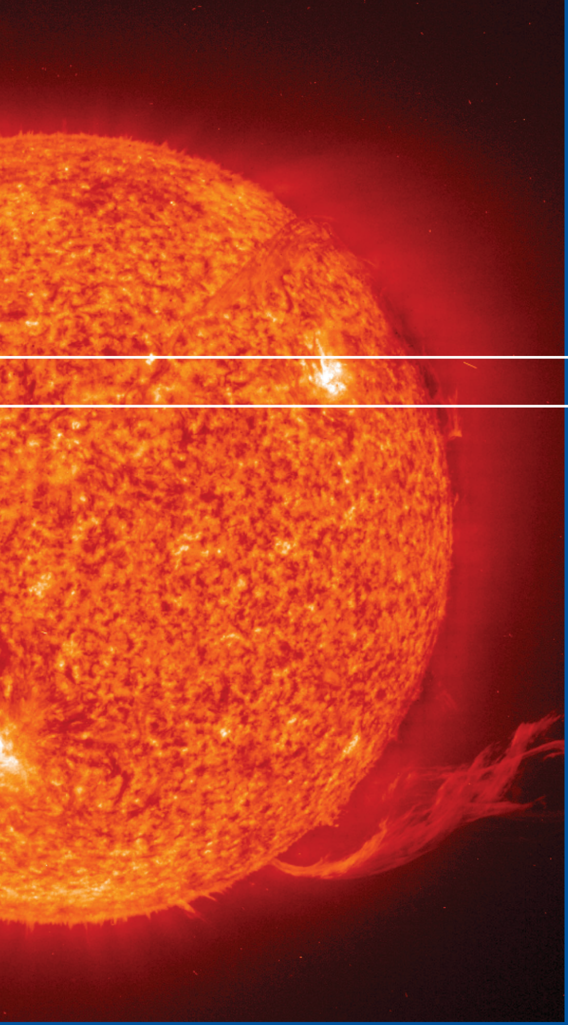
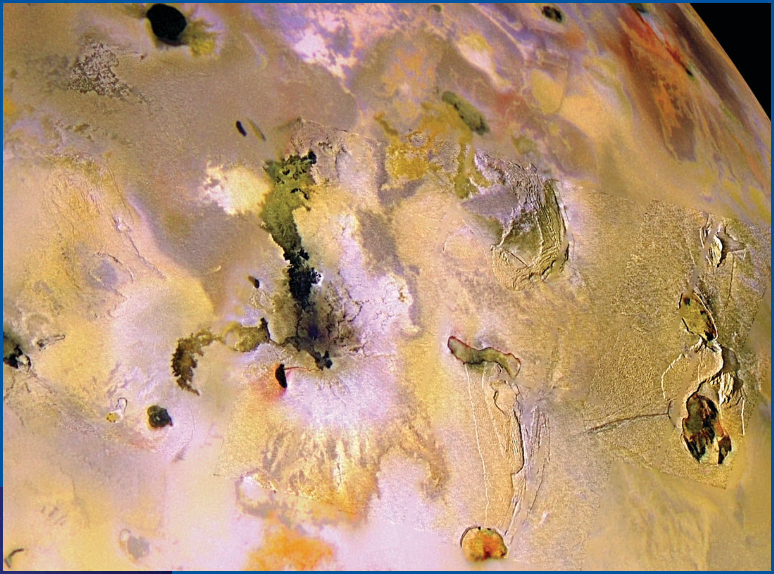


HIGHLIGHTS:

THE SUPPORTING RESEARCH & TECHNOLOGY PROGRAM



OFFICE OF SPACE SCIENCE

THE SR&T PROGRAM

It is a pleasure to present to you our first annual brochure on the "Highlights of the Supporting Research and Technology (SR&T) Program." The brochure provides an overview of some of the most interesting discoveries we have made in the field of space science over the past 3 years.

Our space science program boldly addresses the most fundamental questions that science can ask: how the universe began and is changing, what are the past and future of humanity, and whether we are alone. Dramatic advances in cosmology, planetary research, and solar terrestrial science have allowed us to unravel some of the mysteries behind these questions. But the universe continues to surprise us with new, unimaginable discoveries that change our conclusions about the origin, structure, and future of the universe.

The brochure highlights some of these advances. It is the first in a series of annual publications we will provide on the science resulting from our SR&T program. It is an exciting read, and I hope you enjoy it.

Sincerely,

Edward J. Weiler

Edward J. Weiler
NASA Associate Administrator for Space Science

SUPPORTING RESEARCH AND TECHNOLOGY

The scientific exploration of the universe is a complex human enterprise that relies on a continuing supply of new questions to answer and new technologies to aid in finding their answers. The major achievements of NASA's flight programs would not be possible were it not for an active program of pathfinding research and technology development. These programs support investigators from the academic and industrial communities in their pursuit of answers to today's questions. This often leads to a new round of questions that address still deeper issues. Answering these new questions often requires the development of new technologies that will become the operating basis for future NASA flight missions. Scientific research is a wide-ranging enterprise that relies on ready access to flight data, advanced computing resources, and a reliable supply of investigators, both seasoned investigators and the students who will one day replace them.

The Space Science SR&T program has an annual budget of more than $220 million and supports more than 2,000 researchers. Most of the awards have 3-year durations, although one program has 5-year awards. In addition to the SR&T programs, data analysis programs are attached to Space Science missions, with an annual budget of more than $200 million, providing support for about 2,000 scientists. Data analysis awards have durations from 1 to 5 years.

All of the SR&T and data analysis investigations are funded through specific, competitive grant programs that are open for applications each year.

Several programs support researchers who explore basic issues in astrophysics. These activities lead to fundamental breakthroughs in our deep understanding of physical processes in the universe:

Long-Term Space Astrophysics
Astrophysics Theory Program
Astrophysics Data Program
Astronomy and Physics Research and Analysis

The Sun is an active star, and investigations of its evolution, dynamics, and impact upon Earth form a major focus of the following programs:

Solar and Heliospheric Physics
Sun-Earth Connection Guest Investigator Program
Sun-Earth Connection Theory Program
Living with a Star Program
Geospace/Low-Cost Access to Space Program
Geospace Sciences Program

The search for life in the universe and a deepening understanding of our own origins is a major goal of these programs:

Cosmochemistry Program
Origins of the Solar System
Astrobiology: Exobiology and Evolutionary Biology

Finally, the continued reconnaissance and exploration of nearby planetary bodies is a focus for these programs:

Planetary Geology and Geophysics Program
Planetary Astronomy Program
Planetary Atmospheres Program
Mars Data Analysis Program
Planetary Instrument Definition and Development Program
Sample Return Laboratory Instrument and DA Program

Collectively, these programs and a range of new, targeted efforts pursue a set of specific NASA goals that improve our understanding of the universe, set the stage for future missions, respond to unexpected opportunities, enable breakthroughs in science and most importantly, train the next generations of scientists and engineers. Multidisciplinary programs such as Information Systems also contribute to the SR&T Program.

HOW DID WE GET HERE?

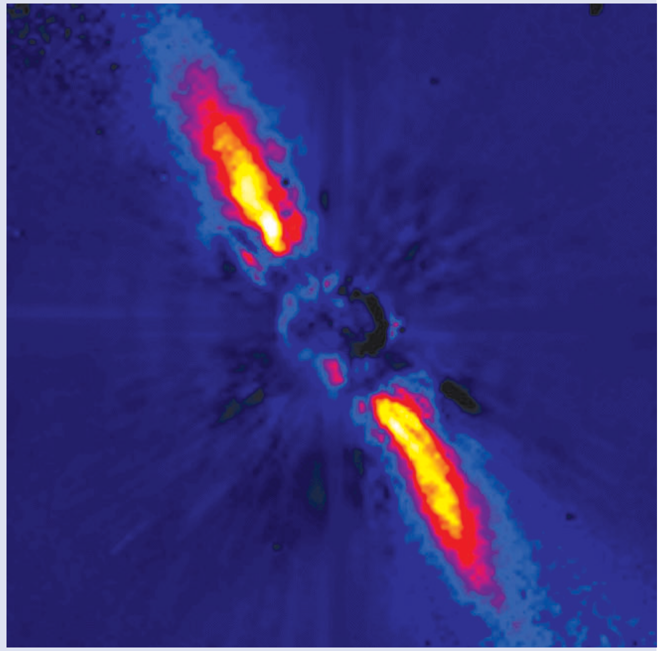
This simple but profound question has captivated humanity throughout recorded history. Today, we explore the mystery of our existence by studying the formation and evolution of the solar system, and Earth within it. We have reached beyond our planetary system and discovered planets orbiting other stars. We have begun the task of determining their properties and are now poised to search for worlds that could or do harbor life. These undertakings form one of the core strategic goals of NASA's Supporting Research and Technology (SR&T) program.

The story of how planets and stars form seems like such a simple one, now that we have studied many cosmic examples and searched among them for the clues to how this story unfolds. After a century of research and refinement, one wonders, in looking back, how the story could possibly have been anything different!

In the depths of a distant interstellar cloud, a clump of gas and dust forms slowly over the millennia. In time, it begins to collapse under its own weight. A swirling disk soon appears, and within a few million years, the enveloping gases are blasted back into space by the fury of powerful winds from the infant star. As another 10 million years pass, this young star begins to settle down into adulthood, a state in which it will remain for the next 12 billion years. Hidden beyond the limits of our technology, another genesis story plays itself out. Planetary masses also congeal from matter out of the dusty disk. Within a few million years, Jupiter-sized bodies appear in the clearing murkiness of these disks. Their powerful gravitational fields sculpt the orbiting dust into Saturn-like rings or even pinwheel-like arms. In time, smaller, rocky planets appear, but sometimes this process is defeated before it can even run its course.

In the dazzling images of the heart of Orion, we see a terrible pageant of events that has marched through this cloud. Powerful radiations from a handful of young stars have driven back the clouds that would normally hide the planet-forming process.

SR&T investigations [NASA Grants, Boss NAG5-10201 and 10547] of the Orion Nebula, as well as the circumstellar disks that have been identified there, now show that the powerful ultraviolet light produced by the youngest, most massive stars can indeed play a defining role in the process of planet formation. This work was funded by the Origins of Solar Systems Program. Although many of the disks in the most radiation-filled regions are evaporating at a swift rate, in other regions, evaporation need not lead to the destruction of the most massive planets. Massive planets such as the gas giants in our own solar system tend to form much more rapidly than the smaller rocky planets, so the Orion Nebula and other nurseries for the most massive stars may be vast birth places for a steady stream of free-floating Jupiters.

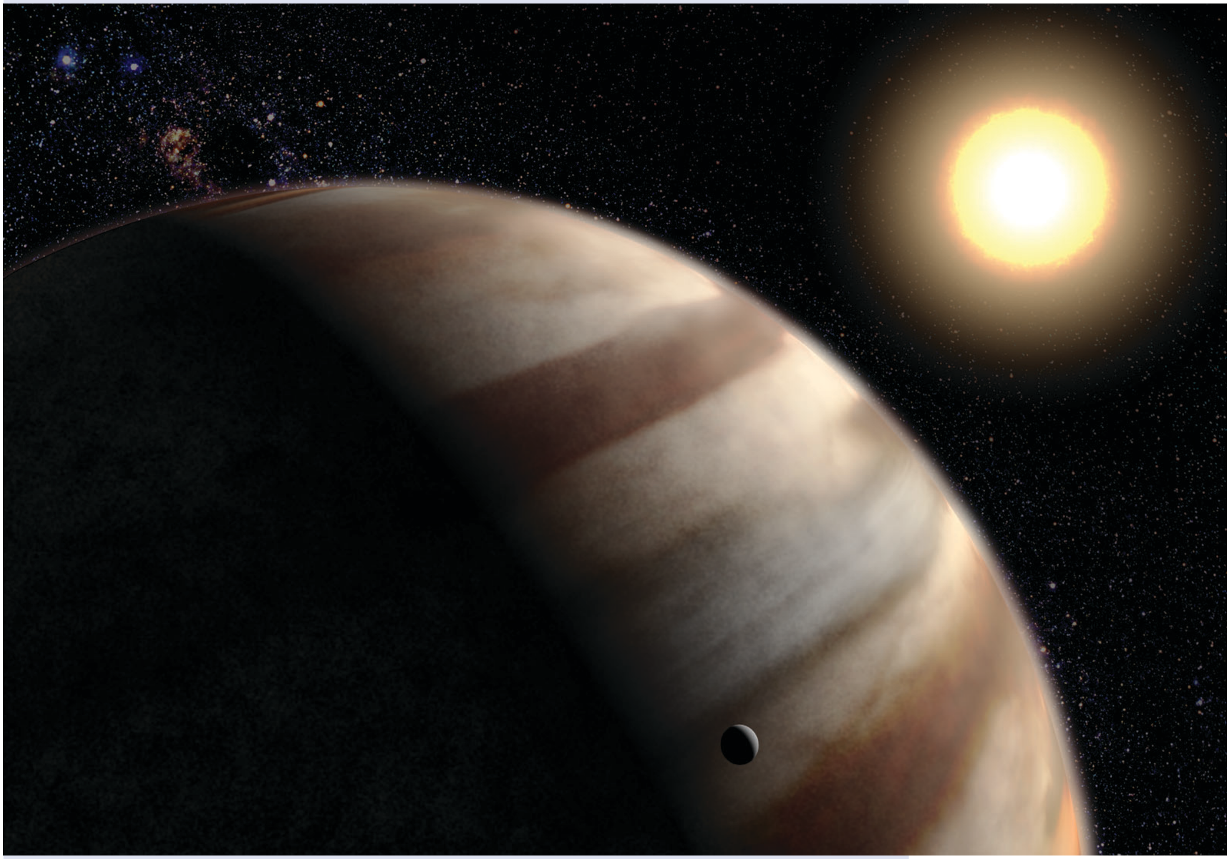


Ground-based image of the gas and dust orbiting the star Beta Pictoris.

Disks of gas and dust are being evaporated, in some cases just fast enough to let planets form before the central star disintegrates. Like flotsam and jetsam, the planets, no longer anchored by stellar gravity, drift into the iridescent nebula and vanish into the interstellar darkness. But many other planets have far less violent births.

For generations, it has been a leap of faith to believe that our solar system is not alone in the Milky Way. Surely there must be planets orbiting the distant stars that speckle the night sky. Since 1995, this dream has graduated from science fantasy to the hard reality of science fact. Astronomers have cataloged 100 planets orbiting 87 nearby stars, including 11 multiplanet systems. At first, only the most massive planets were detected—each one putting our own mighty Jupiter to shame. Their orbits hugged their stars and heated their atmospheres to near incandescence. As planet-finding techniques evolved, the masses have fallen and orbits have expanded outwards. An important threshold was crossed in March 2000 when two planets smaller than Saturn were detected in orbit around 79 Ceti and HD46375, each star some 100 light-years distant. But this was only the beginning of even more amazing milestones achieved, seemingly, overnight.

As planets crossed in front of the star, atmospheric gases left their discernible mark on the stellar spectra.



Artist rendition of the planet orbiting the star HD209458.

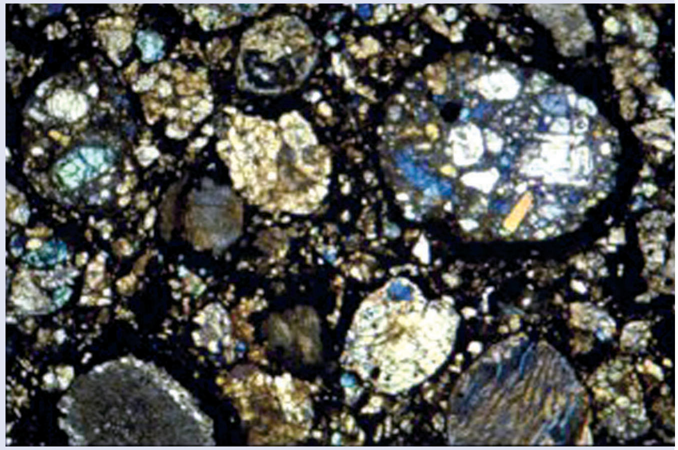
In the shapes and combinations of distant planetary systems, we will finally learn just how unique our own solar system may be. As technology and investigator confidence has improved, so have the prospects for uncovering an even larger bounty of planetary systems. With new planetary systems to explore, we also see in their many possibilities a reflection of the forces that shaped our own solar system long ago.

We live in a galaxy where star birth is still active; it contains a multitude of examples of every major stage from “conception” to “advanced old age and death.” Many of the steps that we are most curious about are hidden from view by light-years of distance and the limitations of even our best technology. But we do have an intimate view of how our own solar system is put together.

Under the right circumstances, planetary orbits as viewed from Earth can be tilted so that the planet transits the star. In one instance, HD 209458, a team of astronomers supported by SR&T funds in the Origins of Solar Systems Program [NASA Grant, Noyes, NAG5-10854] followed four of these transits spectroscopically and were the first to identify the element sodium in the atmosphere of an extra-solar planet.

Investigations supported by the Origins of Solar Systems Program that incorporate computer modeling and the results of isotope studies portray the earliest moments of solar system formation as a dynamic era triggered by the passage of a supernova shock wave. This impact caused gases from the supernova remnant to suffuse the presolar cloud and distribute a wide range of short-lived radio isotopes throughout the cloud. The impact may also have destabilized the cloud, triggering the eventual formation of a proto-sun and circumstellar disk [NASA Grant, Vanhala NAG5-4306].

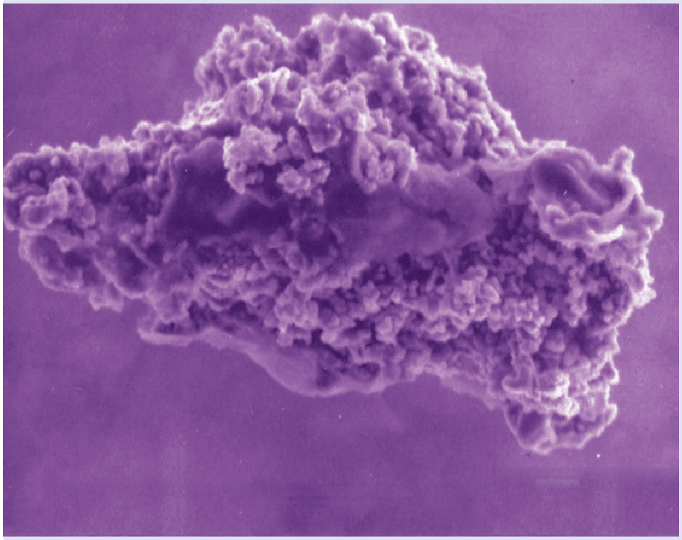
Chondrules within a meteorite.



As we look around us today, we see a fully mature world and a solar system where no ancient genesis events still occur among the planets. However, by carefully studying meteorites, interplanetary dust, and the dense clouds of gas between the stars, we see an emerging picture of an ancient solar system and the events that formed it.

The most ancient materials were formed at low temperature and are mixtures of small bits of rock called chondrules embedded in a larger matrix. Each entombed dust grain and rock fragment has its own unique contribution to make in the great puzzle that is planetary genesis.

In some cases, these smaller pieces can be identified by their elemental fingerprints as "pre-solar"—interstellar dust grains captured into the solar nebula millions of years before planet formation began. This celestial material contains not merely rock, but captured molecules of astonishing complexity. Carbon-rich meteorites bear traces of molecules previously seen only by astronomers with their telescopes.



Interplanetary dust grain.

Investigators can dissect these stones and, by weighing their constituent elements, explore the history of their formation and transformation. The biggest surprise, however, is that we are not exploring a genesis that came to an end long ago. In the hailstorm of dust and stone we can see, planet formation is still continuing today, though now the results are no longer quite so welcome. Earth is constantly under attack from incoming rocks and meteoroids. We accumulate nearly 50,000 tons each year from this debris, mostly in the form of interplanetary dust.

But every month or so, larger objects several meters in size enter the atmosphere and explode with the force of several thousand tons of TNT. Still larger bodies hundreds of meters across are rarer and enter the atmosphere every millennium or so. The history of impacts upon Earth during the last 100 million years has forced us to confront an uncomfortable future in which the next major impact could spell the end of the human race, or even the entire biosphere as we know it. Identifying these "doomsday rocks" is only half the challenge. We must also develop the means to dispose of them. In order to find effective methods to do this, we will need to understand how asteroidal material is actually put together. Looks can often be deceiving.

Researchers supported by the Origins Program [NASA Grants, Yin, NAG5-4430, NAG5-10484] have added and refined two new chronometers to the toolkit of radioactive dating. The hafnium-tungsten clock has discovered that the bulk of metal-silicate separation in the solar system took place within 3 million years for the formation of asteroid-sized bodies and 10 to 30 million years for larger, planet-sized bodies. The new technology has indicated that the interior of Earth formed with remarkable speed—nearly twice as fast as previous radioisotope techniques had implied—but the new speed record was well in line with dynamical calculations for planetary accretion.

Recent SR&T research in the Planetary Geology and Geophysics Program [NASA Grant, Britt, NAG5-8926] has revealed that the densities of asteroids such as Eros, Matilda, and Ida are substantially lower than plausible rock densities, and that the asteroids probably have considerable internal fracturing. Objects such as 16 Psyche fare even worse and have densities so low that, in many respects, they are floating gravel banks with minimal cohesiveness, rubble trapped in a common gravitational well.

Meteors and the asteroids that often produce them are not all made from the same rock. We can identify individual families of asteroids by their color and reflectivity and compare them with recovered meteoritic material. The impression that they are solid in the usual sense was dispelled when asteroids such as Mathilda and Eros were examined in detail during spacecraft flybys. Investigators have now discovered that meteorites may seem solid enough, but their parent asteroids may be mechanically very different.

If we are ever to use rockets or other kinetic means to deflect the courses of asteroids likely to harm us, this option is now made substantially more problematical. For the lowest-density asteroids that resemble their denser counterparts in all other ways, the effect may be more akin to striking a pillow with a hammer. Not only is planetary genesis continuing today, but we continue to exist in unsettled times.

ARE WE ALONE IN THE UNIVERSE?

No other question we can ponder in the 21st century seems to offer as much opportunity for spectacular and revolutionary discoveries. The SR&T program plays a leading role in the search for life beyond Earth. NASA researchers are developing the techniques and insights we will need in order to search for signs of life among the environments within our own solar system and beyond.

Ancient mariners and explorers often wondered about the unexplored reaches of Earth and the exotic life they might find there. Modern explorers turn to space as their new frontier and wonder if life exists beyond Earth and in what exotic forms. Just as the journey of the mariners forever changed the course of human history, one can only wonder what the triumphs of modern explorers may bring. At the current breakneck pace of discovery, it seems only a matter of time before life-bearing worlds are at last sighted. But how will we recognize a living world and distinguish it from one in which life was stillborn, or whose chemistry never took the next step? We know from our own world that the path to a life-sustaining world is often a torturous one. It is a path that can be followed in our own fossil record.

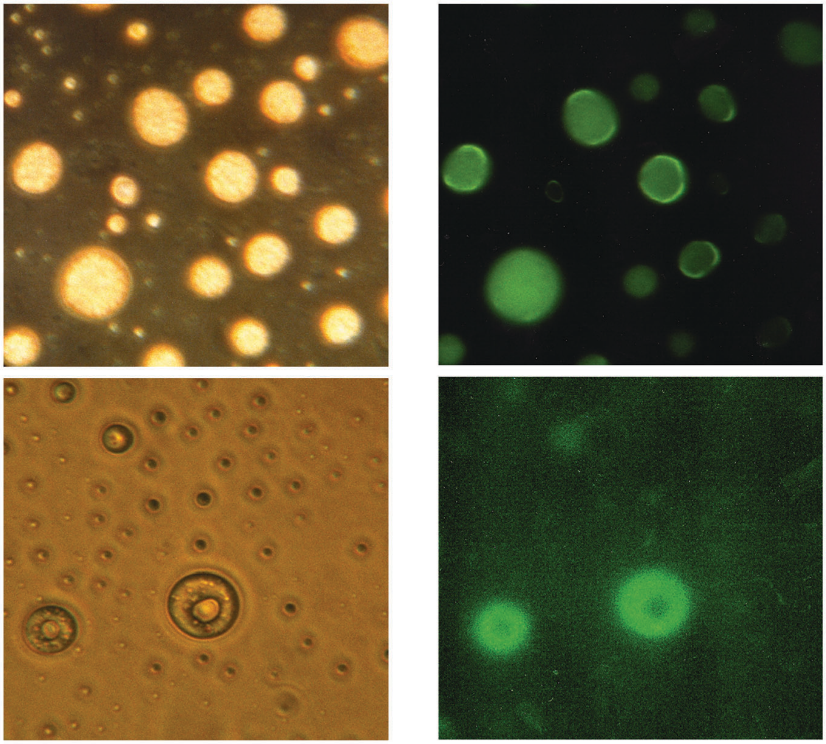
About 4.4 billion years ago, Earth congealed from a disk of gas and dust, along with the Sun and other planets. The major phase of intense asteroidal bombardment ended about 3.8 billion years ago. Some form of planetary atmosphere may have existed briefly, only to be eroded away by the powerful wind from the Sun during its brief, few-million-year sojourn as an infant star. A second atmosphere, rich in methane and ammonia, developed quickly, perhaps through planetary volcanism, although the details remain somewhat speculative. It was a fainter Sun that rose in the east each morning and heated space with barely 1/3 its modern brilliance. The thick blanket of methane, a powerful greenhouse gas, was the fortuitous ingredient that warmed the surface above the freezing point of water. One of the oldest zircon crystals from

At first, investigators supported by the Planetary Astronomy and Planetary Atmospheres Programs [NASA Grants, Disanti and Russo, NAG5-7905, NAG5-7753] studied Comet Hale-Bopp and concluded in 1999 that its deuterium abundance was far higher than that of ocean sea water. This led to wide-spread reports that comets could not have provided terrestrial water. However, a year later, the breakup of Comet LINEAR seemed to show evidence that its deuterium abundance was more in keeping with that of ocean water. The mystery of the origin of terrestrial water still continues, but has now been complicated by the possibility that the deuterium abundances of cometary water may depend on where in the solar system the comets originated.

Australia shows that temperatures at least as high as 100 °C appeared in some areas of the forming crust about 4.4 billion years ago. Liquid water existed by this time. It is still not known from whence our huge oceans of liquid water arose, although perhaps as much as half of it may have been deposited by the comets that swarmed through the solar system at that time.

Whatever the origin of Earth's vast reservoir of water, within 50 million years, the stage had been set for chemical reactions to take the next giant step to living systems. This step may have been negotiated numerous times during the Bombardment Era, a violent page in Earth's history when city-sized asteroids pummeled the planet. Each time, life may have been annihilated by a devastating impact, until the rain of asteroids slackened and, in some isolated and safe pool of water, the reactions could take a firm hold. It is also possible that these impacts were a critical part of the entire story of life on this world. To find out whether asteroids and comets played a role in the delivery of organic compounds to the young Earth, it is vital to recover this pristine matter today.

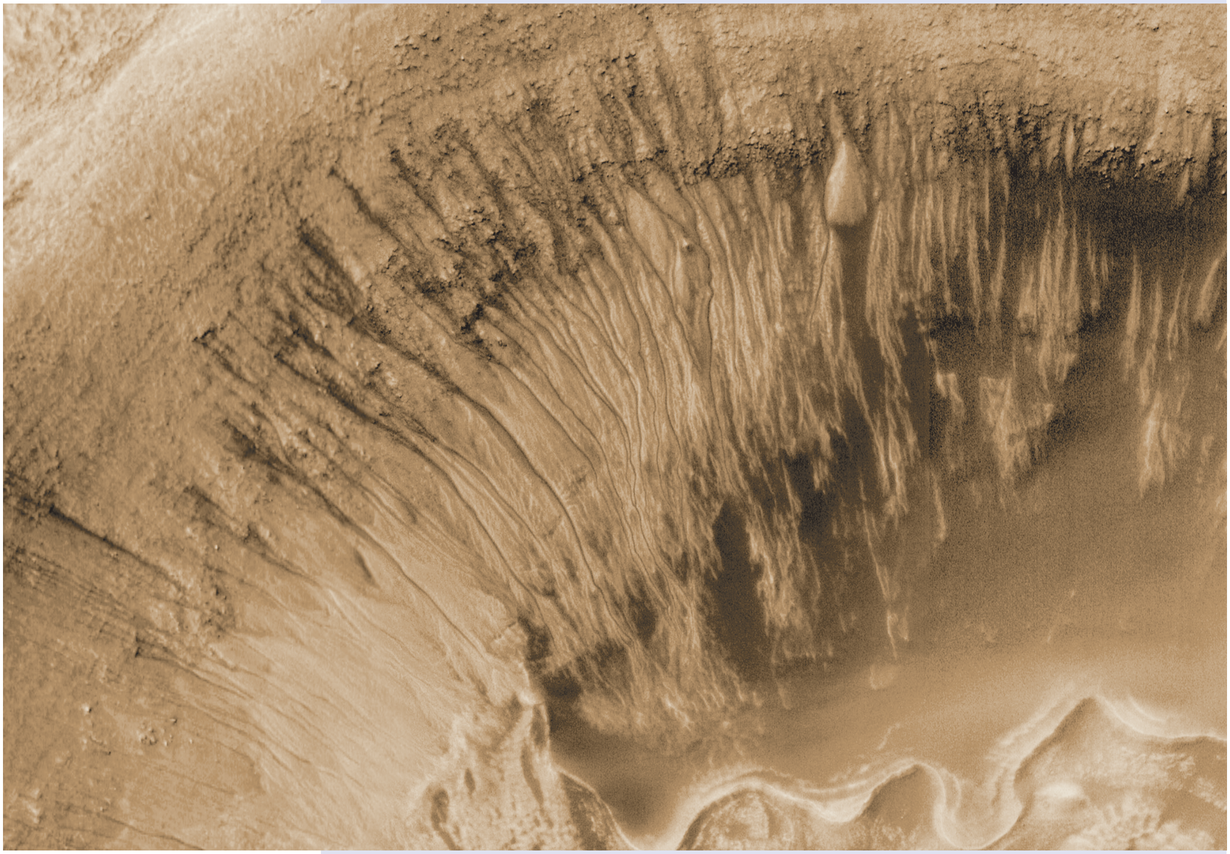
The close connection between interstellar molecules and more complex varieties recovered in the 4.95-billion-year-old Murchison meteorite may lead to a new chapter in the story of life, loosening its bonds to a particular planet and making its primordial chemistry a nearly universal constant.



Primitive membranes formed from meteoritic molecules under laboratory conditions.

The oldest record of the emergence of life can be found in fossil stromatolites recovered from the Barberton Greenstone Belt in South Africa. Ancient mats of bacteria were living on Earth about 3.5 billion years ago, not long after the end of the Bombardment Era. Without free oxygen, however, there could be no ozone layer to protect life on the land from damaging levels of solar ultraviolet light. Living organisms buried themselves under the shielding effects of ocean water or perhaps a blanket of soil.

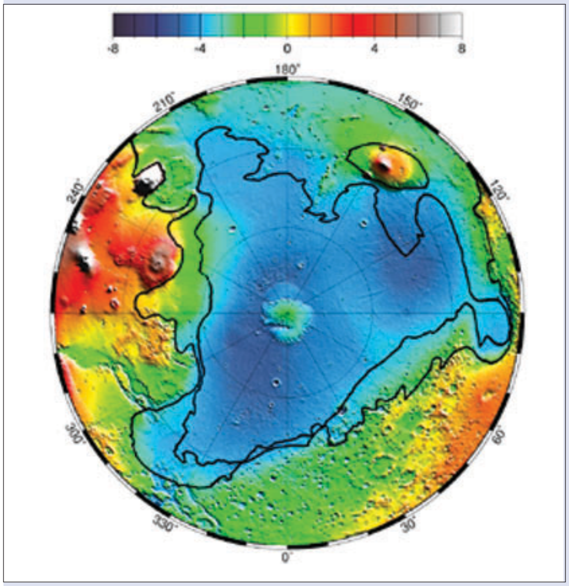
The difference between a living system and its environment is no more obvious than in the fact that living systems possess membranes that keep the outside world "out" and allow more complex chemistry to occur inside. SR&T-supported research, funded by the Exobiology and Origins of Solar Systems Programs [NASA Grants, Dworkin, 344-38-12-04 and 344-37-44-01], has produced the startling discovery that some form of proto-membrane can be created by simply mixing together the ingredients found in interplanetary ices such as methanol, ammonia, and water. Laboratory studies of this interstellar chemical "soup," when processed under conditions that mimic interplanetary space, produce microscopic bubbles that could help to sequester chemical reactions. Sugars, amino acids, and a variety of alcohols have been discovered in interstellar clouds, so the prospect exists that biogenesis may not actually need a planetary surface.



Evidence for liquid water on Mars (MGS Archive).

As we begin the search for life beyond Earth, no other potential abode in the sky holds as much spellbinding hope as the planet Mars.

For millennia, Mars has figured prominently in both human mythology and imagination. When author Edgar Rice Burroughs wrote of six-legged thoats grazing near the lush canals of Mars, a generation of young scientists were captivated by the idea of life on Mars. They were hopeful that one day they might stand on the banks of the same canals, feel the dusty Martian wind at their face, and gaze back at Earth. Only during the last half century have we begun to realize that this mysterious red planet was once indeed similar to Earth. But that verdant time for Mars passed by nearly 4 billion years ago. In the near future, scientists will have to explore this still-mysterious planet, not in shirtsleeves, but in bulky spacesuits.



Possible basins (shown in blue) for ancient Mars oceans.

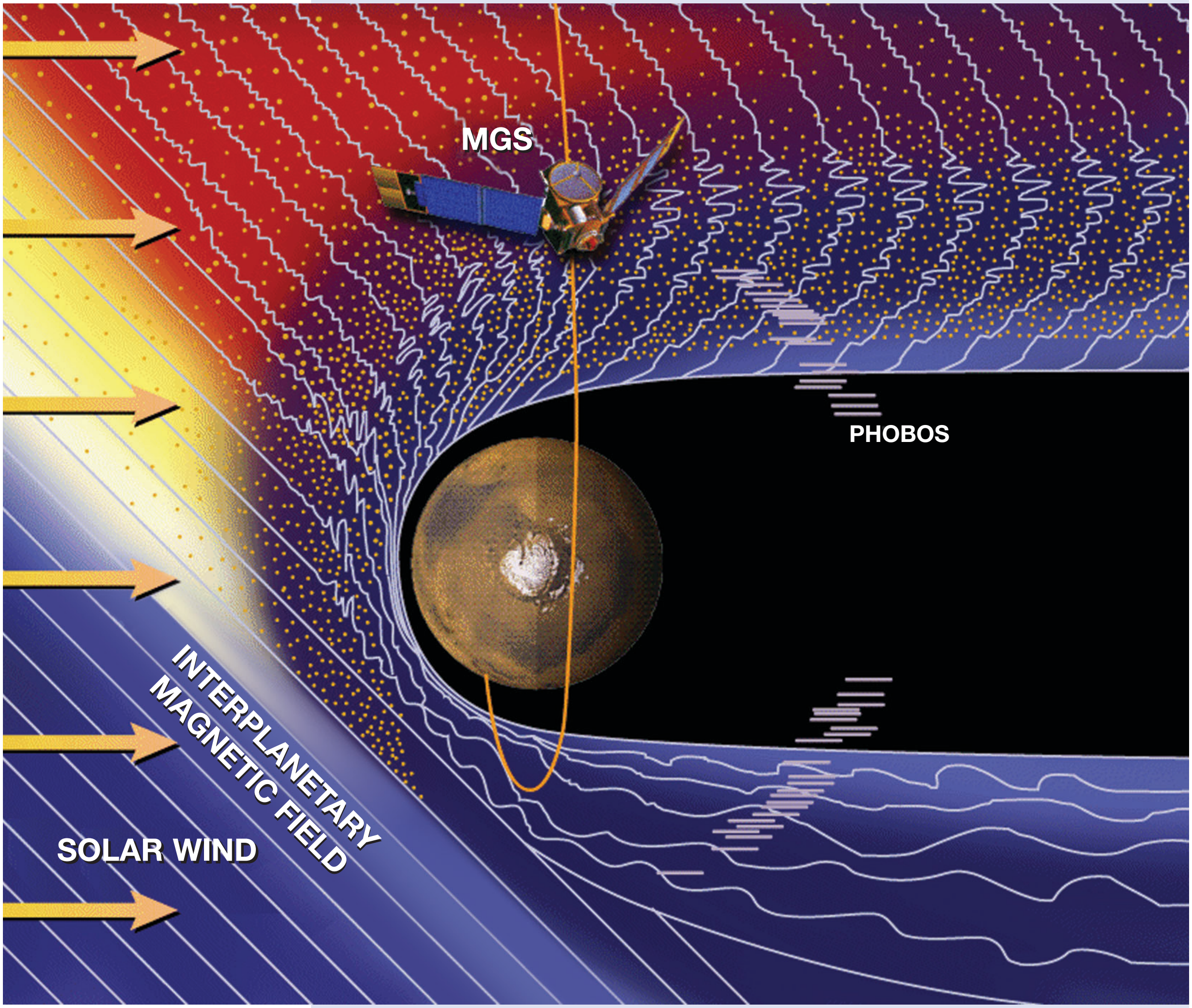
Scientists supported by the Exobiology and Astrobiology Programs [NASA Grants, Watanabe, NAG5-9089 and NCC2-1057] made the startling discovery of the chemical traces of microbial mats that must have existed on land about 2.6 billion years ago. Prior to 1999, it was "common knowledge" among paleobiologists that it wasn't until about 2.2 billion years ago that atmospheric oxygen levels reached the concentration needed to offer some biological shielding. The new dating for the emergence of life on land rocked the community, and it occurred nearly a full billion years earlier than previous fossils had indicated.

The destiny of Mars was sealed by something as simple as its smaller mass, which forced a rapid evolution of its atmosphere and interior. Eons later, it has become a cold planet that has largely lost what may have been an Earth-like atmosphere. Yet in its exposed, ancient crust, we see a fascinating story of rivers that once flowed and vast but shallow oceans that once graced its rusty-red lowlands. There are no thoats there today. But perhaps in its brief, billion-year flourish of atmosphere and water, life may have scrabbled a fleeting existence, leaving fossils behind on the ancient shorelines and embedded in sedimentary deposits near Acidalia.

There is even the hope that bacterial life may still exist in the apparently subsurface aquifer of Nirgal Vallis.

Since the earliest telescopic viewing of Mars, its north polar cap has given us tantalizing hints that water ice may be present at the surface in vast, exposed deposits. Water is present in many forms, from atmospheric cloud condensations to vast subsurface reservoirs bound up in the rock strata.

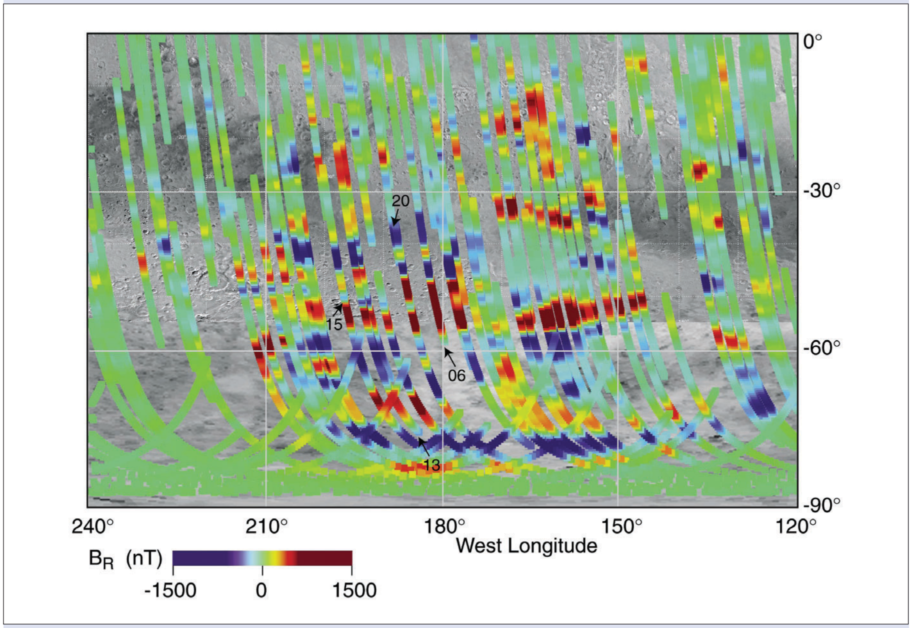
Water continues to be a perishable resource on Mars. Intense solar ultraviolet radiation breaks water molecules into free hydrogen and oxygen. Released from its molecular prison, oxygen flows into the atmosphere and is quickly lost by incessant collisions with solar wind particles at a rate of 90,000 tons per year.



Solar wind interaction with Mars.

On Earth, this loss is slowed to only a few hundred tons per year. Part of the vast difference is in the masses of the planets, but it is also a matter of a much less obvious ingredient: their magnetism. Earth's magnetic field deflects much of the solar wind away from Earth's atmosphere like an invisible umbrella. Mars also has its own magnetic umbrella, but it is far weaker.

In its infancy some 4 billion years ago, Mars may have had a magnetic field nearly as strong as Earth's. All that now remain are its fossil traces spread here and there across a desolate red landscape like fingerprints.



Mars magnetic surface anomalies.

Investigations (supported by the Planetary Atmospheres and Mars Data Analysis Programs) of the solar wind interaction with Mars have begun to show why such small relic fields can play such a major role in Martian atmospheric physics [NASA Grants, Luhmann, NAGW-1347, NAG2-2573]. The presence of these very few but intense magnetic features seems to be the reason that Mars continues to have an atmosphere today. The combined effects of water photodissociation and solar wind erosion are so effective, however, that it is unlikely Mars will be able to retain the water it now has for another 100 million years.

It is fortunate that Mars has even this feeble magnetism, since there seems to be just enough of it to slow down the loss of the Martian atmosphere by solar wind erosion.

Mars is most certainly an example of a geologically dead planet, which we see perhaps 4 billion years after its brief tenure as a Garden of Eden with planet-girding oceans and rivers. But in the dim red mirror of that world, scientists have found the reflection of how planetary evolution can go wrong. With the example of Mars so close by, it is not unreasonable to wonder what might be in store for our own world in the eons to come.

Like miners panning for gold, modern investigators mine the growing mission data archives in search of a deeper understanding of Earth and a glimmer of hope for precious traces of Martians in whatever shape or condition.

WHAT WILL THE FUTURE BRING?

Since the dawn of human history, we have always been hopeful that the future could be forecast so that we might anticipate when the weather will turn stormy. Thanks to investments made by NASA during the last 30 years, our ability to predict the future is reaching beyond Earth. It now includes predicting when changes in our Sun will cause stormy conditions in space that directly impact our space technology and the well-being of our astronauts. The SR&T program has made dramatic advances in the accuracy of our space weather forecasting ability. It provides improvements in today's theoretical understanding of how this vast system operates; it also provides new questions for future investigators to address.

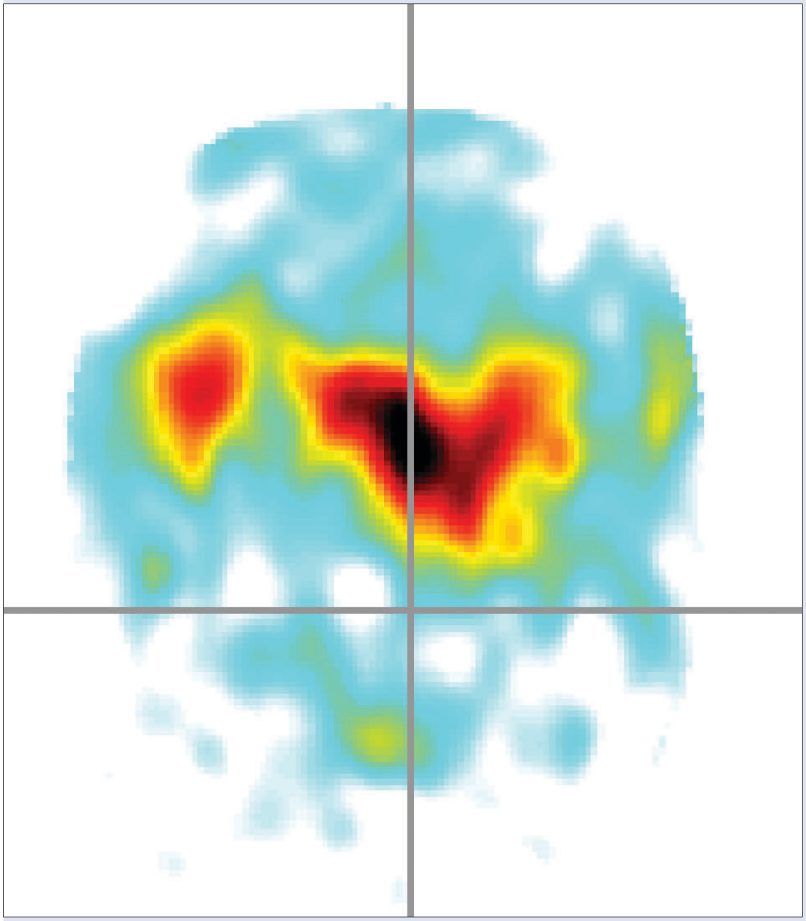
The Sun has always been to us a constant of nature separating night from day, allowing Earth's living creatures to thrive. It has been worshiped as a deity; poems and songs have been written about it; massive temples and ancient monuments have been erected in its honor. Today, in the light of centuries of accumulated wisdom and science, we understand the Sun in deeper ways beyond merely accounting for its warmth and light. The Sun generates light and flows of particles, which travel from its boiling surface, rush past the Earth in a few minutes or days, and eventually leave the solar system en route to infinity.

The Earth interacts with these sources of matter and energy with invisible readjustments to its magnetic field and its outer atmosphere.

An auroral curtain produced by current flowing into the atmosphere.

One spectacular form of these changes is the curtains of light that encircle the polar regions. For thousands of years, the aurorae have been a staple of human folklore, but now we see them, like the miner's canary that detects harmful gases, as a sign of more complex changes taking place in the space surrounding our world. We call this invisible give and take between Sun and Earth "space weather." The Sun's impulsive storminess is set against a background wind that flows outwards at speeds up to several million kilometers per hour. It is a vast conveyor belt, transporting solar storms throughout the solar system and beyond. If we want to anticipate when these disruptive storms may be coming our way, we must take a closer look at the Sun, which is the ultimate source of this weather. It all begins with its deep interior.

The science of seismology allows geologists to probe the interior of Earth. The new science of helioseismology similarly allows scientists to open a window into the interior of the Sun. The constant gas motions at the surface, along with sudden explosions of plasma into space, act like terrestrial earthquakes sending sound waves through the interior of the Sun.



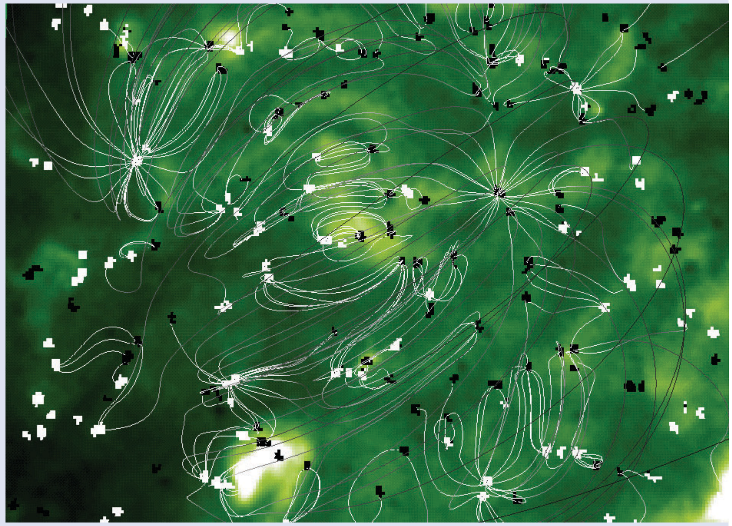
Detecting storms on the far side of the Sun.

As the Sun rings like a bell under this seismic activity, patterns form on its surface like the wavelets from a tossed stone.

Research sponsored by the Solar and Heliospheric Physics Program has demonstrated with spectacular success that active regions on the Sun's far side can be seen as their acoustic signals travel through the bulk of the Sun and disturb the side that we see from Earth [NASA Grant, Lindsey, NAG5-10984]. An increase in activity from these regions can even be detected in the subtle rearrangements of the base of the solar convective zone weeks before it peaks at the surface.

SR&T investigations in the Sun-Earth Connection Theory Program now show that the dynamo process acting in the sheared gases at the base of the solar convective zone also appears to be responsible for the solar cycle changes in solar activity [NASA Grant, Toomre, NAG5-8133]. A similar dynamo mechanism may be at work on the solar surface to produce small-scale fields from the turnover of plasma in convective granule cells [NASA Grant, Stein, NAG5-1695].

Small-scale magnetic fields on the solar surface.



But the Sun is more than simply a glowing ball of turbulent gases. Nearly all of its surface blemishes—its sunspots, solar flares, and coronal mass ejections (CMEs)—would not be possible were it not for complex magnetic fields threading the gas. As the upwelling gases get twisted below its convecting surface, these motions spawn the Sun's powerful magnetic field, which floats to the surface and erupts in a bewildering variety of structures and phenomena.

Solar flares appear to be the key, the battery that runs the entire spectrum of solar pyrotechnics. Individual clumps of magnetism, about the size of the State of Massachusetts, wander about on the solar surface along the edges of upwelling gas and form a patina of networks and intersections like some alien roadway system.

When opposing polarities come together at thousands of kilometers per hour, they can annihilate each other rapidly. The resulting energy release is seen as bright pinpoints of x-ray light. The incessant release of energy not only fuels other explosions of mass near the solar surface, but also heats the vast coronal halo of the Sun through powerful waves of energy like the cresting waves on a beach.

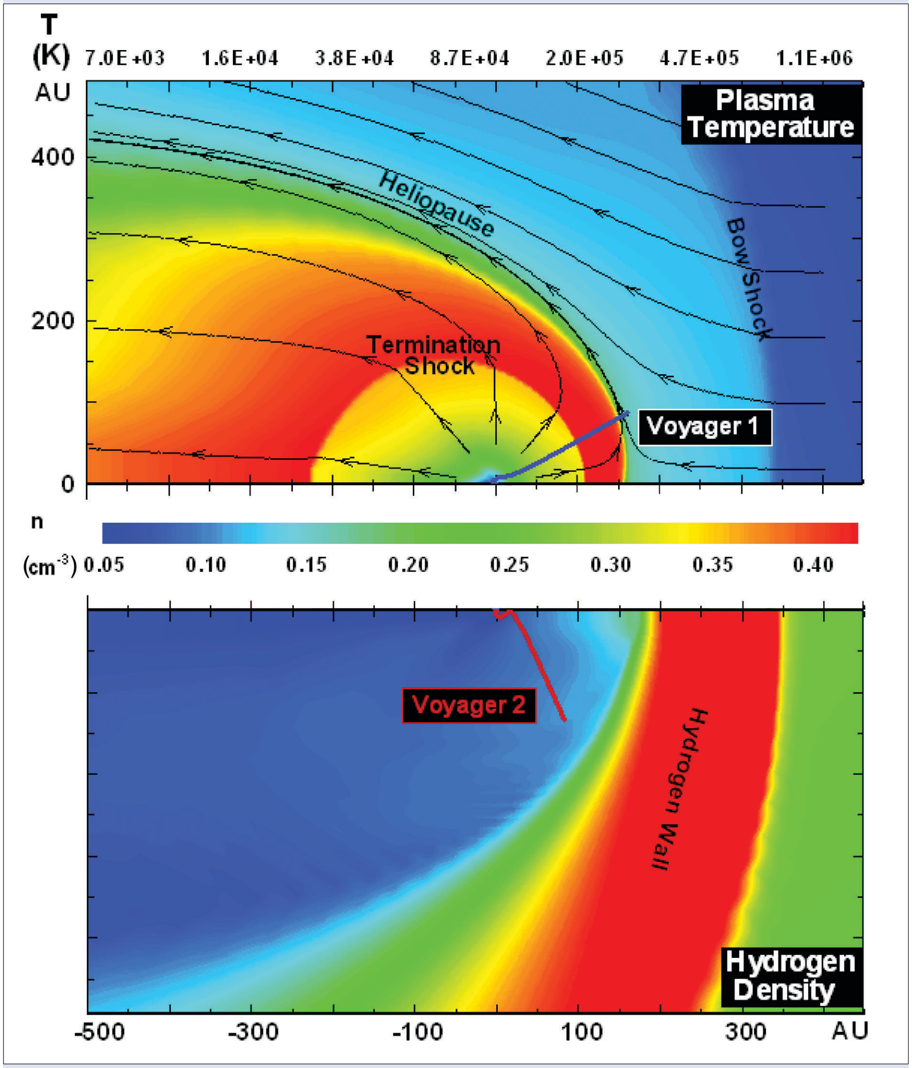
Solar flares caused by still larger explosions of magnetic energy lead to powerful bursts of x-ray radiation, which travels through the solar system at the speed of light. These as yet unpredictable “lightning bolts” in the space weather system are a major hazard for humans working in space and for our sophisticated satellite technology. It is these human-scale consequences that are by far the most troubling and costly.

As important to space weather as solar flares might be, either Earth’s atmosphere or a properly designed spacesuit will shield us from their impacts. But other solar phenomena, the CMEs, provide a more severe challenge. Their billion-ton combinations of particles and magnetic fields traveling at a million kilometers per hour produce a more potent punch as they encounter Earth's magnetic field. Their consequences trickle down into every level of our space technology and ground-based electrical systems. They even siphon our atmosphere into space like an invisible pump. Can we understand them well enough to anticipate their Earthly consequences?

The Sun's magnetic field creates bright streamers of luminescent plasma that we see during solar eclipses. Below them, cold arches of gas are precariously balanced within a much hotter corona. This arrangement can last for months, but for reasons not fully understood, something forces this balancing act to become unstable.

A major discovery related to the CME triggering mechanism was made in 1999 when specific S-shaped coronal features called "sigmoid loops" were identified in soft x-ray studies using Yohkoh data [NASA Grant, Canfield, NAG5-6110]. This research, supported by the Solar and Heliospheric Physics Program, has significantly improved the ability to rapidly identify active solar regions that are in the process of erupting as CMEs at a later time.

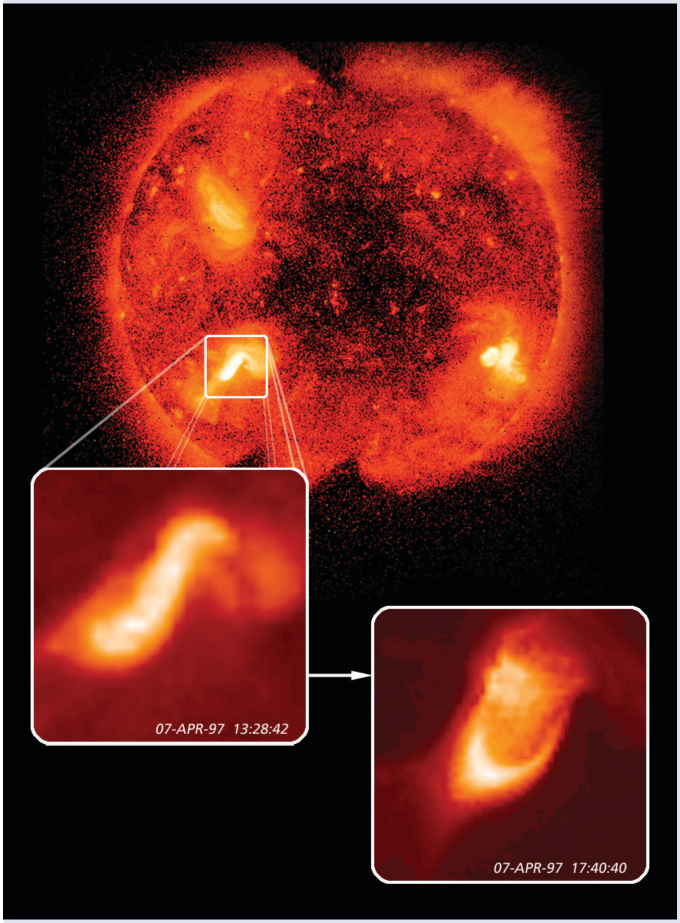
Another discovery made by SR&T investigators supported by the Solar and Heliospheric Physics Program is that the clockwise or counterclockwise twist seen in the sigmoid feature is preserved as the resulting CME reaches Earth's orbit [NASA Grant, Rust, NAG5-7921]. This offers forecasters the opportunity to predict how strongly a CME will interact with Earth's own field by viewing the way it is twisted near the solar surface many days before arrival.



The solar wind interacts with interstellar space in the heliopause region.

Within a few hours, a billion-ton cloud of gas is launched into space from the solar corona like a released toy balloon. This gas flows out through the solar system beyond the orbit of earth and the distant planets until it eventually collides with interstellar gas in a region known as the heliopause. Even now the Voyager I and II spacecraft are continuing to measure this mysterious region of space at the outer limits of our solar system.

The most interesting aspect of the Sun's storminess, however, has to do with its impact upon our own planet, not at the astronomical scale, but at the human one.

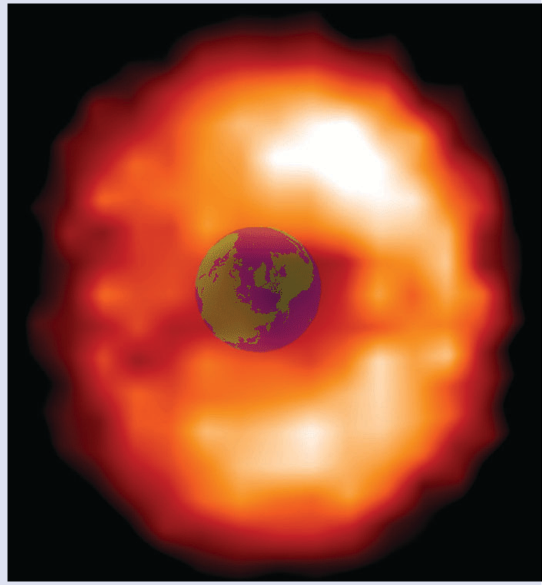


The solar wind interacts with interstellar space in the heliopause region.

Like an invisible umbrella, Earth's magnetic field deflects most solar storms away from Earth and back into interplanetary space. This effort also changes Earth's field in complex ways. We don't notice these changes on the ground with a compass, but in the outer reaches of its field, it flaps like a flag on a windy day. Meanwhile, the contorting field boosts the energies of particles already trapped within Earth's magnetosphere. These particles can flow into the polar regions to cause beautiful curtains of light known to millennia of humans as the northern lights, or swirl around the equator of the planet like some invisible Saturnian ring.

Although no one has ever been harmed by an aurora, during the last few centuries, we have made ourselves increasingly vulnerable to these invisible phenomena that bring them to life in ways that have become more dramatic as time has passed. At first, the impact was to a few hundred messages traveling upon telegraph lines. Then the execution of the D-Day invasion of World War II hinged upon whether x-rays unleashed from

An invisible current of particles flows around Earth during a solar storm.

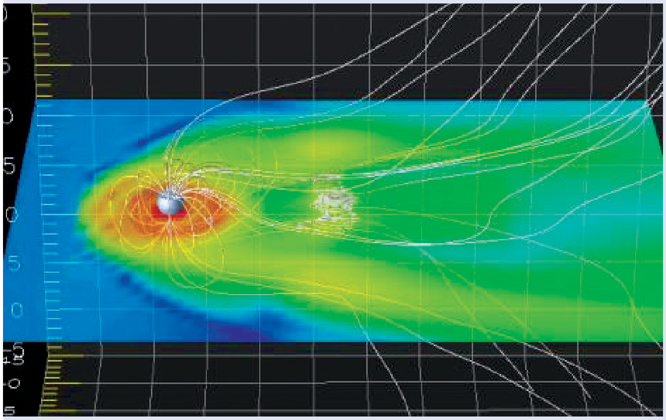


a solar flare might disrupt shortwave communications at a critical moment. With the advent of commercial satellite communication, hundreds of millions of users are now severely impacted when cellular telephone, pager, news, and entertainment sources suddenly cease operations. Even our electrical utilities on the ground are not immune to costly disruptions and blackouts. As we continue to move into space to further our commercial, scientific, and military goals, we have little choice but to improve our ability to predict when space weather will take a turn for the worse.

Since the dawn of the space age, a growing armada of satellites has probed Earth's magnetosphere to uncover its major pieces and the ways in which they interact. Meanwhile, sophisticated physics-based computer models have explored pieces of this vast four-dimensional puzzle to account for the ebb and flow of matter and energy. It has been a daunting challenge.

Even a compact summary of this system must connect a vast number of phenomena happening in a number of time scales (from seconds to days), at different levels of particle energies, and in locations of varying sizes (measured in units from meters to thousands of kilometers).

A space weather storm has a dramatic effect upon Earth's environment because the coronal mass ejections from the Sun are magnetic. This magnetism interacts with Earth's own field, allowing solar wind particles and energy to flow into the Earth environment. This does not happen all the time because in order for the worst of the storm effects to



Modeling reconnection in the magnetotail.

appear, a magnetic valve must first open like an invisible doorway. Investigators call the opening of this doorway "magnetic reconnection," and the details of how it works remain partly obscure. It is one of the most important "dominoes" that must fall before our satellites and space technology are placed in harm's way. Understanding this process in detail has been one of the major goals in space research since the dawn of the space age. It is a vast process that dwarfs the laboratory environment of otherwise well-regulated research.

The volume of space involved in magnetic reconnection can span millions of cubic kilometers. The sequence of events that unleash its energies can take place in minutes or days. The details of how this phenomenon unfolds also depend on which kinds of particles you are watching. It is vital for astronomers to understand just how it works, since something like this process takes place on the solar surface, near black holes in the distant universe, and even in the accreting disks of gas and dust which form solar systems like our own. Luckily, Earth's magnetic doorway gives us a ringside seat to this phenomenon, although one that is not easily accessible.

The local universe flows at many different tempos. Pulsars flash in milliseconds, while solar flares and CMEs take minutes or days to complete their motions. In the fullness of cosmic space, we hardly expect to see events play out their existence at a similar cadence. Yet, from time to time, supernovae burst forth in distant galaxies, and millions of years later, Earth-bound astronomers measure their waning light signals over weeks and months. Some cosmic events rise and fall in a vastly different cadence.

Recent SR&T-supported research in the Geospace Sciences Program [NASA Grant, Chang, NAG5-9111] have suggested that, due to the temporal behavior of Bursty Bulk Flows, reconnection events are not smooth, but suffer from complex, multiscale turbulent processes. Modeling efforts that include self-organizing criticality and the fractal nature of these flows are now being developed.

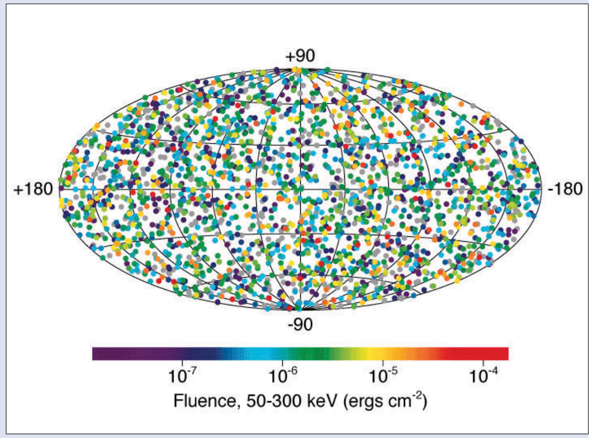
HOW DID THE UNIVERSE BEGIN?

One of the great discoveries of modern science is that our very existence is intimately connected to a larger universe astonishingly rich in details that often dwarf the human scale of events. SR&T research in the cosmic domain is both a breathtaking and a humbling undertaking that seeks to deduce the limits to our physical world and discover the manner in which it came into existence billions of years ago. These investigations are the proving grounds for our most advanced theories of matter, energy, and the nature of space itself. We seek nothing less than to understand the destiny of our universe and to find relicts of its infancy at the limits to our visible universe.

Astronomers have always been intrigued by the mystery of deep space and the exotic things they have found there. In the menagerie of the deep cosmos, few things have been as puzzling as gamma-ray bursts. For nearly 30 years, flashes of gamma-ray energy, lasting only a few brief seconds, have arrived at Earth, invisible to ground-based instruments but quite apparent to satellite sensors. Their locations in space gave no hint of favoring the jumbled star clouds of the Milky Way. Instead, the nearly 3,000 bursts show a random pattern across the sky.

The bursts are also unique in their individuality as they silently flash in the night sky to their satellite observers. Astronomers enjoy a good mystery, so it comes as no surprise that the origins of these gamma-ray bursts became the Holy Grail of astronomy for decades, until patience and luck finally coincided in space and time.

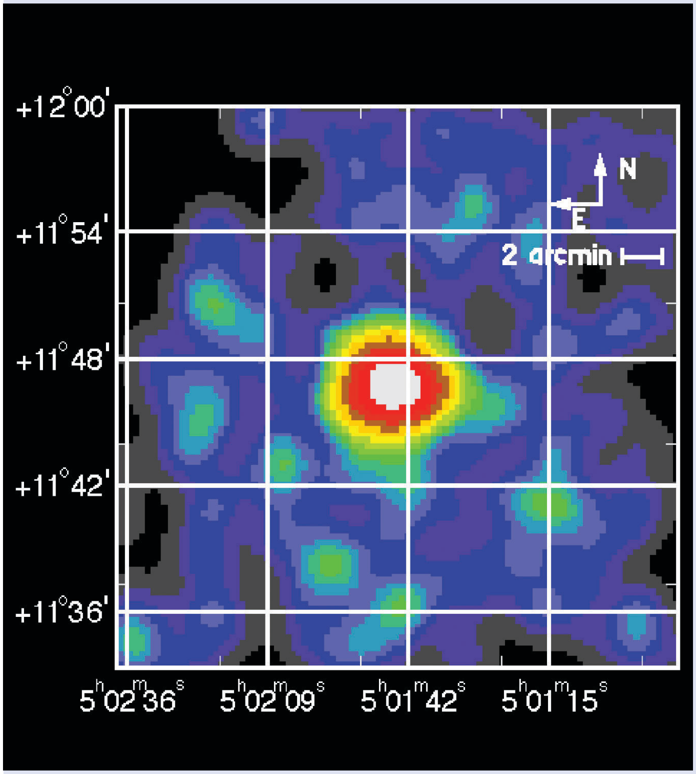
Gamma-ray bursts seen by Compton Gamma-Ray Observatory.



Through the coordinated efforts of NASA and ground-based investigators, one of these fleeting explosions of energy was tracked back to its origin in 1997. The host for GRB970228 was an unremarkably faint galaxy billions of light years from the Sun.

It was certainly not an object in the halo of our Milky Way or a nearby galaxy as some scientists once thought.

In the ensuing years, many more "afterglows" were seen at x-ray, optical, and even radio wavelengths. Every afterglow that investigators could pinpoint in space seemed to come from a galaxy where stars were being born at hundreds of times the rate of those in our Milky Way—the outcome of galaxies in collision. But there was more to the gamma-ray burst genesis than simply an overactive, dim galaxy.



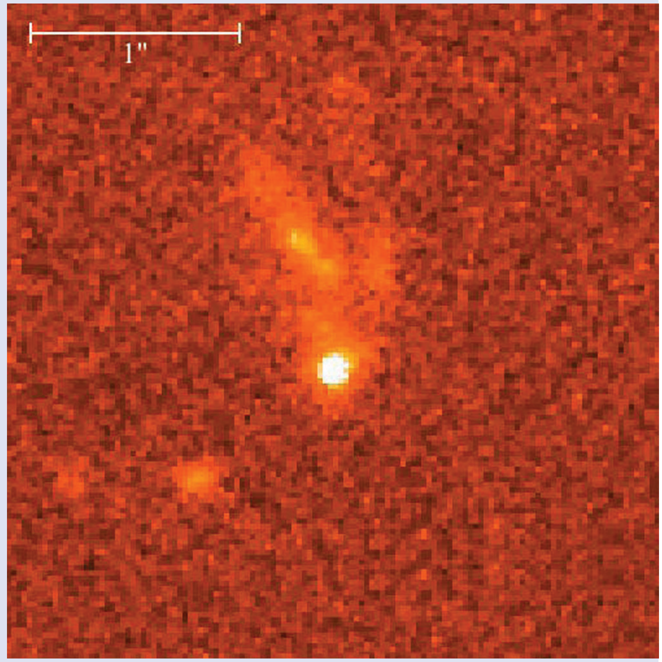
Afterglow of GRB970228 seen by the x-ray satellite BeppoSAX.

When GRB020405 flashed into view, researchers supported by SR&T funds from the Long-Term Astrophysics Program [NASA Grant, Hurley, NAG5-11451] were able to discover and localize this event using the Inter-Planetary Network (IPN) (Ulysses, Mars Odyssey/HEND, and BeppoSAX). This SR&T funding has been essential to keeping the IPN operating.

Like a firefly overwhelmed by a flashlight, the bright burst camouflaged a fainter glow beneath it. When this faint glow was at last detected and studied in detail, its fading light announced nothing more unusual than the passage of a supernova explosion. The origin of these outbursts in what appeared to be a common supernova explosion only deepened some of their former mystery.

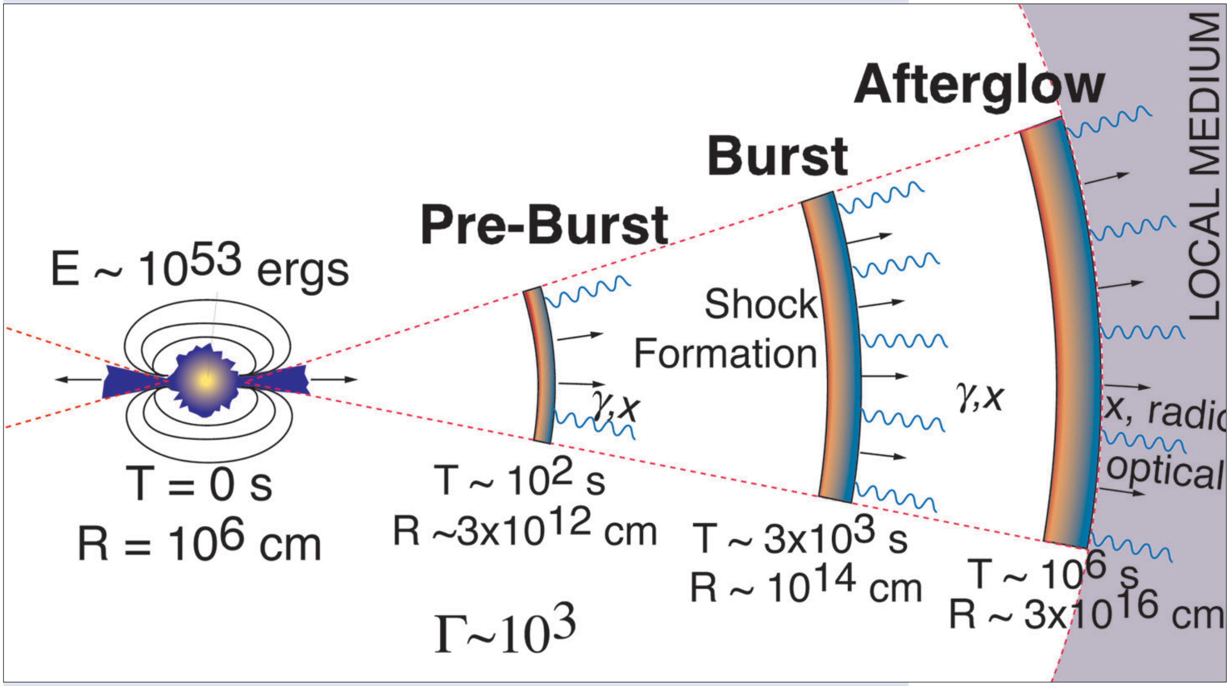
The fading light from GRB971214 revealed an object with the largest distance from the Sun on record. If the light had flowed out in the manner of a normal supernova, the flash's brightness meant an equivalent power equal to 100 billion billion Suns. It would be like expecting a firefly's flash and finding in its place a lighthouse beacon. Even though the origins were in star-forming clouds and were likely associated with supernovae, the energies involved were not at all those of ordinary supernovae. It seemed, at first, that something far more powerful was needed for them to shine with such brilliance across billions of light-years of space. A new class of "hypernova," perhaps?

GRB 990123, the farthest-known Gamma-Ray Burst.



Such an enormous amount of power, delivered in only a few hours, strained even the most exotic ways that the most adventuresome theorists said it could happen. A few years later, when GRB990123 erupted, theoreticians realized that they had not been imaginative enough.

Its brightness was equal to what would be produced by the total conversion into pure energy of two stars like the Sun within a few hours. Something about the underlying physics would have to be rewritten to encompass this gargantuan blast of energy. Or perhaps there was, instead, some missing ingredient to the models being used to mimic the supernova outburst?



A model of a GRB event showing the major features within 300 billion kilometers of the source.

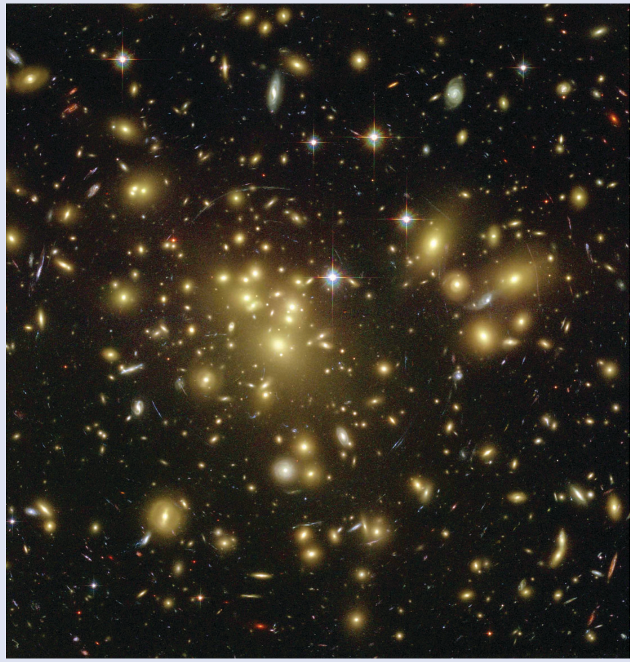
Researchers supported by the Astrophysics Theory Program have computed models of the evolution of massive stars, each of whose cores has collapsed into a black hole with an accretion disk. A jet of material traveling at nearly the speed of light flows out along the rotation axis of the star. Its interaction with the star and circumstellar material accounts for many of the characteristics of known gamma-ray bursts at cosmological distances [NASA Grants, Zhang and Woosley, NAG5-8128 and NAG5-12036].

Most supernovae explode in a very messy way with matter and energy ejected in all directions. But what if something was putting a corset on this flow? Could the emission actually be beamed or collimated, with Earth luckily within the axes of a few of these explosions, caught like a dust mote in a laser beam? Calculations showed that the power would be substantially amplified 100-fold. Beaming would also mean that the thousands of sightings recorded since the 1960s were only the lucky few whose beams were aligned with Earth. What investigators had so diligently recorded over all these years was only the tip of a very large iceberg. In a single day there might be thousands of these bursts happening in all directions in the cosmos across the entire sky.

The possibility that beaming could happen in certain supernova explosions was soon investigated by a number of researchers. What seemed to be needed was some reason for the material in a supernova not to explode like a perfectly round ball of nuclear fire and gas. Calculations and computer models soon showed that just before the supernova detonation, core material with insufficient energy to exit the doomed star would form a temporary disk within the star. As the supernova detonated, a powerful jet of matter traveling at nearly the speed of light would punch its way out of the star along the axis of the disk along the path of least resistance. The jet would escape the star to cause the flash moments before the supernova began its slow rise to maximum light.

Research supported by the SR&T Astrophysics Theory Program suggests that some GRBs are probably related to an unusual class of supernovae which occur about 1 percent of the time, compared to Type II SNs once every 50 years, and involve stars 20 to 40 times more massive than the Sun [NASA Grants, Dermer, NAG5-11451 and DPRS-137569].

A cluster of galaxies warps space and creates multiple (blue) images of a still more distant galaxy.



Beaming now makes the energy source of even the most gargantuan gamma-ray burst look much more like an ordinary supernova. It also provides an early warning system for astronomers that announces the onset of the star's detonation.

In a galaxy such as the Milky Way, a gamma-ray burst might happen about once every 5,000 years. The star cluster Eta Carina has a number of stars that could serve as unfortunate hosts, at a distance of only 4,000 parsecs. It poses a rather uneasy future for our progeny. Closer to home, even the bright stars Betelgeuse and Antares, a few thousand light-years away, may someday erupt as a gamma-ray burst. Earth may be in for a spectacular light show in the next few million years. If we are in a favored location along a future Eta Carina gamma-ray beam, night will be turned to day for hours or even weeks. An avalanche of particles and cosmic rays will flood the solar system, perhaps destroying the ozone layer for decades or centuries.

In the brief flashes of light that we see in the distant universe, we also see a brief image of an infant cosmos. We live in a phantom universe where things appear as they once were, not as they are today. The bursts show us a time in cosmic infancy when the triggering of these flashes was far more numerous. Their mere existence tells us about the earliest generations of stars and provides a glimpse of the rise and fall of creation itself.

While NASA investigators have puzzled over the brightest outpourings of light and energy in the cosmos, another aspect of the distant cosmos has come into view. It has posed to scientists one of the most philosophically troubling conundrums of all time: it isn't the starry matter of the universe that steers its destiny, but the invisible gyrations and forces of space itself that will eventually seal its fate.

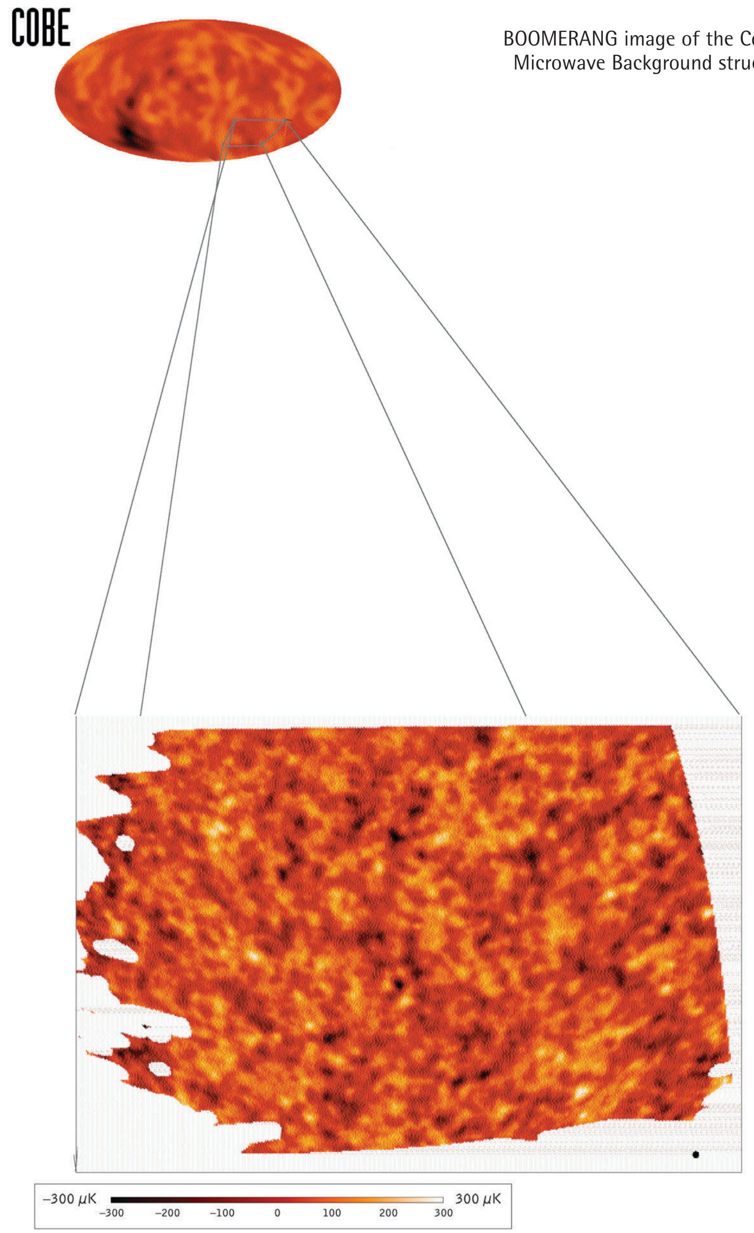
Each night, nature gives us a glimpse of the infinite. On a clear dark night, what you see in those dark spaces between the stars is nature's best approximation of what mathematicians call infinity. The universe is expanding while the gravity from all its mass and energy is trying to pull it back together. Its destiny hinges on which of these will win in the end. As astronomers continue to study the speeds of ever more distant galaxies, the universe proves itself to be more complex than the sum of its most visible and conveniently nearby parts. Those dark spaces hide a secret that modern investigators have begun to uncover through a painstaking bookkeeping of the cosmic gravity and mass.

It was an old star system in a young universe. The larger of the two stars was a distended red giant, an obese star whose blood-red gases wafted out into space. Some of the expelled gas was captured by its companion star, a small white dwarf no bigger than Earth. As the millennia passed, gases steadily piled up on the white dwarf's surface. Then, like a table collapsing from its accumulated load of books, the sheer weight of the dwarf caused the core to implode, triggering an incredible release of energy. The fusion wave tore the dwarf apart, ejecting the star's matter into space. Eighteen billion light-years away and 10 billion years into the future, a feeble flash of light from an indistinct galaxy in the constellation Pegasus passed across the Milky Way. The light-gathering instruments of the Keck II telescope in Hawaii greedily drank in the light from this supernova, tracking its waning brilliance. It was the most remote supernova ever detected. For the second time in 2 years, astronomers had found a supernova in the dark pool of the distant universe. Together, they seem to be telling the same story about our universe: the distant supernovae are both measurably fainter than they should be if the expansion of the universe had been slowing down the way the most favored Big Bang models said that it should.

When all of the possibilities were eliminated for measurement error, only one conclusion remained: the universe is expanding faster today than it was 10 billion years ago when the light from these supernovae first started on their way. It was a backwards answer for a universe that should by now be coasting to an eventual stop under its own gravity. An even more powerful force than gravity had to be at work to steer the destiny of matter. What could it be? The answer was already built into the cosmic equations.

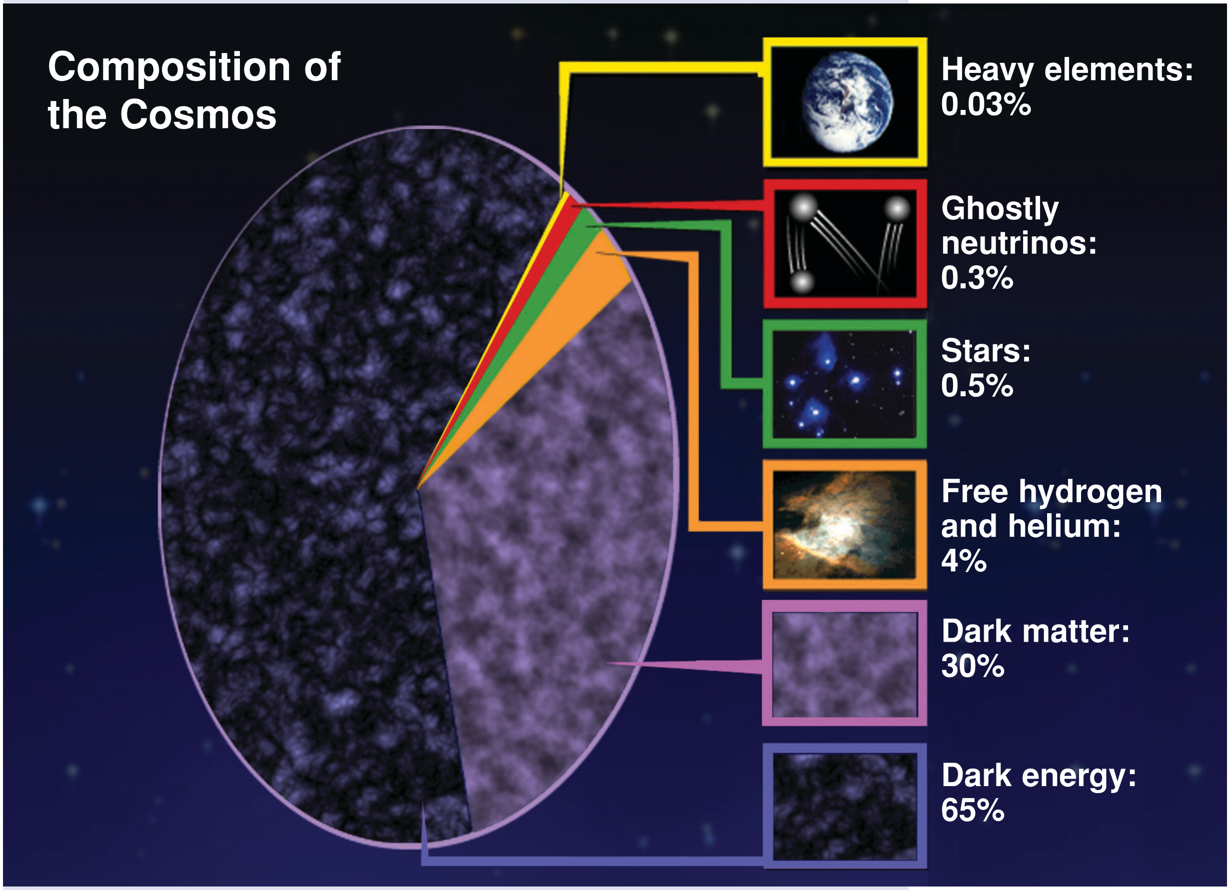
Recent SR&T research in the Long-Term Astrophysics Program (NASA Grant, Lamb, NAG5-7092) has used the Type Ia events to constrain cosmological models and to show that much of the universe is in a "dark" form that drives an accelerated expansion of the universe. Moreover, the favored values of the cosmological parameters are in complete agreement with those determined from investigations of the cosmic microwave background.

Investigations supported by the Space Astrophysics Research and Analysis Program and using BOOMERANG and MAXIPOL instruments have also turned up additional exciting results: the emission is polarized. This discovery is an important confirmation that the CMB radiation was once in intimate contact with a high-temperature plasma dominated by electron-scattering opacity [NASA Grant, Richards, NAG5-4454].



BOOMERANG image of the Cosmic Microwave Background structure.

This force has gone by many names over the last 80 years: cosmological constant (1920s), vacuum energy (1970s), dark energy (1990s). It is the oldest ingredient ever to have been introduced into the equations describing the cosmos—introduced by Einstein himself in 1915. Many studies spanning the last half of the 20th century have tried to nail down its value. Only a range of possibilities that often included zero came up as a statistical answer. By the 1990s, however, this all began to change as new instruments



The vast majority of the universe is in a form of matter and energy that we currently do not understand.

let astronomers probe the properties of still more distant galaxies. Although the accelerated expansion was written into the light from distant supernovae, it was also written into the sound and light from the Big Bang's fireball.

Detailed analysis of the relict fireball light by investigators using data from the COBE satellite in 1991 gave the first convincing evidence that it, currently called "dark energy," was not zero; instead, it was the largest reservoir of energy in the cosmos. In fact, it was large enough to bend the fabric of space so that the universe would continue to expand for all eternity.

Other investigations using sensors aboard the BOOMERANG balloon-borne receiver moved beyond the COBE results and confirmed the imprint of the sound energy within the patina of the ancient fireball light, just as the timbre of a note can tell you whether a

SR&T-supported investigations in the Long-Term Space Astrophysics Program suggest that the further analysis of distant supernova and galaxy number counts will actually be more effective probes of the nature of this mysterious ingredient [NASA Grant, Turner, NAG5-7092].

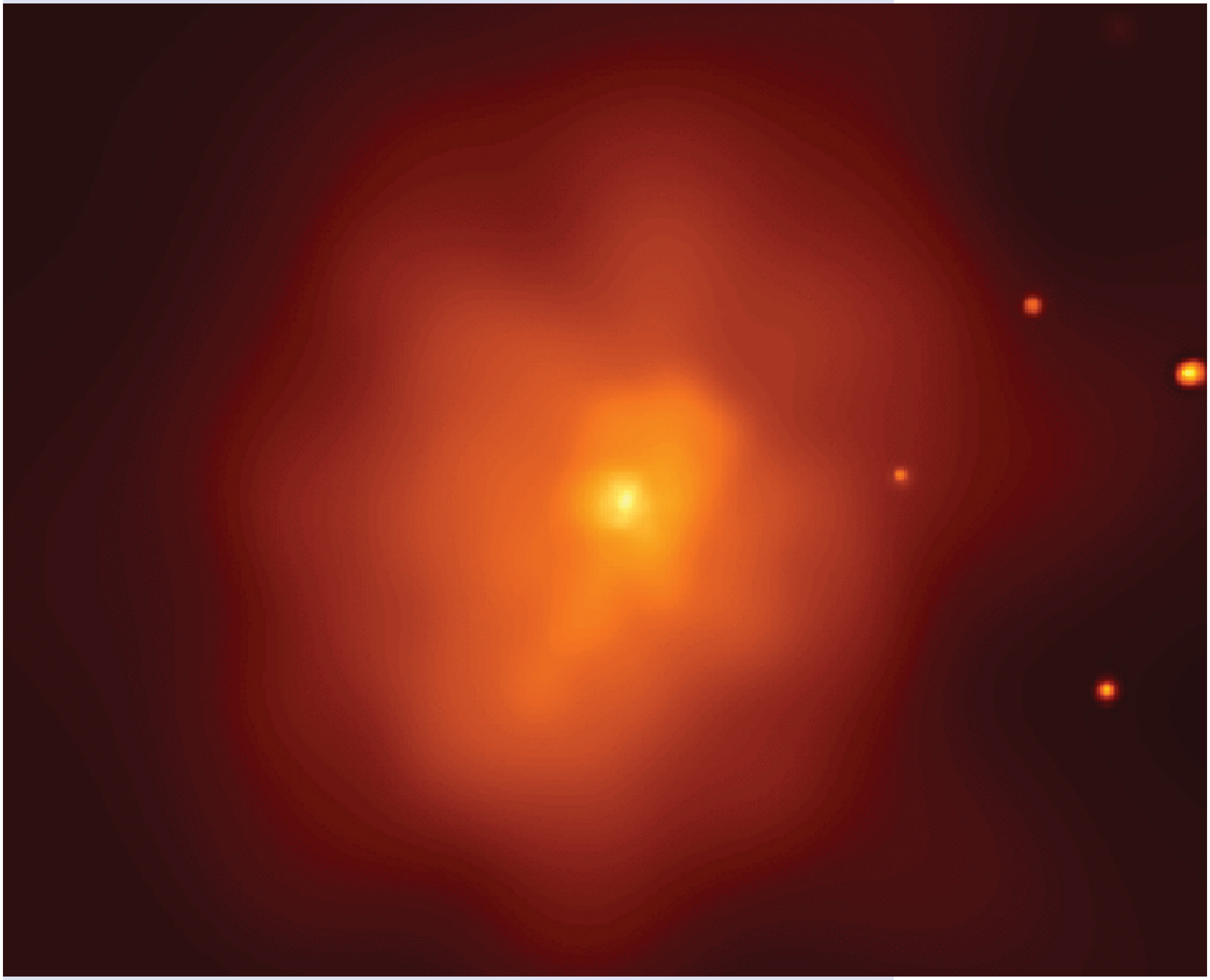
flute or a violin produced it. The timbre of the cosmic sound again pointed toward a lavishly dark cosmos.

We now live in a universe where dark energy is, for the time being, considered an ingredient of cosmic space, although we have little idea what it might be. The good news is that it allows the universe to be much older than original estimates had suggested. So the universe is once again just a little bit older than the oldest known stars. In the coming decades, astronomers expect to perfect their measurements of how strong this mysterious ingredient is and how its strength has changed over the eons. But knowledge of any of its detailed properties seems beyond reach, given the incomprehensibly vast scales it occupies in both time and space. The only hope of studying it at the human scale seems to lie in recreating, via computer models, what the universe ought to look like today for various assumptions about how this hidden vacuum energy works. Some trace of this new field may be dimly seen in the pattern imprinted on the filamentary web work of millions of galaxies sprinkled through space.

Given where the data stand today, after a half century of hard work by thousands of astronomers, there is a good chance that we may not like the picture of the universe that is beginning to take form.

We seem to know what the basic script of the cosmos is for today and for the billions of years to come. If the existence of dark energy continues to be confirmed, the future of the universe will be unimaginably bleak.

The universe seems destined to expand for all eternity to come, with no opportunity for rejuvenation in a future Big Crunch. But the idea of an accelerated cosmos must paint an even more unsettling picture. In only 100 billion years, our Milky Way will find itself alone in an empty cosmos. The expansion, which has been in progress for the last 6 billion years, will propel our galactic neighbors beyond the horizon of the then-visible universe. We will be left utterly alone for the remainder of eternity.

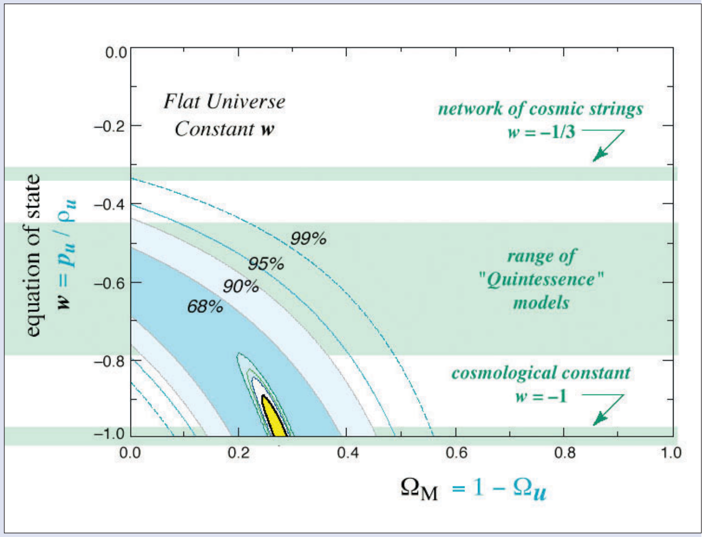


The hot gases within the core of a cluster of galaxies reveal the presence of dark matter.

An equally puzzling partner to the dark energy mystery is the dark matter mystery. For decades, galaxies and clusters of galaxies have come up short in the amount of luminous matter they contain to offset the motions of the matter, which would cause galaxies to fly apart. Something had to be holding these vast systems together, but whatever it was, it did not shed much light for astronomers to see it by. Physicists and astronomers continue to be perplexed by this "dark matter," which cannot be black holes, dim stars, or even ordinary matter as we know it. Yet this unseen matter is nearly 10 times more abundant in the universe than the luminous matter we see in stars and galaxies.

Investigations supported by the Space Astrophysics Research and Analysis Program [NASA Grants, Sellwood, NAG5-10110, NAG5-6037, and NAG5-7015] are looking into the possibility that the need for dark matter, an equally mysterious and thorny issue in galaxy halo studies, may be simply a sign of the breakdown of the Newtonian theory of gravity on galactic scales.

Dark matter and its most elementary properties compared to various models and their predictions



The main reason investigators were confronted with this curious mixture of dark matter and dark energy was that they had started from Einstein's original Theory of General Relativity. The many experiments that had verified this theory of gravity and matter seemed to provide firm ground upon which to stand in exploring distant space. But what if, under cosmological conditions, this theory has become unreliable? There are, after all, many historical examples of a good theory pushed to its breaking point. Even Newton's theory of motion had to be replaced by relativity theory when speeds became too large or gravity became too intense. Could our need for so much darkness in the equations be simply a sign of a failing theory?

Such a prospect would have profound implications. General relativity and Newtonian mechanics would no longer have much in common in the domains of gravity and motion in which they are now in total agreement. Although new theories might not dispel the existence of black holes and the currently successful tests of general relativity, they may tamper with gravitational physics in the domain of the very large and open up new possibilities for still more exotic discoveries in this century and the next.

ACROSS THE GENERATIONS . . .

The pace of discovery during the 20th century has been nothing less than spectacular. At the same time, one can't help but wonder what the new century would have been like had the scientific enterprise not been so ardently supported. Might we still be rooted in 19th-century ideas and dreams of discovery? Our solar system is now our backyard. A more distant universe beckons us to explore it. Were it not for the development of new technologies to push the science frontier forward, questions posed at the dawn of the space age would remain unanswered. We would know very little of the space weather system. Gamma-ray bursts would remain undiscovered. The landscape of Mars and the intriguing ice flows of Europa would still be indistinct smudges in a telescope. There would be no picture books of stars and planets in the making. Instead of this limited prospect, however, we find ourselves at the threshold of a century with reachable goals promising unimaginable opportunities.

The 20th century can be thought of as a time of completion of our understanding of the basic physical ingredients of the cosmos—its underlying fields and organized matter. We now understand how stars form and evolve; how common planets can be formed under even the most impossible circumstances; and how the observable cosmos is only the tip of a much larger, and darker, iceberg. We also understand the events following the Big Bang and the critical steps linking the ancient past with the modern cosmos. In the 21st century, we will move beyond debates over the basics and explore the limits of the biological universe—a journey of discovery only now beginning as we contemplate Mars, Europa, Titan, and distant planetary systems beyond our own. Having fathomed how cosmos and Earth have changed over the eons, we now ask, "What is life?" and "Where else in the cosmos does it dwell?" In a cosmos destined to expand into unending darkness, it would be good to find more company!

The scientific exploration of the cosmos, from the brilliant surface of the Sun to the dark forces that prowl intergalactic space, has been a partnership among generations of investigators. Each generation teaches and inspires the next one to take the stage. The life blood of the SR&T endeavor is the mentoring of hundreds of undergraduate and graduate students; the next generation working side-by-side with current investigators to design sensors, computer models, experiments, and theories. We inspire our children to appreciate the scientific exploration of the universe and to make their own contributions when the time comes for them to replace us.

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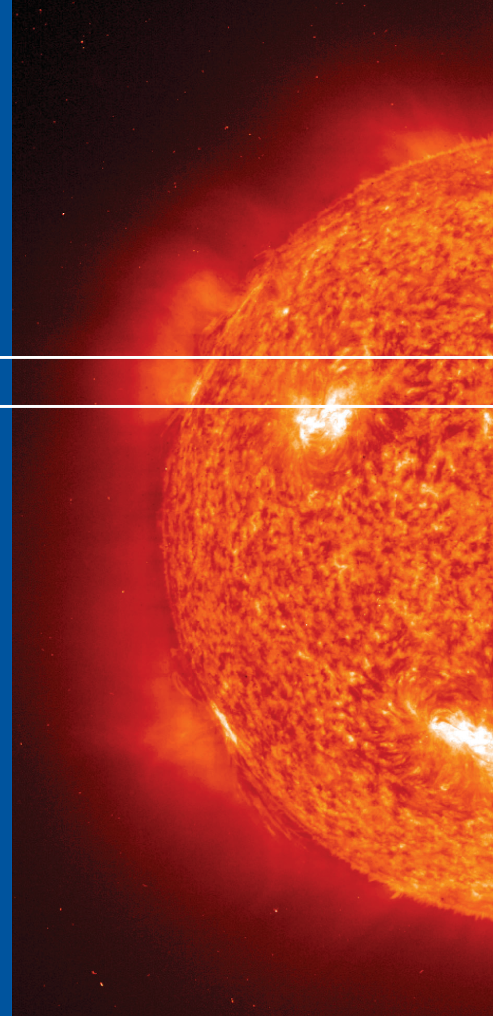

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http://spacescience.nasa.gov/questions/index.htm
http://spacescience.nasa.gov/admin/themes.htm

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