibrium with the existing atmosphere. It could be the product of a martian version of the methanogenic bacteria we know on Earth. But already there have also been published papers suggesting explanations in terms of martian geochemistry. Atmospheric chemistry consistent with biological sources may provide hints of life, but it evidently it does not in itself provide decisive arguments for the existence of life.

SETI[1]

Besides the three techniques for searching for extraterrestrial life so far discussed—in situ investigations, examination of samples delivered to Earth, and remote sensing of planetary atmospheres—there is one other

[1] "This and the following three sections draw on a more technical discussion in Christopher F. Chyba and Kevin P. Hand, "Astrobiology: The Study of the Living Universe," *Annual Review of Astronomy and Astrophysics*, vol. 43 (2005), pp. 31-74.

approach to the search for life that human civilization currently has underway. This is the search for extraterrestrial intelligence (or, rather, technology), or SETI. SETI need make no assumptions about the biochemical or other makeup of extraterrestrial life. It must, on the other hand, rely on the existence of technology capable of communicating across interstellar distances.

The most powerful targeted search to date has been the SETI Institute's Project Phoenix, which observed roughly the thousand nearest Sun-like stars for radio-frequency broadcasts. Phoenix completed its search at the Arecibo radiotelescope in Puerto Rico, the world's largest, and therefore most sensitive, radio receiver (Figure 5.10). Radio frequencies are the natural frequency to use for interstellar communications, because of the so-called microwave window where galactic background noise is lowest. For each target star, Project Phoenix examined billions of frequencies. Algorithms assumed that the frequency would drift, as a real transmission certainly would due to the motion of the source of the transmission relative to Earth. To be a credible detection, any signal received had to stand up against multiple tests, including a check against all known confounding signals (e.g., from Earth-orbiting satellites or interplanetary probes), a requirement that the frequency be so well defined (i.e., that the bandwidth be narrow) as to only be possible artificially, and a demonstration that the source was detected not only at Arecibo but on a follow-up radiotelescope in Britain as well. No source has ever passed through all of these filters.

It is sometimes said that humanity has looked and looked and looked for extraterrestrial radio transmissions without finding any, so it must be that we are alone. Superficially, this might seem to follow from the fact that SETI radio searches have been carried out since the first search was conducted by Frank Drake nearly 50 years ago. But in fact, even Project Phoenix has only scratched the surface. The nearly 1,000 stars it has searched account for just a ten-millionth of the stars in our galaxy. The SETI Institute and the University of California are now constructing the Allen Telescope Array (ATA) in northern California using almost entirely private funds (Figure 5.11). This array will

FIGURE 5.10 The 1,000-foot (305-meter) dish at Arecibo, Puerto Rico, is the most sensitive radio telescope in the world. It was used by Projects Phoenix and SERENDIP, and it's currently feeding huge volumes of data to SETI@home. SOURCE: NAIC Arecibo Observatory, a facility of the National Science Foundation.

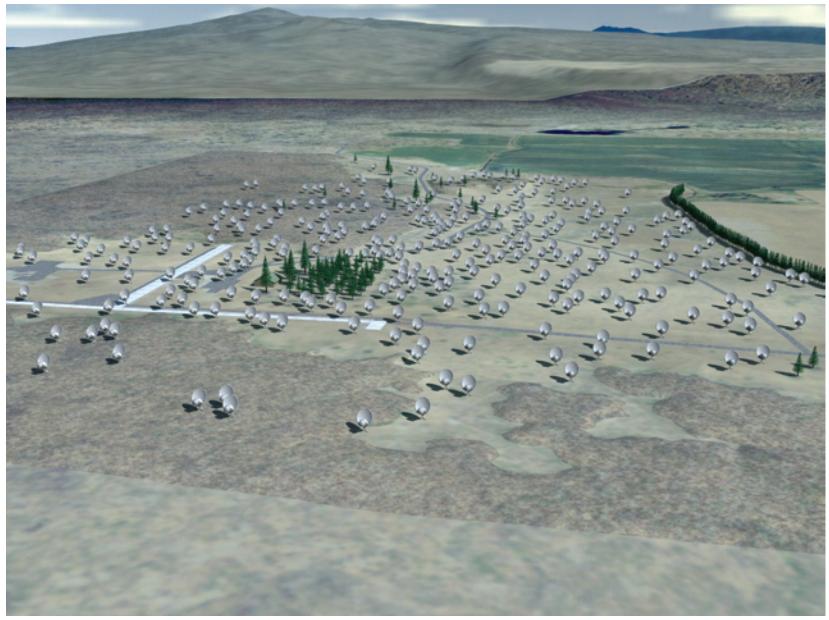

FIGURE 5.11 Artist rendering of completed ATA-350. SOURCE: Courtesy of Isaac Gary.

perform SETI searches all day every day (rather than the few weeks per year that were possible at Arecibo), using the most recent technology. Once completed, the ATA should examine around a million stars in a decade of observing. But even this will represent just a hundred-thousandth of the stars in our galaxy. If technical civilizations beaming signals across interstellar distances are more rare than one in every hundred thousand stars, even the ATA will not be successful anytime soon. But in the absence of any mature theory about the prevalence of intelligent life and technology, the search is the best that we can do.

Nevertheless, arguments have been put forward regarding the likelihood of extraterrestrial intelligence. Perhaps the most common and intuitive is the simple comment that with so many stars—hundreds of billions in our galaxy alone—it just can not be that we're the only civilization. On the face of it, this assertion also seems consistent with the Copernican principle, the idea that Earth has no unique status in the universe. But in fact, this line of reasoning does not hold up. The reason is that we do not know the probability of the origin of life, and then intelligence, and then technology, on an Earth-like world. If this probability were extremely small—say, less than one in a hundred billion—then Earth could be the only planet in the galaxy harboring an intelligent civilization. There could still be a hundred million other Earth-like worlds, but only one would have hit the jackpot. This would be like rolling six identical dice and having only one came up with a six. There is nothing special about that particular die; any one of them could have rolled a six but statistically most of them would not. The Copernican principle is not violated, but Earth could still be unique.

The Drake equation summarizes this way of looking at the problem. Frank Drake wrote down his equation as a meeting agenda for a workshop on SETI in 1961. The Drake equation reads: $N=R_*f_pn_ef_lf_if_cL$, where N is the number of technically communicative civilizations in our galaxy, R_* is the galaxy's rate of star formation, f_p is the fraction of those stars around which planets form, n_e is the number of planets in such systems suitable for the origin of life, f_l is the fraction of those planets on which life originates, f_i is the fraction of those on which life evolves intelligence, f_c is the fraction of those intelligent species that become communicative across interstellar distances, and L is the average lifetime of a communicative civilization.

Obviously this equation is not an equation analogous to, say, the ideal gas law equation. The ideal gas law hypothesizes a relationship among the pressure, volume, and temperature of gases in the laboratory, so is subject to empirical test. The Drake equation does not pose this kind of testable hypothesis. Rather it is a type of "Fermi problem," an example of the sort of back-of-the-envelope thinking made famous by Enrico Fermi in his graduate examinations, by asking questions like "How many piano tuners are there in the city of Chicago?" At first glance, you either know the answer to this question or you do not, and if you do not, there is no easy way to figure it out. But in fact, by breaking the calculation down into a product of numbers that may be estimated (such as the population of Chicago, the number of people per family, the fraction of families that own pianos, how often pianos have to be tuned, and so on) one can make a reasonable estimate of the correct answer.

But this can not be done with the Drake equation. While the three factors R_*, f_p, and n_e can be assigned credible estimates on the basis of what we already know, the remaining factors can only be guessed. L, in particular, moves us into the realm of extraterrestrial sociology and political science, which remain less developed fields. At its upper end we might imagine that L could be as long as the age of the galaxy, $\sim 10^{10}$ years. At its lower end it could be as short as the interval between, say, the invention of radio and the mass production of thermonuclear weapons; based on our experience, this interval could be as short as decades. The average value of L in the galaxy might well be anywhere in this interval, although even a small number of very long-lived civilizations could make the average quite long indeed. In the face of the uncertainties the Drake equation reveals, the large-numbers argument cannot resolve questions about the frequency of civilizations in our galaxy.

INTELLIGENCE ON EARTH

Another way to assess the prospects for other intelligent life is to extrapolate from the history of life on Earth. There is a set of arguments bearing on this question that have been rehearsed for a full century, beginning in 1904 with Alfred Russel Wallace, the co-discoverer of the theory of evolution, and being revived at intervals since by a series of authors. The pessimists in this argument emphasize the contingency of evolution, for example how if one were to replay the evolution of animals, the results would likely be very different, and in particular "the chance becomes vanishingly small that anything like human intelligence would grace the replay" as Stephen J. Gould wrote in 1989. The evolution of human intelligence, after all, depended on a series of contingent factors, including the collision of a major asteroid with Earth 65 million years ago. The counterarguments are equally familiar: convergence is frequently observed in evolutionary history, and nature has evolved complex phenomena such as eyesight and flight many times, so that even though any given evolutionary line might be highly contingent, a large number of parallel paths may lead to the same functional outcome. To this the reply is made that technical intelligence has only evolved once on Earth, so evidently convergence was not operating in this particular case. But things are not this clear-cut; as the marine biologist Lori Marino's work has emphasized, several species of marine mammals developed a level of intelligence that by quantifiable measures is in excess of that of chimpanzees and slightly in excess of that of *homo habilis*, one of modern humans' tool-using ancestors.

Marino and her colleagues begin with a reproducible measurement that correlates with what is meant by intelligence, and that can be employed with the fossil record as well as contemporary organisms. There is at least one such measure, called encephalization. Encephalization is typically expressed as a quotient (hence, encephalization quotient, or EQ) that quantifies how much smaller or larger a particular animal's brain is compared to the expected (via a regression over many animals) brain size for an animal of that body size. Animals with EQs above 1 are brainier than average; those with EQ values below 1 are less brainy than expected for their body size. There is strong evidence that EQ among primates correlates with the ability to innovate, social learning and tool use; among birds it correlates with behavioral flexibility. It seems, therefore, to provide a good measurable proxy for "intelligence." Contemporary humans have the highest EQ on Earth at 7.1, meaning that our EQ is more than 7 times greater than expected for an animal of our body weight.

In well-controlled studies, dolphins have been shown to be capable of mirror self-recognition, an ability demonstrated only by a few other animals besides humans (Figure 5.12). The highest EQ values on Earth after modern humans are those of four dolphin species, with the highest of the four being about 4.5. Great apes have EQs lower than this, with a mean around 1.9. This is about the same as that of the human ancestor

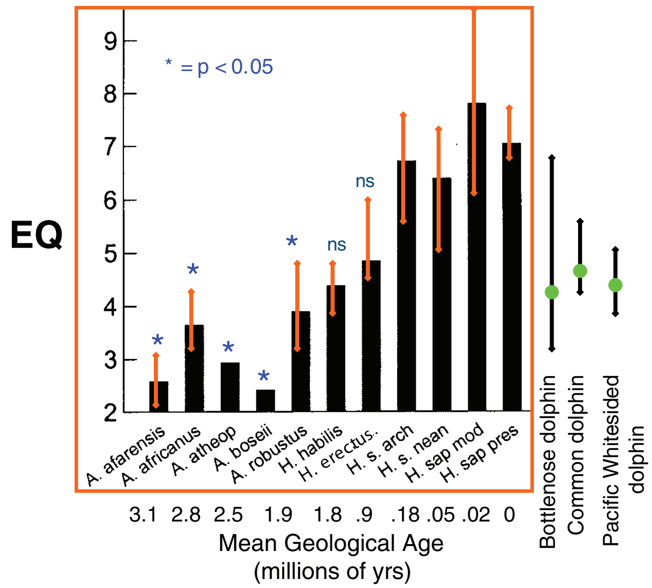

FIGURE 5.12 SOURCE: Courtesy of L. Marino.

Australopithecus. Among our more recent ancestors, the tool-users *Homo erectus* and the earlier *Homo habilis* had EQ values of about 5.3 and 4.3, respectively.

These results suggest that the evolution of human intelligence on Earth is not an entirely exceptional phenomenon. With a sufficiently large database of EQ measurements for fossil whale species, one can go further, and begin to test other long-standing assertions about intelligence, such as the claim that increases in encephalization should be pervasive because of the selective advantage that is conferred by bigger brains. Marino and her colleagues have done this analysis, applying statistical tests to data for modern and fossil whales going back 50 million years. They show that while the overall trend in encephalization has been increasing, at any given speciation event, the successor species was as statistically likely to have a lower EQ as a higher one. That is, encephalization was not pervasively advantageous; the increase in intelligence at the high end of encephalization seems better modeled as a random walk rather than a pervasive selection pressure favoring bigger brains. But it should be emphasized that the size of the data set here is so far very small, and nearly no funding is available for this kind of work.

These results are those of only a nascent research program, but they emphasize that there are reproducible, quantitative methods that can be applied to begin to address some long-standing assertions about the likelihood of the evolution of intelligence in the universe. Just as studies of microscopic life on Earth inform thinking about the prospects for microorganisms elsewhere, so can rigorous exploration of the evolution of intelligence on Earth inform our thinking about the prospects for intelligence elsewhere. Treating "intelligence" as a property of the biological universe that can be quantitatively investigated should allow us to move beyond polemics and begin to push back the boundaries of our ignorance in a data-driven fashion.

ASTROBIOLOGY AND THE HUMAN FUTURE

Fermi posed his famous question "Don't you ever wonder where everybody is?" to three colleagues at Los Alamos National Laboratory in 1950. In its modern version, the "Fermi paradox" maintains that if other civilizations exist in the Milky Way galaxy, some must be much older, perhaps billions of years older than ours; that such civilizations would long ago have developed interstellar travel; that they would then have explored or colonized the galaxy on a timescale that is short compared with the galaxy's lifetime; and that they would therefore be here. But since they are not here, they must not exist! The paradox obviously does not hold in a strict logical sense, since each of its assertions is at best a claim of probability, but it has been a powerful force on thinking about the prospects for extraterrestrial intelligence.

Whatever the rigor of the Fermi paradox, there have been many solutions proposed for it. The challenge to most of these solutions is the large-number assertion: while this or that explanation might explain the failure of some, even most, civilizations to colonize the galaxy, the timescale for colonization is putatively so short that unless the total number of civilizations in galactic history were quite small, the galaxy would indeed have been colonized. These colonization scenarios have posited exponential reproduction and paid little attention to ecological factors, such as the evolution of predation or other behavior that could have the effect of reducing the rate of expansion of a space-faring population. What parameters does one choose in predator-prey modeling to depict accurately the expansion timescales of competing technical civilizations? It is hard to make such parameter choices with a feeling of confidence. And it is close to impossible to know whether such simple analogies from life on Earth are or are not applicable.

Various practical arguments against galactic spaceflight being commonplace have been countered by invoking either genetic engineering or artificial intelligence in the form of self-replicating and evolving machines. We should not exaggerate the ease or casualness with which substantial genetic manipulation of human beings will be done, but as Robert Carlson has shown, basic measures of human bioengineering power, such as the time or cost required to sequence or synthesize short sequences of DNA, show that biotechnology is exponentially advancing at a rate even faster than that of Moore's law in computing. It is hard to know what comes after this exponential lift-off. It may prove generally true that there is only a brief interval during which a species is technically intelligent yet still retains its biologically evolved form. If so, we should expect that any civilization with which we make contact through SETI or otherwise is unlikely to resemble its biological predecessor species. If the question is "what will they look like?" the answer may be "whatever they want to."

But well before biotechnology permits the reengineering of the human species, it will put great power for extremely dangerous manipulations of microorganisms into the hands of small groups of the technically competent. Indeed, it is doing so already. (The National Academies has already convened two committees to examine this issue.) We do not have adequate models from Cold War arms control or nuclear nonproliferation for how to manage this new world, gaining the benefits of biotechnology for public health and food security while preventing disaster. The same technological expertise that makes possible our increasingly sophisticated searches for life brings with it powerful new opportunities, if mishandled, for destruction. Astrobiology is defined as "the study of the living universe." If so, then the discipline must also speak to the future of human civilization, a thing uniquely precious regardless of whether it is entirely alone or one of many in the galaxy.

CHRISTOPHER RAPLEY is director of the Science Museum London and professor of climate science at University College London, following a decade as director of the British Antarctic Survey and 4 years as executive director of the International Geosphere-Biosphere Programme at the Royal Swedish Academy of Sciences in Stockholm. Prior to that, Dr. Rapley spent an extended period as professor of remote sensing science at University College London. He and a U.S. colleague were the driving force behind the International Polar Year 2007 to 2008. He is a fellow of St. Edmund's College in Cambridge, a fellow of University College London, and an honorary professor at the University of East Anglia. His interests are in climate change and Earth-system science, as well as a more general interest in the organization, leadership, and communication of science. He was awarded the 2008 Edinburgh Science Medal for having made a significant contribution to the understanding and wellbeing of humanity.

Understanding the Poles of Earth, the Moon, and Mars

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INTRODUCTION

Al Gore, on the inside front cover of his book *Inconvenient Truth* displays a familiar image (Figure 6.1). He points out that it is the most published image of anything, Earth in particular, that you will come across. It's a photograph that was taken on December 7, 1972, by the astronauts on the last Apollo mission, Apollo 17, soon after the astronauts had left Earth orbit. It's an impressive photograph because it's one of the very few where the Sun is behind the camera so you see a fully illuminated globe. It's also impressive from the point of view of those of us interested in the poles, particularly the Antarctic, because as you look carefully you'll see that the picture was taken well out of the equatorial plane of the planet and you can see Antarctica quite prominently at the bottom of the globe.

FIGURE 6.1 Earth from Space. SOURCE: Courtesy of NASA. Available at http://apod.nasa.gov/apod/ ap010204.html.

Quite honestly, you could devote the whole of this paper to simply discussing the many facets of this image. It should be pointed out that in spite of the best efforts to discover life on other planets, we have not actually done that yet. In order to understand this object, you not only need geologists and physicists and chemists, but you need biologists. The sort of green color you can see on Africa is, of course, due to biology. To fully understand this image you also need economists, technologists, sociologists, and what have you. You need to assemble all of these scientists together to understand this object because it operates blissfully unaware that we've divided it into little pieces and studied them separately. We need to recognize that its various components, the atmosphere, the ocean, the ice, the biology, the humans, all interact in hugely complex non-linear ways.

It can be argued that Earth is, as far as we know, the most complex object in the universe and therefore a really worthy object of our study, not least because it happens to be our home. It's a puzzle to me that more Earth images were not taken on the Apollo missions. Figure 6.2 is one of the relatively few photographs of Earth that were taken by the Apollo astronauts. This lack of Earth images is a bit puzzling until one accepts that the whole point of the Apollo program was to leave Earth and to get to the Moon, which was therefore the focus of everybody's attention.

FIGURE 6.2 The Moon with a red dot indicating where Apollo 17 landed. SOURCE: Moon image courtesy of P.-M. Heden of Vallentuna, Sweden.

The red dot shows roughly where Apollo 17 was heading. It got there a few days after that photograph was taken. Then on December 14, 1972, we reached the end of the heroic age when Gene Cernan and Jack Schmitt lifted off from the Moon. Just in the same way that the exploration of Antarctica had its heroic age, this remains the end of the heroic first age of lunar exploration.

What is particularly interesting is that the first human landing on the Moon took place just under 12 years after the launch of the Soviet Union's Sputnik 1, which was launched on the fourth of October 1957, heralding the start of the space age that we all celebrate today.

THE FIRST INTERNATIONAL POLAR YEAR

Sputnik 1 was part of the International Geophysical Year (IGY; 1957 to 1958), which had it's origins in something that had happened considerably earlier, in the 1880s. The first International Polar Year (1882 to 1883) was proposed by George Neuymeyer but was actually developed, although not completely executed because he did not live to see it completely, by an Austrian naval lieutenant, Karl Weyprecht. He developed the principles of the International Polar Year as follows.

- Nations should collaborate,
- Coordinated research expeditions using standardized instruments and methods would give a bigger bang for their collective buck,
- Observations should be over at least one annual cycle, and
- Observations should be a synchronized.

This showed great foresight for its time, but it has remained the basis of all the international collaboration on terrestrial, and if you like, space research that has followed.

There were 12 nations involved, undertaking a total of 12 expeditions to the Arctic and 3 to the Southern Ocean and the Antarctic. Fourteen meteorological stations were operated and there was a wide range of science undertaken: polar meteorology, atmospheric electricity, geomagnetism, auroral studies, ocean currents, tides, ice motion, and so on. All benefited from this joint collective standardized approach.

The Second International Polar Year

Fifty years later there was a second International Polar Year, organized by the World Meteorological Organization, which had also been involved in the earlier event. Forty nations participated with 40 Arctic observ-

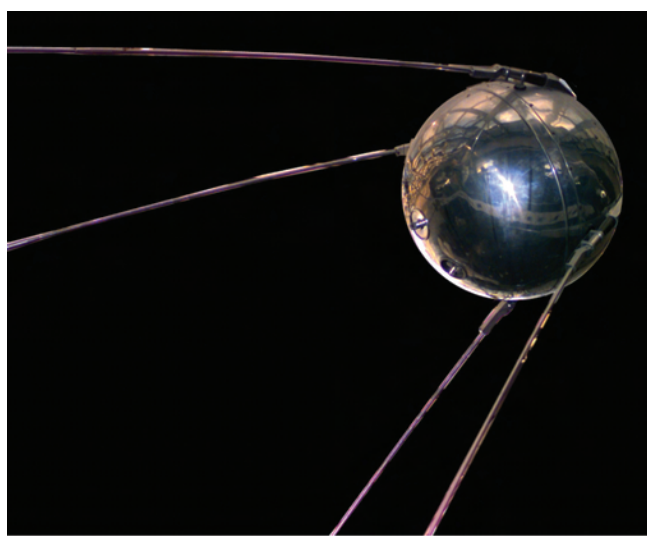


FIGURE 6.3 A model of the beachball-sized Sputnik 1. SOURCE: Courtesy of NASA National Space Science Data Center. Available at http://nssdc.gsfc.nasa.gov/planetary/image/sputnik_asm.jpg.

ing sites. The United States established the first inland Arctic research stations, so beginning the penetration of the Antarctic for research purposes. Meteorology, including the "jet stream" and ionospheric studies were the subjects of a lot of the effort. The initiative was not quite as successful as it might have been because it took place during the Great Depression, and there simply was not the financing available for it to be anymore than it was.

The International Geophysical Year

Twenty-five years later, after World War II, and with the huge surge of technological and scientific advance that that stimulated, it was decided that it would be a good idea to have a third International Polar Year. This grew to become the International Geophysical Year. It was organized by the World Meteorological Organization and by the International Council of Science, or Scientific Unions (ICSU) as it was in those days, and involved 67 nations and 8,000 stations; 12 nations went to the Antarctic and set up 40 stations, mainly around the coastline. Eighty thousand scientists and volunteers were involved and a very broad range of science was addressed.

It took place, of course, in the shadow of the Cold War, but it fostered that wonderfully creative mix of both international cooperation and rivalry that stimulated huge amounts of progress. Some examples of what emerged from the IGY are:

- The discovery of the Van Allen belts,
- The first measurements of the thickness of the Antarctic ice sheet—thickness in nature, if you like, of the Antarctic ice sheet, and
- Establishment of the first Arctic and Antarctic permanent bases and research programs, which have endured since.

FIGURE 6.4 The official logo of the 1957–1958 International Geophysical Year. SOURCE: Courtesy of International Council for Science, World Meteorological Organization Joint Committee.

Furthermore, the establishment of:

- The scientific committees for Antarctic research, SCAR, and for ocean research, SCOR,
- World data centers,
- COSPAR,
- World Climate research programs, and
- The International Geosphere-Biosphere program

all have their origins in the IGY.

Basically, all of the international coordinated Earth-system science that you see today owes its origins to this historical thread. Of course, another extremely important outcome of the IGY was the Antarctic Treaty system. The nations with land claims in the Antarctic, particularly those with disputed land claims, agreed to set them aside during the period of the IGY. They then decided that "if we can do it for a couple of years why don't we do it in perpetuity," and indeed that is the way that the government of the Antarctic was established. This joint government now involves 34 nations and has been an extraordinary successful, if slightly arcane, way of managing a major part of the planet, which is reserved for peace and science.

IGY made the news. The public was aware of it. It was a very exciting time, not least because of the beginning of space age and the birth of space research. However, it was also a time when the public took a greater interest, at least for a short while, in science and what science can do.

EARTH OBSERVATION

The beginning of what many people recognize as quantitative Earth observation started with SEASAT in 1978. This was followed by a whole series of other satellites which have provided us with a unique view of Earth. To use a term coined by Hans-Joachim Schellnhuber at the Potsdam Institute for Climate Impact Research, we can now view Earth through a "macroscope" (Figure 6.5). Just as you use microscope to study something that is very small compared with you, you can use a macroscope to study something that is very large compared with you. Earth is that object.

With the convergence of the ground tracks at polar orbiting satellites at the poles, not only do you get a

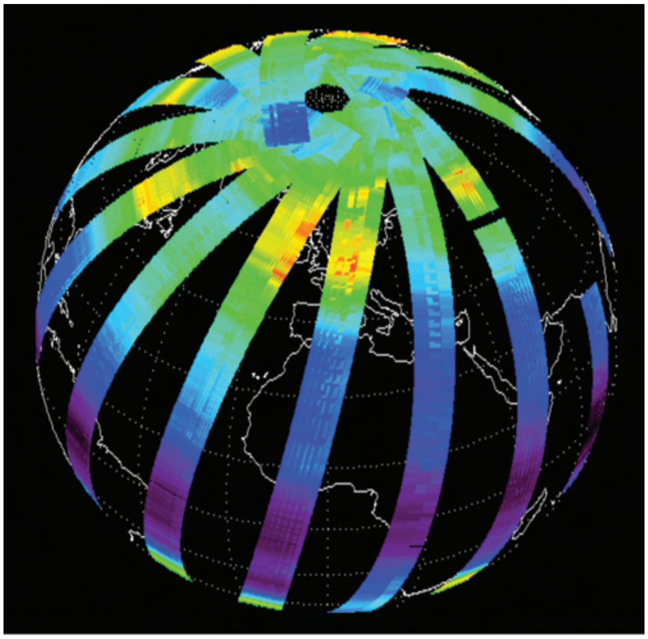


FIGURE 6.5 A model of a macroscope.

fantastic view of what is going on over the whole Earth if you build the right instruments and put them on the right satellites, but you also get a spectacularly good view of what is going on in the polar regions.

What have we learned from this? It is a combination of the work done by all of the scientists involved in the space-Earth observation initiatives over the past three decades and also all of the work that has gone on the ground and in the atmosphere using ships, aircraft and research stations. What we have learned is that human-induced climate change is real and serious.

If you're looking for a dramatic non-linear effect of warming, then watching a piece of ice melt is pretty dramatic, and in a warming world, ice retreats. It does not necessarily have to melt, at least not initially, but it can slide off into the ocean and do things and then melt at its leisure; so ice retreats. Now one of the things that you often hear is that the polar regions see an amplification of global warming, and this is true. The fastest warming spots on the planet are in Alaska, Siberia, and the Antarctic Peninsula. At least in part, this is because as you melt white ice or snow, it reveals dark ocean or land, so instead of reflecting away 80 percent of the incoming solar heat or light, you absorb it.

One thing to bear in mind is that for half the year in the polar regions it is dark, and if the ice cover has been removed the ocean and the atmosphere are far better coupled than they would otherwise be. Quite a lot of that heat comes back out again. However, it is not entirely obvious which way this will work out. It is the difference of two large numbers, but it does turn out that by and large the ice-albedo feedback does have its affect, and this is why we have seen this extra warming in the polar regions. However, because you get this amplification in the polar regions, the system amplifies the noise as well as any systematic signal. It's not at all obvious that you would detect climate change or human-induced climate change more easily in the polar regions than in the tropics. The signal to noise ratio issue is not fully resolved. However, if there are impacts of humans on the planet, they will have a big impact in the polar regions.

THE ARCTIC

Figure 6.6 shows the sequence of satellite-derived minimum-Arctic-sea-ice measurements that extends from the summer minimum of 1979 through to the summer minimum of 2005. Despite the large amount of inter-annual variability, it can be seen that there has been a steady decline of about 25 percent over that period. In 2005 there was bit of a dip, and people speculated about whether they're seeing an acceleration of the loss of sea ice, especially because of a rather dramatic decline in the multi-year ice. The thicker ice that survived several annual cycles was noted, but in 2006, measurements were back up on the curve again, and then last year (2007) there was an extraordinary decrease.

The previous minimum of 5 million square kilometers is shown on the right in Figure 6.7. The 2007 minimum of 4 million square kilometers is shown on the left. This is an excellent example of what satellite data can tell us.

The image in Figure 6.8 was taken by passive microwave instrument. You can see the pole with a sort of black hole where there is no observation and you can clearly see Greenland. You see the ice melting back to the minimum, and if you know where to look, the northwest and northeast passages open up in a way that is quite unprecedented. Somebody decided to see if they could sail a sailing boat through the Northwest Passage last year, and they found themselves in the

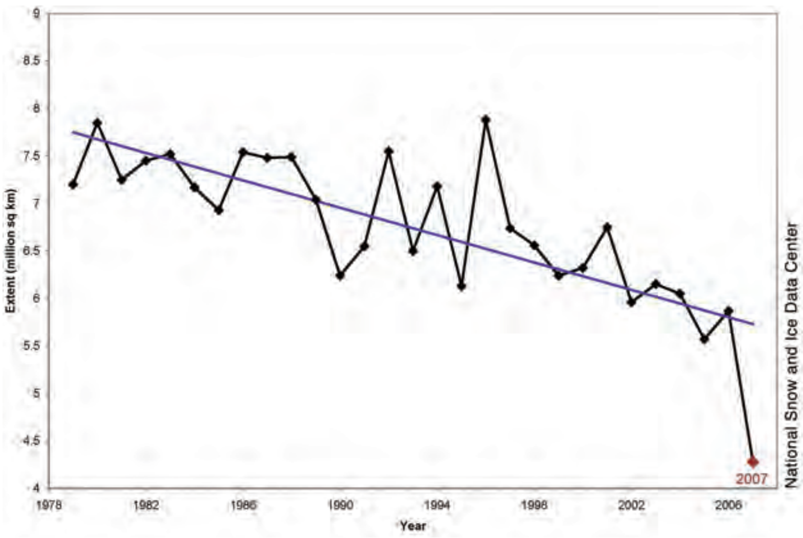


FIGURE 6.6 Arctic sea ice summer minimum extent. SOURCE: Courtesy of National Snow and Ice Data Center.

Pacific without having seen a single piece of ice. That is a measure of the dramatic change that has been seen. The Northwest Passage is marked in yellow on the left. The Northeast Passage, which still required a little bit of ice breaking to get through last year, is marked in blue on the right. Trying to get ships through these passages was something that the British Navy and others struggled to do for the best part of 50 years. This is a good thing for those who wish to transport goods during these brief summer months, and in South Korea

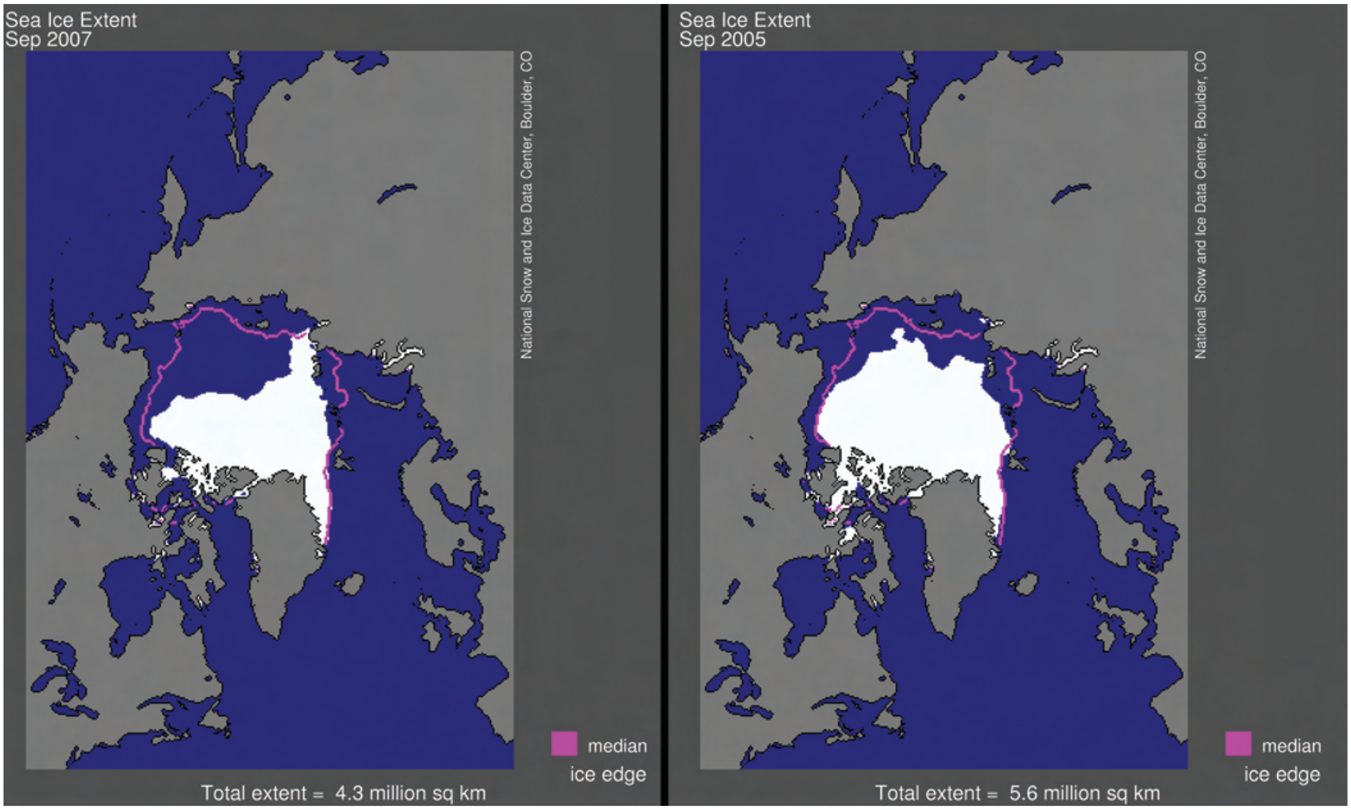


FIGURE 6.7 Average arctic sea ice extent for September 2007 *(left)* and September 2005 *(right)*. National Snow and Ice Data Center.

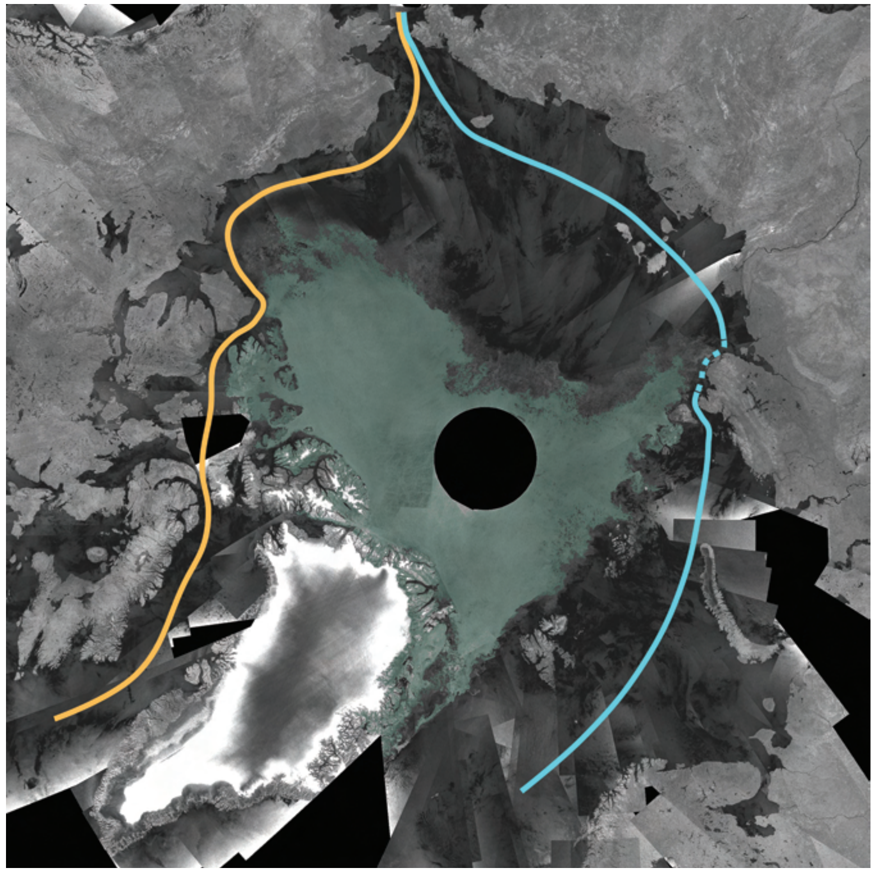


FIGURE 6.8 Envisat ASAR mosaic of the Arctic Ocean for early September 2007. SOURCE: Courtesy of European Space Agency.

the shipyards are building vessels for this purpose. On the other hand, it's not such a good thing if you're a polar bear or if you're a frontier person whose livelihood depends on having sea ice to fish from or to catch seal from.

Floating sea ice, if it melts, does not change sea level. Archimedes would have understood that. Up on the Greenland ice sheet, the area of summer melting has increased in size and progressed steadily northwards. The summer melt area has increase dramatically over the time period during which the area has been monitored by satellites. This surface melting is not just a few little puddles that get your feet wet. These are torrents of water that can make their way down through the ice sheet, lubricate the underside of it and indeed cause it to accelerate in its gravitational extrusion towards the periphery of the continent and the ocean. There has been some increased snowfall in the interior in Greenland, but not enough to compensate for this increased acceleration. The ice discharged by melting and sliding has increased dramatically between 1996 and 2005. It is making a significant contribution now to sea level rise, which previously was dominated by thermal expansion and the melting of glaciers.

Synthetic Aperture Radar has proved to be one of the most extraordinary of instruments available to the remote sensing community and has absolutely transformed our ability to monitor the movement of ice. However, a new weapon has arrived in our armory recently and that is the extraordinary capacity to measure the gravity field, and indeed the changes—very, very subtle changes—in gravity due to the changing distribution of the ice mass, or indeed the loss of ice in this particular case.

The graph shown in Figure 6.9, derived from gravity data obtained by the Gravity Recovery and Climate Experiment (GRACE) mission (twin satellites launched in March 2002 that are making detailed measurements of Earth's gravity fields) show the rate of change of mass of the Greenland ice sheet—quite an extraordinary feat.

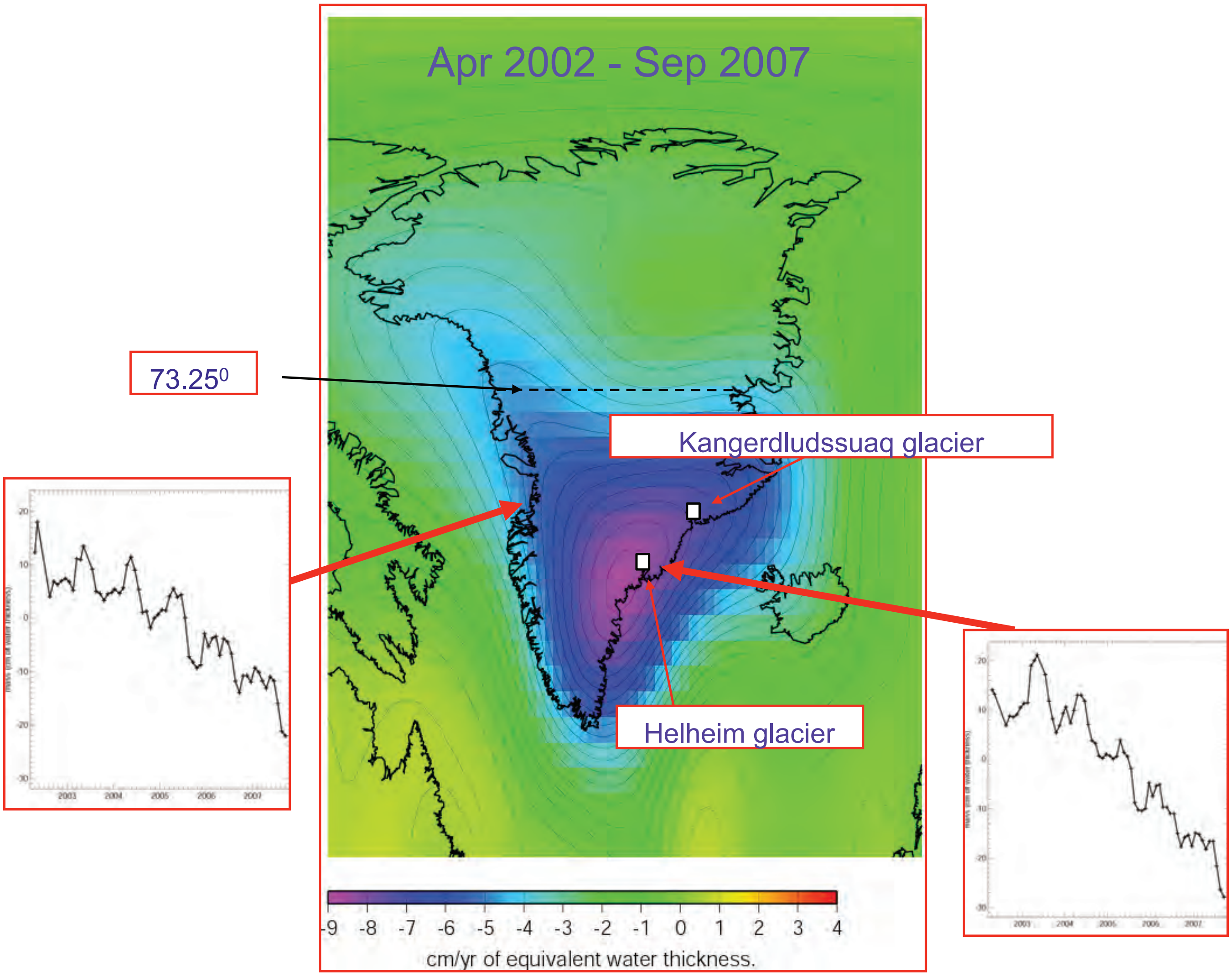


FIGURE 6.9 Rate of change of mass from GRACE. SOURCE: Courtesy of Isabella Velicogna and John Wahr, Cooperative Institute for Research in Environmental Sciences and Department of Physics, University of Colorado, Boulder.

THE ANTARCTIC

Let us look at the Antarctic now. One of the things that has happened in the past 15 years is that the "Westerlies" (prevailing winds in the middle latitudes between 30 and 60 degrees latitude, blowing towards the poles) have increased in intensity around the Antarctic. It has also been noted that the place that has warmed the fastest around the planet (2½ degrees or more) in the last 40 years is the Antarctic Peninsula. Indeed, there has been a study that indicates that these things are connected. With the intensification of the Westerlies, there have been a greater number of events where warm winds make it over the Antarctic Peninsula, and a succession of ice shelf collapses all due to human-induced global warming, combined with an effect of the ozone hole.

Whether or not you accept that, there is no doubt that there has been warming, and that 90 percent of the glaciers on the peninsula are in retreat. The ecology is also changing. For example, penguin colonies and distributions are shifting in response, indicating that there is a major upheaval going on. However, one thing that can be done when an ice shelf has collapsed is take a research ship into where it was, get some samples of the sediment from underneath it, and try and figure out whether it had collapsed in the past. When that has been done, it has been found that the northern most ice shelves had collapsed perfectly naturally in a climatic fluctuation 3,000 to 5,000 years ago. However, when it comes to the Larsen ice shelf which collapsed in 2002, allowing sediment to be removed from that area of the continental shelf, it was found that that ice shelf had been in place for at least 10,000 years and probably longer. Warming is reaching locations it has not reached before.

One of the things that the Larsen ice shelf collapse did for us was resolve a long-standing dispute amongst glaciologists as to whether these ice shelves provide a back pressure obstructing the flow of the feed glaciers. Monitoring the behaviors of those feed glaciers after the Larsen B collapse indicated that this was in fact the case. Just a month ago on the western side of the peninsula the Wilkins ice shelf suddenly lost a very substantial segment of ice. Almost exactly a month ago, the ice was still in place. One day later, an almost explosive collapse of the ice took place, and it is now drifting off to sea. The thing about the Wilkins ice shelf is that it is 5 degrees of latitude further south than Larsen B. This suggests the warming is penetrating yet further south.

Figure 6.10 is a high resolution image of these huge blocks of ice moving out to sea. Interestingly Larsen B had been weakened by melt ponds on its surface that had broken up its structure and fabric.

If you look at these pictures of the Wilkins ice shelf that were taken by a research aircraft just a week or so ago (Figure 6.11), you'll see that it seems to have suffered a different sort of fracture. It will be very interesting to see what the glaciologists make of this. They are flying along a fracture between two major pieces, but look at these extraordinary perfect pieces of ice shelf that have broken almost at right angles and with almost plain "R" cracks.

In Figure 6.12, the area circled in red is part of the West Antarctic ice sheet, the so-called Amundsen Sea Embayment. Radar altimetry has show us for some while that the drainage basins marked H and G are discharging ice very dramatically. The green colors show a substantial loss of ice. Notice that over in east Antarctica there are a couple of other areas that are discharging ice as well.

It turns out that those areas have a very substantial volume of ice sitting on rock below sea level. The West Antarctic is a marine ice sheet (Figure 6.13); it is ice that is sitting on rock up to 2 kilometers below sea level, which means this is a substantial hydrostatic uplift, trying to lift it off the rock. It is very heavy, so that uplift is not winning at present. As that ice begins to slide, it is apparent that the very-high-pressure water

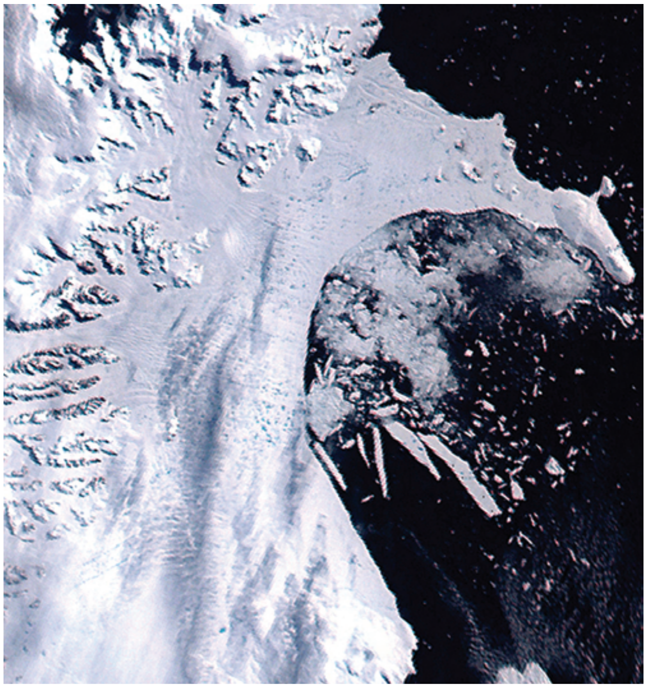


FIGURE 6.10 The Larsen ice shelf as seen by MODIS on February 23, 2002. SOURCE: NASA/Goddard Space Flight Center and Scientific Visualization Studio.

FIGURE 6.11 Wilkins ice shelf. SOURCE: Courtesy of the British Antarctic Survey.

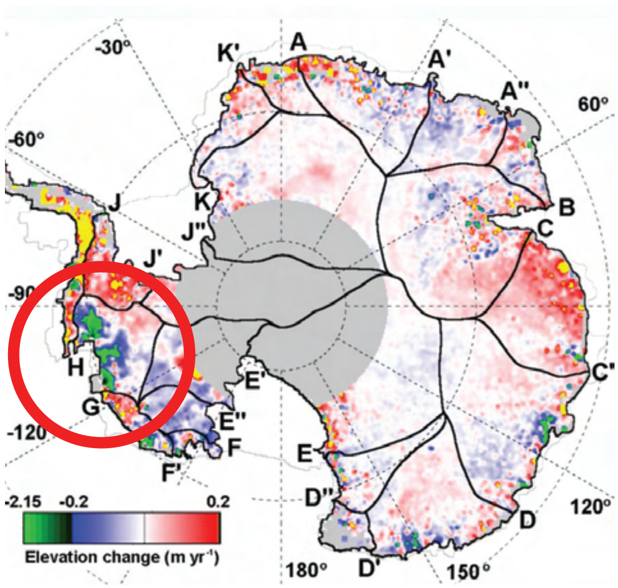


FIGURE 6.12 Radar altimeter data. SOURCE: D.J. Wingham, A. Shepherd, A. Muir, and G.J. Marshall, Mass balance of the Antarctic ice sheet, *Phil. Trans. Royal Soc. (Lond) A*, 364:1627–1635, doi: 10.1098/rsta.2006.1792, 2006. Courtesy of Duncan Wingham, Earth Sciences, University College London.

at the ground line can begin to force its way in, under the ice sheet.

What we do not know, because we do not have the physics to put into the models, having never seen a marine ice sheet collapse before, is whether this retreat will come to a halt, or whether it will continue until all of the ice that could discharge has discharged. Indeed, if that were to happen, how long would that take?

Using Interferometric Synthetic Aperture Radar, you can see where major discharges are taking place around the Antarctic. It has been said that the increased snowfall on the Antarctic domes, the high parts of the ice sheet, would compensate for some of the losses. Indeed that has been assumed by the Intergovernmental Panel on Climate Change, up until now.

Interestingly, the radar altimeter data which seemed to show the effect are a bit in dispute. It is a very tough measurement to make, because the changes are so small. Something like 70 ice cores taken over the whole of that area showed no change in snowfall over the last 50 years at all. It seems that a compensating mechanism may not be taking place. It's still an unresolved issue.

Now consider, what would be the consequence of that continuing discharge running its course? The Amundsen Sea Embayment is a very difficult area to reach, and indeed it was not until Carl Herb at the National Science Foundation deployed some C130s to put in major fuel dumps that the British Antarctic Survey and the University of Texas managed to get into the area a couple of years ago. They flew 30,000 kilometers of flight lines with two Twin Otters with ice penetrating radars on board and produced a map of the underside of the ice sheet. This showed that the ice accessible for discharge is equivalent to a one and a half meter, mean sea level rise. Of course, the whole of the West Antarctic ice sheet would raise sea level by 5 meters if it melted. The area that is currently discharging; if it continued to do so, it would raise sea level by one and a half meters or thereabouts.

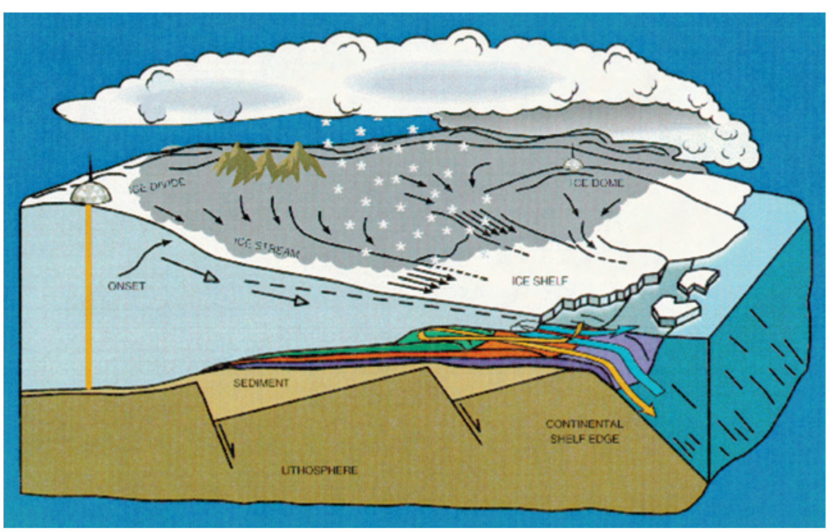


FIGURE 6.13 Schematic diagram of the West Antarctic ice sheet. SOURCE: *WAIS Science and Implementation Plan*, NASA Conference Publication 3115, Volume 1, September 1995, available at http://neptune.gsfc.nasa.gov/wais/documentation/toc.html. Courtesy of NASA.

How quickly could that happen? The discharge that we are seeing at present is of the order of a half a millimeter a year, sea level equivalent. Even if that accelerated, even if that doubled, we would still be talking about 1,000 years before that one and a half meters was delivered, all things being equal. The ice sheet model simply can not tell us, because the ice dynamics is not properly included, and there are even numerical issues about modeling the ice sheet near the ground inline.

Just looking at what is going on at present: there is what appears to be a slow acceleration of sea level rise that has been running at about 1.8 millimeters a year during the last century (Figure 6.14). It is now about 3 millimeters a year.

If we look at what has happened since the last ice age, there was a 9,000-year sustained period where sea level was rising at about one meter per century, and there were a couple of bursts that were substantially faster than that (Figure 6.15). Of course, sea level was stable for about 3,000 years. Whether or not the present configuration of ice sheets could deliver a meter per century or whether, because the warming that we are imposing, is at a rate 100 times faster than anything in the natural system—or at least if it follows the rate at which we are injecting carbon dioxide into the atmosphere—is an open question. Just how quickly could this happen?

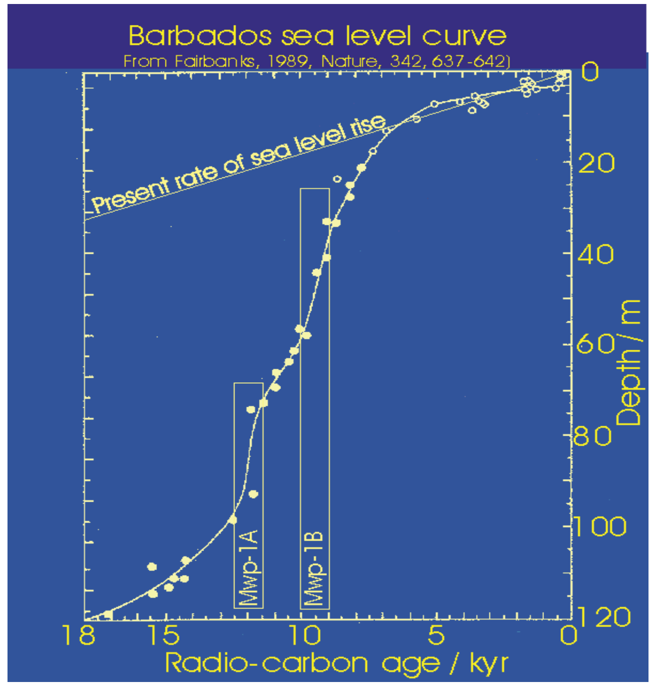


FIGURE 6.15 Past Sea Level Rise 1 m/C for 9000y 2–5 m/C bursts? NOTE: Mwp, meltwater pulse. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: *Nature* (R.G. Fairbanks, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *Nature* 342, 637–642, doi:10.1038/342637a0, 1989) Copyright 1989).

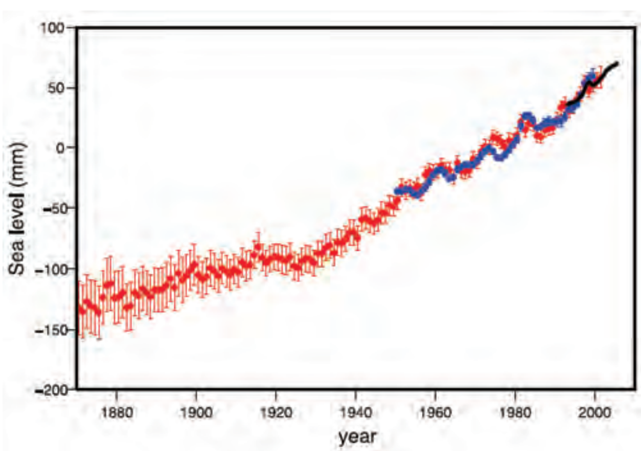


FIGURE 6.14 Annual averages of the global mean sea level (mm). SOURCE: N.L. Bindoff, J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan, Observations: Oceanic Climate Change and Sea Level. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds.), Cambridge University Press, Cambridge, United Kingdom and New York, N.Y., USA, 2007.

A few years ago, if I had discussed the flooding of London, I would have been concerned to be accused of alarmism. Increasingly these days, serious people are taking the threat very seriously.

INTERNATIONAL POLAR YEAR

In order to try and sharpen up on the answers to some of these questions, such as how much, how quickly, what is going on, the International Polar Year was established by ICSU and the World Meteorological Organisation, encompassing a wide variety of sciences.

It involves 63 nations, 50,000 individual participants, and some 229 projects, of which 170 are science based and 58 are for education and outreach. It has resulted in more than $300 million in new funding worldwide. IPY has a complex structure covering the Arctic, the Antarctic, land, ocean, atmosphere, ice,

FIGURE 6.16 International Polar Year 2007–2008 SOURCE: Courtesy of International Council for Science, World Meteorological Organization Joint Committee.

people, and so on. As is to be expected, it has a major space component.

One of the most ambitious projects being undertaken is called GIIPSY, the Global Interagency IPY Polar Snapshot Year. This is an attempt to get a comprehensive series of "snapshots" by planning and synchronizing IPY satellite acquisition data requests, ultimately resulting from approved IPY projects.

Figure 6.17 provides an indication of the satellites that can be brought to bear to study the polar regions. Not shown is the CryoSat mission, scheduled for launch in 2009, which will provide a new view on the cryosphere. IPY set itself the task of leaving a legacy that changes the way polar science is executed. GIIPSY will be a major contribution to this task.

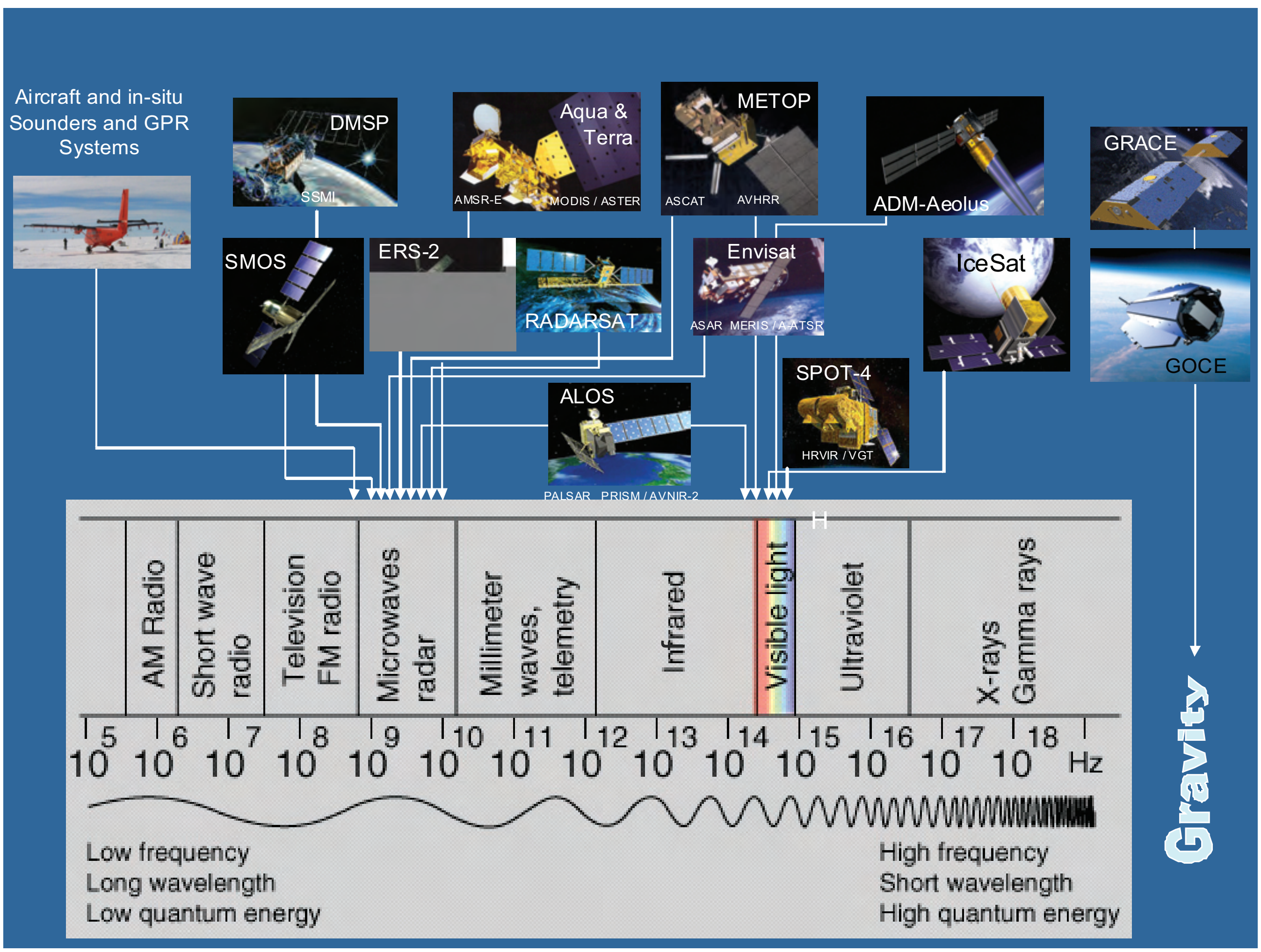


FIGURE 6.17 Global Inter-agency International Polar Year Polar Snapshot Year, the IPY 2007–2008 Snapshot. SOURCE: Courtesy of International Council for Science, World Meteorological Organization Joint Committee.

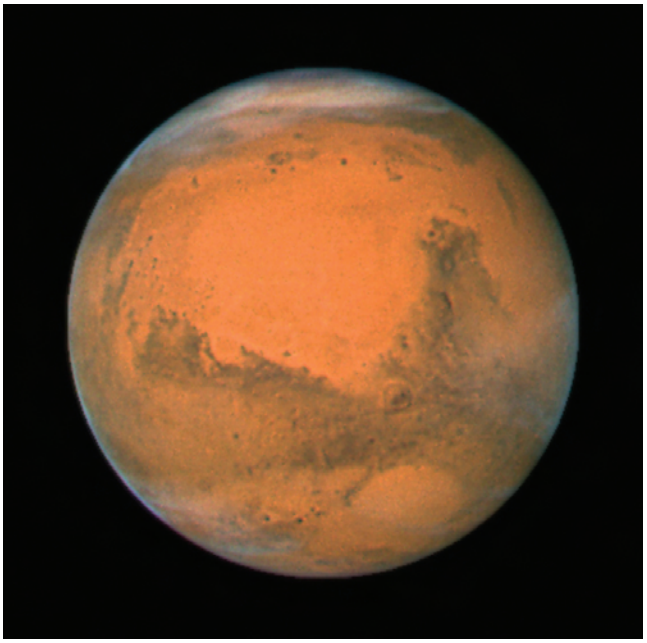


FIGURE 6.18 NASA's Hubble Space Telescope took this close-up of Mars when it was just 55 million miles away on December 18, 2007. SOURCE: Courtesy of NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Bell (Cornell University), and M. Wolff (Space Science Institute, Boulder).

MARS

The martian year is 1.9 times that of Earth. Its atmosphere has only one percent of the surface pressure of Earth's, is 95 percent carbon dioxide, and includes trace amounts of oxygen and water. Surface temperature ranges, from minus 143 degrees centigrade in the depths of the martian polar winter through to as much as 20, maybe even 25, degrees centigrade in the hot summer, with a mean of about minus 63 degrees centigrade. Clouds, fog, and frost all exist on the planet as do surface winds of about 400 kilometers an hour. There is also evidence (relic water flows) that there was free-flowing water on the surface of the planet in the past. Interesting questions therefore abound such as What was Mars like before? and What caused it to change? Mars has an obliquity very similar to Earth. If obliquity is important then, that matching between the two planets simplifies our understanding or our ability to understand.

Given the above, a lot of the Mars science has to do with "following the water" and also "following the carbon dioxide." Indeed, it is interesting to note that the north polar cap, about 1,000 kilometers in diameter, has substantial water ice, up to 1.8 kilometers thick; with the seasonal carbon dioxide frost there, up to a meter thick.

In Figure 6.19 you can see in these two images of the north polar cap taken one martian year apart, a very substantial difference from one season to another, or if you like, one annual cycle to another. It is also apparent that the dust cover is critical, because blowing dust onto the ice, whether it's carbon dioxide or water, changes its albedo, and that will change its ability to absorb or reflect heat.

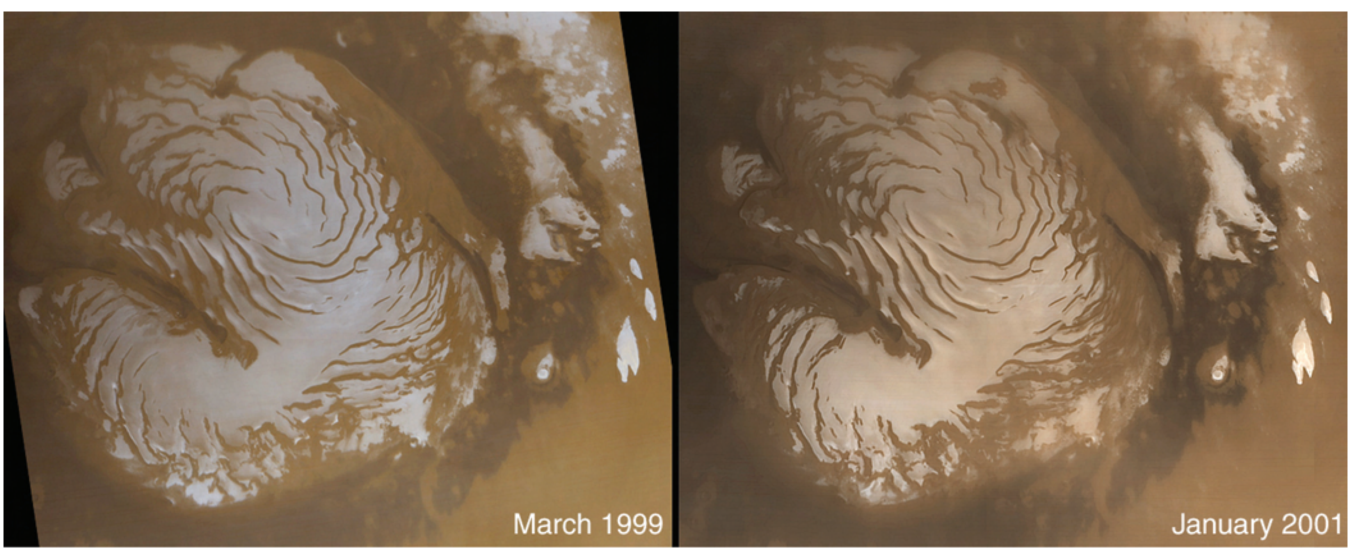


FIGURE 6.19 The north polar cap of Mars in summer. SOURCE: Courtesy of NASA/JPL/MSSS.

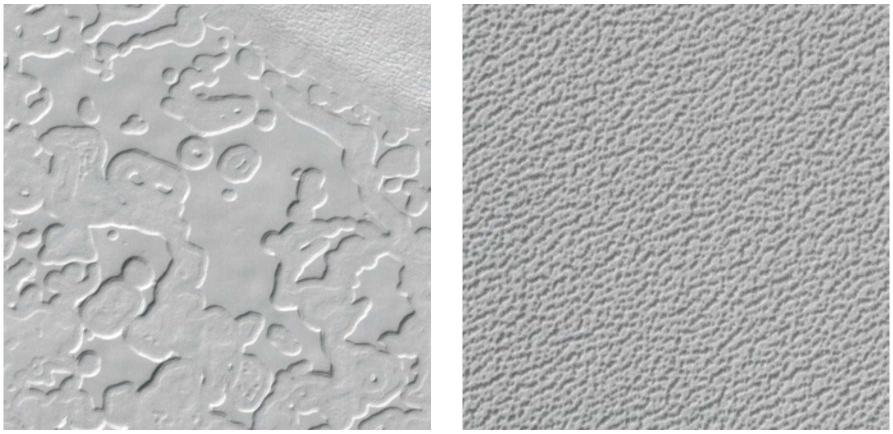


FIGURE 6.20 Terrain differences of the polar caps of Mars: south "Swiss Cheese" *(left)* and North Pits *(right)*. SOURCE: Courtesy of NASA/JPL/MSSS.

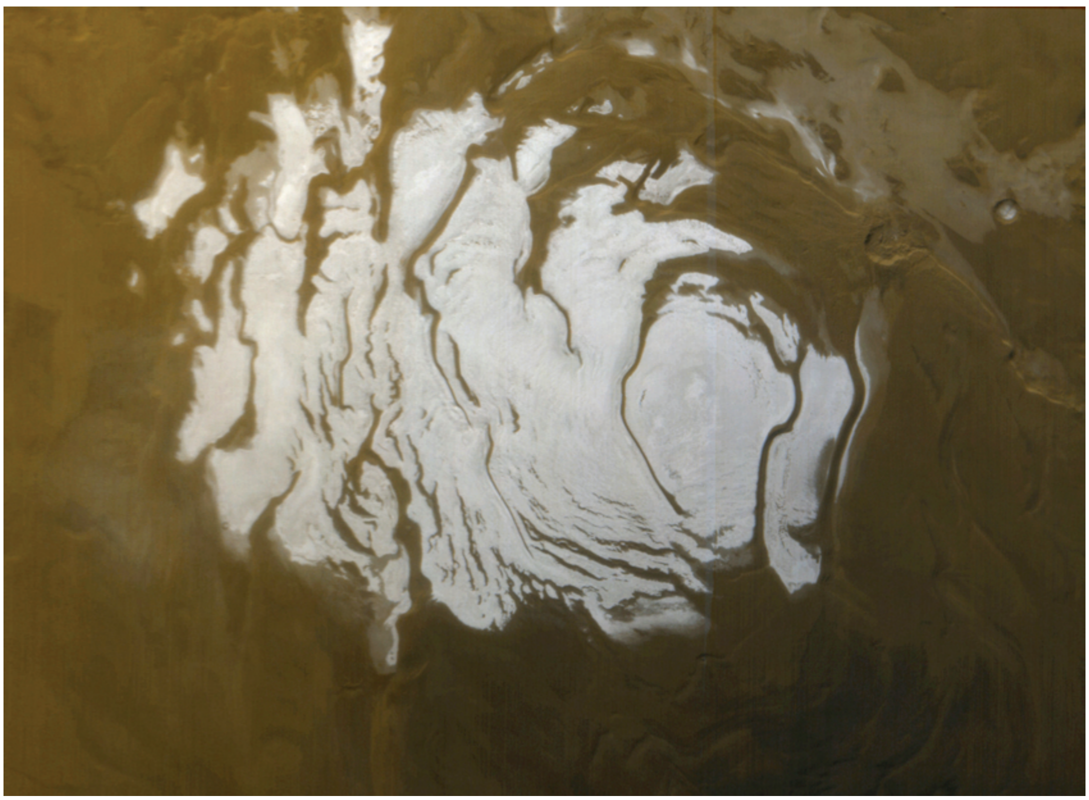


FIGURE 6.21 South polar cap of Mars, summer 2000. NASA Photo ID PIA02393. SOURCE: Courtesy of NASA/JPL/MSSS.

Interestingly, there are quite substantial differences between the north polar cap and the south polar cap. They have quite different long-term histories, and the morphological features of their ice are substantially different.

In Figure 6.20, note the so-called "Swiss Cheese" appearance of the south polar cap and the very pitted nature of the north polar cap.

The south polar cap possesses water ice (Figure 6.21) plus a substantial carbon dioxide ice that seems permanent, although it varies in thickness. It is currently estimated that there is sufficient ice (water ice) in this polar cap that, if you melted it all, would cover the planet to a depth of 11 meters, i.e., a very substantial store of ice.

A number of spacecraft have provided different sorts of data concerning the martian polar regions. For instance we have MARSIS data, from the subsurface radar sounder on the Mars Express spacecraft which has allowed us to measure the thickness

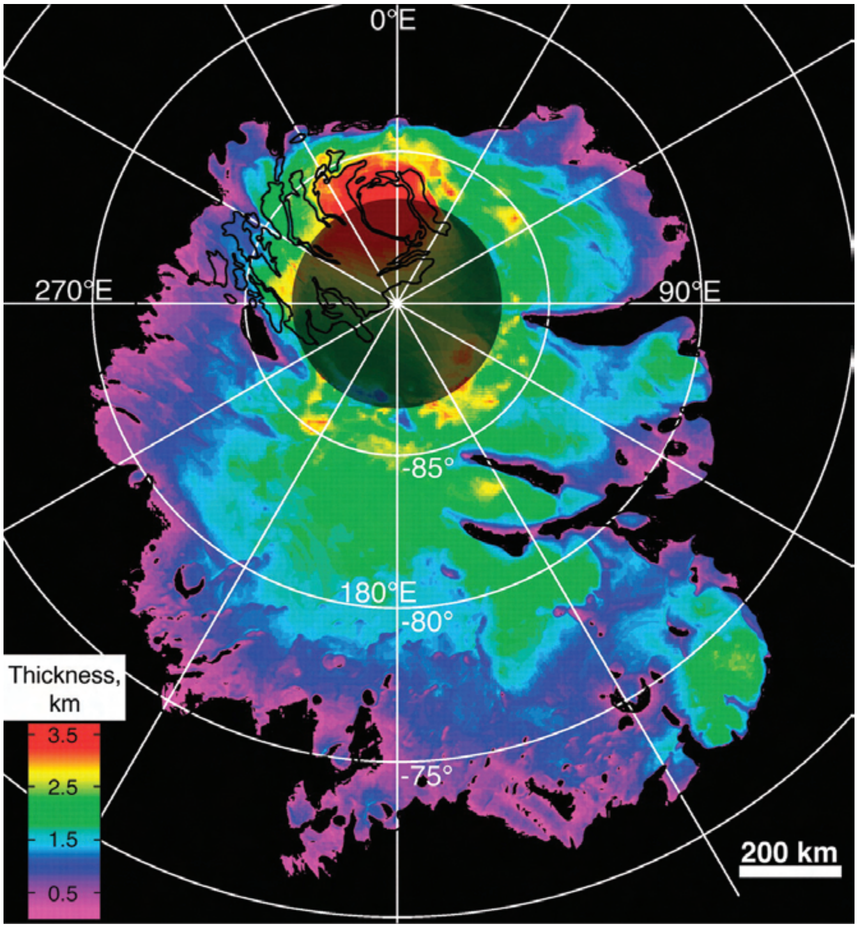


FIGURE 6.22 Map of the thickness of the southern polar layered deposits of Mars from MARSIS and MOLA surface topography. SOURCE: Courtesy of NASA/JPL/ASI/ESA/University of Rome/MOLA Science Team/USGS.

of these polar caps and indeed map that thickness (Figure 6.22).

So, what can we learn from such data? Obviously trying to understand the behavior of Mars itself is a scientific challenge. However, given that there is currently no evidence of biological activity, we are then talking mainly about dynamics and physics.

The next major spacecraft event will be arrival of the Phoenix spacecraft a little bit later this year (May 25, 2008). It is actually scheduled to land on the edge of the northern polar ice cap and start to perform some tests, drilling down into the ice.

THE MOON

After the Apollo program ended, the United States rather lost interest in the Moon. The Russians completed their initial program of lunar rovers, orbiters,

FIGURE 6.23 The Moon. SOURCE: Courtesy of P.-M. Heden of Vallentuna, Sweden.

FIGURE 6.24 Earth-set high-definition image shot onboard the KAGUYA. SOURCE: Courtesy of Japan Aerospace Exploration Agency and NHK (Japan Broadcasting Corporation).

landers, and sample return missions in 1976. There was then an extended hiatus in lunar missions.

The 1990s saw a rekindled interest, and missions have been flown by the United States, Japan, the European Space Agency, and recently by China and India. These last two nations have used such missions to demonstrate technological skills and capabilities.

NASA's Lunar Reconnaissance Orbiter will begin to tell us a little bit more about the Moon, including whether or not water ice really does exist in shaded spots at the poles, and if so, how much there is.[1] It will also be looking for safe landing sites for future crewed missions, locating potential resources, characterizing the radiation environment, and demonstrating new technologies.

CONCLUSION

Coming back to Earth, we need to remember that, in spite of all the rhetoric, carbon dioxide emissions into the atmosphere are firmly on, or indeed accelerating above, the business as usual curve. If we do not take action to stabilize these emissions at acceptable levels, temperature-projection models indicate the potential for a severe future a century from now and a planet which is completely transformed, with major social implications.

This is not the whole story. The global climate system is a complex interconnected non-linear system, capable of going through major reorganizations. A case in point: there is a 50 degrees centigrade temperature differential between the equator and the poles, and that, combined with the angular momentum effects or coriolus effects of being on a rotating planet, is what determines the flows of the fluids, the atmosphere, and the ocean. It's interesting to note that because of the amplification of warming at the poles (by a factor of 2 or more), at some point, one would reach a situation where that temperature differential has been very substantially changed. Whether there would be a major non-linear reorganization, is something about which we need to be a little concerned.

[1]The LRO was launched on June 18, 2009.

The image in Figure 6.24 was taken from lunar orbit by the Japanese SELENE spacecraft. It was images of Earth such as this one that arguably crystallized in humanities mind the finite nature of the planet, its limited resources and the need to take care of it. This image, I think, should also inspire us to consider how serious the prospect of global climate change really is. To quote Socrates (ca. 450 B.C.): "Man must rise above Earth—to the top of the atmosphere and beyond—for only thus will he fully understand the world in which he lives."

EDWARD C. STONE is the David Morrisroe Professor of Physics and vice provost for special projects at the California Institute of Technology (Caltech) and a former director of the Jet Propulsion Laboratory. Since 1972, Dr. Stone has served as the Voyager chief scientist in the exploration of Jupiter, Saturn, Uranus, and Neptune and continues to lead the study of the outer heliosphere as the two Voyager spacecraft continue their journey to interstellar space. He has also had oversight of the construction and operation of the two 10-meter W.M. Keck telescopes on Mauna Kea, Hawaii, and of the design development of the 30-Meter Telescope. Dr. Stone is a member of the National Academy of Sciences and the American Philosophical Society, president of the International Academy of Astronautics (IAA), a vice president of COSPAR, and on the board of the W.M. Keck Foundation. Among his scientific awards and honors, he has received the National Medal of Science (1991), the Magellanic Award from the American Philosophical Society, the IAF Alan D. Emil Award, the IAA von Karman Award, and three NASA Distinguished Service Medals. In 1996, Asteroid 5481 was named after him.

Voyager's Journey to the Edge of Interstellar Space

Edward C. Stone
California Institute of Technology

INTRODUCTION

The journey to interstellar space began 50 years ago with a discovery and a prediction. Launched during the International Geophysical Year, Explorers 1 and 3 revealed that belts of energetic protons and electrons trapped in the geomagnetic field encircle Earth. Soon to be named the Van Allen belts, they were the first major discovery of the Space Age that had begun only months earlier with the launch of Sputnik 1 by the Soviet Union.

During this time, Eugene N. Parker predicted that the solar atmosphere was expanding outward at supersonic speeds, filling interplanetary space with a dilute plasma of protons and other electrically charged ionized atoms of solar matter. Four years later during the first foray to another planet, Mariner 2 confirmed Parker's prediction of a solar wind continuously streaming radially away from the Sun at more than a million kilometers per hour.

Although its density is much lower than the best laboratory vacuum, the solar wind is strong enough to create the heliosphere, a giant bubble around the Sun that envelops the planets (Figure 7.1). Outside the bubble lies interstellar space filled with matter from the explosions of nearby supernovas.

In the years ahead, the two Voyager spacecraft will be the first human-made objects to reach interstellar space, completing a journey that began with a discovery and a prediction during the International Geophysical Year nearly 60 years earlier.

THE HELIOSPHERE

The motion of the heliosphere relative to the local interstellar medium creates a wind that distorts the heliosphere into a long-tailed, comet-like shape. In front, a curved interstellar bow shock resembles the bow wave of a ship. Although there are no images of the heliosphere, there are Hubble images of bow shocks in front of astrospheres around other stars (Figure 7.2). Fortunately, the two Voyagers are headed toward the nose region of the heliosphere where the distance to interstellar space is shortest.

The interaction of the Sun with the interstellar wind is complex. Models show the supersonic solar wind expanding outward until it is balanced by the pressure of the local interstellar matter outside. Near the edge of the heliospheric bubble, a termination shock marks where the supersonic wind abruptly slows to subsonic speeds, forming a thick layer called the heliosheath. In this outermost layer of the heliosphere, the subsonic wind is deflected toward the tail of the heliosphere.

The outer boundary of the heliosheath is the heliopause, where the solar wind finally makes contact with interstellar matter that lies beyond. The two Voyager spacecraft have crossed the termination shock and are

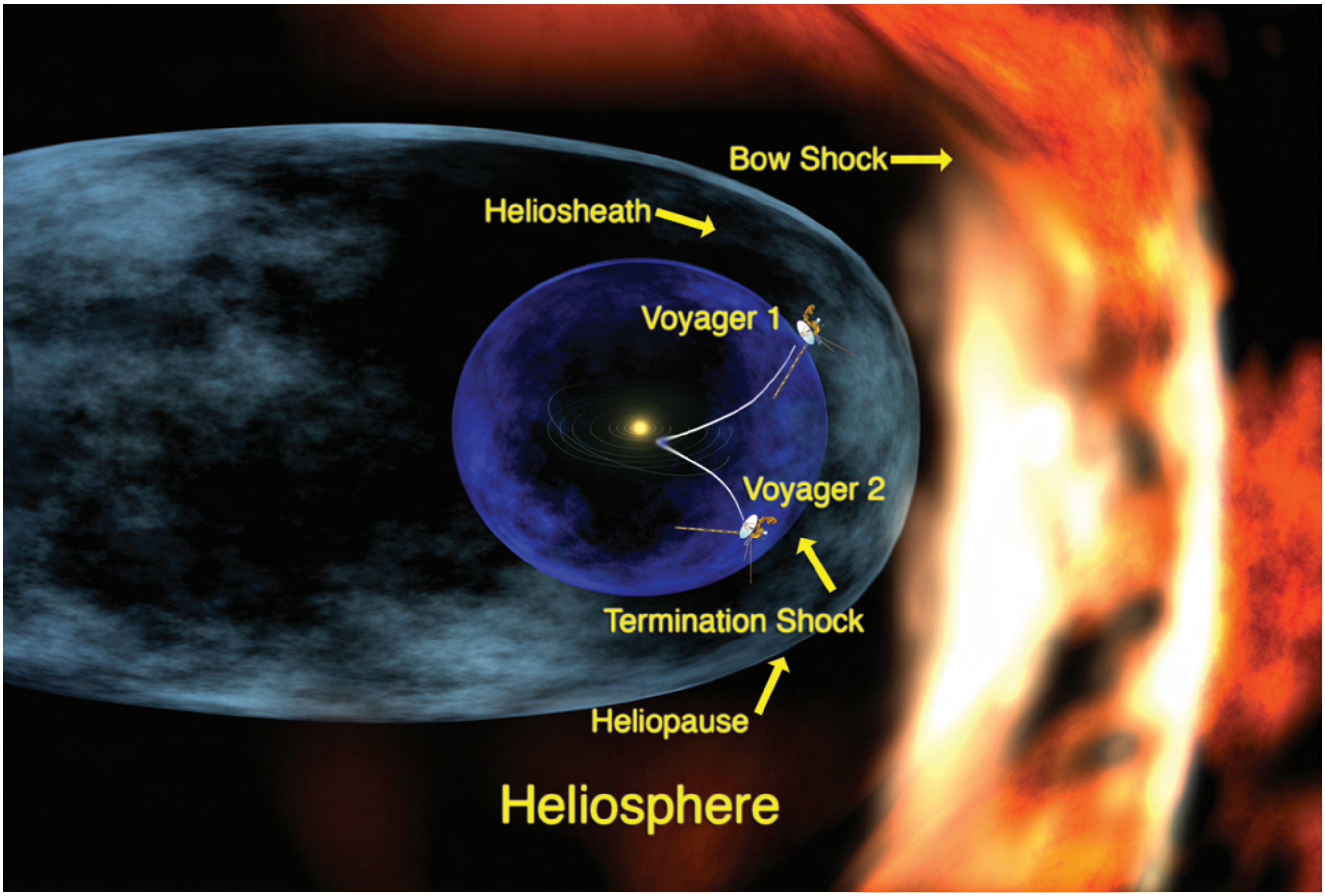


FIGURE 7.1 The Heliosphere. The solar wind creates a bubble around the Sun, enveloping the planets. A bow shock forms as the interstellar wind from the left is deflected around the heliosphere, resulting in the formation of a comet-like heliospheric tail. SOURCE: Courtesy of Walt Feimer, NASA GSFC.

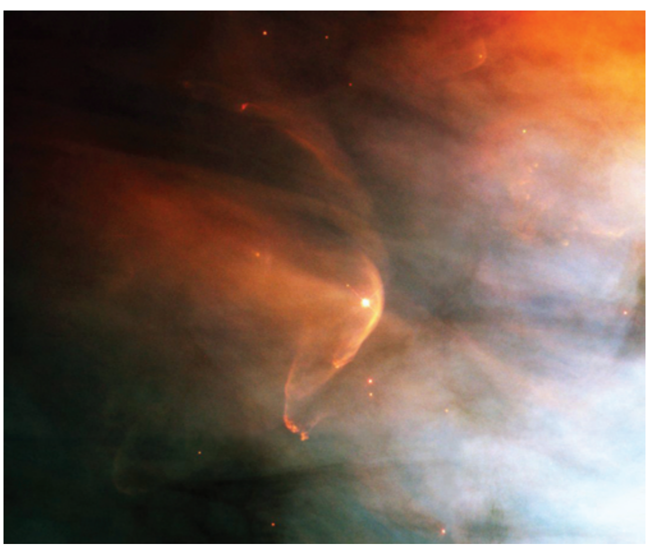


FIGURE 7.2 Bow shocks in the Orion Nebula. The large bow shock in the center and the smaller one above it form in front of invisible astrospheres surrounding two bright stars. SOURCE: Courtesy of NASA and the Hubble Heritage Team (STScI /AURA) and C.R. O'Dell (Rice University).

exploring the heliosheath on their way to interstellar space.

THE VOYAGER MISSION

Voyager's primary mission was to study the giant outer planets. It began in 1965 when the Jet Propulsion Laboratory was looking for times when the outer planets were aligned so that swinging by one could be used as a gravitational slingshot to speed a spacecraft onto the next. Although there are frequent opportunities for gravity assists involving two or three planets, once every 175 years Jupiter, Saturn, Uranus, and Neptune are aligned so that a spacecraft can swing by all four, picking up speed at each flyby. This Grand Tour trajectory reduced the flight time to Neptune from 30 years to only 12.

Fortunately, an opportunity for launching on a Grand Tour trajectory came in the late 1970s. However, a twelve-year flight proved to be too bold a step, so rather than losing such an opportunity, an ambitious project named Mariner Jupiter-Saturn '77 was planned for a 4-year mission to Jupiter and Saturn as the first leg of the Grand Tour. With 5 years to develop and test the first autonomous planetary spacecraft, the renamed Voyager 1 and 2 were launched on slightly different trajectories that increased the likelihood of at least one successful encounter with Saturn and maintained the option for a step-by-step completion of the Grand Tour if both were successful.

Voyager 1 led the way past Jupiter, which gave it a big enough boost to reach Saturn, with its rings and the moon Titan as primary scientific objectives. They lie in Saturn's equatorial plane, which is inclined to the plane of the planets. So, for an optimal study of Titan and the rings, the Voyager 1 flyby trajectory was also inclined, sending the spacecraft northward out of the planetary plane with no further planetary encounters possible.

With the success of Voyager 1, Voyager 2 remained in the planetary plane during its Saturn flyby, continuing on to Uranus and Neptune. A flyby over Neptune's north pole deflected Voyager 2 southward for a close flyby of the moon Triton. As a result, Voyager 2 is heading southward and Voyager 1 northward as they leave the solar system.

THE GIANT PLANETS

The Voyagers discovered unexpected diversity. Unlike the rocky inner planets—Mercury, Venus, Earth, and Mars—the outer planets are giant bodies of gas and liquid with no solid surfaces (Figure 7.3). Deep inside Jupiter and Saturn, hot, rocky cores lie buried under a deep layer of mainly hydrogen and helium, with ammonia ice crystals forming visible clouds in their atmospheres. Uranus and Neptune have similar cores but are smaller because there is much less hydrogen and helium in their outer envelopes. Clouds of methane ice form at the top of their very cold atmospheres.

There are dozens of moons orbiting the giant planets, several the size of the planet Mercury, but most much smaller than Earth's Moon. Because it is so cold, some moons are half water ice and half rock. Even so, Voyager found each was distinctive, with icy surfaces often showing evidence of past geological activity.

Voyager observed distinctly different ring systems about the four planets. The broad icy rings of Saturn were rippled with waves caused by the gravity of nearby moons, and two moons were found to shepherd finer ring material into a narrow ring between them. Both Uranus and Neptune have multiple narrow, dark rings, while Jupiter's faint broader rings are formed of dust from nearby moons.

Even the magnetic fields of the giant planets were surprising. Jupiter's magnetic field is the largest structure in the solar system, inflated by the pressure of oxygen and sulfur escaping the surface of the moon Io. Equally unexpected was the orientation of the magnetic fields of Uranus and Neptune, with their magnetic poles nearer their equators than their rotational poles as on Earth and the other planets.

There were many such unexpected discoveries at each planet.

Jupiter, Io, and Europa

Jupiter's Great Red Spot, a giant counterclockwise rotating storm system nearly three Earth diameters across, is the largest of dozens of storm systems continuously forming and merging in the turbulent atmosphere (Figure 7.4). Clouds of ammonia ice crystals mark bands of jet streams circling the globe at speeds of more than 300 kilometers per hour.

Four large moons orbit Jupiter, each with distinctive characteristics. The outer two, Ganymede and Callisto, are half water ice and as large as the planet Mercury. Impact craters scar the ancient icy surface of Callisto, while faults and grooves from past geological activity mark much of Ganymede's surface.

In contrast, Io and Europa, the inner two large moons, are mainly rocky objects the size of Earth's Moon. Io was the site of the astonishing discovery that set the stage for the mission's subsequent revelations. There were eight active volcanoes, with plumes rising up to 300 kilometers above a surface pocked by hot, dark lava-filled volcanic craters (Figure 7.5). Driven by the tidal flexing of its crust as it orbits Jupiter, Io has one hundred times the volcanic activity of Earth. It sheds a ton of sulfur and oxygen ions per second that forms a doughnut-shaped torus around Jupiter, inflating Jupiter's giant magnetic field to twice the size it would otherwise be.

Like Io, neighboring Europa is a rocky object, but is

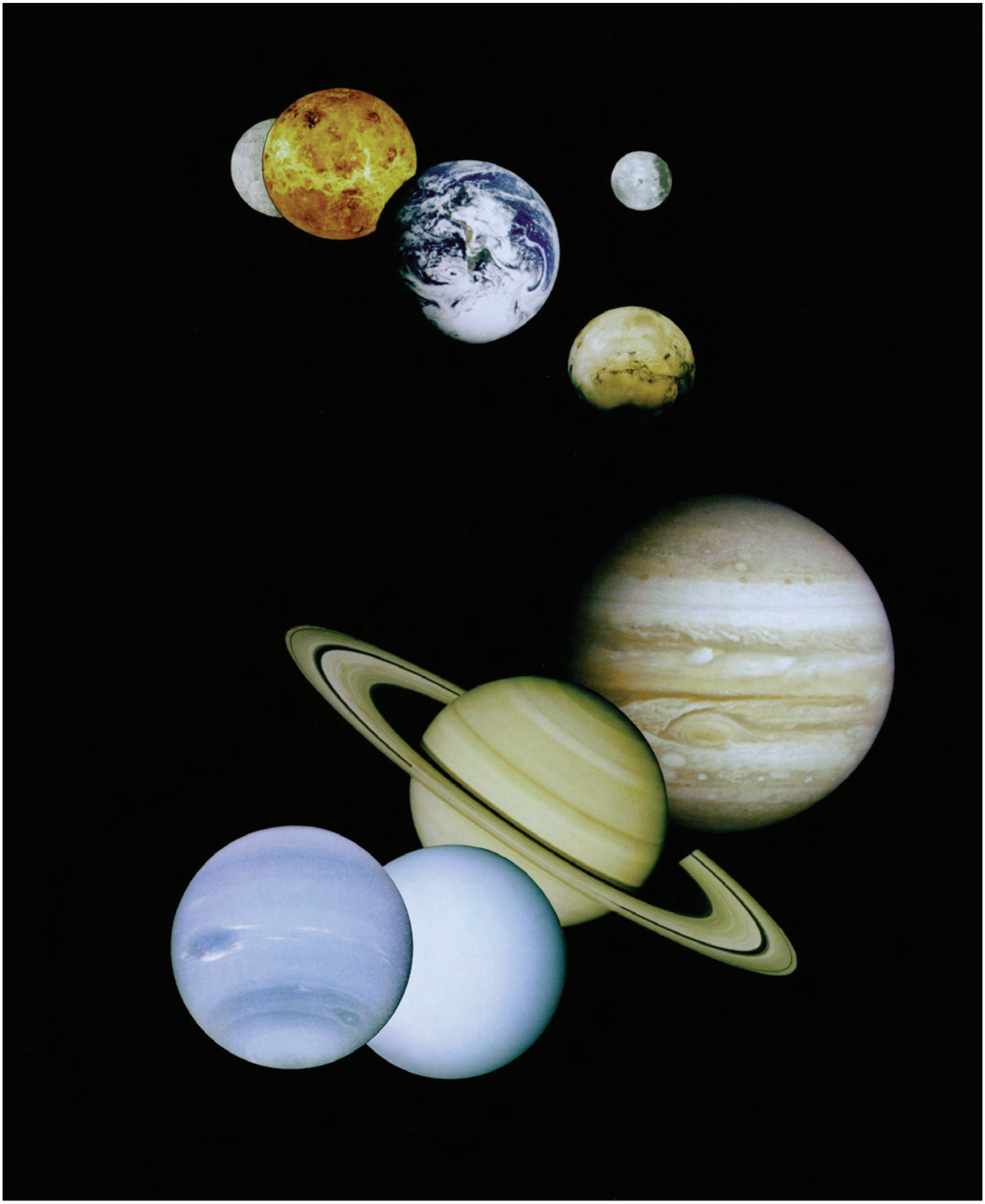


FIGURE 7.3 The planets. The rocky terrestrial planets, Mercury, Venus, Earth, and Mars, are at the top with the Moon. The lower four are the giant outer planets, Jupiter, Saturn, Uranus, and Neptune (not to scale). SOURCE: Courtesy of NASA/JPL.

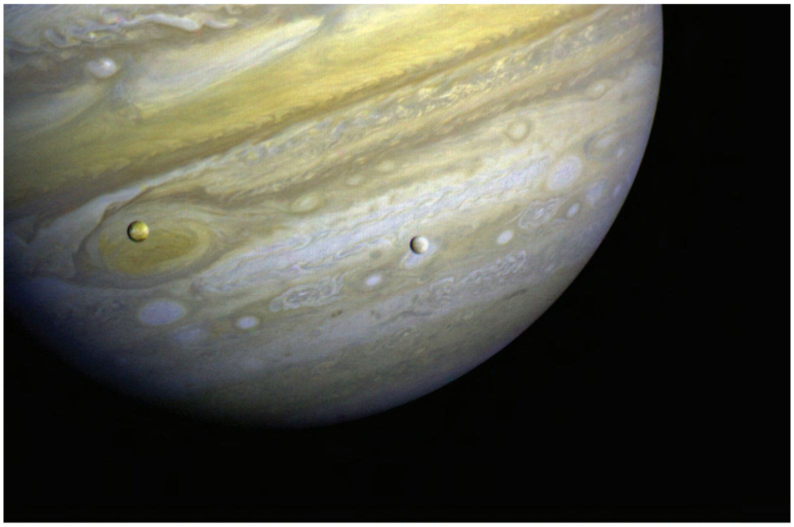


FIGURE 7.4 Jupiter, Io, and Europa. Jupiter's Great Red Spot is a storm system nearly three times the diameter of Earth. There are orange deposits on volcanically active Io and a white icy crust on Europa. SOURCE: Courtesy of NASA/JPL.

covered with water ice. Europa's surface, the smoothest in the solar system, resembles a floating ice pack, with faint streaks marking where tidal flexing has cracked the surface (Figure 7.6). Although Europa is further from Jupiter and the tidal effects are weaker than on Io, there is likely enough tidal heating to create an ocean of melted ice beneath the frozen crust. Evidence of such an ocean was found by the Galileo spacecraft in its close flybys of Europa during its mission in orbit about Jupiter in the late 1990s.

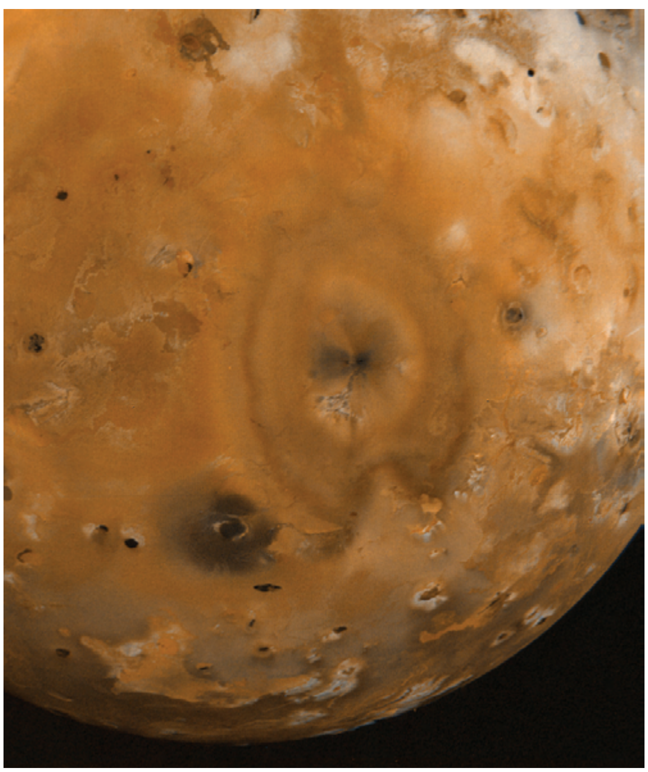


FIGURE 7.5 Jupiter's moon Io. The large heart-shaped pattern is the deposit of a volcanic plume erupting at its center. The many black features are volcanic calderas. SOURCE: Courtesy of NASA/JPL.

Saturn, Enceladus, and Titan

Saturn is colder than Jupiter and the atmosphere is less turbulent and hazier. Unexpectedly, winds race at up to 1,800 kilometers per hour, more than five times faster than in Jupiter's atmosphere

Saturn's rings make it the most beautiful of planets (Figure 7.7). These swaths of countless small icy fragments orbiting the planet also held surprises. Rippled by waves generated by the gravity of small nearby moons, the broad rings resemble an old phonograph record. At the outer edge of the broad rings, two small moons shepherded debris between themselves, creating a narrow, multi-stranded ring kinked by the gravitational effect of the moons.

The shepherd moons and many other small moons appear to be irregularly shaped fragments of larger moons shattered by comet impacts. Such collisions left craters on the larger moons, some with diameters one-third that of the moon itself. Any larger impact would likely have shattered those moons as well.

Enceladus, an icy moon only 500-km across, boasts a snowy white surface that is the brightest in the solar system (Figure 7.8). Reflecting nearly all of the incident sunlight, the average surface temperature is only 75 degrees above absolute zero. Some of the surface is ancient

FIGURE 7.6 Jupiter's moon Europa. The icy crust is the smoothest surface in the solar system, with streaks formed by tidally induced cracks in an icy crust likely floating on an ocean. SOURCE: Courtesy of NASA/JPL.

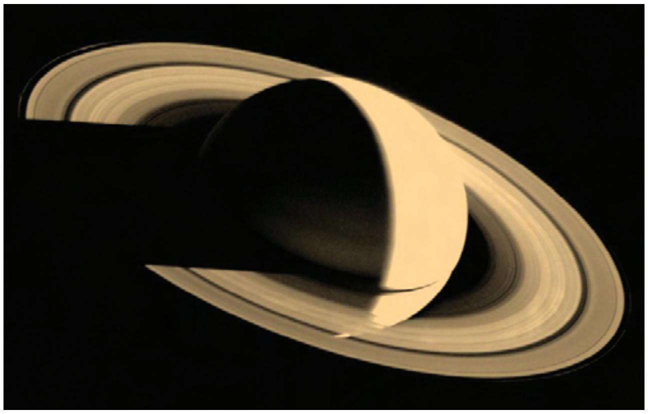


FIGURE 7.7 Saturn and its rings viewed from above and behind Saturn. The outermost A-ring, the brighter B-ring, and the fainter inner C-ring are composed of countless icy fragments with ripples and gaps due to moons orbiting nearby. SOURCE: Courtesy of NASA/JPL.

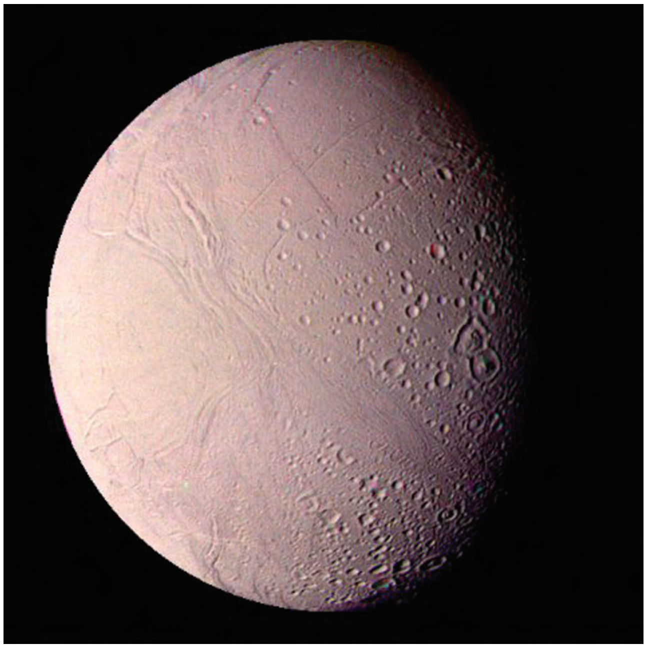


FIGURE 7.8 Saturn's moon Enceladus. The grooves, faults, and smooth regions are the result of extensive, continuing geological activity. SOURCE: Courtesy of NASA/JPL.

and heavily cratered as expected, but on such a small cold body it was surprising to find tectonic features such as grooved terrain and long rift valleys. Other younger areas are smooth, having few impact craters.

The Cassini spacecraft, launched in 1997 and now in orbit about Saturn, discovered why Enceladus boasts an unexpectedly bright and youthful surface. Geyser-like plumes erupt from fractures in the south polar region and deposit fresh ice on the surface, some escaping to form the faint E-ring.

Saturn's largest moon Titan is slightly larger than the planet Mercury. Unlike Mercury or any other moon, Titan has a substantial nitrogen atmosphere as on Earth, but with a surface pressure one and a half times greater. There is no oxygen, which on Earth was originally produced by microbes. Instead, there is methane, or natural gas. Irradiation produces organic compounds that rain onto the surface. More complex molecules form opaque haze layers that optically obscure Titan's surface.

Because of the opaque haze, Voyager could not image Titan's surface, but in 2005 the Huygens probe carried by Cassini parachuted down to Titan's surface, revealing stream-like drainage systems and flat, dry lake beds. Subsequently, Cassini's imaging radar peered through the haze layer, finding large lakes, likely formed from methane and other hydrocarbons that rain onto Titan's surface. The complex organic chemistry in Titan's atmosphere may resemble that which occurred in Earth's early atmosphere before microbial life evolved.

Future missions will study the chemistry of Titan's atmosphere, the water beneath Europa's icy crust, and the geysers erupting from Enceladus. They may tell us about the conditions necessary for the origin of life.

Uranus and Miranda

Uranus is tipped on its side, so its seasons differ from the other planets. At the time of the Voyager 2 encounter, Uranus' south pole was facing the Sun. Nearly twice as far from the Sun as Saturn and lacking a significant internal heat source, Uranus has the coldest planetary atmosphere in the solar system and much less energy to drive atmospheric activity. Even so, a few faint cloud features revealed wind speeds of nearly 900 kilometers per hour at mid-latitudes.

All smaller than Earth's Moon, five icy moons orbiting Uranus were expected to have cooled off and frozen quickly after forming. Unexpectedly, faults and other indications of past geological activity were found on the surfaces of several. Miranda, the innermost, is less than 500 kilometers across, yet has one of the most complex geological surfaces that Voyager observed (Figure 7.9). Heavily cratered older regions surround patterns of parallel ridges and grooves, some 20 kilometers deep, indicating that the surface of even such a small body was reshaped by an era of intense geological activity likely caused by tidal heating.

Neptune and Triton

Neptune is 30 times as far from the Sun as Earth, so there is only one 900th as much solar energy to drive its weather (Figure 7.10). Surprisingly, winds of 2,100 kilometers per hour are the fastest in the solar system, and there was a Dark Spot that resembled Jupiter's Greater Red Spot. However, a few years later the Hubble Space Telescope found that the Dark Spot had disappeared and other spots have since appeared.

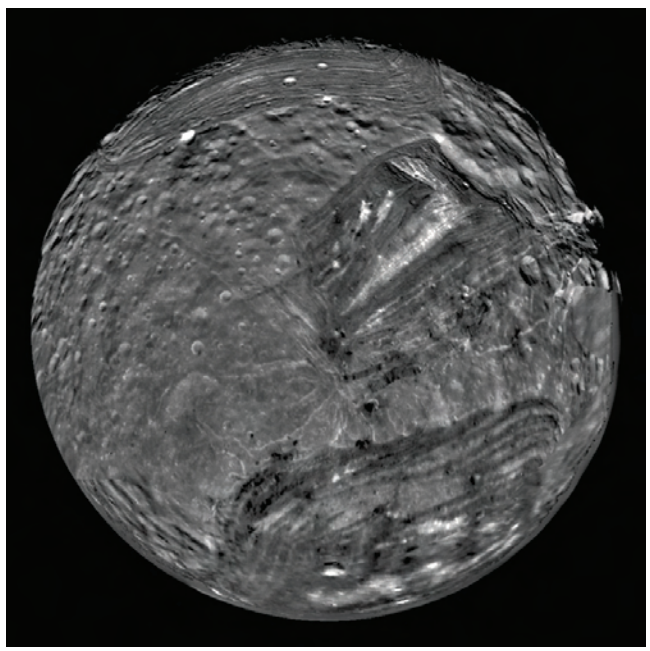


FIGURE 7.9 Uranus' moon Miranda. Extensive geological activity in the past has created a complex surface on this tiny moon with a diameter of less the 500 kilometers. SOURCE: Courtesy of NASA/JPL.

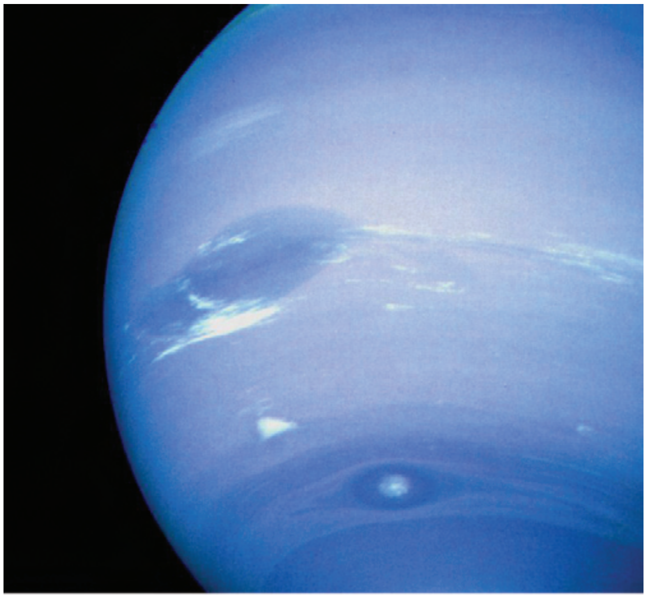


FIGURE 7.10 Neptune. The Great Dark Spot is a large storm that has now disappeared. Clouds of methane ice revealed the fastest winds in the solar system. SOURCE: Courtesy of NASA/JPL.

Triton, an icy Pluto-like body from the Kuiper Belt, was captured by Neptune and orbits in the opposite direction to the planet's rotation (Figure 7.11). Initially, Triton was in an elliptical orbit, causing tidal flexing of its surface that heated and melted its interior. This produced a uniquely textured surface resembling a cantaloupe, along with ridges and valleys and smoother regions produced by icy flows. As a result, the surface is among the youngest in the solar system with most impact craters erased by the icy volcanism.

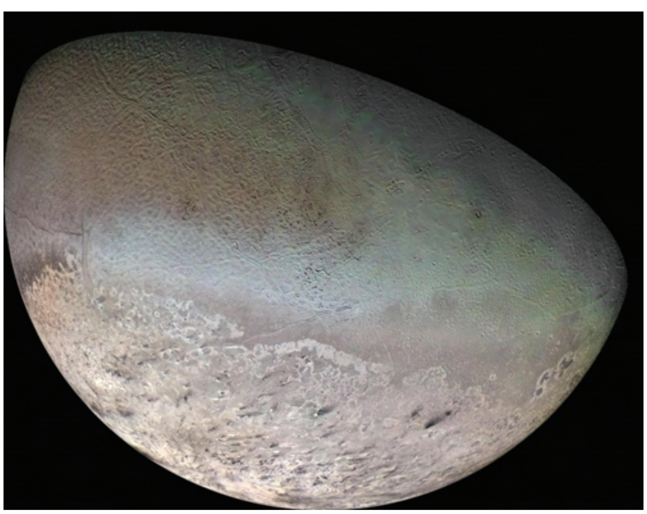


FIGURE 7.11 Neptune's moon Triton. The coldest body Voyager 2 observed has a polar cap of frozen nitrogen marked by dark streaks of dust deposited by plumes of geysers erupting from its surface. SOURCE: Courtesy of NASA/JPL.

Its icy surface reflecting much of the solar heat, Triton is the coldest object Voyager encountered. With a surface temperature only 38 degrees above absolute zero, most of the nitrogen freezes, forming a nitrogen ice polar cap. Surprisingly, even at this low temperature, geyser-like plumes erupt 8 kilometers upward into a thin atmosphere, depositing dark streaks of dust on Triton's surface.

THE OUTER HELIOSPHERE

Because of our limited knowledge of the local interstellar medium, the size and shape of the heliosphere were unknown. When the Voyager spacecraft finally crossed termination shock and began exploring the heliosheath, they revealed unexpected complexity (Figure 7.12).

Voyager 1 is headed northward from the solar equator. In December 2004, it crossed the termination shock at 94 astronomical units (14 billion kilometers; an astronomical unit (AU) is the distance from Earth to the Sun). As Voyager 1 moved deeper into the heliosheath over the next 3 years, the solar wind pressure began decreasing, causing the heliosphere to shrink and the shock to move inward to 91 AU in the northern hemisphere.

Voyager 2 is headed southward, and in August 2007 it found the shock at 84 AU, 1 billion kilometers closer to the Sun. So, the termination shock is pushed closer to the Sun in the southern than in the northern hemisphere, as could be caused by an interstellar magnetic field tilted so as to press inward more strongly in the south (Figure 7.12).

As it crossed the shock, the solar wind plasma lost 75 percent of its kinetic energy as the speed dropped from 1 million kilometers per hour to half that speed in the heliosheath. It was predicted that the missing kinetic energy would heat the slow solar wind in the heliosheath to 1 million degrees celsius. However, the temperature reached only 100,000 degrees, indicating that most of the energy lost by the solar wind did not heat the wind itself, but heated interstellar ions that had entered the heliosphere as neutral interstellar atoms and were subsequently ionized.

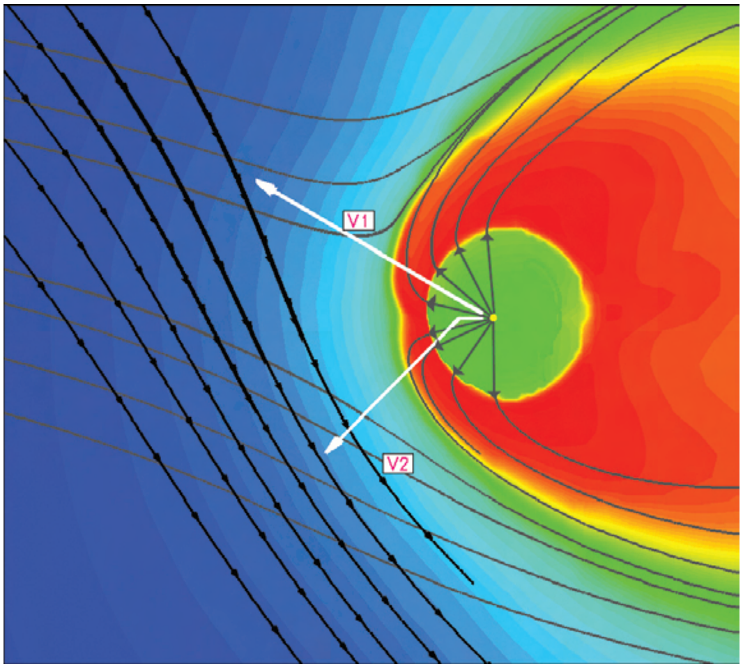


FIGURE 7.12 A side view showing the paths of Voyager 1 and 2 out of the heliosphere. In this model, the supersonic solar wind (green) streams radially outward from the Sun (gray arrows). The wind abruptly slows at the termination shock, forming the hot heliosheath (red) as it turns to flow tailward. The cooler interstellar wind from the left (blue with gray streamlines) carries the interstellar magnetic field (black arrows) with it. The wind is deflected around the heliosphere, pressing the magnetic field strongly inward in the southern hemisphere and pushing the shock closer to the Sun at Voyager 2. SOURCE: Courtesy of Merav Opher, George Mason University Department of Physics and Astronomy.

It was predicted that some of the interstellar ions would bounce back and forth like cosmic ping pong balls between the magnetic fields on opposite sides of the shock, becoming low energy cosmic rays as they slowly gained speeds up to half the speed of light. As a result, it was expected that the intensity of these cosmic rays would be highest at the shock. However, neither Voyager found an intensity maximum at the shock. Instead, the intensity is higher further out in the heliosheath away from the shock, indicating that the source of these low energy cosmic rays is not the shock regions crossed by the two spacecraft. Future observations may reveal whether anomalous cosmic rays originate at remote regions of the shock or in the outer regions of the heliosheath.

As the two Voyagers continue to explore this new region of the solar system, the Interstellar Boundary Explorer (IBEX) launched in 2008 will make a two-dimensional map of the heliosheath as viewed from Earth orbit. Measuring the intensity of neutral atoms streaming toward Earth from the heliosheath, IBEX will provide a new estimate of the distance across the heliosheath to the edge of interstellar space.

Although uncertain, current indications are that Voyager 1 may cross the heliosheath and enter interstellar space by 2015. Surrounded for the first time by matter from other stars, it will measure the direction and strength of the local interstellar magnetic field draped around the heliosphere and the intensity of low energy cosmic rays from the galaxy that are blocked from entering the heliosphere. If the spacecraft remains healthy, there is enough electrical power from its radioisotope thermoelectric generators to last well beyond 2020 when Voyager 1 will be more than 150 AU from the Sun.

A NEW VIEW OF THE SOLAR SYSTEM AND THE HELIOSPHERE

The International Geophysical Year ushered in the Space Age. The subsequent era of space science has given us a new view of the solar system, revealing dozens of unexpectedly diverse worlds enveloped in a giant heliospheric bubble created by the Sun. It has also given us our first journey to interstellar space, setting the stage for even more distant journeys. But most importantly, it has given us the both knowledge that there is much more to be discovered and the impetus to launch future journeys of exploration.

CHARLES ELACHI was appointed director of the Jet Propulsion Laboratory (JPL) in 2001. Dr. Elachi joined JPL in 1970. Prior to becoming director, he was JPL's director for space and earth science programs, where he was responsible for the development numerous flight missions and instruments for Earth observation, planetary exploration, and astrophysics. Dr. Elachi is a member of the National Academy of Engineering and has served on a number of Academy committees. He has received numerous awards, including the Sigma Xi William Procter Prize for Scientific Achievement (2008), International von Kármán Wings Award (2007), the America's Best Leaders by *U.S. News & World Report* and the Center for Public Leadership at Harvard University's Kennedy School of Government (2006), the Royal Society of London Massey Award (2006), the Lebanon Order of Cedars (2006), the Philip Habib Award for Distinguished Public Service (2006), the American Astronautical Society Space Flight Award (2005), the Bob Hope Distinguished Citizen Award (2005), NASA Outstanding Leadership Medal (2004, 2002, 1994), Takeda Award (2002), Wernher von Braun (2002), UCLA Department of Earth and Science Distinguished Alumni Award (2002), Dryden Award (2000), NASA Distinguished Service Medal (1999), the COSPAR Nordberg Medal (1996), the NASA Outstanding Leadership Medal (1994), the IEEE Medal of Engineering Excellence (1992), the IEEE Geoscience and Remote Sensing Distinguished Achievement Award (1987), and the NASA Exceptional Scientific Achievement Medal (1982).

Future of Space and Earth Robotic Exploration: Scientific and Technological Challenges and Opportunities

Charles Elachi
NASA Jet Propulsion Laboratory
California Institute of Technology

INTRODUCTION

Throughout the ages humans have explored the world around them to gain more knowledge and apply it to better our physical as well as intellectual life. From the early cave dwellers, to the Phoenicians, Greeks, Ptolemy, Zheng He, Marco Polo, Ibn Battuta, da Gama, Columbus, Magellan, Cartier, Cook, Lewis, Clark, Powell, Sir Hillary, Hubble, Hale, Armstrong, you, me and each one of us have been driven to explore for a variety of reasons, be it economical, intellectual, military, survival, or just the pure joy of expanding our horizon. All of these quests were limited to our planet or using observations of the heavens from Earth bound tools until half a century ago when advances in rocketry freed us to explore beyond our "Blue dot" and to look back at our own world in a whole different way.

Today's generations take it for granted to "Google™" any location on Earth (and in the sky) and get detailed images acquired by satellites. You can access weather satellites data on the Web. Use digital coding techniques on our cell phone, which have been developed for deep space communications. Apply image enhancement techniques in the doctor's office which were developed for planetary images analysis. Purchase medical thermometers and scanning devices with infrared detectors developed for orbital telescopes. These are just few examples of technological payoffs which were first developed in our adventure of space exploration, and now are embedded in our daily lives.

Fifty years ago, two small satellites, Sputnik and Explorer 1, changed our world from then to now. As of now, just NASA alone, has more than 58 robotic scientific explorers across the solar system, not counting the Space Station, and satellites developed by other U.S. agencies and other nations. We are in a Golden Age of Exploration, but we have only barely got a glimpse of the first chapter of the "Book of the History and Future of Our Universe."

EXPLORING OUR SOLAR SYSTEM

Many people are surprised when they hear that the United States has had continuous robotic presence on or around Mars. Since the arrival of the Mars Global Surveyor a decade ago, orbiting scientific spacecraft and surface rovers have been providing us with information about the surface and atmosphere of our neighboring planet in order to better understand its evolution and why it took a different path than our home planet, even though we share the same "solar system neighborhood." Technological advances in electronics, light weight structures, heat shields, imaging systems, and so on, have enabled us to put "robotic geologists" on another planet to explore on our behalf, and within the next decade we will have "robotic chemists" and "robotic biologists" roving on Mars to enable us to better understand the past, present or future potential habitability of another world which is the same size of the landmass on Earth, and prepare for future human expeditions.

Mars tends to get a lot of public attention due to being a popular topic for science fiction writers, and because of the two long-lived explorers Spirit and Opportunity. But the solar system has a wide variety

FIGURE 8.1 Opportunity tracks in Meridiani Planum. SOURCE: Courtesy of NASA/JPL.

of exciting targets to explore and better understand planetary evolution and potential habitability.

The Jovian and Saturnian systems are effectively miniature planetary systems with disks of particles (rings) and a wide spectrum of satellites which have volcanic, tectonics, geyser-like, atmospheric and weather activities, among others. Europa and Enceladus seem to have subsurface oceans directly expressed in surface activities or morphology. Io has present volcanic activity that is reshaping its surface. Titan has a methane cycle similar to our planets' hydrologic cycle and its North pole has numerous large lakes of hydrocarbon. Enceladus is ejecting water particles from its surface in a geyser-like fashion. We are truly having a first glimpse at a wide variety of other worlds. This was done with a small number of flyby and/or orbiting spacecraft which are the Lewis and Clark of the solar system. Over the next few decades we will be sending more sophisticated orbiters, balloons, landers, penetrators, submarines, and so on, which will explore in depth these new worlds.

Every time we send a mission to a new celestial object, we are surprised, and in the process gain new knowledge, be it from the analysis of the particles in comet tails acquired by Stardust, to the unexpected larger ejecta from Tempel 1 Deep Impact encounter. In addition to its eight planets (nine if you count Pluto), and their satellites, the solar system has thousands of small objects which can give us clues of how we came here. These includes active comets, main belt asteroids, dead comets, Trojan objects, Kepler belt objects, Earth crossing objects, and so on. With our technology we will be able to encounter, observe, land and possibly nudge some of these objects to better decipher the history of our solar system, and in some rare but important cases, avoid a major catastrophic impact.

Mercury, Venus, Uranus, Neptune and Pluto are also key pieces in the puzzle of the history of our

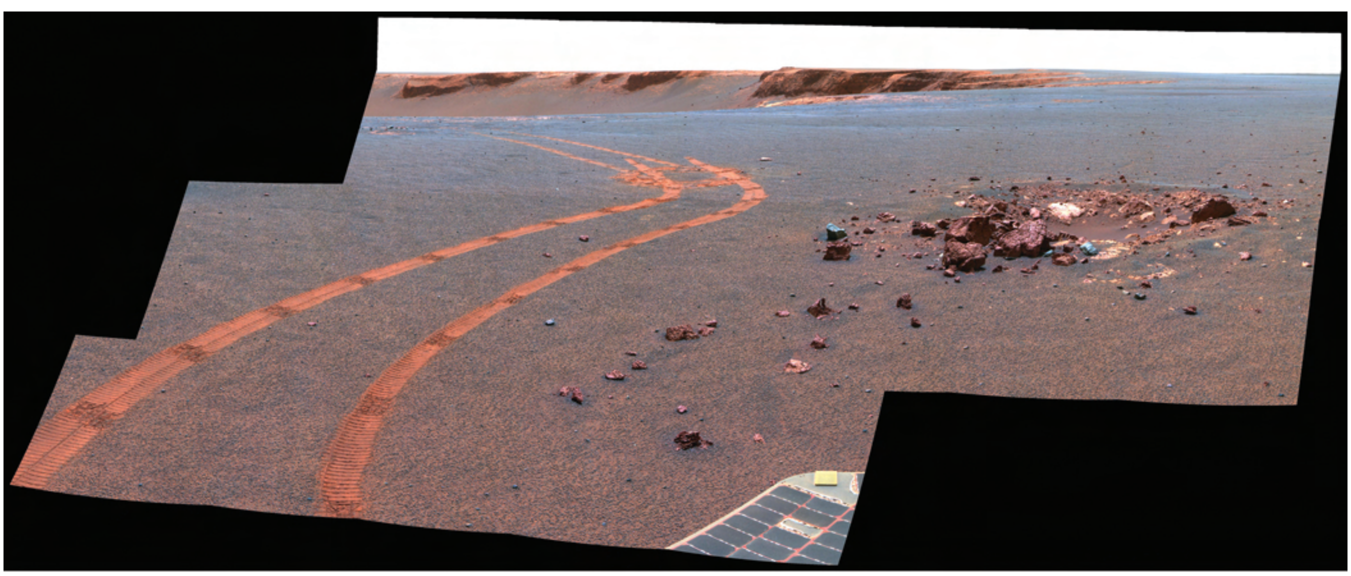


FIGURE 8.2 Opportunity tracks at Victoria Crater. SOURCE: Courtesy of NASA/JPL-Caltech/Cornell University.

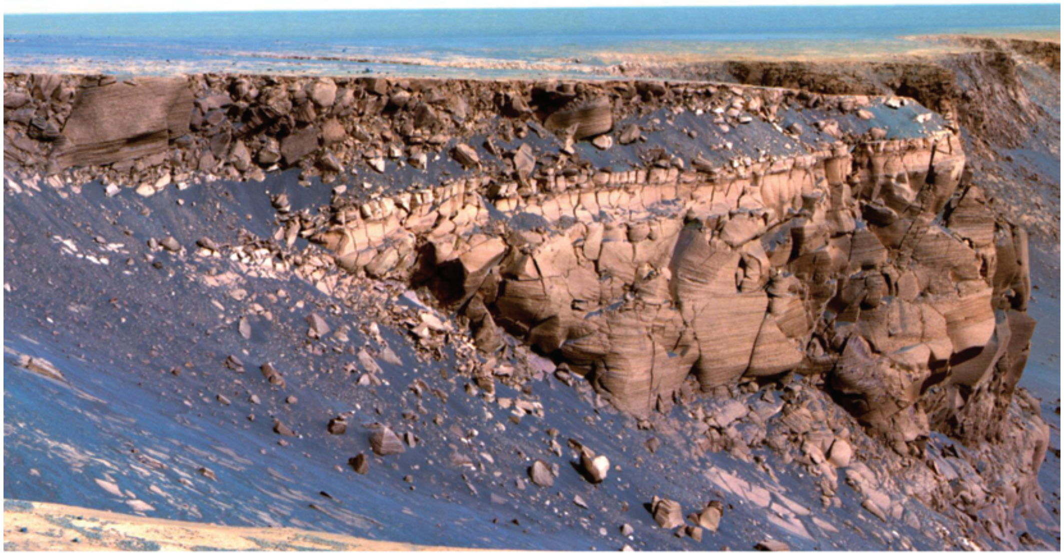


FIGURE 8.3 Opportunity Image of Cape Vincent in Victoria Crater. SOURCE: Courtesy of NASA/JPL/Cornell University.

neighborhood. For example, why is Venus, a planet similar in size to ours, have such a different atmospheric environment and a hellish temperature and pressure at its surface? Is our planet heading in that direction as we dramatically increase the amount of greenhouse gases in our atmosphere? Missions planned in the next decade with sophisticated remote sensing instruments, balloons, probes, and possible surface stations will hopefully shed more light on its evolution path.

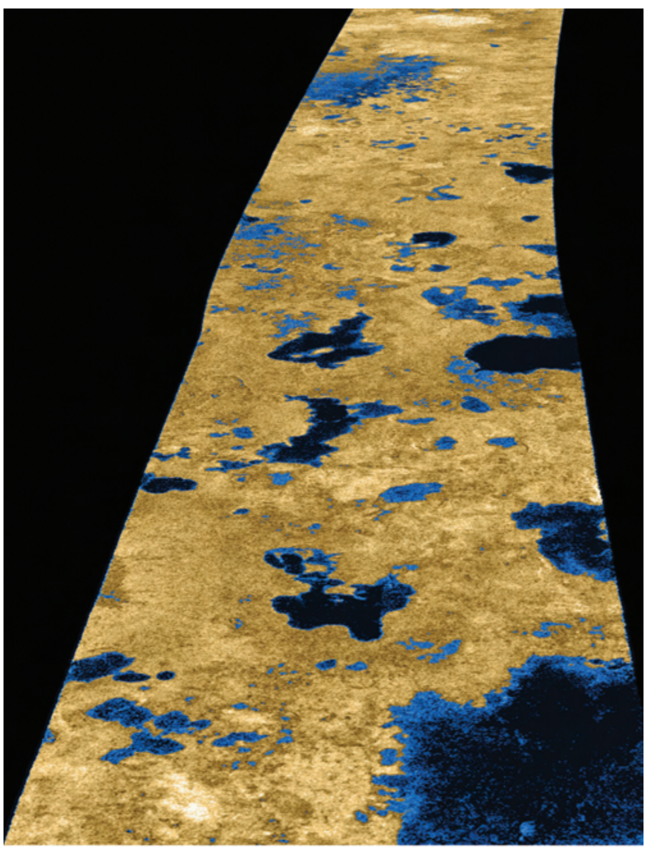


FIGURE 8.4 Methane lakes on Saturn's moon Titan (Cassini Radar). SOURCE: Courtesy of NASA/JPL/USGS.

NEIGHBORING SOLAR SYSTEMS

A decade ago, the topics of the presence and, if so, characteristics of planets around other stars was left to few science fiction writers and "fringe" scientists. Today, the field of "Exoplanet" studies is one of the most active and exciting scientific fields of research and has captured the public imagination. Detection of planets around

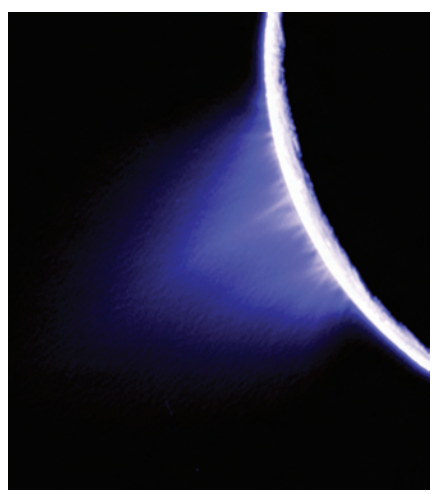


FIGURE 8.5 Geysers on Saturn's moon Enceladus (from Cassini). SOURCE: Courtesy of NASA/JPL/Space Science Institute.

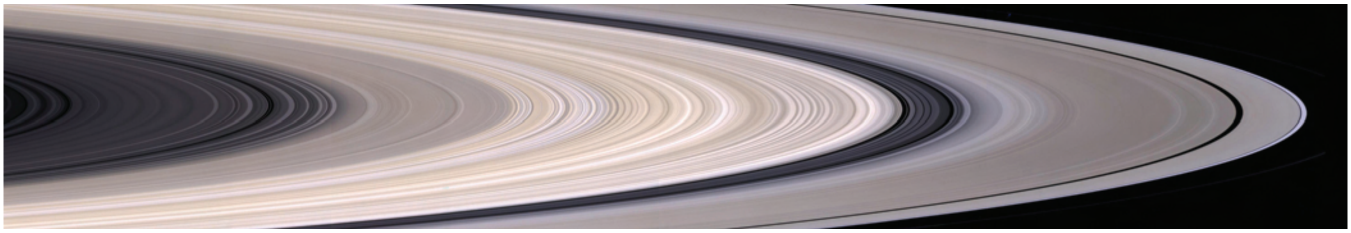


FIGURE 8.6 Saturn's rings (Cassini). SOURCE: Courtesy of NASA/JPL/Space Science Institute.

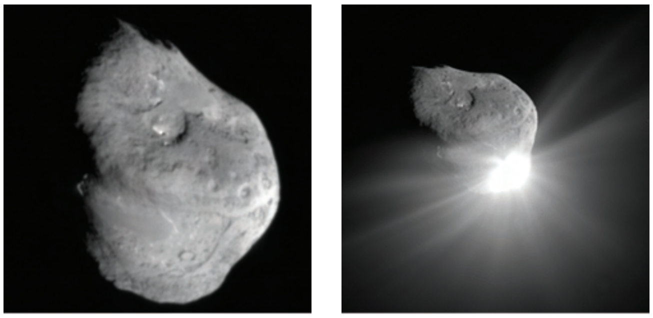


FIGURE 8.7 Comet Temple 1 before and after Deep Impact. SOURCE: Courtesy of NASA/JPL-Caltech/University of Maryland.

other stars with what seems to be exoteric astrometric techniques, makes front cover headlines. More than a hundred planets have been detected and their properties (mass, orbit, composition) are turning upside down our models of how planetary systems look like, showing significant differences from the simple orderly model of our own solar system.

Within the next decade, we will be able to get "family portraits" of the neighboring few thousands planetary systems and statistical assessment of how common they are in our galaxy and beyond. This will

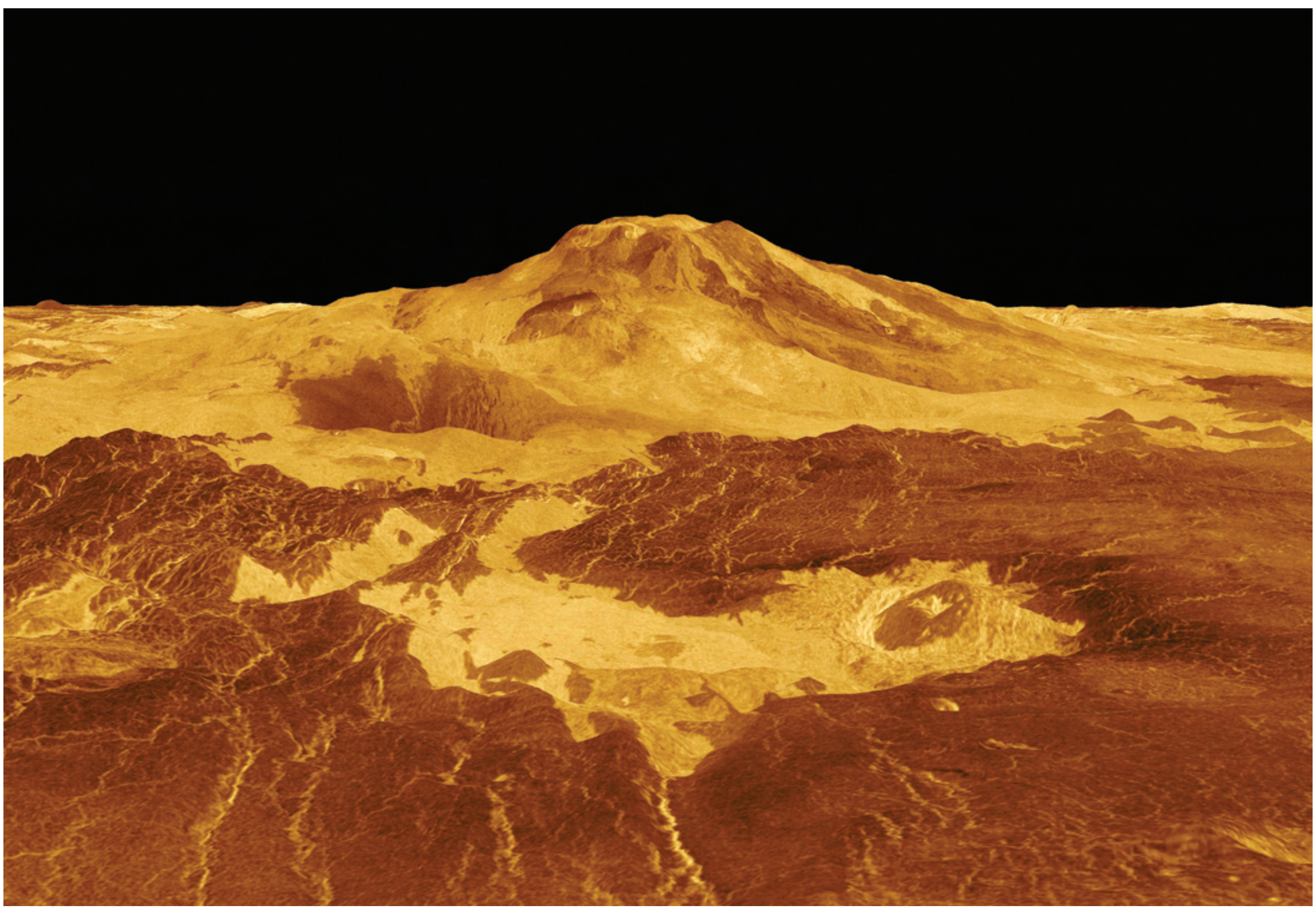


FIGURE 8.8 Venus surface perspective view (Magellan). SOURCE: Courtesy of NASA/JPL.

be done through a series of techniques which require continuous advances in technology ranging from very large arrays of detectors (for transit surveys like on Kepler), very high accuracy metrology (for astrometric missions), advanced adaptive optical systems (for direct imaging coronographs), and very accurate formation flying (for interferometric direct imaging). Acquiring significant information about other planets can be done even if we detect them as single points of light. Their mass, orbit, size, temperature, atmospheric composition and some temporal variation can be determined without resolving the planet beyond one pixel. Getting resolvable planet images might be a herculean endeavor, but it is not any more far fetched than having rovers on Mars as viewed by the technologists of 1958 who were working on Sputnik or Explorer 1.

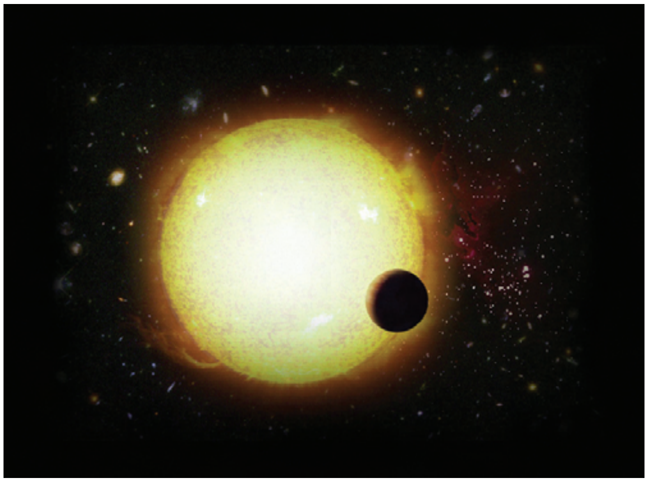


FIGURE 8.9 Kepler will observe transits of exoplanets. SOURCE: Courtesy of NASA/JPL.

FIGURE 8.10 Exoplanet Astrometric Mission (Planet Quest). SOURCE: Courtesy of NASA/JPL.

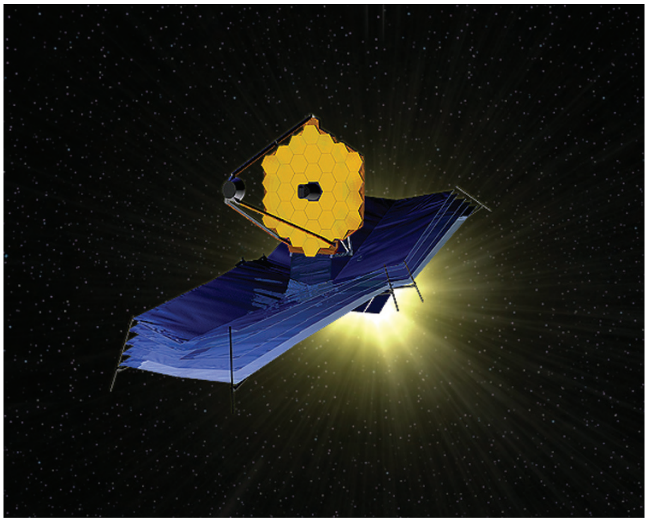


FIGURE 8.11 James Webb Space Telescope. SOURCE: Courtesy of NASA/GSFC.

ADVANCES IN ASTRONOMY

Advances in astronomy has been always driven by technological advances. Getting better resolution simply requires larger optics. Deeper viewing requires more sensitive detectors. Mitigating the atmospheric "blurring" requires adaptive optics or getting above the atmosphere. The advent of space telescopes, with large light weight optics, large high sensitivity focal planes across the spectrum, have been a critical element in advancing our knowledge of the universe around us. Images from the Hubble Telescope, Spitzer, Chandra and other space telescopes are now embedded in our textbooks, used by artists and advertisers, and are common front cover news. Over the next decade, the advent of the James Webb Space Telescope (JWST), Herschel, Planck, NuSTAR, GLAST, and other telescopes presently under study (Con-X, LISA, JDEM, and so on) will allow us to see back to the early dawn of our universe, trace its evolution, and better understand its composition and detect gravitational waves emanating from violent astronomical events. The recent discovery that we do not even understand what most of the universe is made of clearly shows that our quest of space exploration still has many discoveries to be made.

OBSERVING OUR PLANET

It is hard to believe that only a century ago we could only observe to the horizon at any time. Today we routinely can observe, monitor and study our planet on a global and continuous basis. We now regularly moni-

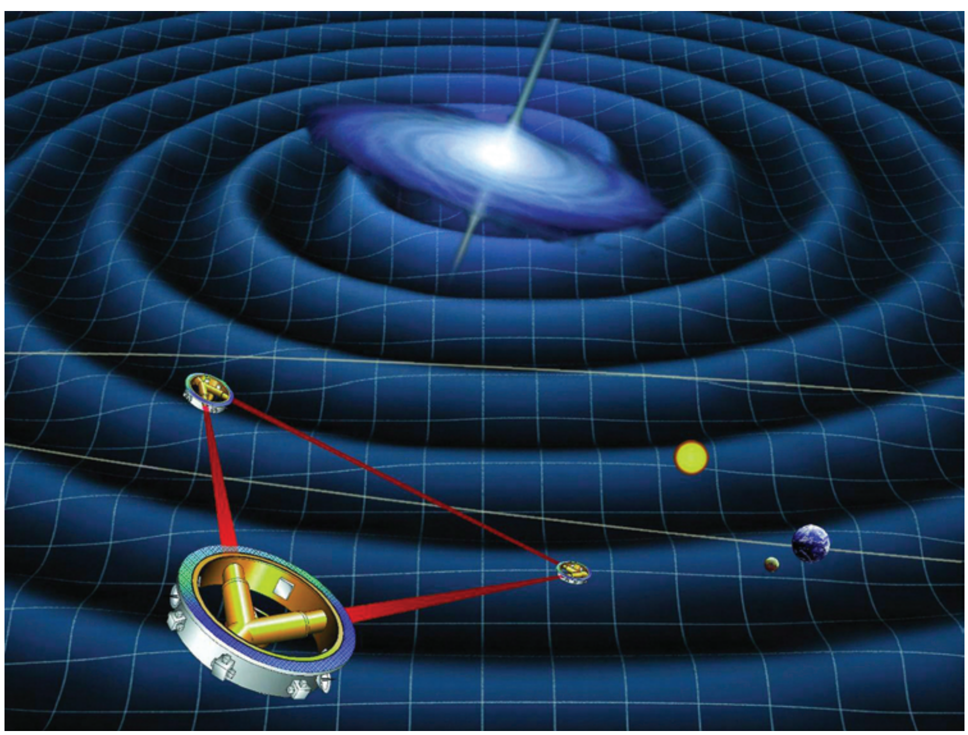


FIGURE 8.12 Laser Interferometer Space Antenna (LISA). SOURCE: Courtesy of NASA.

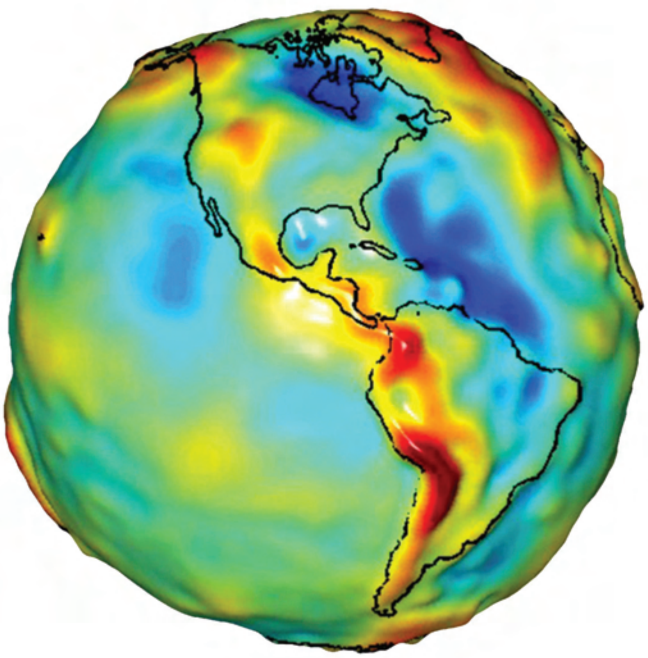


FIGURE 8.13 View of Earth's gravity field acquired with the Gravity Recovery and Climate Experiment (GRACE). SOURCE: Courtesy of University of Texas Center for Space Research and NASA.

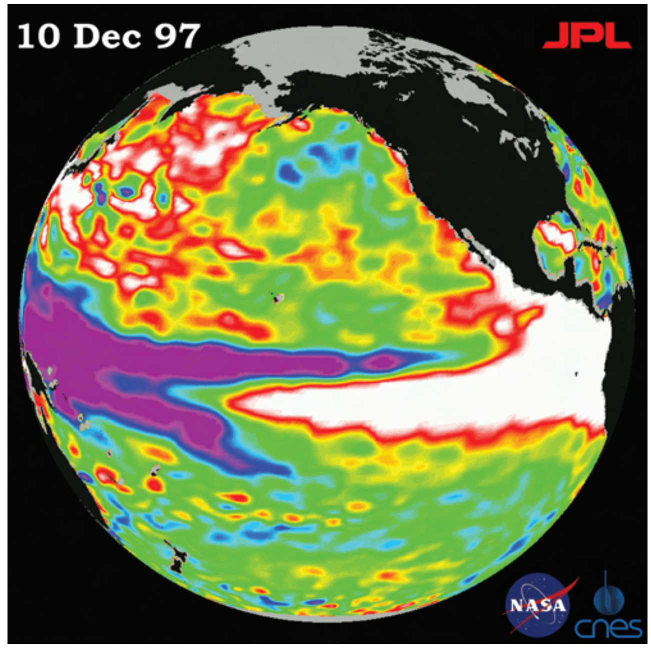


FIGURE 8.14 Topex/Poseidon and Jason missions ocean elevation monitoring. SOURCE: Courtesy of NASA/JPL.

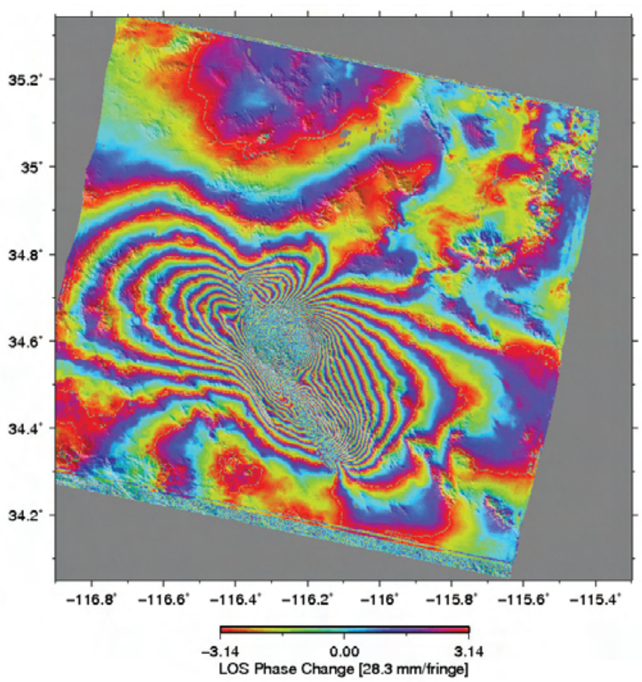


FIGURE 8.15 Interferometric synthetic aperture radar mapping of earthquake displacement. SOURCE: Courtesy of Andrew Newman, Georgia Institute of Technology, http://geophysics.eas.gatech.edu.

tor the ocean temperature and currents, wind patterns under the cloud cover of hurricanes, changes of the ice cover at both poles, the dynamics of the ozone layer that protects life on Earth, the changes in the vegetation cover, among many other environmental elements. Within the next decade we will be able to measure the ocean salinity from space, map in three dimensions the emissions, circulation and absorption of carbon dioxide, the subtle tectonic motion of plates leading to assessment of high risk areas, monitor the changes in biomass and the full inventory of atmospheric gases, detect subtle changes in the surface water (with altimetric changes), and subsurface water (with gravity changes). Our ability to monitor from space almost all the "health symptoms" of our planet is putting us at the threshold of being able to provide the public and the policymakers with scientifically based knowledge of the present and future impact that we are having on our planet. As we better understand, improve and verify our global model, we will then be able to assess the impact of specific actions that are proposed to be a better custodian of our home planet.

FRANK McDONALD is a pioneer and world-renowned leader in space physics and cosmicray astrophysics. His career of more than 50 years began with James Van Allen at the University of Iowa. He has devoted much of this time to studies of galactic cosmic radiation, solar energetic particles, and planetary magnetospheres. With their experiments on Pioneer 10 and 11, McDonald and Van Allen gave us the first comprehensive close-up look of energetic particles trapped in the magnetospheres of Jupiter and Saturn. With his many space-borne instruments, McDonald explored vast regions of our solar system, from the orbit of Mercury with the twin Helios spacecraft to distances of over 100 astronomical units with the Voyager 1 and 2 spacecraft that have now entered a new frontier, the heliosheath beyond the solar wind termination shock. McDonald's pioneering work began in the mid 1950s when he led two Rockoon (sounding rockets launched from balloons—a system invented by Van Allen) expeditions in 1954 and 1955 to study cosmic rays and what was then known as "soft radiation." McDonald opened up the new area of cosmic ray astrophysics—being first to use a multi-parameter electronic detector system to determine both the atomic number and kinetic energy of individual nuclei of the primary cosmic rays.

Over the years, he has made definitive observational and interpretive studies of the energy spectra and elemental as well as isotopic composition of galactic cosmic radiation, the dependence of the intensity of this radiation on solar activity and on distance from the Sun, and of the composition, energy spectra, and propagation of energetic nuclei accelerated at the Sun and by shock waves in the heliosphere. He discovered co-rotating streams of energetic nuclei in the heliosphere beyond a few AU. He discovered quiet time fluxes of 3 to 12 MeV electrons. In the early 1970s he co-discovered a new component of low-energy cosmic rays with a highly unusual elemental composition, which he named "anomalous cosmic rays." His subsequent discovery of anomalous cosmic ray N and Ne paved the way to our current understanding of the role of interstellar neutrals in the heliosphere. He discovered the important role of radially propagating merged interaction regions in modulating cosmic rays.

Still very active in his research, McDonald is focused on understanding the basic acceleration and transport processes of solar, anomalous and galactic cosmic rays. Using data from the two Voyager spacecraft, he is studying the dynamics of one of the last unexplored regions of our solar system, the regions close to the termination shock and the heliosheath.

Dr. McDonald served as chief of the Laboratory for High Energy Astrophysics at the NASA Goddard Space Flight Center, as NASA chief scientist, and as associate director/chief scientist at Goddard. Dr. McDonald made numerous important contributions to national and international activities in high-energy astrophysics, both by his own work and by his effective advocacy. He served as project scientist on nine NASA missions and was principal investigator on fifteen space experiments. Dr. McDonald is the author of more than 300 scientific publications and has written articles on space policy and space related subjects in *Science* and *Physics Today*. He served as chair or member on almost 35 committees and panels. He is a member of the National Academy of Sciences as well as the recipient of numerous honors and awards, among them the Lindsay Award and the Presidential Rank of Meritorious Excellence Award.

Explorer 1: Gateway to the Never Ending Wonders of Space Science

The Space Studies Board Van Allen Lecture
delivered by
Frank B. McDonald
Institute for Physical Science and Technology
University of Maryland

PREFACE

On June 26, 2008, on the occasion of the 50th anniversary of the Space Studies Board, Dr. Frank McDonald delivered the first Space Studies Board Van Allen Lecture. The following is excerpted from the transcript of this lecture and is intended to convey, in his words, the thoughts that Dr. McDonald shared with us on that evening.

Lennard A. Fisk
Chair, Space Studies Board
(2003–2008)

INTRODUCTION

I am very pleased to accept the Van Allen Award of the Space Studies Board, and to deliver the Van Allen Lecture this evening. I received my Ph.D. in 1953 from the University of Minnesota and then joined Van Allen's group at the University of Iowa from 1953 through 1959. Van Allen was an exceptional mentor. He paid close attention not only to me but all the other people that were in his group and gave us the support that we needed. He kept encouraging me to follow the right path in spite of a tendency I had to wander about a bit.

I remember a great deal about those early days in the space program, and the impact and advice that I received from Van Allen. I am pleased to be able to share some of those experiences with you tonight. NASA has been one of the great adventures in my life. I am so lucky to have seen the beginning of the space age with Van Allen. I saw Explorer 1 and 3. I was able to get my own programs going at the Goddard Space Flight Center, starting in 1959 when Goddard first opened. Even today, I am still looking at Voyager data. NASA has been really one of the world's most exciting places to be, and so in addition to describing how we began, I want to share some thoughts concerning where the space program is going in the immediate future.

I have also witnessed, as we all have, the tremendous impact of satellites on our lives. If we looked out tonight and we could count the satellites in the sky, we would find on the order of 875 satellites. Most are communications satellites, 15 percent are used for scientific purposes: Earth sciences, astrophysics, space physics, and planetary physics. If we consider only Earth and space science satellites by country, we find that from Europe there is on the order of 40 satellites. Here in the United States there are 52. China comes in third, with 21. Space science is predominantly an American and European endeavor.

Satellites have had an enormous impact on our lives. Just imagine if you would take them away, how the military would function and how other areas of our society would function. It would be a great loss. These 875 satellites are a routine part of our lives, so much so that when there is a major launch you might read about it in the trade journals, e.g., in *Aviation Week*, but you probably will not find a mention of it in the *Washington Post*.

THE EARLY PIONEERS

Let us begin in the beginning and trace the activities of the people who put the space age into motion.

In the very beginning there was Isaac Newton, who taught us the Laws of Motion. Force equals mass times acceleration; to every action there is always opposed an equal reaction. Newton's objective was to understand Kepler's Laws, to understand the motion of planets and the Moon. To make his life easier, he also invented calculus.

The modern day icons of the space age were Konstantin Tsiolkovsky, Herman Oberth, and Robert Goddard, who are shown in Figure 9.1, along with their immediate scientific descendants: Sergey Korolyov in the case of Tsiolkovsky; Wernher Von Braun in the case of Oberth, and all the American space program, symbolized by NASA/JPL, from Goddard.

Tsiolkovsky was born in a small village south of Moscow; he had a Polish father and Russian mother. He was left profoundly deaf at the age of 10 from scarlet fever, but he still read widely. At age 16, his parents sent him to Moscow for study, where he existed on brown bread. The librarian at the main library provided him with a place for him to work, so that at age 19 he was able to become a high school teacher. In the early 1900s, he published a number of articles, science fantasies. However, in 1903, he published his significant article in a Russian science journal: Exploring Space with Reactive Devices.

In the center of Figure 9.1 is Herman Oberth, who at the age of 12 read Jules Vern and was strongly influenced by him; indeed all three of the space icons were influenced by Jules Vern. Oberth's parents sent him off to study Medicine at the University of Munich. He did not like that, so he went to Heidelberg, where he wrote a Ph.D. thesis on interplanetary travel. It was not accepted by Heidelberg so he never officially got his degree. In 1923, he wrote a book, *Rockets into Interplanetary Space*, which sold surprisingly well. Oberth

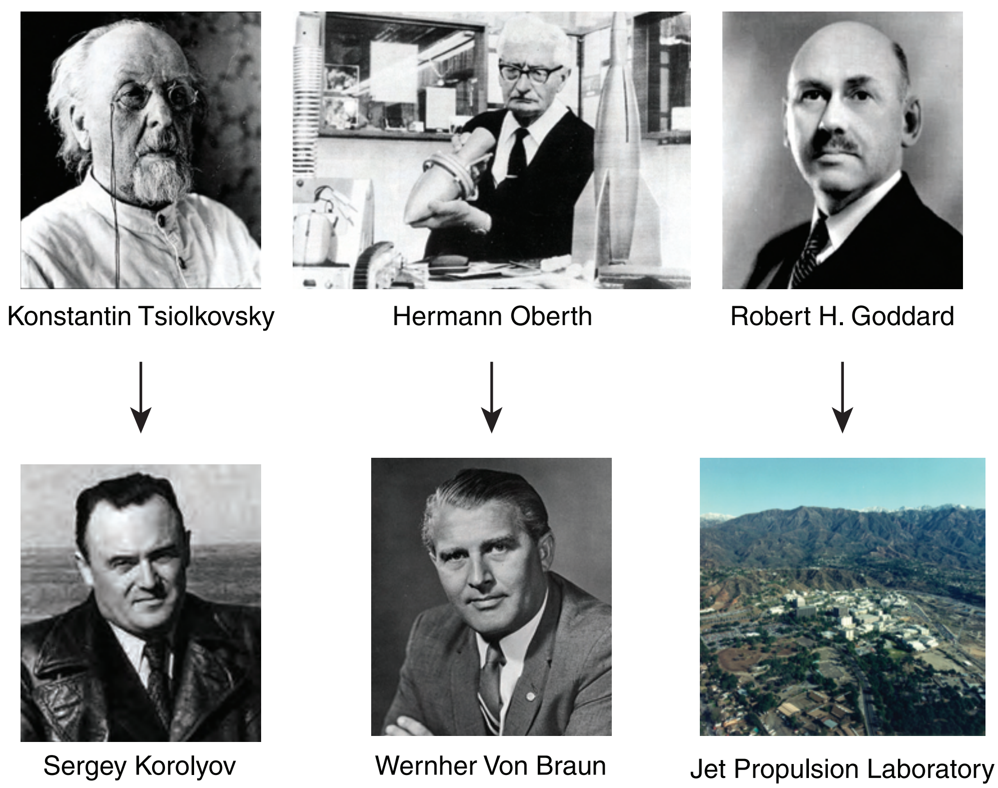


FIGURE 9.1 The three icons and their descendents. *Left to right, top row:* Konstantin Tsiolkovsky (NASA), Hermann Oberth (courtesy of the Hermann-Oberth-Spaceflight Museum, Feucht, Germany), and Robert H. Goddard (NASA). *Left to right, bottom row:* Sergey Korolyov (NASA), Wernher Von Braun (courtesy of NASA/MSFC), and the Jet Propulsion Laboratory (NASA).

had a great effect on Wernher Von Braun, who we will discuss later.

Robert Goddard, on the right of Figure 9.1, was also very interested in space. He received his Ph.D. from Clark University, after which he went to Princeton University where he developed tuberculosis and then returned home to continue his research at Clark. He submitted a proposal to the Smithsonian, which awarded him $5,000 to support his research. He published his research in 1921: A Method of Reaching Extreme Altitudes. Interestingly, he discussed at the end of that paper how he might send an object to the Moon, and then impact it with some flash powder that you could see from Earth. JPL is shown in Figure 9.1 as a descendant of Goddard, but in reality there was a very negative interaction between the two. JPL could never work with Goddard; he simply wanted to have his own show.

Oberth wrote to Goddard and asked him for a copy of his 1921 paper, a Method of Reaching Extreme Altitudes. Goddard reluctantly sent it, but gradually there emerged a conflict. The Germans claimed that Oberth had done it before Goddard, for which there is no evidence. The Russians pointed out that Tsiolkovsky published back in 1903, two decades before Goddard and Oberth, and to reinforce their point they raised the status of Tsiolkovsky, who had lived in total obscurity up to that point. The Soviets elected him to the forerunner of the Soviet Academy of Sciences, gave him a generous pension, and he was supremely happy.

A famous *New York Times* editorial on January 13, 1920 made the cutting statement that Goddard did not know the relation of action to reaction, stating that you have to have something better than a vacuum against which to react. It noted that Goddard should have learned this in high school. It was one of the most cutting editorials and damaged Goddard's self-esteem greatly. At least in July 1969 when Apollo 11 was making its way to the Moon, the *New York Times* put out a retraction and said, "Further investigation and experimentation have confirmed the findings of Isaac Newton and it is now definitely established that a rocket can function in a vacuum as well as in an atmosphere." One can argue that the media should stay out of things they do not understand.

Goddard did receive support from Charles Lindburgh who was very impressed with what Goddard was doing. Lindburgh went to Harry and David Guggenheim and got funding for Goddard, at the rate of $25,000 a year for 4 years. Back in the early 1930s, $100,000 was a lot of money, so Goddard picked up and moved from Massachusetts to Roswell, New Mexico, before we had all the flying saucers there. There he developed the liquid propellant rocket, occasionally blowing it up, but eventually getting it to reach an altitude around 9,000 feet. The Caltech folks and Frank Malina from JPL went to visit Goddard, but he would not show Malina the rockets that he had. He did let Malina into his shop but would not uncover the rocket that he was putting together. Goddard just did not play well with others, but he was a great pioneer of the space age.

THE GERMAN ROCKET PROGRAM OF WORLD WAR II AND THE BEGINNING OF THE U.S. ROCKET PROGRAM

In the meantime, back in 1929, the Germans made a decision that they wanted to have what would come to be known as Intermediate Range Ballistic Missiles. They turned the task over to Captain Walter Domberger, who recruited Wernher Von Braun, and they put together a rocket team and opened up a rocket test sight in Peenemunde, in September 1941. The war at that time was going well for the Germans, and so Hitler cut back on their budget and they limped along, developing what would become the A7.

However, as the war worsened for the Germans, they received increased funding for a production rocket, the V2 shown in the center panel of Figure 9.2, which they produced by using concentration camp labor. The rockets were reasonably successful in their flight history. The V2 rockets did some damage to England, and some 5500 people were killed. More than 12,000 of the concentration camp laborers died. It was really an inhumane exploitation of these people that went beyond anything I think we can imagine.

The development of the V2 was the beginning of the modern Intermediate Range Ballistic Missile. At the end of the war, the U.S. scooped up the rockets, the parts, the drawings, and the people, in Operation Paperclip. They brought 100 rockets to Whitesands and the Naval Research Laboratory (NRL) convinced the U.S. Army that they should launch payloads—that the Army had a need to learn about what the upper

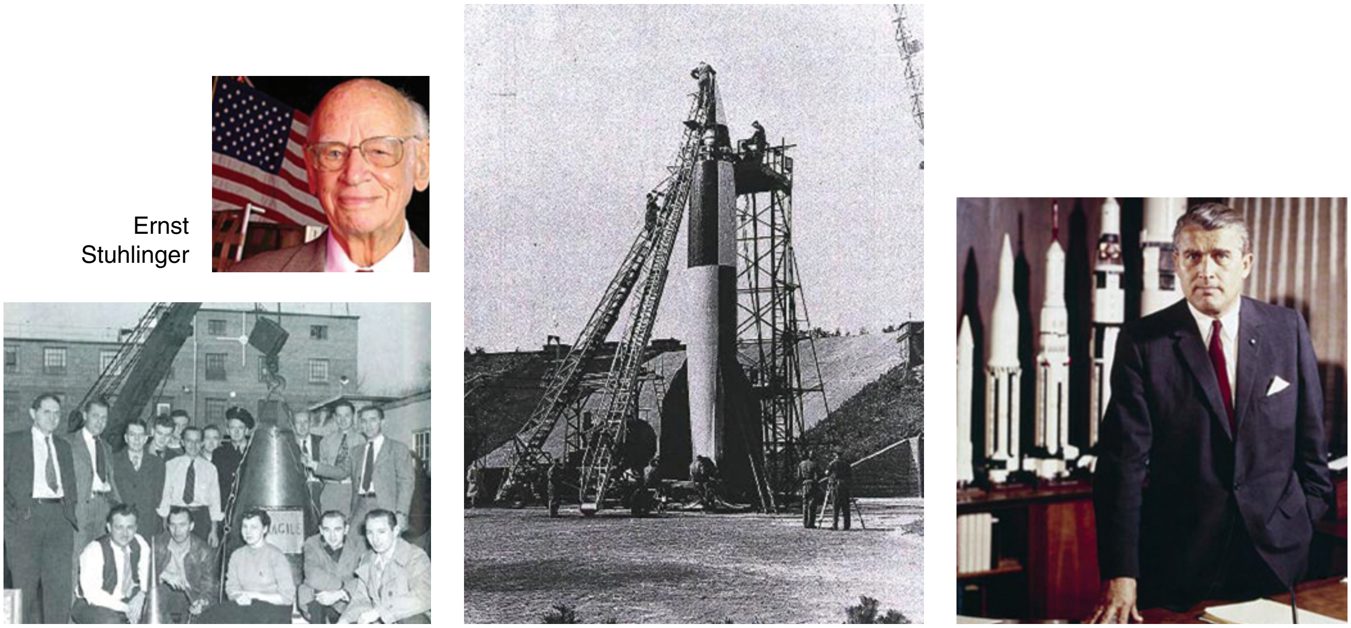


FIGURE 9.2 Ernst Stuhlinger (courtesy of Patricia Miklik Doyle); Applied Physics Laboratory (APL) Upper Atmospheric Research Group (courtesy of Johns Hopkins University APL); V2 rocket (courtesy of NASA Glenn Research Center); Wernher Von Braun (courtesy of NASA/MSFC).

atmosphere was like. Ernst Stuhlinger, also shown in Figure 9.2, was part of Von Braun's group and had done his PhD thesis on the development of Geiger counters. He became the scientific liaison to the scientific community.

Shown in the lower left hand corner of Figure 9.2 is Jim Van Allen, looking as young as always, with a large group. At that time, he was with the Johns Hopkins University Applied Physics Laboratory and, as one might expect, when he came to town to fly the first rocket, he had his experiment ready and he flew it. Unfortunately, the rocket failed, but he did eventually get a successful flight, number 33. At the same time, Eric Crowther organized a rocket panel to distribute the V2 resources but he left shortly to go into industry. Van Allen took over as chairman of the group that evolved into the Rocket Upper Atmospheric Research Panel, finally the Rocket and Satellite Research Panel. Van Allen remained Chairman until NASA was established, and then the group dissolved. The Rocket Panel did not receive support from anybody. It met roughly three times a year and it was made up of people from universities, government laboratories, and industry.

This was Operation Paperclip and its successor programs. In the end some 67 V2s were fired. The V2s were followed by the Aerobee rocket, which could take a 100-pound payload through a 76-kilometer trajectory. The Aerobees were made by Aerojet under the supervision of Von Kármán and Frank Malina of JPL, and were eventually operated by NRL. The Aerobee was a revised version of the Corporal rocket. It steadily improved over the years and some 1037 Aerobees were fired.

VAN ALLEN AND ROCKOONS

Let's return now to Van Allen. On the left of Figure 9.3 is Van Allen as a graduate student, at what is now the University of Iowa. The middle shot, shows him as a Lieutenant in New Guinea. Van Allen worked first at the Carnegie Institute on the proximity fuse, and so he was one of the people who was sent to the Pacific to introduce the rocket to the Navy. The photo on the right is Van Allen at his desk at the University of Iowa at the end of his career.

One of the technologies that Van Allen developed

FIGURE 9.3 Dr. Van Allen (*left to right*) as a graduate student (NASA), as a lieutenant in the Navy (NASA), and at his desk (courtesy of Tom Jorgensen, University of Iowa Office of University Relations, 1990).

while in the Navy, an idea he got from Lee Lewis, a Commander in the Navy, was the Rockoons. As shown in Figure 9.4, these were rockets that were launched from a balloon. The balloon takes the rocket to about 70,000 feet, and you are able to achieve 350,000 feet when the rocket fired.

The Rockoon program was great fun, but it had its moments that established that we really were not rocket scientists. The photo on the right shows some idiot up there (me) holding a two-stage rocket that we decided to try. We used the same nose cone and the same tail fins that we used on smaller rocket flights. The rocket

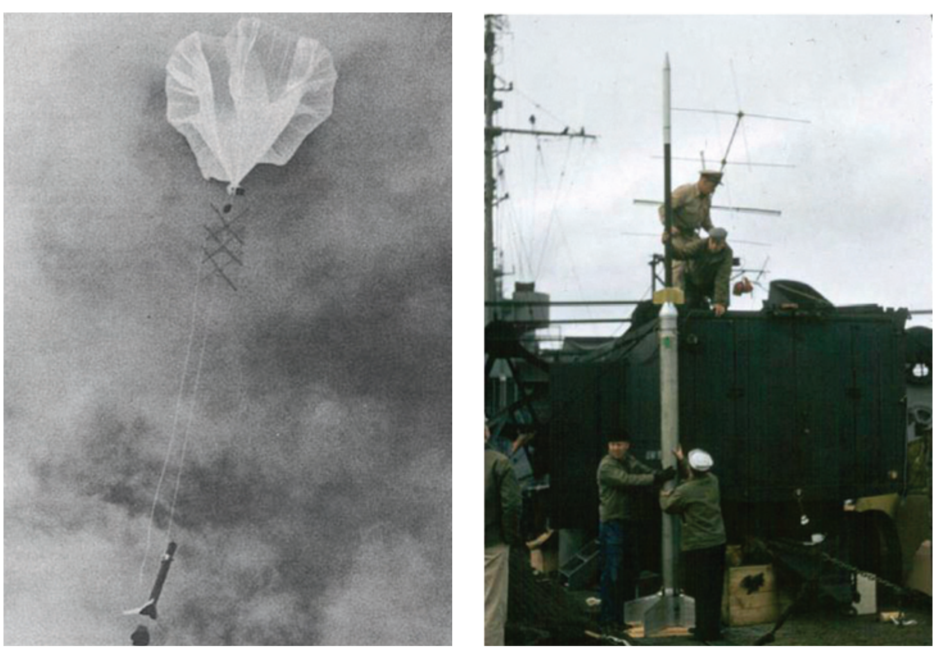


FIGURE 9.4 Rockoons. SOURCE: Courtesy of NASA.

was carried by the balloon to 70,000 feet. It fired, the second stage fired, and everything went blank. We did that twice. Then JPL told us that although the rocket may be at 150,000 feet or so, it still has a great deal of heating that will burn through the tail fins and the nose cone.

Three or four days later, the small rocket that is on the top of the rocket exploded on deck, severely injuring our Navy representative who is up there, right behind me. We got him to shore, he made a complete recovery but I had to come down to Washington and face the Navy. I must say in all of my years, I have never been dressed-down quite as strongly as they did. And with me already feeling very badly about the whole thing. There were roughly 100 Rockoon flights in six expeditions started in 1952, and they were great fun. A lot of the experiments were done, ionization chambers, single Geiger counters, double and the shielded Geiger counters; the same experiments that we would later fly on satellites.

THE FIRST SATELLITES

There was a very interesting study done in 1946 by the RAND project that stated that although the crystal ball into the future is cloudy, two things seem clear: "A satellite vehicle with appropriate instrumentation can be expected to be one of the most potent scientific tools for the 20th century. The achievement of a satellite craft by the United States would inflame the imagination of mankind, and would probably produce repercussions in the world comparable to the explosion of the atomic bomb." Neither of these statements were over-statements by any stretch of the imagination, as proved to be the case when the Soviets launched a satellite first, and there were worldwide repercussions that the Soviets were ahead of us.

Starting in 1954, with the development of ICBMs, it became obvious that a satellite could be launched if you had the will to do it. The U.S. proposed through its International Geophysical Coordination (IGY) committee that they would launch a satellite during the IGY period in 1957 to 1958, and the Soviets came back saying they too were going to launch a satellite. We were distinctly told what their intentions were. They were going to launch Sputnik, as shown in Figure 9.5. Our reaction was one of surprise and dismay, as shown by the strong reaction in Life Magazine.

The Soviet who made Sputnik happen was Sergey Korolyov, who had spent World War II in a Soviet

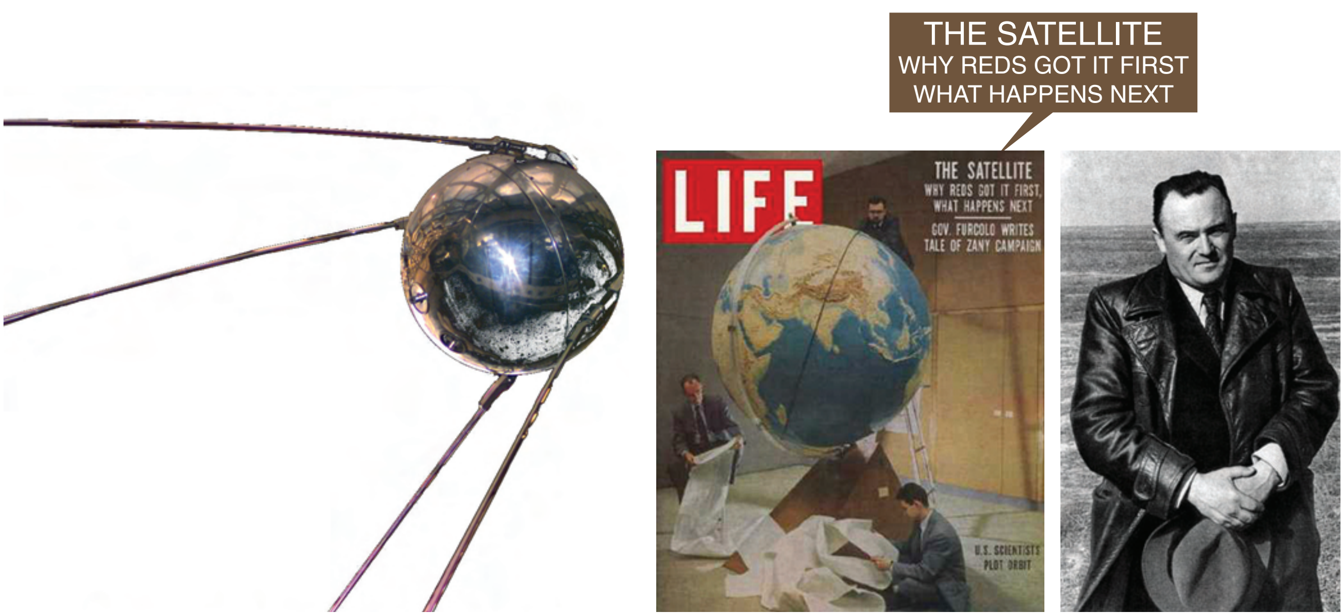


FIGURE 9.5 *Left to right:* Sputnik 1 (courtesy of NASA National Space Science Data Center); Smithsonian Observatory scientists working at Massachusetts Institute of Technology trying to calculate Sputnik's orbit, cover of *LIFE* magazine, October, 21, 1957 (photo by Dmitri Kessel/Life Magazine, Copyright Time Inc./Time Life Pictures/Getty Images); and Sergey Korolyov (courtesy of NASA).

Gulag. One of his so-called friends but really rivals had claimed he was giving information to the enemy. He was sentenced to the Gold Mines in Siberia. His thesis advisor arranged for him to be assigned to the place where they were doing design work for rockets, and he put together the ICBM, the R7 that was flown twice successfully as an ICBM before Sputnik.

There were many people in Washington who worried what would happen if the U.S. launched a satellite first and over-flew Russia. They did not know what the Soviet reaction would be. It was convenient that the Soviets used an ICBM to launch Sputnik. However, the appreciation of letting the Soviets clear up the policy issues was lost on the general public, who were alarmed by the Soviet success.

In the U.S., the Vanguard rocket to be built by NRL had been selected to launch the first U.S. satellite. The Germans, under Von Braun, were now safely ensconced and happy in Huntsville. They were initially denied the opportunity to launch a satellite, and kept their program alive by doing re-entry studies. After Sputnik, and the failure of Vanguard, they were given the go-ahead to launch the first U.S. satellite. General Maderas, who was in charge of the Huntsville effort, made a deal with William Pickering, the Director of JPL, for JPL to build the spacecraft. There was thus a JPL spacecraft and upper stage, Van Allen's University of Iowa experiment, and the main rocket provide by von Braun. This was Explorer 1, launched on January 31, 1958, shown in Figure 9.6 beside the famous celebratory photo of Pickering, Van Allen, and von Braun.

Shown in Figure 9.7, in the upper left hand corner, is the counting rate of Van Allen's Geiger counter on Explorer 3. Explorer 1 did not have a tape recorder, since the spin rate was too high. George Ludwig had to redesign the tape recorder, and is shown in the figure with his redesigned tape recorder, along with Ed Foran, the main machinist at Iowa. It is curious that Ed Foran's father had worked for Robert Goddard back in New Mexico; hence a second generation of space engineers. In the lower right-hand corner of Figure 9.8 is shown the main team at Iowa, the gang of four: Van Allen, Carl McIlwain, George Ludwig, and Ernie Ray. George is currently doing a detail history of this period, which I hope will be published shortly

Within the 14-month period of Explorer 1, the principle scientific instruments for nine space missions were provided by Van Allan and his group in a period Van Allen said was his busiest and the happiest period of his life. The missions were Explorers 1 through 5,

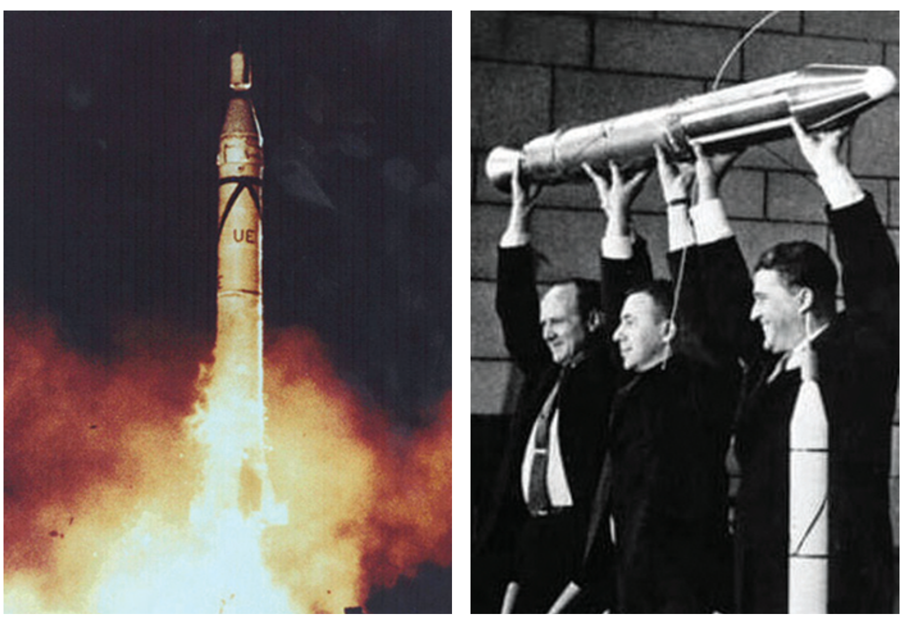
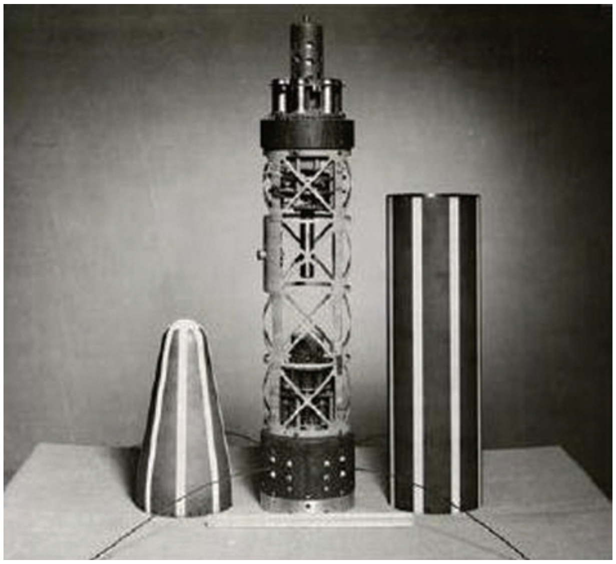
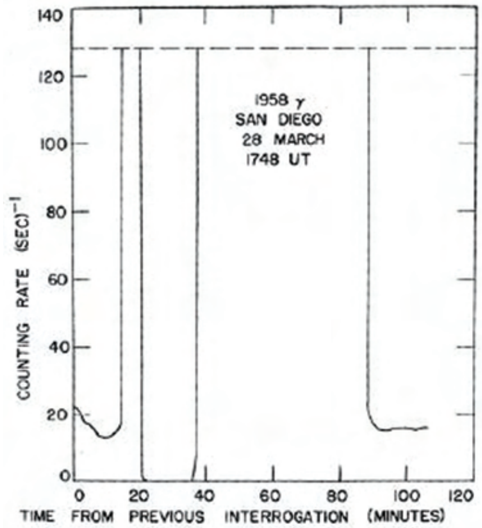


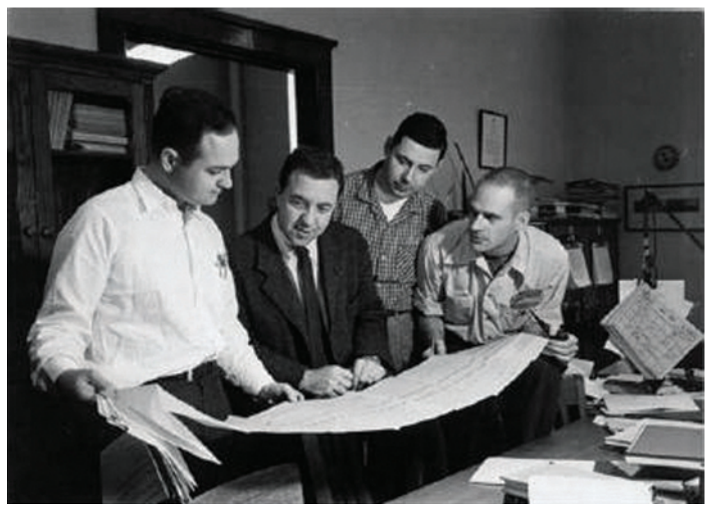
FIGURE 9.6 Explorer 1 was launched on January 31, 1958. SOURCES: (*left*) U.S. Centennial of Flight Commission, image courtesy of NASA; (*right*) courtesy of NASA/JPL.



Photograph of the Scientific Experiment for Explorer 1, with nose cone and outer shell.



The first available full orbital set of radiation data from the tape recorder on Explorer III, obtained from an interrogation over San Diego. The horizontal dashed line at 128 counts per second is the upper counting rate limit of the tape recorder system.



Carl McIlwain, James A. Van Allen, George Ludwig and Ernest Ray examining the strip charts from Explorers 1 and 3.

FIGURE 9.7 Iowa. *Clockwise from top left:* Photograph of the Scientific Experiment for Explorer 1, with nose cone and outer shell; the first available full orbital set of radiation data from the tape recorder on Explorer 3, obtained from an interrogation over San Diego. The horizontal dashed line at 128 counts per second is the upper counting rate limit of the tape recorder system; Carl McIlwain, James A. Van Allen, George Ludwig, and Ernest Ray examining the strip charts from Explorers 1 and 3; Van Allen presented to the Smithsonian Institution a miniaturized tape recorder that is the flight spare for the one that flew on Explorer 3. All images courtesy of NASA.

and Pioneers 1 through 4. Some of these missions were partial launch failures but they did gain enough altitude to obtain orbit. Iowa obtained very useful radiation belt data from seven out of the nine missions. Imagine here at the beginning of the Space Age, Explorer 4 had two Geiger counters, and an iodide scintillation counter. It was incredible that these instruments could be assembled so rapidly. There was, however, nobody to look over ones shoulder. There was no quality control, just your own good engineering sense.

Explorer 4 was interesting in that there were two concurrent H-bomb explosions connected with the Argus test on Johnson's Island: Two 5-mega-ton blasts and a couple of smaller A-bomb tests. The Iowa group noticed that there was a launch opportunity, and they convinced the Army, who was in charge, to launch their experiments. The H and A bomb tests generated a temporary electron belt, which was useful in establishing some of the properties of the radiation belt. This was perhaps the first example of active experimentation in space.

The gang of four at Iowa split up shortly after this string of early missions. Ludwig and eventually Ernie Ray went to Goddard. Carl McIlwain went to UCSD to start up a group. Van Allen kept going at Iowa. Iowa had shown what a University could do and the impact it could have, and that approach to research in space determined how science in NASA would be done. Goddard would shortly become the center of space science research, but it was Van Allen's approach that would guide the development of Goddard's space science activities.

In December 1958, JPL formally transferred to NASA while remaining part of Caltech. This decision was facilitated by William Pickering, the Director of JPL, who decided that JPL would get out of developing rockets, since this was not what Caltech should be doing. JPL felt the Moon and the planets were out there for them and that is where they were going. JPL had a very rocky start for the first few years, but now, as we will discuss later, it has turned into quite a success story.

The Army ballistic missile activities in Huntsville transferred to NASA in July 1960, to become the Marshall Space Flight Center. They developed larger Redstone rockets for Alan Shepard's and Gus Grissom's suborbital manned flights and they began work on the Saturn V rocket for the manned missions to the Moon. Jupiter C was a direct descendent of the V2, and the Saturn V was simply eight Jupiter C's put together in a package, to give you the necessary huge lift to go to the Moon.

When you add the Manned Space Flight Center, now Johnson, to Goddard, JPL, and Marshall, you have the main ingredients of today's NASA. And it was Iowa and its profound impact on space science, together with the Army ballistic missile activities and JPL, and what they achieved with Explorer 1 and 3, that paved the way for the new NASA.

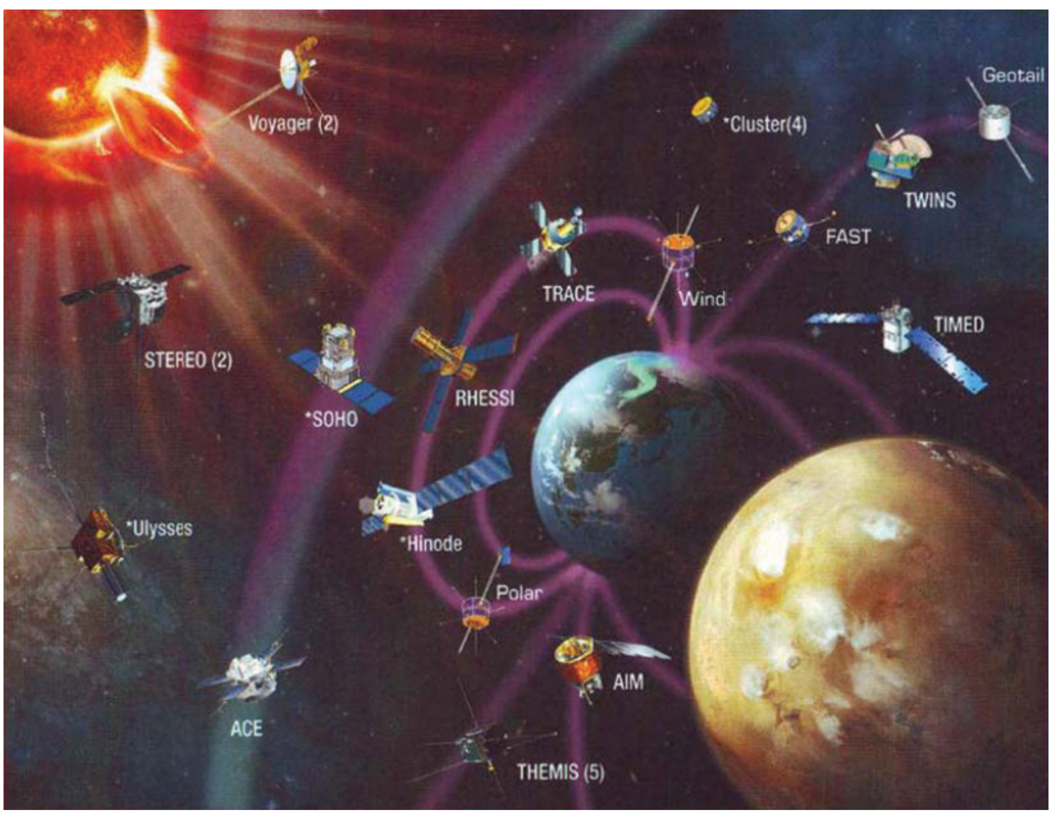


FIGURE 9.8 Heliophysics. The older and current missions in flight are used as an extended observatory, enabling end-to-end surveillance of the Sun–Earth Connection. SOURCE: Courtesy of NASA.

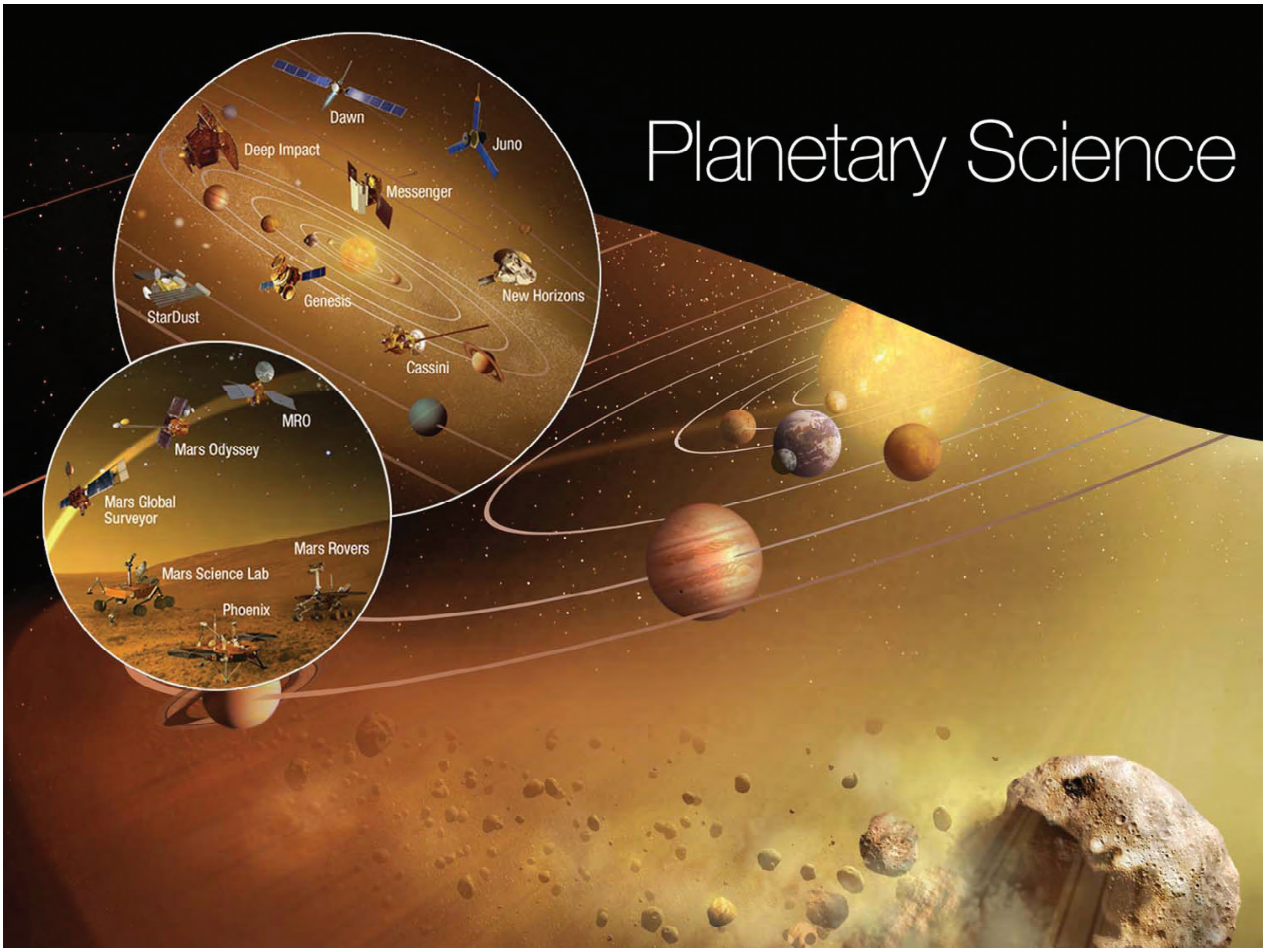


FIGURE 9.9 Planetary science missions. SOURCE: Courtesy of NASA.

THE ROAD AHEAD

The story to date has been inspiring. Let us now consider what lies ahead for us.

As is illustrated in Figure 9.8, there are some 24 missions currently studying the Sun and the heliosphere it creates—the discipline of heliophysics. NASA has been very generous in supporting this disciple. There are the Voyagers now exploring the outer heliosphere; an outstanding array of solar observatories such as SOHO, RHESSI, and TRACE; along with precision measurements from the near-Earth, the ACE mission. Ulysses, which has been orbiting about the poles of the Sun, is now near its end.

The extended observatory in heliophysics provides an end-to-end look at the connection between the Sun and Earth. The Solar Dynamics Observatory will launch in 2009 and replace SOHO. As we look to the future, Solar Orbiter is to be placed in an orbit that is only a few tenths of an AU from the Sun, where the Sun is some 25 times brighter and very detailed measurements of solar phenomena can be made. There is also to be a Solar Probe, a mission that will penetrate to within about 10 solar radii of the Sun, through a series of complex orbits using Venus flybys. Solar Probe will provide us with the first direct measurements of the acceleration region of the solar wind and of the energetic particles that control our heliospheric environment.

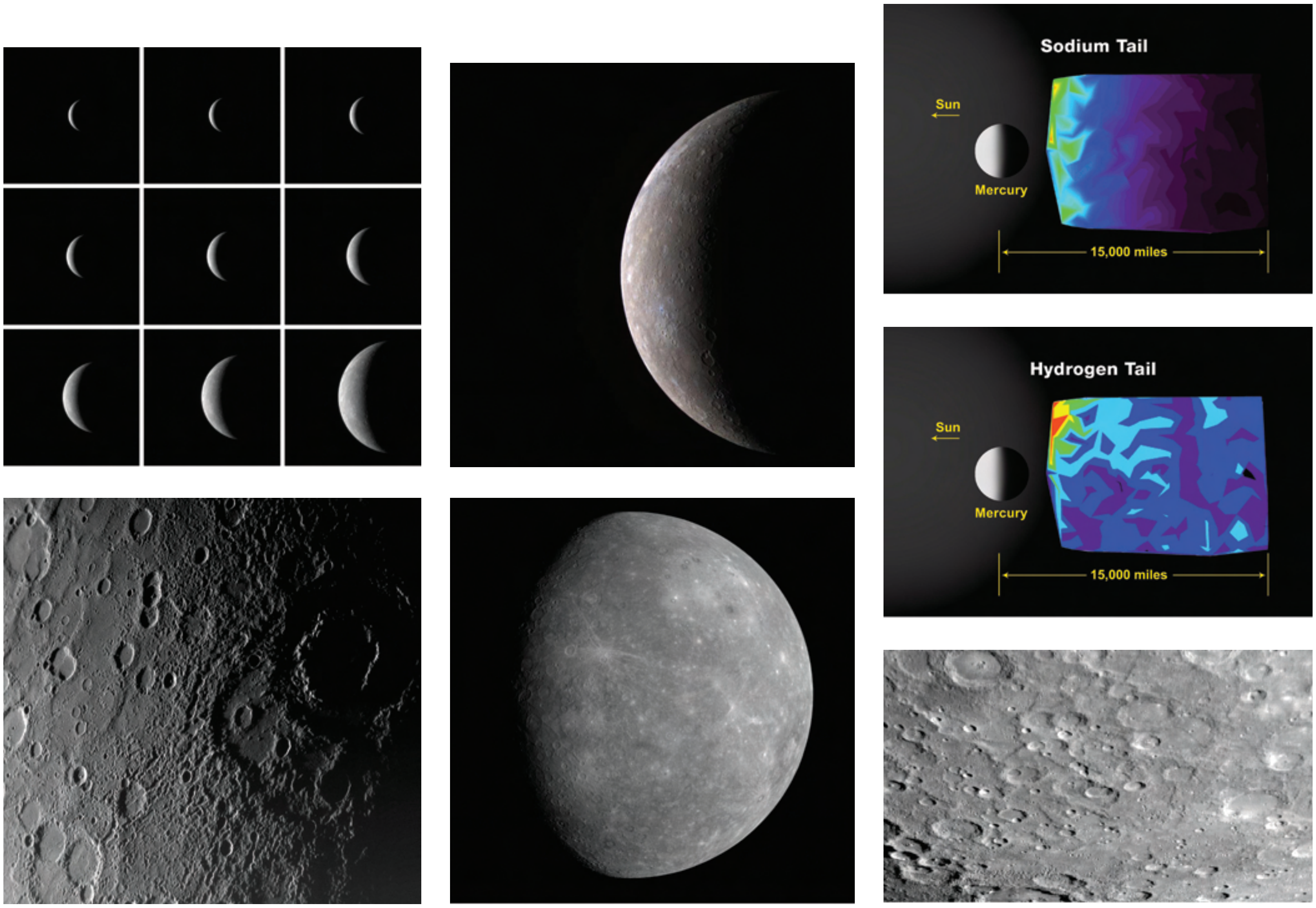


FIGURE 9.10 Some results from MESSENGER's Mercury fly by. SOURCE: Courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

Planetary science is also doing very well, as illustrated in Figure 9.9. There is the Dawn mission currently en route to an asteroid, and the Juno mission to be launched to Jupiter. Deep Impact collided with a comet to study its nucleus. New Horizon is on its way to Pluto. Stardust returned material from a comet. Cassini is orbiting about Saturn.

MESSENGER has flown by Mercury twice and is about to be placed into orbit. The results from the most recent flyby are shown in Figure 9.10.

Finally there are all the missions to Mars, shown in Figure 9.11—rovers on the surface, Phoenix in the polar regions, and the orbiters. My favorite mission is Phoenix, which is shown in Figure 9.12 descending to the martian surface, as observed by a high-resolution telescope from a mission in orbit about Mars. Phoenix will provide definitive proof of water on Mars.

One of the greatest accomplishments of the space age, and of the Goddard Space Flight Center, was the Cosmic Background Explorer (COBE), which, as illustrated in Figure 9.13, made very precise measurements of the 3° black body radiation from the beginning of the universe. As stated by John Mather, the Principle Investigator on COBE, and winner of the Nobel Prize in Physics for this measurement, it is all very simple: Just a giant, very uniform explosion that started the whole universe.

In 2009, the Hubble Space Telescope will be up-

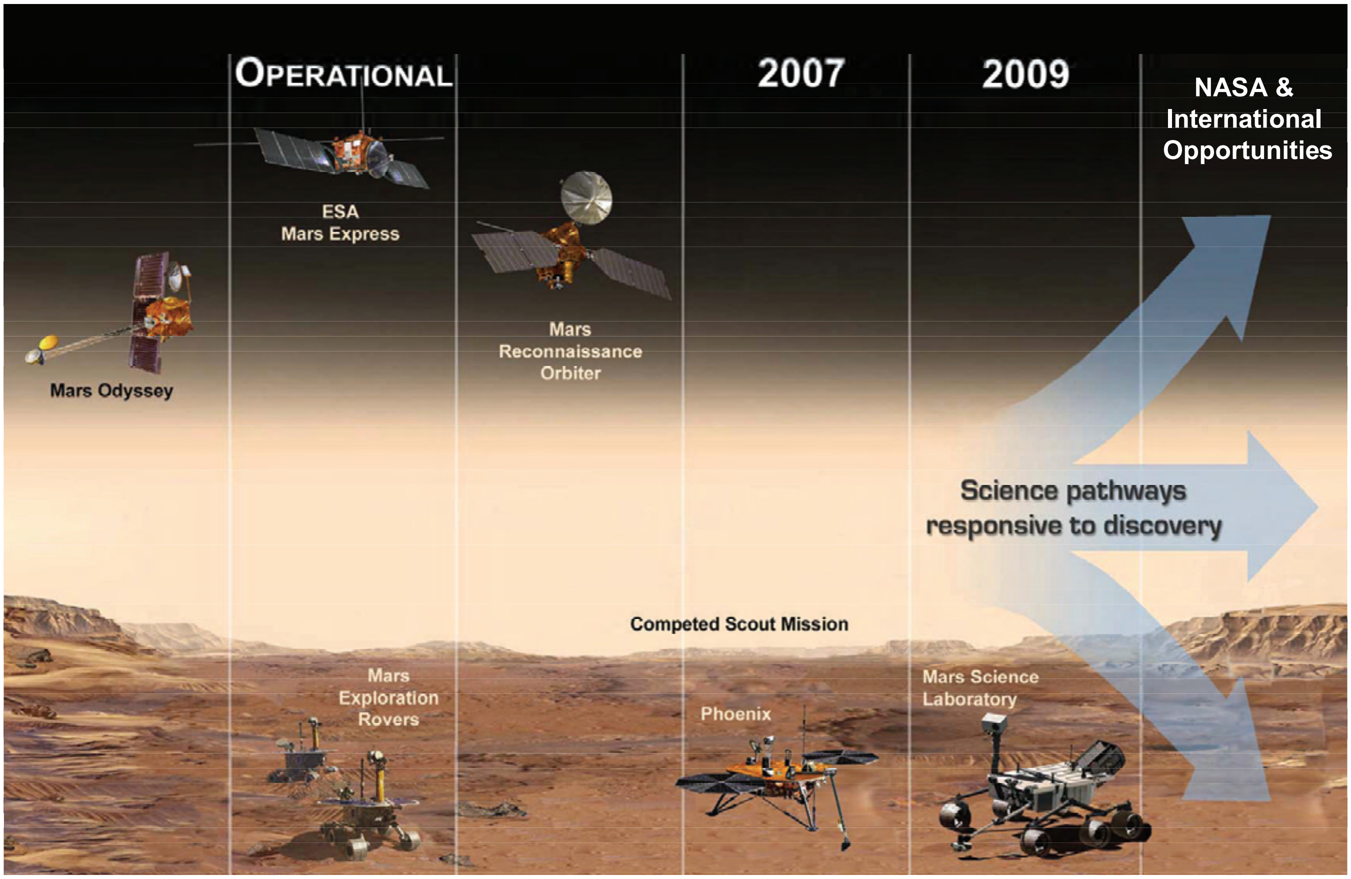


FIGURE 9.11 Current Mars missions. SOURCE: Courtesy of NASA.

graded for the last time, as illustrated in Figure 9.14. We are using Hubble exactly as astronomers have used ground-based telescopes, such as 200 inch at Palomar. They keep upgrading the instrumentation, making it much better, with new instruments that have 20 times the resolving power. Hubble can look at the architecture of the universe, the life story of galaxies, and the birth and death of stars. Hubble as some people describe it is the world's most successful explorer, and it is. Repairing Hubble is a very difficult thing, but if all goes well, we will have an outstanding new observatory.

Swift, which is a Goddard mission and illustrated in Figure 9.15, allows you to detect gamma-ray bursts, find their precise positions, which in turn allows ground-based observatories to study the afterglow of the bursts and identify their origins. Short gamma-ray bursts are from neutron star-neutron star mergers; long gamma-ray bursts are from massive star core collapses.

Finally, there is the James Webb Space Telescope, to be launched in 2013—a 6.5-meter-diameter telescope illustrated in Figure 9.16. I think it is very appropriate to name this mission after James Webb. Although not an astronomer, he was one of the best NASA Administrators, back in the 1960s. Webb maintained a very balanced program of space exploration, aeronautics, and science. The James Webb Space Telescope will be placed at the L2 point, a stable location near enough to Earth so that it can make effective infrared observations. It will observe the very early

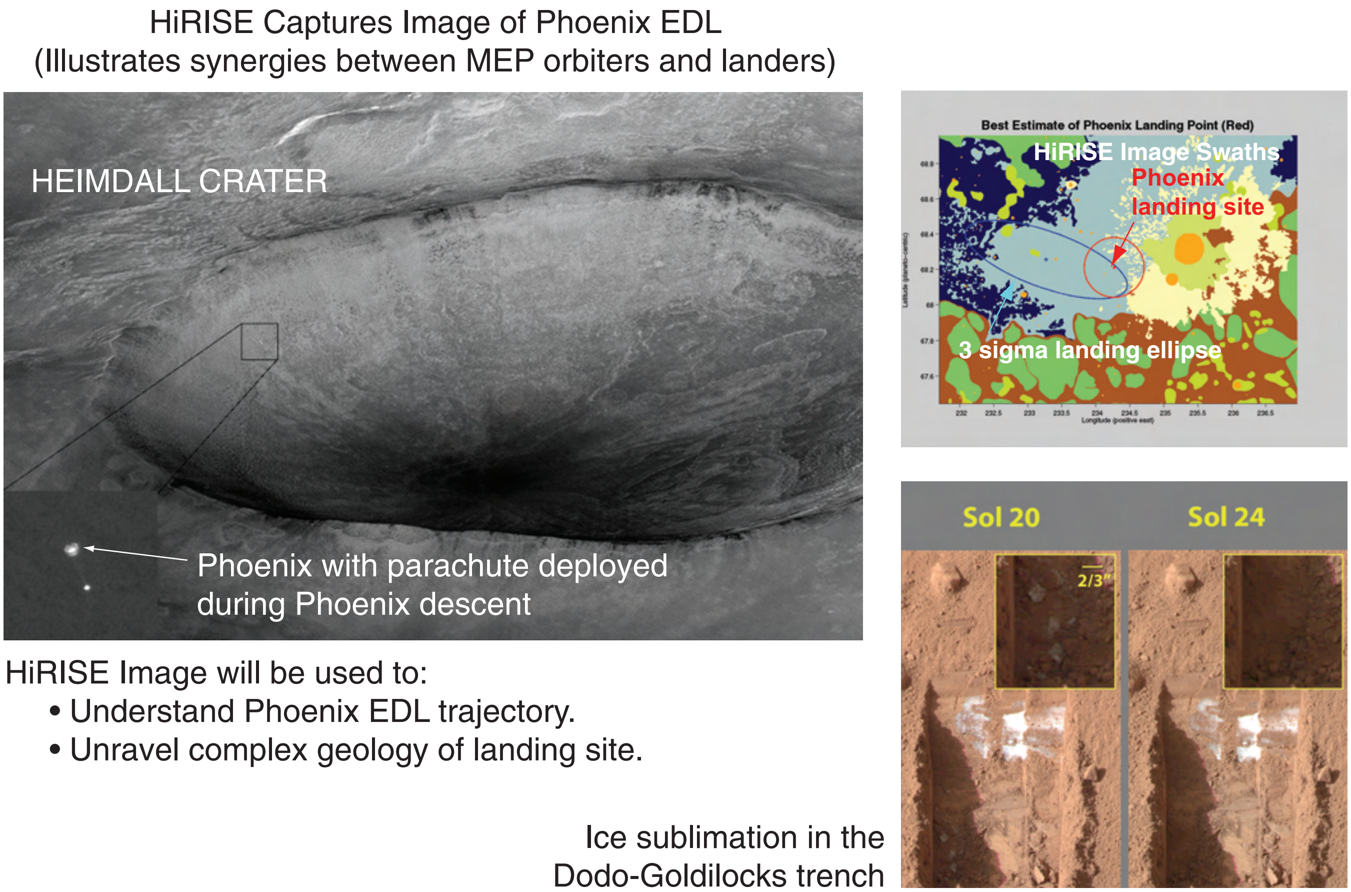


FIGURE 9.12 *Clockwise from left:* HiRISE will be used to understand Phoenix EDL trajectory and unravel complex geology of landing site (MRO-HiRISE/NASA/JPL/University of Arizona); ice sublimation in the Dodo-Goldilocks trench on Mars (NASA/JPL-Caltech); HiRISE captures image of Phoenix EDL; illustrates synergies between MEP orbiters and landers (NASA/JPL-Caltech/University of Arizona/Texas A&M University).

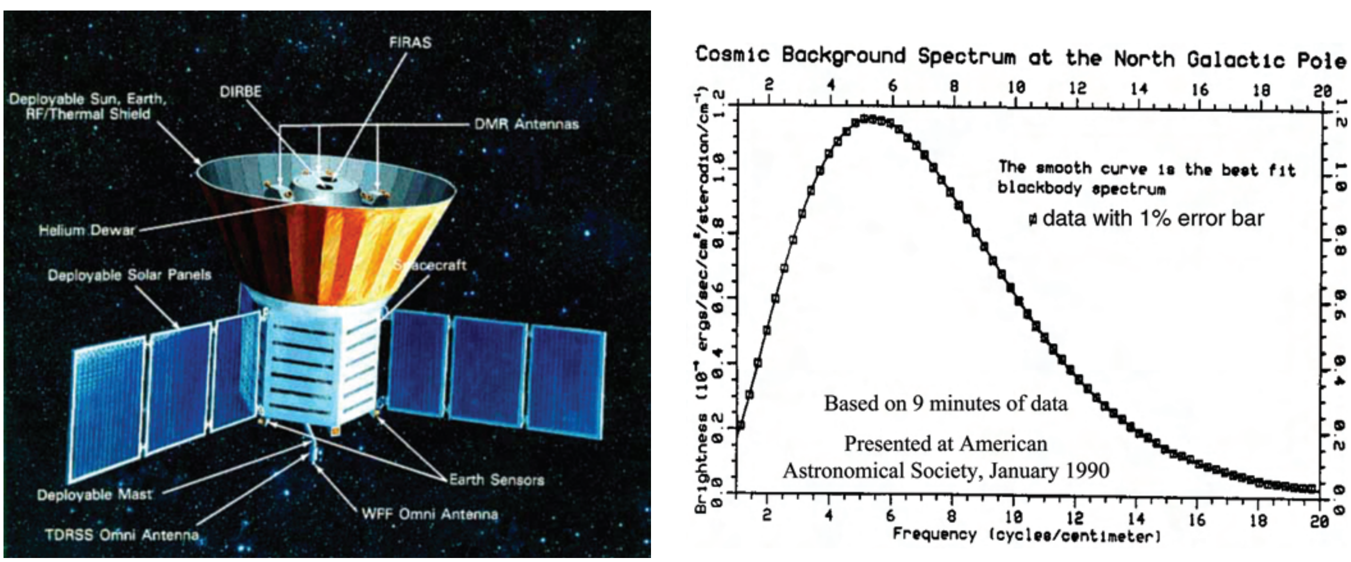


FIGURE 9.13 Cosmic Background Explorer (COBE). Significance of spectrum: Old data were wrong! Old theories explaining bad data were wrong too! Hot Big Bang explains everything here. Steady state theory (main alternative) doesn't. It was all very "simple"—just a single, giant, very uniform "explosion" of the whole universe! SOURCES: (*Left*) Courtesy of NASA/GSFC. (*Right*) Courtesy of NASA and the COBE Science Working Group.

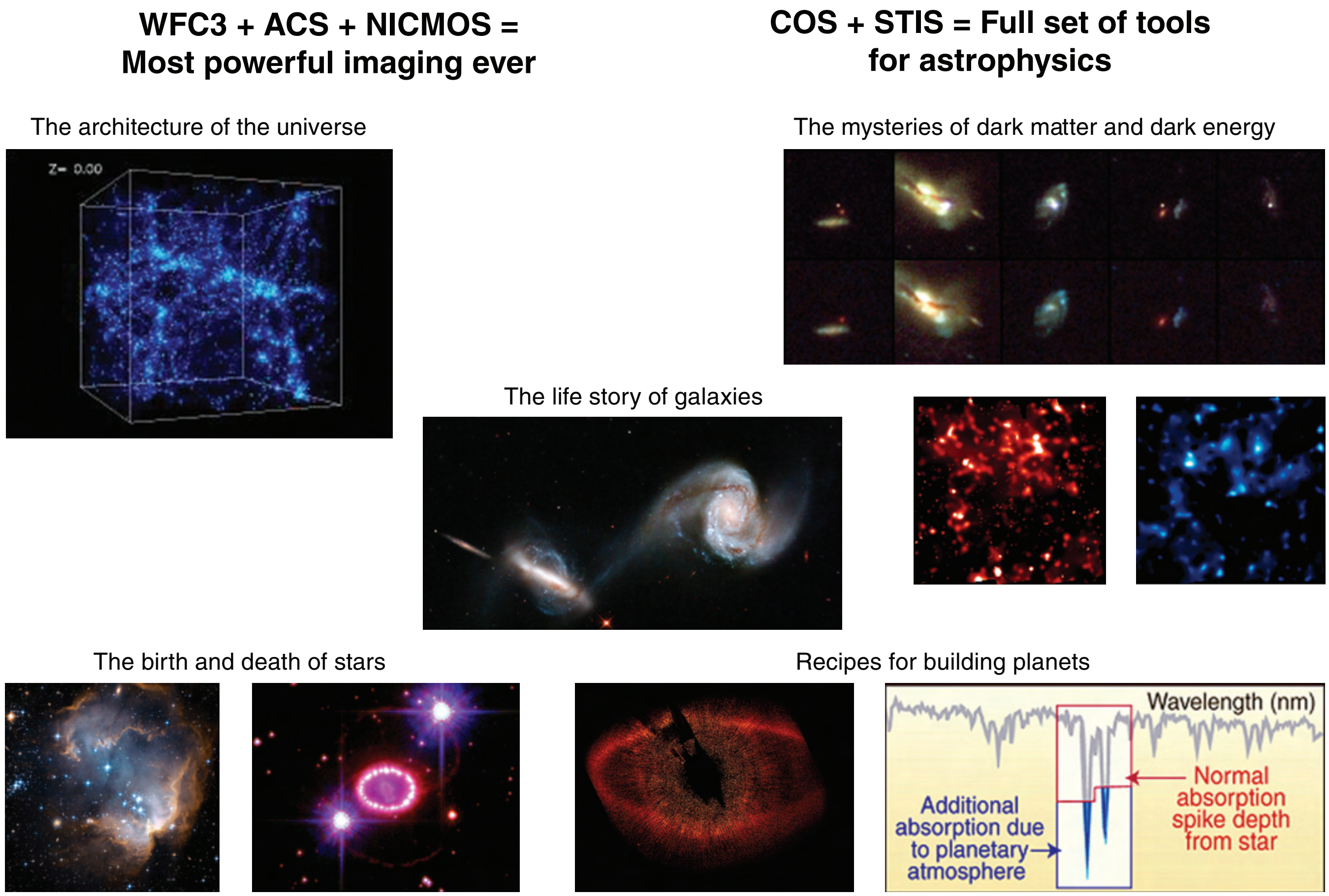


FIGURE 9.14 When the astronauts leave Hubble for the last time, it will be at the apex of its capabilities—better than it has ever been before. The architecture of the universe (NASA/ESA/Hubble Heritage Team (STScI/AURA)/Hubble Collaboration); the birth (NASA/ESA/Hubble Heritage Team (STScI/AURA)/Hubble Collaboration) and death of stars (NASA/ESA/P. Challis and R. Kirshner (Harvard-Smithsonian Center for Astrophysics); the life story of galaxies (NASA/ESA/Hubble Heritage Team (STScI/AURA)); the mysteries of dark matter and dark energy (*left to right,* NASA/ESA/A. Riess (STScI); NASA/ESA/R. Massey (California Institute of Technology); NASA/ESA/R. Massey (California Institute of Technology)); recipes for building planets (*left,* NASA/ESA/P. Kalas, J. Graham, E. Chiang, E. Kite (University of California Berkeley)/M. Clampin (NASA Goddard Space Flight Center)/M. Fitzgerald (Lawrence Livermore National Laboratory)/K. Stelfeldt and J. Krist (NASA Jet Propulsion Laboratory); *right,* NASA).

universe, and see the end of the dark period and first light. It will see the assembly of the first galaxies, and the birth of stars and protoplanetary systems. It will be a truly incredible mission.

CLOSING REMARKS

Let me close with some remarks on the Pioneer and Voyager missions to the outer heliosphere, shown in Figure 9.17. There is a picture of Van Allen at the press conference for the Pioneer encounter with Jupiter. Van Allen was a driving force behind the Pioneer missions, and subtlety led the fight to redirect Pioneer 11 from Jupiter, back across the solar system, to Saturn. I was also one of the principle investigators on Pioneer. I soon learned after one or two of these press conferences that the press had only two interests. They wanted to see Tom Gerald's pictures of Jupiter

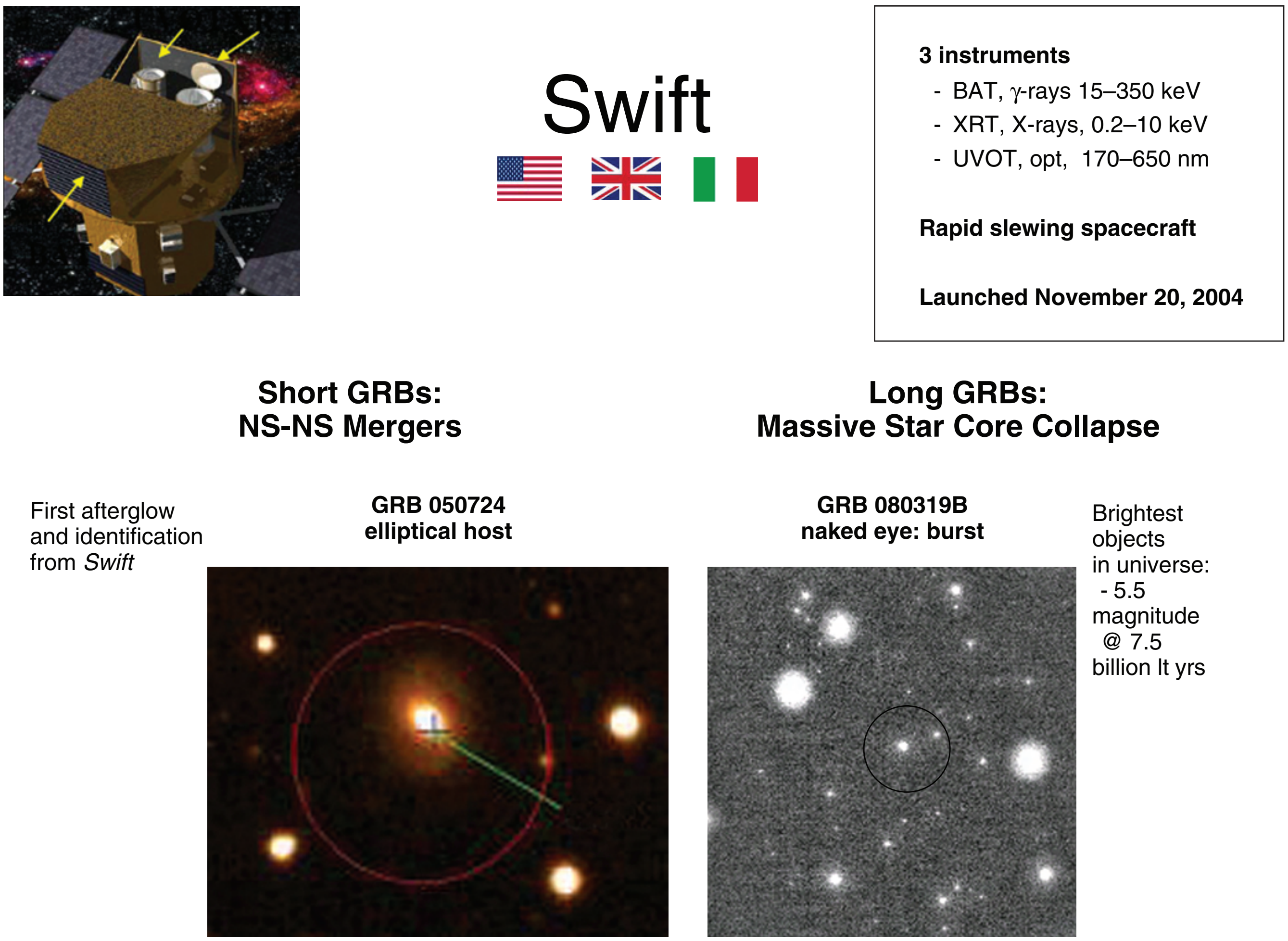


FIGURE 9.15 Swift. Clockwise from top left: Swiftís three scientific instruments work together to learn as much as possible about gamma-ray bursts (NASA/GSFC); long GRBs (Pi of the Sky collaboration); short GRBs (Reprinted by permission from Macmillan Publishers Ltd: Nature, S.D. Barthelmy, G. Chincarini, D.N. Burrows, N. Gehrels, S. Covino et al., An origin for short [gamma]-ray bursts unassociated with current star formation, Nature 438:994-996, copyright 2005).

and Saturn and they wanted to hear what Van Allen had to say.

Also shown in Figure 9.17 is data from the LECP experiment on Voyager 1, low-energy ion data that shows that Voyager has crossed the termination shock of the solar wind, where the supersonic flow of the solar wind goes subsonic to begin the process of merging with the local interstellar medium. We have also recently crossed the termination shock with Voyager 2, each Voyager spacecraft now penetrating into the heliosheath, the subsonic region that is the outermost reach of the region in interstellar space carved out by the Sun. The heliosheath is probably 30–60 AU wide, and at its current speed Voyager 2 could cross the heliopause into the true interstellar medium in a decade or so.

We live in times of unprecedented exploration. Fifty years ago Van Allen and his co-workers began the exploration of space with a simple experiment to understand the near-space environment of Earth. Since

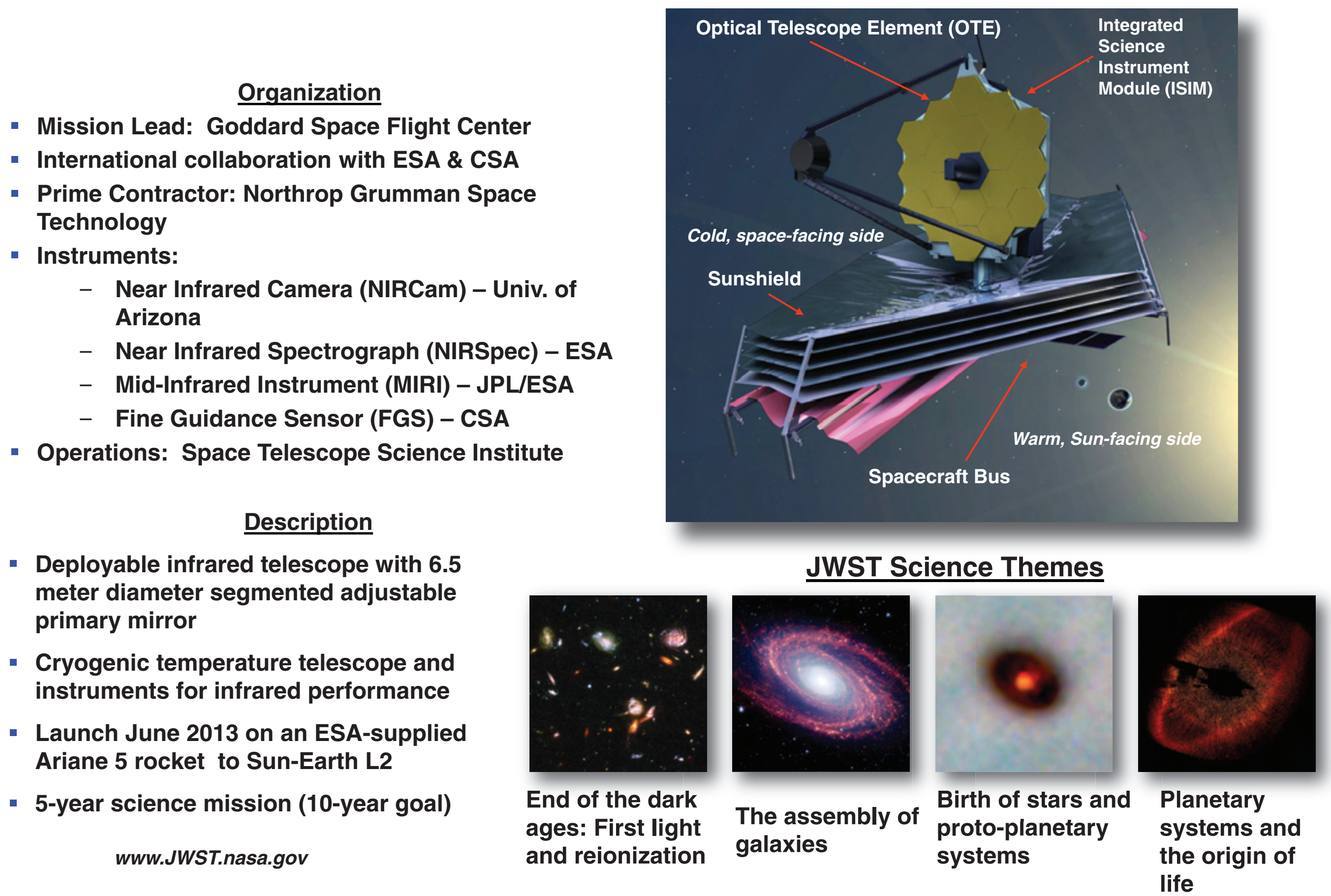


FIGURE 9.16 Finding our origins with the James Webb Space Telescope (JWST) and the JWST Science Themes. *Top:* JWST (NASA). *Bottom row, left to right:* End of the dark ages—first light and reionization (NASA/ESA/S. Beckwith(STScI)/HUDF Team). The assembly of galaxies (NASA). Birth of stars and proto-planetary systems (M.J. McCaughrean (Max-Planck-Institute for Astronomy), C.R. O'Dell (Rice University), and NASA). Planetary systems and the origin of life (NASA).

then we have extended our presence to the farthest reaches of our solar system; we have explored all the planets; we have made detailed observations of our Sun and the space environment it creates; we have observed the wonders of the universe.

I would like to thank the Space Studies Board again for the honor of being able to give the Van Allen Lecture.

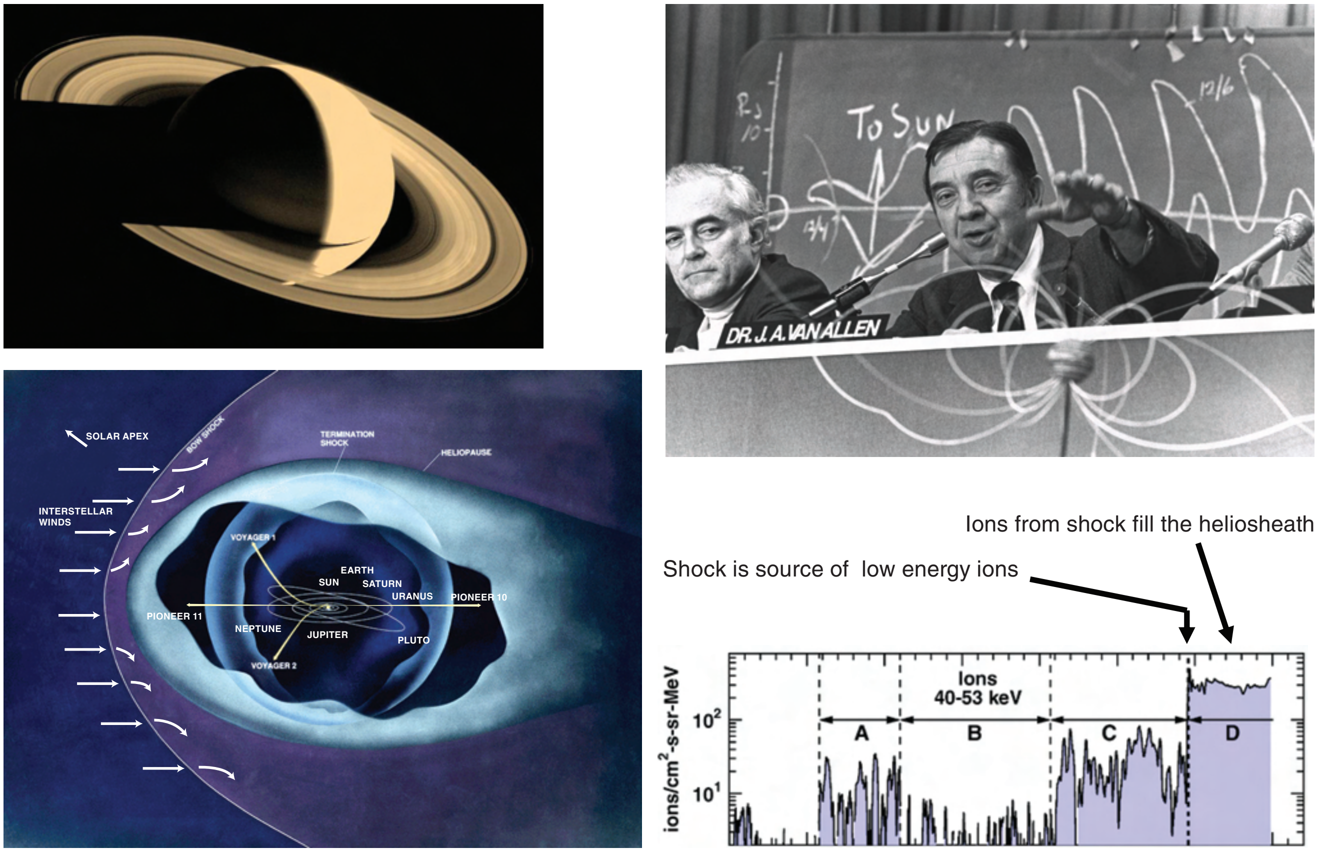


FIGURE 9.17 Pioneer/Voyager. *Top left:* Saturn (NASA/JPL, PIA01969). *Top right:* Pioneer 10 news release image (NASA/ARC). *Bottom left:* Heliopause schematic (NASA). *Bottom right:* Termination shock; showing 5-day smoothed V1 40–53 ion (with kind permission from Springer Science+Business Media: J.D. Richardson and E.C. Stone, The solar wind in the outer heliosphere, pp. 7-20 in *From the Outer Heliosphere to the Local Bubble,* Springer New York, Copyright 2009, Figure 4a).

ACKNOWLEDGMENTS

Dr. McDonald acknowledges the assistance of Victoria Swisher in assembling the figures for the lecture and paper, and also Joe Alexander for looking over her shoulder. Also, George Gloeckler and Randy Jokipii deserve special thanks for their help in preparing the lecture.

Appendixes

A

The International Geophysical Year

Following a suggestion by NAS member Lloyd Berkner, the International Council of Scientific Unions in 1952 proposed a comprehensive series of global geophysical activities to span the period July 1957–December 1958. The International Geophysical Year (IGY), as it was called, was modeled on the International Polar Years of 1882–1883 and 1932–1933 and was intended to allow scientists from around the world to take part in a series of coordinated observations of various geophysical phenomena. Although representatives of 46 countries originally agreed to participate in the IGY, by the close of the activity, 67 countries had become involved.

International organization and funding of the IGY were overseen by the International Council of Scientific Unions (ICSU), an independent federation of international scientific unions. A Special Committee for the IGY (CSAGI, an acronym derived from the French) was formed to act as the governing body for all IGY activities. Care had been taken to ensure that CSAGI would remain non-nationalistic, apolitical, and geared toward a scientific agenda.

American participation in the IGY was charged to a US National Committee (USNC) appointed in March 1953 by the NAS. Joseph Kaplan, Professor of Physics at UCLA, was appointed Chairman of the USNC. Physicist Alan H. Shapley of the National Bureau of Standards (NBS) was appointed Vice-Chairman, and Hugh Odishaw, also of the NBS, was appointed Executive Secretary (later, Executive Director). The core USNC was made up of sixteen members, but the five Working Groups and thirteen Technical Panels that operated under it eventually drew in nearly 200 additional scientists. The technical panels were formed to pursue work in the following areas: aurora and airglow, cosmic rays, geomagnetism, glaciology, gravity, ionospheric physics, longitude and latitude determination, meteorology, oceanography, rocketry, seismology, and solar activity. In addition, a technical panel was set up to attempt to launch an artificial satellite into orbit around the earth.

IGY activities literally spanned the globe from the North to the South Poles. Although much work was carried out in the arctic and equatorial regions, special attention was given to the Antarctic, where research on ice depths yielded radically new estimates of the earth's total ice content. IGY Antarctic research also contributed to improved meteorological prediction, advances in the theoretical analysis of glaciers, and better understanding of seismological phenomena in the Southern Hemisphere.

Given the state of science in the late 1950s, the timing of the IGY was highly opportune. Research technologies and tools had advanced greatly since the 1930s, allowing scientists a scope of investigation without precedent. Cosmic ray recorders, spectroscopes, and radiosonde balloons had opened the upper atmosphere to detailed exploration, while newly developed electronic computers facilitated the analysis of large data sets. But the most dramatic of the new technologies available to the IGY was the rocket. Post–World War II developments in rocketry for the first time made the exploration of space a real possibility; working with the new technologies, Soviet and American participants sent artificial satellites into earth orbit. In successfully launching science into space, the IGY may have scored its greatest breakthrough. Overall, the IGY was highly successful in achieving its goals, which were summed up in an NAS IGY Program Report:

> *...to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in space and time, so that results could be collated in a meaningful manner.*

The IGY's achievements included the discovery of the Van Allen radiation belts encircling the Earth; the charting of ocean depth and currents; the detailed study of the Earth's magnetic field that led to the revolutionary plate tectonic theory; measurements of upper atmospheric winds; the unprecedented setting aside of an entire continent (Antarctica) for scientific research, later embodied in the Antarctica Treaty—and most dramatically, the launching by rocket of the first artificial Earth-orbiting satellites, so inaugurating the space age

B

The Space Studies Board

The Space Studies Board (SSB) is one of the many legacies of the IGY. Originally named the Space Science Board, it was established on June 26, 1958 within the National Academy of Sciences to advise federal agencies on U.S. rocket and satellite research. Dr. Lloyd Berkner, who led efforts to establish the IGY, was the first chair of the SSB.

The impetus for creating the SSB was to enable the nation's top scientists to advise the government on the scientific potential of artificial satellites following the first satellite launches during the IGY. In 1958, when President Dwight D. Eisenhower signed into law the act that created NASA, the SSB was already in place to serve as a bridge between the government and the far-flung, largely university-based scientific research enterprise.

The National Academy of Sciences (NAS) itself was created in 1863 by a law signed by President Abraham Lincoln. One of its major functions is to provide advice to the government on scientific issues. In 1916, the NAS created the National Research Council (NRC) to manage the increasing number of studies that were being requested. In 1964, the NAS created the National Academy of Engineering (NAE), and in 1970 the Institute of Medicine (IOM), to focus attention on those specialties as well. These three institutions, the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine are honorific societies to which individuals are elected because they are distinguished in their fields. Among other tasks, the government turns to these Academies and their distinguished members to help determine scientific priorities for federally-funded research. The NRC is administered through a Governing Board composed of the Presidents and other members of the NAS, NAE and IOM. The NRC is currently organized into about 60 boards that are each focused on a particular topic or discipline.

The Space Studies Board provides an independent, authoritative forum for information and advice on all aspects of space research and applications, and serves as the focal point within the National Academies for activities related to space research. In carrying out these tasks it oversees advisory studies and program assessments and promotes communications on space science and science policy between the research community, the federal government, and the interested public. The SSB also serves as the U.S. National Committee for the International Council for Science's Committee on Space Research (COSPAR). Several other boards in the Academies also deal with space program issues, including the Aeronautics and Space Engineering Board. These boards work closely together.

The SSB has five standing committees: the Committee on Astronomy and Astrophysics, the Committee on Earth Studies, the Committee on the Origin and Evolution of Life, the Committee on Planetary and Lunar Exploration, and the Committee on Solar and Space Physics. These committees and the Board itself provide strategic direction for the Board's activities and serve as a bridge between their communities and the government. Studies are conducted by specially created "ad hoc" study committees whose membership is tailored to the topic of the study. All members of the

Board, the standing committees and study committees are volunteers who serve without compensation. The SSB is very grateful to its volunteers, many of whom were involved in the seminar series.

Consensus-based priority-setting is one of the major tasks of the SSB. There is much research to be done in the space science disciplines, but only a finite amount of money. How does an agency like NASA determine what is the next most important research project to pursue? Is it more important to send a spacecraft to further study Jupiter's moon Europa or Saturn's moon Titan to determine if life could exist in either environment; To build a space telescope to further study the universe in a particular wavelength of the electromagnetic spectrum (infrared, x-ray, gamma ray) or to search for gravitational waves left over from the Big Bang; To solve the riddle of dark energy or of dark matter; To measure carbon in the atmosphere or ocean color? NASA turns to the SSB to convene the top experts in the country to independently and objectively provide consensus recommendations on what are the top priorities.

The SSB performs studies on a wide range of space research issues, but its signature product is the "decadal survey." These studies are performed about once every 10 years (a decade) looking forward to the next 10 years in each of the space science disciplines—astronomy and astrophysics (which also prioritizes ground-based research in this field and is done in conjunction with the NRC's Board on Physics and Astronomy), earth science and applications from space, microgravity biological and physical science, planetary science, and solar and space physics ("heliophysics").

All of the reports that have been generated over the past 50 years of the SSB's existence, including the decadal surveys, are available through the SSB's web site (http://www7.nationalacademies.org/ssb) and on a DVD that is available by contacting the SSB (ssb@nas.edu).

The Space Studies Board was created in 1958 and so, like the International Geophysical Year, is celebrating its 50th birthday. Through the seminar series that led to the production of this book, it sought to engage with the public and the scientific community to talk about the achievements of the past 50 years and look forward to the next 50 years of exciting discoveries that await us.

The SSB would like to thank the extremely distinguished individuals who participated in the panel discussions and presented fascinating lectures at our events. Very special thanks go to Dr. Lennard A. Fisk, former chair of the SSB and chair of the seminar series for his leadership and guidance and the sacrifices he made to ensure that he could participate in every event. Extra special thanks go to the SSB staff who worked tirelessly on the series. While almost everyone on the SSB staff participated at various times, the key individuals without whom the series could not have been accomplished are Ian Pryke, project director; Diana Alexander, event coordinator; Victoria Swisher, research associate; Tanja Pilzak, administrative coordinator; Christina Shipman, financial officer; Carmela Chamberlain, program associate; Celeste Naylor, senior program assistant; Joe Alexander, senior program officer; and Barbara Akinwole, information resource manager. Finally, we would like to thank Harvey Meyerson who was the inspiration for this seminar series and its first project director. As an aide to the late Senator Spark Matsunaga, Dr. Meyerson championed international cooperation in space and established the International Space Year in 1992 to celebrate 35 years of space exploration. His idea that the 50th anniversary of the IGY similarly was worth celebrating was the catalyst for what became this seminar series.

We hope that you enjoy the lectures presented in this book.

Marcia S. Smith
Director, Space Studies Board
March 2006–February 2009

C

Program of Public Events

September 10, 2007 Space Telescope Science Institute Baltimore, Maryland	**Understanding the Universe** *John Mather,* NASA Goddard Space Flight Center, Recipient of the 2006 Nobel Prize in Physics
October 19, 2007 University of New Hampshire Durham, New Hampshire	**Global Climate Change and Human Causes** *Ralph J. Cicerone,* President, National Academy of Sciences
December 1, 2007 University of California at Irvine Irvine, California	**All-day colloquium**
December 7, 2007 National Space Science and Technology Center Huntsville, Alabama	**Science Goes to the Moon and Planets: Celebrating 50 Years Since the IGY** *Wesley T. Huntress, Jr.,* Director Emeritus, Geophysical Laboratory, Carnegie Institution
January 16, 2008 Florida State and Florida A&M Challenger Learning Center Tallahassee, Florida	**Leaving the Planet—Science and Technology Development: Results on the International Space Station** *Carl Walz,* NASA Astronaut, Director, Advanced Capabilities, NASA Exploration Systems Mission Directorate
February 20, 2008 University of Texas Austin, Texas	**The Possibility of Life Elsewhere in the Universe** *Christopher F. Chyba,* Professor of Astrophysical Sciences and International Affairs Woodrow Wilson School, Princeton University
March 27, 2008 Committee on Space Research Paris, France	**Understanding the Poles of the Earth, Moon, and Mars** *Christopher Rapley,* Director, Science Museum, London, England
April 14, 2008 Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder Boulder, Colorado	**Voyager's Journey to the Edge of Interstellar Space** *Edward C. Stone,* Professor of Physics, Caltech; Voyager Project Scientist, JPL

April 25, 2008 West Virginia High Technology Consortium Foundation Fairmont, West Virginia	**Future of Space and Earth Robotic Exploration: Scientific and Technological Challenges** *Charles Elachi,* Director, JPL
June 26, 2008 The National Academies Washington, D.C.	**All-day colloquium**—including the presentation of the Space Studies Board's first James A. Van Allen Lectureship for career achievement in space and Earth science.