1. Identify dark matter and learn how it shapes galaxies and systems of galaxies

- The first year of operation of NASA's Wilkinson Microwave Anisotropy Probe (WMAP) produced spectacular images of the infant Universe. These images are the most detailed all-sky maps ever obtained of the cosmic microwave background, the afterglow of the Big Bang. Precise measurement of the cosmic microwave background anisotropy enable determination of the density of dark matter in the Universe to better than 10% accuracy.

- Combining data from NASA's Far Ultraviolet Spectroscopic Explorer (FUSE) and Chandra X-ray Observatory, astronomers have found evidence for the existence of a large reservoir of normal matter in our Local Group of galaxies. This matter forms a "warm fog" enveloping the Milky Way and its neighbors. The amount of matter discovered is in good agreement with the amount required to gravitationally bind together the galaxies within the Local Group.

- NASA's Galaxy Evolution Explorer (GALEX), a small Explorer class mission, was successfully launched on Apr 28th 2003. This orbiting telescope will observe a million galaxies in ultraviolet light, across 10 billion years of cosmic history, providing data that will enable scientists to determine how galaxies evolve. Additionally, GALEX will probe the causes of star formation during a period when most of the stars and elements we see today had their origins.

- New evidence from Chandra has challenged an alternative theory of gravity that eliminates the need for dark matter. An observation of the galaxy NGC 720 has shown that it is enveloped in an ellipsoidal cloud of hot gas. The shape and orientation of this hot gas cloud require it to be confined by a dark matter halo, and match the predictions of theories of cold dark matter. The alternative theory, known as MOND (Modified Newtonian Dynamics), cannot explain the results of the Chandra observation. This is the first dynamical evidence that successfully distinguishes dark matter from MOND.

2. Determine the size, shape, age, and energy content of the Universe

- Analysis of data from the WMAP satellite has dramatically improved our knowledge of the scale and content of the Universe. One of the biggest surprises revealed in the data is that the first generation of stars first ignited only 200 million years after the Big Bang, much earlier than many scientists expected. In addition, the new portrait precisely pegs the age of the universe at 13.7 billion years old, with a 1% margin of error, and accurately defines the contents of our universe: 4% ordinary matter, 23% an unknown type of dark matter, and 73% dark energy. The microwave background averages 2.73 degrees above absolute zero, and WMAP resolves temperature variations of only millionths of a degree. Taken overall, the WMAP results represent a milestone in how we view our Universe.

- Researchers used the Hubble Space Telescope (HST) to directly observed faint red young galaxies dating from the conclusion of the cosmological epoch known as the "Dark Ages," a time about a billion years after the Big Bang when the universe was seven times smaller than it is today and newly-formed stars and galaxies were just beginning to become visible. The galaxies, thirty in total, were observed in a small portion of the sky that contains no known nearby bright galaxies; researchers estimate that at least 400 million such objects filled the entire universe at this cosmic epoch. NASA's planned seven meter James Webb Space Telescope is expected to see the entire population of these proto-galactic objects.

- Chandra obtained a snapshot of the adolescent Universe from about 5 billion years ago, when the familiar web-like structure of galaxy chains and voids first emerged. The observation reveals distant and massive galaxies dotting the sky, clustered together under the gravitational attraction of deep, unseen pockets of dark matter. Tracing a patch of sky known as the Lockman Hole, Chandra observed a rich collection of active galaxies seven times denser than those detected in previous optical and radio surveys at similar distances.

3. Discover the sources of gamma-ray bursts and high-energy cosmic rays

- NASA's High Energy Transient Explorer-2 (HETE-2) satellite observed one of the brightest and closest gamma-ray bursts ever seen, in the top one percent of all bursts in terms of intrinsic brightness. At its peak the afterglow may have been fleetingly visible to the naked eye; when measured more than one hour after the burst, it was still as bright as a 12th magnitude star. The burst originated approximately two billion light years from Earth, making it the second closest burst with a known redshift. Hundreds of professional and amateur astronomers contributed follow-up observations of this spectacular event. In the week following the burst, astronomers spotted the telltale signs of a supernova in the afterglow, providing convincing evidence that some gamma-ray bursts are directly linked to massive supernova explosions.

- While observing solar flares, NASA's Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) satellite fortuitously observed an extremely bright gamma-ray burst in the background, over the edge of the sun, revealing for the first time that the gamma rays in such a burst are polarized. The high degree of polarization, about 80%, is consistent with the maximum possible polarization from electrons spiraling around magnetic field lines, indicating that the gamma-ray burst itself is powered by a strong, organized magnetic field.

- Following detection of a gamma-ray burst by HETE-2, the optical afterglow of the burst was detected just minutes later. The afterglow, with a brightness of 15th magnitude, marked the location of the burst in a host galaxy more than 10 billion light years from the Earth. The gamma-ray burst itself lasted approximately 100 seconds, a relatively bright and long-lasting event. In the days and weeks following the detection of the burst, it was observed by about 100 telescopes in 11 countries. Further analysis of data from the burst revealed the continued energizing of the burst afterglow for more than half an hour after the burst. The findings support the collapsar model, where the core of a massive star collapses into a black hole.

- Scientists observed a particularly fast-fading type of "dark" gamma-ray burst with HETE-2. Most bursts have optical afterglows that linger for days or weeks, likely caused by the explosion's shock waves ramming into and heating gas in the interstellar medium. "Dark" bursts are so named because they have had no detectable optical afterglow--until now. Activated by the HETE-2 detection, the ground-based RAPTOR automated telescope operated by Los Alamos National Laboratory in New Mexico observed a rapidly-fading afterglow 65 seconds after the burst. HETE-2's rapid dissemination of the burst's position enabled scientists to obtain their most detailed look yet at the rarest type of gamma-ray bursts.

- In research supported by NASA and the Hungarian National Research Foundation, and using data from NASA's now-defunct Compton Gamma Ray Observatory, astronomers analyzed nearly 2000 gamma-ray bursts and concluded that the two major burst varieties (those longer than, and those shorter than, 2 seconds) show different physical behavior with a high degree of statistical certainty. Long bursts originate from explosions of stars more than 30 times more massive than our Sun, whereas short bursts may be mergers of black holes or neutron stars.

4. Test the general theory of relativity near black holes and in the early Universe, and search for new physical laws using the universe as a laboratory

- Using data from Chandra, scientists have discovered that two supermassive black holes exist together in the nucleus of the same galaxy, an extraordinarily bright galaxy at a distance of 400 million light-years. The black holes currently orbit one another, and will merge within a few hundred million years to create an even larger black hole, a catastrophic event that will unleash intense radiation and gravitational waves. The planned NASA-ESA Laser Interferometer Space Antenna (LISA) will directly detect gravitational waves from such galactic mergers.

- Analysis of data from 11 X-ray pulsars observed by NASA's Rossi X-ray Timing Explorer (RXTE) has revealed an apparent limit to the speed at which pulsars can spin. This limit, 760 revolutions per second, is

far below the theoretical breakup speed. As a neutron star spins up, gaining angular momentum from its binary companion star, it may achieve an equilibrium rotation rate where the angular momentum gained is shed by the emission of gravitational radiation.

- Observations of the supermassive black hole at the center of our Milky Way Galaxy using Chandra have revealed that the black hole is prone to outbursts. In a set of observations spanning a two-week period the black hole displayed several X-ray flares. The rapidity of these flares indicates that they occur near the black hole's event horizon; the relative weakness of the emission suggests that the black hole, 3 million times the mass of the sun, is relatively "starved," perhaps indicating that explosive events of the past blew away much of the available gas from its immediate neighborhood.

- Using data from RXTE, researchers have identified the most powerfully magnetic object known in the Universe, a soft gamma-ray repeater, one of ten unusual neutron stars classified as magnetars. The magnetic field strength is about a thousand trillion times more powerful than the Earth's.

5. Reveal the nature of cosmic jets and relativistic flows

- For the first time, astronomers have tracked the life cycle of X-ray jets from a black hole. A series of images from Chandra has revealed that the jets traveled at near light speed for several years before slowing down and fading. Astronomers have used Chandra and radio telescopes to observe two opposing jets of high-energy particles emitted after an outburst from a Galactic double-star system first detected by RXTE in 1998. At that time the X-ray jets were moving at approximately half the speed of light; four years later, the jets were more than three light years apart, decelerating, and fading. These observations mark the first time that an X-ray satellite has caught such jets in the act of slowing down.

- Chandra discovered lobes of unexpectedly hot gas speeding away from a black hole in our Galaxy. The high temperature (50 million degrees) and the distance of the lobes from the black hole (0.25 light years) indicate that violent collisions are occurring between clumps of gas expelled from the vicinity of the black hole. Scientists had previously predicted that no hot gas would be found further than a few million km from the black hole.

- Farther afield, images made by Chandra have revealed the mechanisms by which supermassive black holes control the growth of massive galaxies in the distant universe. X-rays were detected from vast clouds of high-energy particles around two galaxies, respectively 10 and 12 billion light years from Earth. The energetic particles were left over from past explosive events that can be traced through the X-ray and radio jets back to the supermassive black holes in the centers of these galaxies. In each case, the galaxy is undergoing an energetic phase in which the giant black hole transfers energy to the surrounding gas. The galaxy and its black hole will continue to grow until the energy generated by jets near the black hole stops the fall of matter into the black hole. When jet activity subsides, matter will resume falling into the black hole, beginning the cycle anew.

- Using data from Chandra and ESA's XMM-Newton satellite, astronomers have found evidence of winds with speeds of 40% the speed of light, blowing away copious amounts of gas from the cores of two quasar galaxies believed to be powered by black holes. These winds may also regulate black hole growth and spur the creation of new stars.

6. Observe the formation of galaxies and determine the role of gravity in this process.

- WMAP detected a large scale polarization signal in the microwave background. This distinctive signal implies that the first generation of stars formed only 200 million years after the big bang. Since the most distant known galaxies are seen 1 billion years after the big bang, this detection implies the existence of an as-yet unknown class of galaxies and quasars.

- With HST's Advanced Camera for Surveys (ACS), astronomers can now see back to the epoch when stars in young galaxies began to shine in significant numbers, concluding the cosmic "Dark Ages" about 12 billion years ago. The ACS is revealing numerous faint objects that may be young star-forming galaxies seen when the universe was seven times smaller than it is today and less than a billion years old.

- Images made by Chandra have revealed two distant cosmic construction sites buzzing with activity. X-rays were detected from vast clouds of high-energy particles around the galaxies 3C294 and 4C41.17, which are 10 and 12 billion light years from Earth, respectively. The energetic particles were left over from past explosive events that can be traced through the X-ray and radio jets back to the super massive black holes located in the centers of the galaxies. We may be observing indications of a grand cosmic cycle in which black holes are fuelled by infalling gas, activity increases so that gas accretion in this environment is inhibited, halting the activity. Then the cycle is renewed as gas falls in.

- Astronomers used the newly released, NASA-funded Two Micron All Sky Survey (2MASS) and Sloan Digital Sky Survey (SDSS) to take a census of the number of galaxies in our local universe. This census contains information about the stellar mass and stellar composition that will yield new insights into galaxy formation.

- 2MASS has offered the first all sky view of the tidal tail of a satellite dwarf galaxy that is currently being torn apart by the gravitational field of the Milky Way. These tidal tail stars will be targets for the upcoming Space Interferometry Mission (SIM), which will use them stars to trace the distribution of dark matter in our Galaxy.

- Using the deepest visible-light images ever taken in space, astronomers using NASA's Hubble Space Telescope (HST) have reliably measured the age of the spherical halo of stars surrounding our neighboring galaxy, Andromeda. To their surprise, they discovered that about a third of the stars in Andromeda's halo formed only 6 to 8 billion years ago, differing greatly from the 11-to-13 billion year age of the stars in the Milky Way's halo. Also, these young stars in Andromeda are unusually rich in heavy elements. Although a near twin to our Milky Way in many respects, the Andromeda galaxy clearly has a slightly different upbringing, perhaps due to a merger with another large galaxy, or a series of mergers with smaller galaxies, billions of years ago.

7. Establish how the evolution of a galaxy and the life cycle of stars influence the chemical composition of material available for making stars, planets, and living organisms.

- HST observations of light echoing off dust generated in the explosion of an aging star, first identified from observations by amateurs, have uncovered remarkable new features. These details promise to provide astronomers with a CAT-scan-like probe of the three-dimensional structure of shells of dust surrounding the star. The star grew enormously in size, with its surface temperature dropping to temperatures not much hotter than a light bulb. This behavior is very unusual and completely unlike ordinary nova explosions. It is not predicted by present theories of nova outbursts and may represent a rare combination of never-before seen stellar properties.

- Observations by FUSE suggest that our Galaxy is surrounded by a very large, hot Galactic corona. This structure was discovered by the presence of high-velocity ionized gas inferred in over a hundred lines of sight out of the Galaxy. The Galactic corona may contain the fuel for future star formation in the Milky Way.

- FUSE observations show that the abundance of deuterium relative to hydrogen is nearly uniform within about 300 light years of the Sun. Beyond this distance, however, the ratio deviates significantly from the local value, suggesting that processes still poorly understood are controlling this key diagnostic of galactic chemical evolution. Deuterium is a fossil nucleus left over from the Big Bang, and its destruction inside stars makes it a unique tool for probing galactic chemical history.

8. Observe the formation of planetary systems and characterize their properties.

- Theoretical studies yielded new insights into planetary migration. During the early stages of a planetary system, planetary disks exert a dynamical drag on the newly formed planets that alters their orbits. This theoretical work may explain many of the properties of the recently discovered extrasolar planets.

- Using the NASA-funded Keck-Keck interferometer, astronomers may have made the first detection of a planet in formation.

- Data from Chandra have enabled a new approach to determine if a young star is surrounded by a planet-forming disk like our early Sun. These results suggest that disks around young stars can evolve rapidly to form planets, or they can be disrupted by close encounters with other stars. Chandra observed two young star systems in a loose cluster of 10 million-year-old stars. Observations at infrared and other wavelengths have shown that several stars in these systems are surrounded by disks of dust and gas. At a distance of about 180 light years from Earth, these systems are among the nearest analogs to the early solar nebula from which Earth formed.

- The delay of the launch of the long-anticipated Space Infrared Telescope Facility (SIRTF) has slowed the rate of progress in this area. SIRTF should be able to observe many young stars and characterize their properties.

9. Use the exotic space environments within our Solar System as natural science laboratories and cross the outer boundary of the Solar System to explore the nearby environment of our galaxy

- Voyager-1 entered the region of the heliosphere's innermost boundary—the termination shock—at a distance about 100 times further away from the Earth than the Sun. Highly enhanced fluxes of energetic particles suggest the possibility that Voyager may have crossed the termination shock and become the first man-made object to travel beyond it, a historic milestone in space exploration. Although the data are still being examined and interpreted and it is not certain that Voyager has actually crossed this boundary, it is clear that for the first time a spacecraft is at the frontier of the region of space dominated by the Sun. The heliosphere is much larger than predicted when Voyager started its journey toward this frontier, and it is filled with galactic gas that penetrates into the solar system and becomes picked up by the solar wind. These direct observations will also shed light on "astrospheres" that we can image around stars in other parts of our Galaxy.

10. Discover planetary systems of other stars and their physical characteristics.

- HST's crisp view has allowed an international team of astronomers to make the first astrometric measurement of the mass of a planet outside our Solar System. These results place the mass of the planet at 1.89 to 2.4 times the mass of Jupiter. It is only the second extrasolar planet for which a precise mass has been determined. NASA's planned Space Interferometry Mission (SIM) will use astrometry to measure the mass of smaller, Earth-like extrasolar planets.

- For the first time, astronomers using HST have observed the atmosphere of an extrasolar planet evaporating into space. Much of the planet may eventually disappear, leaving only a dense core. This scorched planet orbits only 7 million kilometers from its yellow, Sun-like star. The observations reveal a hot and puffed up evaporating hydrogen atmosphere surrounding the planet. This huge envelope of hydrogen resembles a comet with a tail trailing behind the planet. The planet circles the parent star in a tight, 3.5-day orbit, and is too close to the star for HST to photograph it directly. But astronomers could observe the planet indirectly since it blocks light from the star during transits across the disk of the star, thereby dimming it slightly. Light passing through the atmosphere around the planet is scattered and acquires a spectroscopic signature from the atmosphere. Astronomers used the HST's Space Telescope Imaging Spectrograph (STIS) to measure how much of the planet's atmosphere filters light from the star. They saw a startling drop in the star's hydrogen emission, and a huge, puffed-up atmosphere can best explain this result.

- Astronomers confirmed the presence of a planet in the metal-poor, dense stellar environment of a globular cluster. This planet probably formed 13 billion years ago in a Jupiter-like orbit, at a time when our Galaxy was still being assembled. Formed at a time when there were many fewer rocky solids available for building planets, this discovery suggests that the formation process must be very robust and that planet formation has been taking place for a very long time in our Galaxy.

- A spate of new extrasolar giant planet discoveries confirms the ubiquity and orbital diversity of such objects around solar-type stars. Recent dynamical modeling sponsored by NASA's Origins R&A program suggests that migration of such objects from larger to smaller orbital distances is the most likely mechanism for the observed orbital distribution, with important implications for the occurrence and stability of terrestrial planets around such stars.

11. Search for worlds that could or do harbor life.

- Accurate measurements of radial velocities of nearby stars by the NASA-funded Keck telescope have led to the discovery of Jupiter-like planets around nearby stars. For the first time, the observations have a long enough time baseline to be able to detect planets in orbits like Jupiter's. The nearest known solar system analog is 55 Cancri, a stellar system only 41 light-years away from the Sun. This is important for the evolution of life on Earth, because over the age of the solar system the presence of Jupiter reduces the rate of life-threatening collisions of comets with the Earth.

- New dynamical models of the final stages of terrestrial planet formation show that this is a chance process involving the assembly of a relatively small number of Mercury-sized bodies. In consequence, the abundance of volatiles and organics acquired by each of the terrestrial planets may vary significantly from one to another, and from one planetary system to another. This would lead us to expect extreme diversity among terrestrial planets around other stars.

12. Inventory and characterize the remnants of the original material from which the Solar System formed

- HST has measured the diameter of the largest object discovered in the solar system since the discovery of Pluto 72 years ago. Approximately half the size of Pluto, the icy world 2002 LM60, dubbed "Quaoar" (pronounced *kwa-whar*) by its discoverers, is greater in volume than all the asteroids combined (although probably only one-third the mass of the asteroid belt, because it is icy rather than rocky). The NASA-funded Near Earth Asteroid Tracking project discovered Quaoar. This finding yields important new insights into the origin and dynamics of the planets, and the mysterious population of bodies dwelling in the solar system's final frontier: the elusive, icy Kuiper belt beyond Neptune.

- New measurements sponsored by NASA's Cosmochemistry Research and Analysis (R&A) program have shown for the first time that individual silicate grains in interplanetary dust particles have variable oxygen isotopic composition, confirming that they could not have formed during the condensation of the Solar Nebula, but must have pre-existed it. Although previous studies of primitive meteorites found pre-solar grains in rare refractory phases (*i.e.*, materials formed at extremely high temperatures), they had not been found in the much more abundant silicates. Thus, it now appears that the least altered samples of pre-solar grains are to be found in cosmic dust, not in meteorites.

13. Learn why the planets in our Solar System are so different from each other.

- A series of laboratory experiments sponsored by NASA's Planetary Geology and Geophysics R&A program has demonstrated that isolated pockets of melted material can be reorganized dramatically by deformation-driven melt processes. This creates ways for iron-rich melts to flow from the mantles to the cores of terrestrial planets as part of the core formation process that occurs early in the planet's life.

- A new, detailed model of the formation of the moons of planets in our Solar System postulates a 2-component circumplanetary accretion disk: a dense inner disk in which the large inner satellites formed quickly, and a sparse outer disk in which outer satellites may have formed by slow accumulation of material that drifted inward owing to gas drag. This difference can explain otherwise puzzling differences in interior structure and composition between, for example, Jupiter's moons Callisto and Ganymede. The diversity among natural satellites in our Solar System is a small-scale reflection of the diversity seen among the planets themselves.

- Data from a recent stellar occultation by Pluto have been fully analyzed to reveal that the Solar System's most distant planet is experiencing an increase rather than a decrease in atmospheric density as the planet retreats from the Sun along its elliptical orbit. This surprising result emphasizes the importance of the distribution of ice on Pluto and the ice's detailed properties as a determinant of the planet's climate.

- Recent Earth-based radar observations of Titan sponsored by NASA's Planetary Geology and Geophysics R&A program show that the satellite has longitudinal variations in surface roughness that correlate with infrared brightness differences measured by telescopes. The variability in radar properties across Titan supports the suggestion of large-scale differences between smooth regions (possibly liquid lakes or oceans) and rougher solid surfaces.

- Recent theoretical work sponsored by NASA's Origins R&A program has shown that the Solar System may have formed in a region of high-mass star formation, where intense extreme ultraviolet radiation evaporated the gaseous envelopes of the outermost giant planets, reducing them to mostly ice and rock cores (Uranus and Neptune, and Saturn to a lesser degree), while leaving Jupiter and the terrestrial planets intact. This provides an alternative mechanism for the formation of ice-giant versus gas-giant planets in our Solar System.

14. Learn how the Solar System evolves.

- Precise tracking of the Mars Global Surveyor (MGS) orbit combined with Mars Pathfinder data reveals a tidal bulge that implies that the Martian core is currently at least partially molten. This constrains the internal thermal and compositional evolution of Mars to a much greater extent than was previously possible.

- The known number of small bodies in the solar system, including irregular satellites of the giant planets and Kuiper Belt objects, continues to increase based on ground-based observations. One of the most puzzling problems about the Kuiper belt is how it lost most of its mass. Models of the growth of the large objects in the Kuiper belt show that there must have been at least tens of Earth-masses of material at the outset, but much less than one Earth-mass remains today. A new model has been developed to solve this problem: some of the bodies in the original, massive Kuiper belt were temporarily captured in an unstable resonance with Neptune, and eventually most were ejected from the Solar System. As Neptune's orbit migrated outward, the location of this resonance also migrated outward through the Kuiper belt and progressively cleared objects ahead of it. This new hypothesis correctly predicts many of the observed characteristics of the Kuiper belt.

- Object 1459 Magnya is a basaltic asteroid, but it is located in the outer part of the main asteroid belt, far from the only other known basaltic asteroids, 4 Vesta and its family of impact fragments ("Vestoids"). Recent observations with NASA's Infrared Telescope Facility (IRTF) at Mauna Kea Observatory reveal that while Magnya's composition is similar to Vesta's in its broad features, it is significantly different in detail. This result leads to two conclusions. First, it confirms that Magnya is not a fragment of Vesta, but of some other parent body that underwent melting and differentiation, similar to Vesta, before it was disrupted by a collision. Second, none of the meteorite samples in our collections are mineralogically similar to Magnya. The work emphasizes the extent to which asteroids have been melted, as well as the incompleteness of known meteorites as samples of original planet-forming material.

- A spate of new extrasolar giant planet discoveries confirms the ubiquity and orbital diversity of such objects around solar-type stars. Recent dynamical modeling sponsored by NASA's Origins R&A program suggests that migration of such objects from larger to smaller orbital distances is the most likely mechanism for the observed orbital distribution, with important implications for the occurrence and stability of terrestrial planets around such stars.

- New mapping of Europa from Galileo images shows that the style of geologic features has changed qualitatively over geologic time, suggesting long-term evolution of the satellite's ice shell.

15. Investigate the origin and early evolution of life on Earth, and explore the limits of life in terrestrial environments that might provide analogues for conditions on other worlds.

- NASA-sponsored astrobiology research has discovered a hypersaline environment in Lake Vida, Antarctica, which has a perennial ice cover 19-m thick, the thickest lake ice-cover recorded. The underlying brine is 7 times saltier than seawater and hosts a microbial community that includes photosynthetic organisms. This habitat represents an extreme of ice-covered lakes on Earth and can serve as a terrestrial analog for Europa or potential brine environments on Mars. Study of Lake Vida has extended the number of "habitable zones" on Earth and our understanding of where life might flourish elsewhere.

- It is now generally accepted that meteorite-size fragments of rock can be ejected from planetary bodies, with transfer of material from Mars to Earth and even vice-versa. A new modeling study examined the probability that meteorites ejected from our solar system by Jupiter and Saturn might be captured by a distant star and fall on a terrestrial planet there. The overall conclusion is that it is very unlikely that even a single meteorite originating on Earth or Mars has fallen on a terrestrial planet in another stellar system, over the entire history of our solar system. This answers one part of the question of whether planetary systems are biologically isolated from one another—other systems have not inherited Earth life. The implication for planning for NASA's planned Terrestrial Planet Finder (TPF) is that it is essential that we consider independently evolved, possibly quite different, biochemistries in modeling spectral signatures of habitable worlds.

16. Determine the general principles governing the organization of matter into living systems and the conditions required for the emergence and maintenance of life.

- In the past year, NASA's Astrobiology R&A program has sponsored significant progress in developing experimental models of life-like systems based solely on RNA, motivated by the hypothesis that RNA preceded DNA as the repository of the cellular genetic code. By evolving molecules in the test tube, an RNA molecule has been found that can catalyze the formation of a copy of itself from two smaller molecules, thus approaching the goal of true autocatalytic self-replication.

- An even simpler catalytic RNA molecule was made from just two types of nucleic acid bases, instead of the four that modern organisms use. These results, supported by NASA Astrobiology R&A, indicate that RNA could have been present in early life forms before the full complement of modern biopolymers was available. Moreover, by removing the constraint that planetary conditions for the origin of life must be conducive to the formation of the current four nucleic acid bases, this discovery increases the likelihood of life existing elsewhere.

- Recent NASA-funded astrobiology experiments challenge the commonly accepted hypothesis that life began in a marine environment. Two fundamental processes relevant to the origin of life — the self-assembly of primitive cell membranes and the non-biological synthesis of RNA polymers — were shown to be adversely affected by sea salts, even at concentrations that are much lower than that in today's oceans. The challenge now is to discovery suites of organic compounds that can undergo self-assembly in the presence of sea salts. The alternative is that life began in lake environments requiring land platforms—protocontinents or Hawaiian-type basaltic islands—and later spread to marine environments.

17. <u>Chart the distribution of life-sustaining environments within our Solar System, and search for evidence of past and present life.</u>

- Data from the MGS and Mars Odyssey spacecraft show multiple lines of evidence for the presence on Mars of a succession of meters-thick, latitude-dependent surface deposits that are young, that were ice-rich when formed, and whose deposition and removal is driven by rotational-axis-tilt-induced climate change over the last 5 million years. The diverse observations span a large range of scales (meters to hundreds of kilometers) and are remarkably consistent with models of current and past ground-ice stability.

- Analysis of MGS images and Odyssey data suggests that the young gullies observed on Martian crater walls may be caused by the melting of a remnant snow pack deposited during a time when Mars' rotational axis was more tilted — a surprising source of water at mid-latitudes.

- Recent analyses of MGS topography data reveal an enclosed drainage basin within the Martian highlands whose ancient catastrophic discharge led to the formation of a previously identified fluvial feature and flooding of a crater. This is the first time the sequence of flooding and drainage of a highland basin has been ascertained.

- Based on analyses of MGS data, valleys over a wide area of Arabia Terra on Mars appear almost as complex as terrestrial drainage networks. This suggests that portions of Mars not only had substantial running water early in the planet's history but perhaps even precipitation.

<u>18. Identify plausible signatures of life on other worlds.</u>

- NASA's Astrobiology R&A program has sponsored significant progress in the development of non-invasive, non-destructive techniques for detecting signs of life *within* rocks and rock cores. Using computer tomography with X-rays and neutrons, researchers are progressing toward imaging current and past mineralized microbial communities within rocks. The method shows great promise for sample selection during future planetary exploration.

- NASA's Astrobiology R&A-sponsored studies of the ways that microbes utilize the toxic heavy metal arsenic to generate energy have furthered our understanding of how arsenic is recycled in the environment, and how it moves between the solid and liquid phases. Furthermore, on potentially habitable planetary bodies that are rich in sulfur compounds, such as Mars and Europa, arsenic could play a significant role in supporting an ecosystem and might offer an additional suite of compounds to serve as "biosignatures" that would indicate the presence of extraterrestrial life.

- A new technique for detecting chirality (right- versus left-handedness) in organic molecules that weighs less and needs less power than current approaches has been demonstrated in NASA's Astobiology R&A program for potential use in organic-rich environments such as Titan.

- The spectrum of our own Earth, measured by observing the "Earthshine" reflected from the Moon, has been analyzed in detail. The spectrum provides information on the appearance of biomarkers and the variability in brightness and color of the only habitable planet now known. Extension to the infrared is underway and will inform the development of TPF.

- The use of sulfur as an atmospheric indicator of life on an extrasolar terrestrial planet has become a topic of study based on NASA astrobiology-sponsored work on extremophiles on Earth. Hypersaline microbial mats are sediment-layered ecosystems that are able to generate large volumes of sulfur-containing gases, dimethyl sulphides and methanethiol. The excess production of these volatile sulfur-compounds appears in the overlying atmosphere, so they can be considered as signatures of this ecosystem. Significantly, because microbial mats are thought to have dominated much of Earth's history, atmospheric sulfur compounds could be useful biosignatures for detecting the presence of life remotely.

19. Understand the origins of long- and short-term variability

- A new, controversial view of supergranulation as a wave phenomenon was motivated by SOHO observations of motions below the solar surface. Supergranules are immense convective cells, up to ten times the size of the Earth, that blanket the entire surface of the Sun. Each cell lives for several days. It has long been a mystery why individual supergranules, tracked as they move across the solar surface, appear to rotate faster than the surrounding material. Helioseismologists used waves that penetrate the outer layers of the Sun to infer that the pattern of supergranules rotates at the rate of the surrounding plasma, even though individual cells move faster (analogous to fans doing "the wave" in a football stadium).

- SOHO obtained the first spectroscopic evidence of post-flare line-of-sight oscillations in the corona, complementing earlier and ongoing SOHO imaging of oscillating coronal loops. The decay rates of these oscillations imply surprisingly high energy-dissipation rates, possibly altering our understanding of the coronal heating process--the most important source of solar extreme ultraviolet radiation on timescales longer than flares, and hence a significant driver of variability in the Earth's ionosphere and upper atmosphere.

- The VAULT sounding rocket obtained the highest resolution extreme ultraviolet images of the Sun obtained to date, revealing fine structure (less than 100 km across) throughout a wide range of dynamic magnetic features, from tiny loops in the supergranulation network to 100,000-km prominences. This shrinks the upper limit for the size of the basic magnetic "building blocks" of the solar chromosphere.

- The first images of gamma rays from solar flares demonstrated the value of the RHESSI mission soon after launch. These high energy "snapshots" revealed that flare-accelerated high-energy electrons and ions are located in separate areas of the flaring region, implying significant differences in the way they are accelerated or the ambient conditions through which they propagate, or both. In addition, the first spatially resolved images of a flare in gamma-ray emission lines revealed that the gamma rays emanate neither from the same location nor at the same time as other flare emissions.

20. Understand the effects of solar variability on the solar atmosphere and heliosphere

- Coordinated observations by the ESA Ulysses and NASA Advanced Composition Explorer (ACE) spacecraft have measured the composition and structure of the solar wind at solar maximum at various different heliographic latitudes for the first time. These observations provide strong support for the concept of a two-component solar wind, and confirm the poorly-understood differences in elemental composition between the faster wind originating in coronal holes and the slower and more variable wind originating in active regions.

- Unprecedented opportunities for simultaneous solar and heliospheric data (obtained from the SOHO, Ulysses, ACE, and Wind spacecraft), combined with sophisticated modeling efforts, has yielded both greater understanding and lively controversy about the solar footprints of magnetic fields in the heliosphere. We are finally able to tackle long-standing fundamental questions about how the evolving solar magnetic field extends into the Solar System and interacts with the existing field there.

- For the first time, SOHO detected signatures of highly ionized iron in the solar corona consistent with the passage of a bubble of hot ionized material that is part of a coronal mass ejection. These spectroscopic observations, together with SOHO coronagraph images of density concentrations during CMEs, provide new challenges to current theories of where and how CMEs are triggered and evolve.

- A three-spacecraft collaboration among RHESSI, SOHO, and NASA's Transition Region and Coronal Explorer (TRACE) recorded the entire initiation process of a high-speed solar eruption, for the first time, providing crucial clues about how, why, and where these drivers of "stormy space weather" occur. The dominant scenario for these eruptions, in which both flares and coronal mass ejections result from energy buildup in the low corona through magnetic confinement followed by sudden release through magnetic

reconnection, was confirmed. In addition, these observations strengthen the growing body of evidence that flares do not cause the mass ejections or vice versa.

21. <u>Understand the space environment of Earth and other planets</u>

- Data from two satellites (NASA's IMAGE and ESA's Cluster) have demonstrated, surprisingly, that the energy transfer from the solar wind to the Earth's magnetosphere is continuous under certain conditions. The physical mechanism responsible for the energy transmission, magnetic reconnection, is fairly well known. Reconnection has been observed in the laboratory and on the Sun. However, all previous observations and most theories of reconnection show that the process is explosive in nature. The new data from IMAGE and Cluster show that when the magnetic field in the solar wind aligns with the Earth's northward-pointing field, exactly the opposite happens: the energy transfer is continuous rather than bursty. An analogy would be finding that, under certain electric-storm conditions, currents flow in steady streams rather than in sporadic lightning bolts. The small fraction of solar wind energy that leaks past the Earth's magnetospheric shield is enough not only to generate spectacular aurorae but sometimes also to disable satellite communications and electricity grids. In order to mitigate effects on the human environment, this research result is a step in understanding how this energy transfer works.

- Since the 19th century, measurements of the Earth's magnetic field have revealed a wide variety of characteristic oscillations, like the low throbbing of immense bells. To explain these quasi-periodic fluctuations, researchers have tried, with only partial success, to determine all of the natural resonant frequencies of the Earth's magnetosphere. The reason for their limited success is now clear. Using data from our extensive fleet of near-Earth research satellites, NASA scientists have shown that some of the commonly observed pulsations in the Earth's magnetic field are directly driven by regular fluctuations in the solar wind. So the Earth's magnetosphere doesn't ring like a bell, it reverberates like a beaten drum.

- The solar energy deposited into Earth's upper atmosphere must be balanced by the energy radiated back into space, or the atmosphere would become very hot. Sometimes the energy input increases, either because of a solar flare or because of the arrival of a solar disturbance that causes a magnetic storm. Such disturbances dump much more energy into the upper atmosphere than normal. During April 2002, comprehensive energy measurements of a major magnetic storm made by the TIMED satellite revealed the key processes by which increased atmospheric radiation balances the additional inflow of solar energy to the upper atmosphere. Huge increases in radiation from a minor gas species, nitric oxide, were found to be the principal process for cooling the upper atmosphere back to normal temperatures.

- The source of intense fluxes of solar energetic particles is not what scientists expected. Shocks in interplanetary space accelerate particles, and the shocks are often caused by coronal mass ejections. Coronal mass ejections frequently interact with each other, especially near the maximum of the solar cycle when solar energetic particles are most common. Scientists had hypothesized that the strong shocks that develop when coronal mass ejections interact could play an important role in the acceleration of solar energetic particles. However, observations from the WIND satellite refuted this hypothesis.

22. <u>Understand forces and processes, including impacts, that affect the habitability of Earth</u>

- Between July 1, 2002, and June 30, 2003, 68 Near Earth Objects (NEOs) with diameters larger than 1 kilometer were discovered and catalogued. Almost all of these discoveries resulted from search efforts supported by NASA's Near Earth Object Observations Program. The total number of these objects is estimated to lie somewhere between 1000 and 1100, of which 655 have been discovered and catalogued to date. We are on schedule to achieve our metric of cataloging 90 percent of NEOs with diameters greater than 1 kilometer by the end of calendar year 2008.

- A NASA-chartered science definition team chartered to analyze the benefit versus cost of searching for Near Earth Objects (NEOs) smaller than 1 kilometer in size assessed the risk associated with an impact of one of

these objects as less than 25% of the risk posed by NEOs larger than one kilometer in size. The risk posed by a comet impact was estimated to be only about 1% of the risk from all asteroid impacts.

- The structural properties of an asteroid can be inferred from fundamental physical characteristics such as its size and mass. Various technical advances have dramatically increased the number of asteroids for which these characteristics have been determined. For example, the availability of adaptive optics on ground-based telescopes has made it possible to detect a significant number of binary asteroids whose masses can be determined from their mutual orbital periods. Recently, the number of asteroids with measured physical characteristics has grown large enough to allow statistically valid conclusions to be drawn about the general population of asteroids. Asteroids appear to fall into three broad structural categories: "coherent objects" that are essentially solid, "highly fractured" objects that have porosities (empty pockets) of 15-25%, and "rubble piles" that have porosities greater than 30%. A study conducted during the past year found that the vast majority of asteroids are either highly fractured or rubble piles. The structural properties of asteroids can be used to model the effects of potential impacts on Earth.

23. <u>Develop the capability to predict space weather</u>

- Surprisingly, the Northern and Southern Lights (aurorae) are not symmetric. NASA scientists have used an instrument on the Polar spacecraft to simultaneously image both the northern and southern auroral regions. The aurorae in both hemispheres dramatically intensify two or three times a night. During several of these explosive events, called substorms, a significant delay between the onsets in the two hemispheres was found. Our current understanding of auroral processes cannot account for these differences. Some NASA investigators believe a major cause of the difference is related to the effects of different levels of solar illumination in the two hemispheres.

- Communications blackouts can be caused by the aurora at high latitudes and by ionospheric plasma bubbles near the Earth's equator. Observers from equatorial observatories in Peru have investigated plasma bubbles for some time. However, observations from over the oceans and Africa have been sparse. NASA's TIMED spacecraft is now providing a high-resolution global view of these events. These data will make it possible to see what, if any, relationship there is between solar events (i.e. space weather) and equatorial communications blackouts.

- Until this year there has been no good way to predict the intensity of gradual solar energetic particle events. For the first time, NASA researchers have put together a complete approach that includes a coronal mass ejection-driven shock, a consistent model of particle acceleration, and a detailed mechanism for transporting the escaped particles through the interplanetary medium to Earth. The new method provides the first credible predictions for intensity profiles, particle distributions and anisotropies, and time-dependent spectra of such events throughout the heliosphere.

- Why does the Sun shine brighter when it is covered with dark sunspots? The answer is that subtle bright features more than make up for the deficit. The bright regions appear where the magnetic field isn't quite as strong as in sunspots and they are especially bright when we see them from the side, as the Sun's rotation carries them to the edge of the solar disc. Exactly what makes them so bright is not well understood, but we now have some important new information. NASA-supported researchers, using the new high-resolution Swedish Solar Telescope, have determined the three-dimensional texture of the solar surface. They found that the convective structures that cover the entire surface are raised up and have brighter walls in magnetic regions. The bright structures are about 300 km high. Raising the hot material above the surrounding surface enhances emission, particularly when seen from the side. This goes a long way toward explaining why the Sun is brighter when there is more solar magnetic activity. Learning how solar irradiance varies with the solar cycle is an important factor in understanding climate variations on Earth.

24. Find extraterrestrial resources and assess the suitability of Solar System locales for future human exploration

- Mars Odyssey results show that the upper meter of the northern plains and some equatorial areas are dominated by ice, complementing the southern hemisphere discoveries of last year.

- MGS has inventoried the gully systems it previously discovered, revealing a population of such landforms that were formed in the more distant past and subsequently buried, only to have been "unburied" more recently. These "fossil landscapes" indicate that overland flow of liquid water has been a significant process for more of martian history than previously thought, raising the possibility that habitable zones have existed on Mars throughout its history.

- Mars Odyssey results show that the upper meter of the northern plains and some equatorial areas are dominated by ice, complementing the southern hemisphere ice discoveries of last year and opening the possibility that significant resources exist in the smooth plains of the astrobiologically interesting northern hemisphere.