2020 VISION

An Overview of *New Worlds, New Horizons in Astronomy and Astrophysics*

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An Overview of *New Worlds, New Horizons in Astronomy and Astrophysics*

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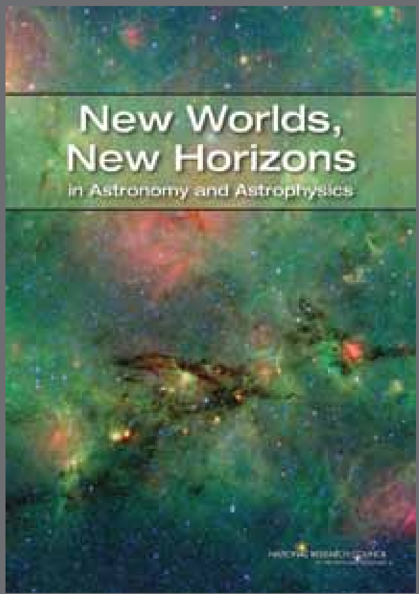
About the Decadal Survey on Astronomy and Astrophysics

Science advances our understanding of the universe. Each generation of scientists builds on the discoveries and advances of the last, enabling researchers to address progressively deeper questions across ever wider frontiers. In addition to the expected developments in astronomy and astrophysics, horizons are inexorably broadened through frequent unexpected discoveries.



This booklet provides an overview of the sixth, most recent, National Research Council decadal survey of astronomy and astrophysics, *New Worlds, New Horizons in Astronomy and Astrophysics* (The National Academies Press, Washington, D.C., 2010). The Astro2010 Survey identifies the big science questions in astronomy and astrophysics for the decade 2012-2021 and prioritizes the investments needed to maintain and strengthen the foundations of the astronomical enterprise. *New Worlds, New Horizons* recommends a vital and timely scientific program that contains a balance of small, medium, and large initiatives on the ground and in space. To optimize the overall science return, provision of major new facilities must be combined with ongoing support for the core research programs. In addition, the survey report identifies unique ways that astronomers can contribute to solving the nation's challenges and can help sustain and improve the broad scientific literacy that is vital to a technologically advanced democracy.

To download or purchase copies of the full 290-page report, visit the National Academy Press online at www.nap.edu.

The Big Questions

Our view of the universe has changed dramatically over the several past decades. Hundreds of planets of startling diversity have been discovered orbiting distant suns. Black holes are now known to exist at the centers of most galaxies. Precision measurements of primordial radiation left from the big bang have enabled astronomers to determine the age and structure of the universe. Other astronomical observations have revealed that most of the matter in the universe is invisible (i.e., "dark") and that the expansion of the universe is accelerating in an unexpected and unexplained way. Such recent discoveries, coupled with powerful new observing techniques and bold new ideas, have created unprecedented scientific opportunities for astronomy and astrophysics for the coming decade. To focus the science return from these opportunities, *New Worlds, New Horizons* identified priority science objectives under three themes: "new worlds," "fundamental physics," and "cosmic dawn." In addition, an even broader scientific strategy is essential for a healthy program in astronomy and astrophysics for the United States.

In the coming decade, astronomers are poised to achieve major advances in answering a number of big questions. These new discoveries would be made possible only through access to facilities at the forefront of astronomical research, such as the existing suite of telescopes carrying out observations across the electromagnetic spectrum from the ground and in space; those now under construction, like the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA); and the high-priority new facilities recommended in *New Worlds, New Horizons*.

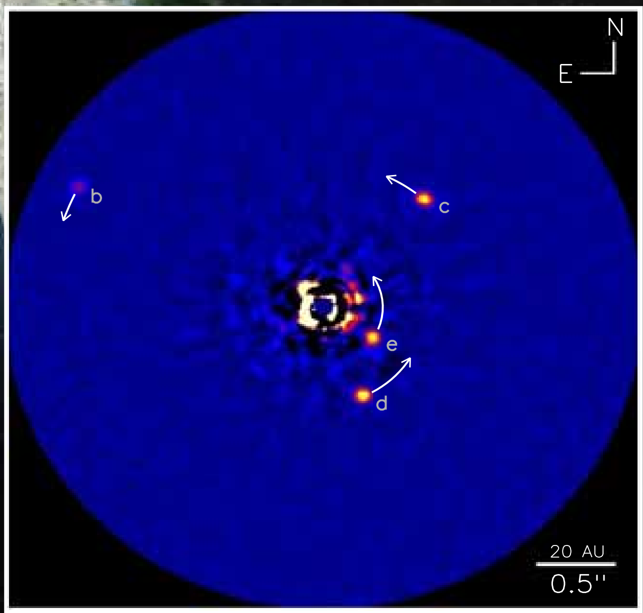
What Are Planetary Systems Like?

Since Copernicus first described the structure of our solar system nearly 500 years ago, ours has been the only planetary system known to astronomers until quite recently. In 1995 astronomers discovered the first planet orbiting a star other than our Sun. Astronomers have since discovered almost 500 more extrasolar planets, called exoplanets, with masses ranging from a few times the mass of Earth to several times the mass of Jupiter. Many such systems contain several planets, and almost all have structures very different from our own. This diversity challenges theories of the formation of planetary systems and is producing great intellectual excitement.

Among the major scientific objectives for the coming decade are discovering new exoplanets, learning more about the hundreds already known, and determining whether any of them may harbor life. Astronomers are poised to make great strides in understanding these new worlds—learning about their physical and chemical properties, improving theories of their structure and formation, directly imaging some exoplanets, identifying Earth-like ones, and perhaps even discovering telltale signs of life on one or more. The next 10 years would also see preparatory technology development for future missions. Just as the discovery of other planetary systems is revolutionizing our understanding of planet formation, so too would the discovery of even one other world that exhibits conditions suitable for life as we know it. The discovery of life itself—in our solar system or elsewhere—transform our understanding of biology and the origin and evolution of life. It would rank among the most important discoveries of all time.

An Exoplanet Family (Below)**.** An image of the system of exoplanets surrounding the star HR8799. Light from the central star has been blocked mechanically and further reduced electronically from the image. The four exoplanets are circled in red.

Other Worlds (Background)**.** Artist's conception of a possible world in the habitable zone around the red dwarf star Gliese 581.



How Do Stars and Planets Form?

Newborn stars, initially known as *protostars*, form as gravity causes dense clouds of gas and dust within galaxies to contract. Studies of these clouds have characterized their physical and chemical properties, yielding valuable information about the nurseries in which stars spring to life. High temperatures and pressures in the centers of the young stars eventually ignites nuclear fusion, an energetic process that powers stellar luminosity and, in the case of our own Sun, supports life on Earth.

Astronomers have also learned that new planets can form in the dusty, rotating disks that surround protostars and very young stars. Such *circumstellar disks* have been detected around more than 80 percent of stars in nearby stellar nurseries, strongly implying that planets are a frequent outcome of star formation. However, we do not yet know how many of these disks form planetary systems. Images from the optical Hubble Space Telescope, the infrared Spitzer Space Telescope, and the largest ground-based millimeter and optical telescopes, together with theoretical studies and computer modeling, are helping to elucidate the process of star and planet formation.

Because of great uncertainties about the details of stellar and planetary formation, we currently have only the most rudimentary ideas about the conditions necessary for, and conducive to, the formation of life. We possess even less knowledge about the extent of change in those conditions throughout the lifetime of our Milky Way Galaxy. Resolving such uncertainties would do much to help us understand the origins and frequency of occurrence of life in the universe.

A Stellar Nursery (left) Stars a hundred times as massive as our Sun forming in dense clouds of gas and dust in the nebula NGC 6357. At lower center, a very blue, massive, young star is ionizing and dispersing the surrounding cloud, creating a void.

A Supernova On The Outskirts Of A Spiral Galaxy (background). During its few-month lifetime, a violent supernova, such as the one that appears as a bright spot at the lower left of this image, produces an energy output rivaling the radiant energy from the entire galaxy, which contains perhaps a hundred billion stars.

What Happens When Stars Die?

Stars are powered by nuclear fusion in their cores. Light elements, like hydrogen and helium, fuse to form heavier elements like carbon, oxygen, and iron, releasing great amounts of energy in the process. In low-mass stars, these reactions occur slowly, allowing the stars to exist quietly for billions of years.

Stars a bit more massive than our Sun end their lives as dense white dwarf stars, which fade and cool over billions of years. Some white dwarfs occur in binary systems, and when sufficient matter from the companion star falls onto the surface of the white dwarf, it is compressed and heated, igniting a violent thermonuclear explosion in the dense carbon-and-oxygen interior, producing a *Type Ia supernova* and completely disrupting the white dwarf. Searches for such luminous events would help to map the geometry of the universe.

Stars containing more than about 10 times the mass of our Sun, however, burn hot and fast, ending their lives as *Type II supernovae* when the fuel for nuclear fusion is exhausted in their deep interiors. Within fractions of a second, this energy crisis triggers the core to collapse. If the core contains no more than a few times the mass of our Sun, it becomes a stable *neutron star*—an object with a density as enormous as those found in atomic nuclei. Otherwise, the collapsing material overwhelms the young neutron star, causing a further collapse to a *black hole*. The core collapse powerfully ejects the outer layers of the star, carrying heavy-element-enriched material back into space, where it can be incorporated into subsequent generations of stars and planets.

Over the next 10 years, planned wide-field sky surveys are expected to reveal tens of thousands of core-collapse supernovae every year. Detection of speedy but weakly interacting neutrinos and gravitational waves, both emitted during a core collapse, would enable astronomers to probe interactions between the collapsing inner cores and the exploding outer layers. If conditions are right, as happens in a minority of supernovae, intense *gamma-ray bursts* are emitted, providing further information about the explosion. Supercomputer simulations will further improve our understanding of both types of supernovae.

What Are Black Holes?

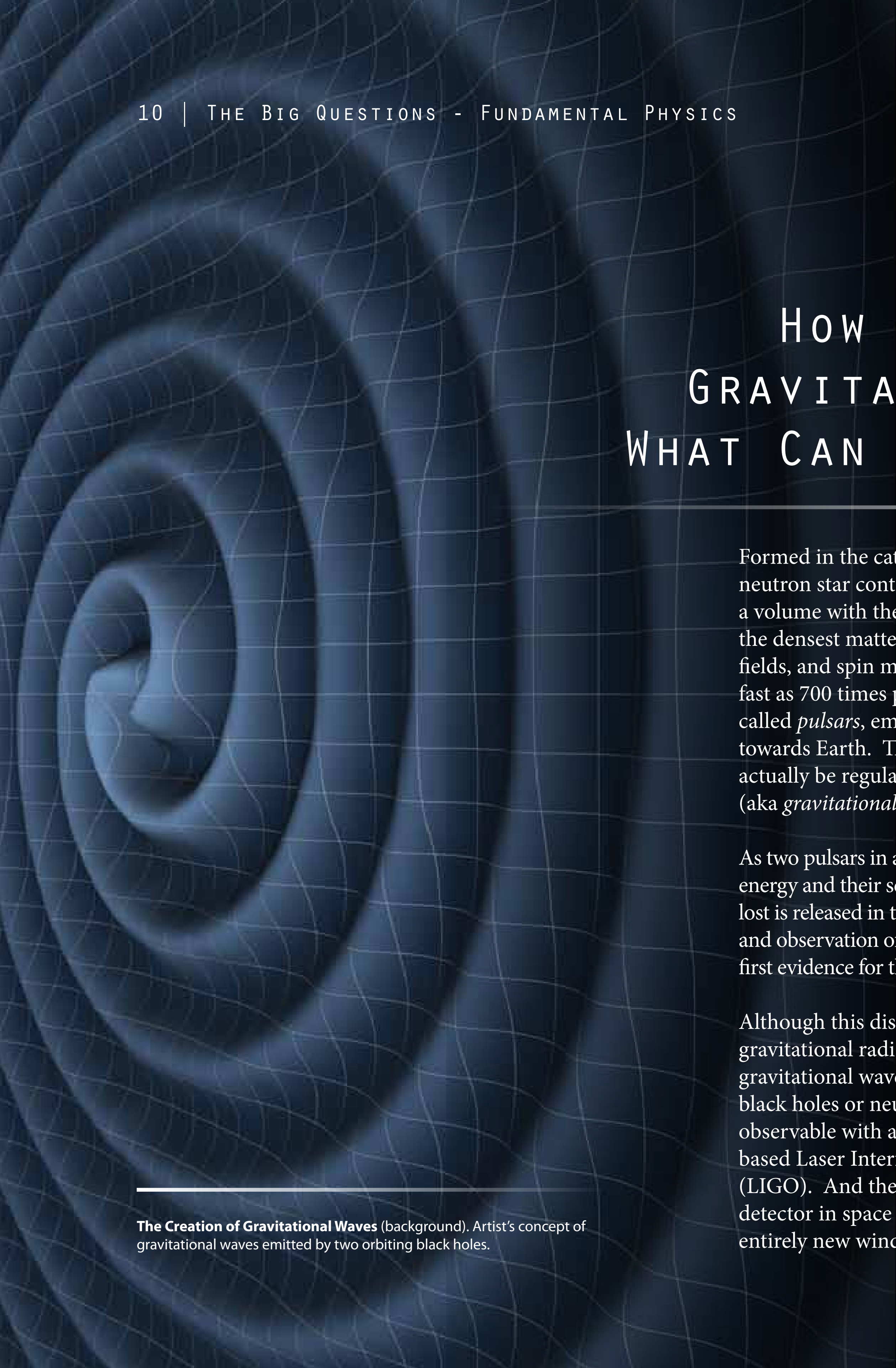
The strength of gravity on an object's surface depends on its mass and its size. The more dense and massive an object, the stronger its gravitational field is, making it harder for particles ejected from its surface to escape. When an object's gravity is so strong that even light cannot escape, it becomes a black hole.

Black holes form as the largest stars die. Once formed, a black hole can grow as matter—gas and dust, planets, stars—falls into it. Matter falling toward a black hole flattens into an orbiting disk. As it spirals inward through the disk toward the central object, the matter is heated to extremely high temperatures, producing x-rays, ultrahigh-energy cosmic rays, and powerful jets of plasma traveling at close to the speed of light. In fact, a significant amount of the matter is converted directly into energy!

The immense gravitational fields around black holes provide opportunities for perhaps the most challenging tests of Einstein's theory of gravitation, the *general theory of relativity*. This theory is not yet well understood in environments as extreme as those around a black hole. Understanding how jets of plasma are ejected at velocities close to the speed of light by massive, spinning black holes in *active galactic nuclei* may also lead to better understanding of gravity around a black hole. Over the next decade, x-ray observations will probe the nature of *space-time* very close to a black hole, and proposed space-borne observatories would use observations of infrared and perhaps gravitational radiation to provide additional insights into black holes.

The Black Hole in Cygnus X-1 (below). Artist's concept of matter drawn from a companion star and spiraling through a disk onto the black hole in the Cygnus constellation.

How Can We Detect Gravitational Waves? What Can They Tell Us?



The Creation of Gravitational Waves (background). Artist's concept of gravitational waves emitted by two orbiting black holes.

Formed in the catastrophic core collapse of a dying star, a neutron star contains a mass larger than the Sun's packed into a volume with the diameter of a city. Neutron stars contain the densest matter in the Universe, have the largest magnetic fields, and spin more rapidly than any other stars—some as fast as 700 times per second. Some rotating neutron stars, called *pulsars*, emit periodic beams of radiation directed towards Earth. The spin rates of millisecond pulsars may actually be regulated by the emission of *gravitational waves* (aka *gravitational radiation*).

As two pulsars in a binary system orbit each other, they lose energy and their separation distance grows smaller. The energy lost is released in the form of gravitational waves. The discovery and observation of just such a binary pulsar system provided the first evidence for the existence of gravitational waves.

Although this discovery provides strong evidence that gravitational radiation exists, it is not a direct detection of gravitational waves. Produced by interactions or mergers of black holes or neutron stars, gravitational waves may soon be observable with advanced instruments, such as the ground-based Laser Interferometer Gravitational-wave Observatory (LIGO). And the construction of an exquisitely sensitive detector in space during the next decade promises to open an entirely new window on the Universe.

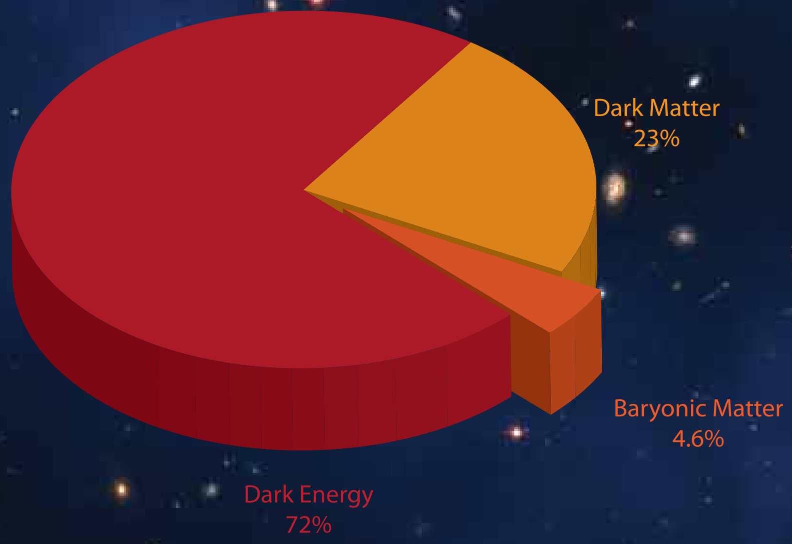
What Are Dark Matter and Dark Energy?

Dark Matter

Beginning in the 1930s, astronomers began to suspect that there was much more matter in the universe than met the eye. Measurements of galactic rotations revealed that there simply was not enough visible matter present to account for their rotation speeds. Since then, much additional evidence has been gathered that suggests that only about one-sixth of the total matter in a galaxy is in the familiar, everyday forms of atoms, molecules, ions, and electrons. The remainder, called *dark matter*, which seems to be found in all objects the size of a galaxy or larger, may consist of some exotic new elementary particle produced in the big bang but not yet detected by Earth-based particle accelerators. In the next decade, gravitational lensing, measurements of hot, x-ray-emitting gas, and radio measurements of rotation speeds in the disks of spiral galaxies would determine the distributions of the invisible dark matter in galaxies and clusters.

Dark Energy

Gravity tends to pull objects together, and so astronomers expected that the expansion of the universe would slow over time. But in 1998, measurements of supernovae showed that the expansion of the universe was actually accelerating! This is an outstanding puzzle in our modern picture of the universe. The observed acceleration is consistent with the idea that empty space is permeated with some gravitationally repulsive *dark energy*, a mysterious substance that accounts for more than 70 percent of the energy content of the universe. Alternatively, cosmic acceleration might indicate that Einstein's theory of gravity—general relativity—requires modification on large scales. Testing either theory requires high-precision observations, such as measuring the distances to supernovae, studying the growth of large-scale structure, investigating the effects of baryon acoustic oscillations in the cosmic microwave background, and observing weak gravitational lensing. Comparing the expansion of the universe with the growth of structure over time would enable astronomers to test whether either is responsible for the cosmic acceleration.



Most Of Our Universe Is Dark (left): The inferred proportion of mass and energy in the Universe in the form of dark energy, dark matter, and ordinary matter (called baryonic matter in the image) is shown in this pie chart.

Dark matter modeled onto galaxy cluster CL0024+17 (background): The distribution of dark matter inferred from observations of the motions of individual galaxies in the cluster CL0024+17.

What Goes on Inside Galaxies?

One of the greatest astronomical discoveries of the 20th century was that our own Milky Way Galaxy is but one of hundreds of billions of galaxies sprinkled throughout the almost inconceivably vast extent of the observable universe. Each consists of billions of stars, myriad clouds of gas, and—lurking in the very centers of sufficiently massive galaxies—*supermassive black holes*, objects with masses millions to billions of times larger than that of our Sun. These components are surrounded by a large halo of invisible dark matter that accounts for more than 80 percent of the mass of a galaxy and provides the gravitational "glue" to bind it together.

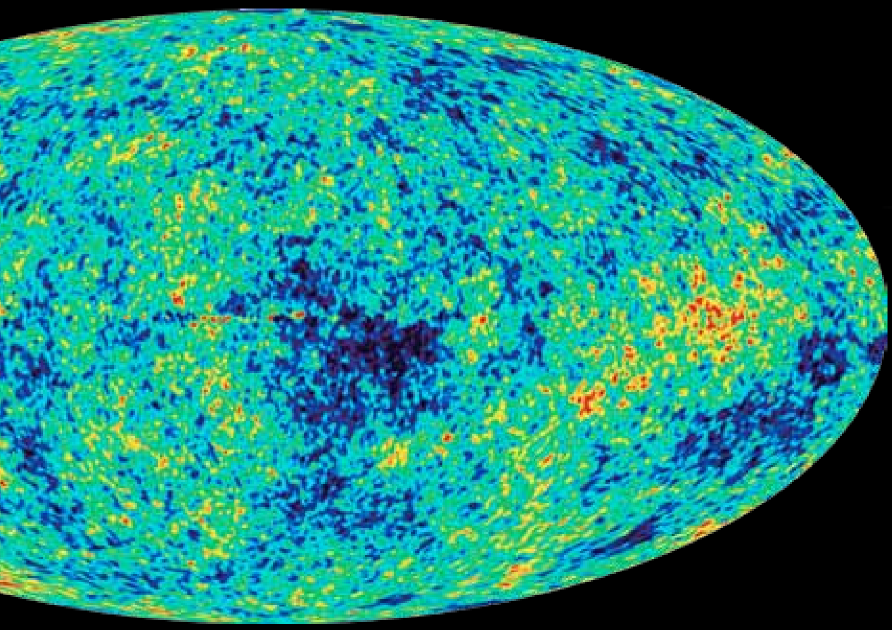
Inside a galaxy, most gas clouds eventually collapse to form new stars, although some are captured and consumed by the massive black hole near the galactic center. Nuclear reactions inside stars create new chemical elements, which are expelled back into the galaxy as stars die, providing raw material to form new stars, planets, and even life.

As the gas inside a galaxy is used up, it is replenished by gas flowing in through the galactic halo from a primordial repository of gas in the vast spaces between the galaxies themselves. Gas flows out of a galaxy as well. When a supernova explodes, it heats the surrounding gas to temperatures of millions of degrees and blasts it violently outward. Some galaxies go through episodes in which supernova explosions are so frequent that the galaxy's gas supply may be blasted completely away. Intermittent powerful eruptions of the massive black hole may do the same. Collisions between galaxies also affect these processes. These cycles of matter and energy into and out of galaxies determine how they evolve.

Understanding these complicated interactions among stars, black holes, and gas inside and outside galaxies is a central goal in astrophysics for the next decade.

Colliding Galaxies (left): Two spiral galaxies, together named Arp 271, are undergoing a collision in this image. The pink dots tracing out the spiral arms are star-forming regions where hot, bright, young stars are ionizing the surrounding hydrogen gas.

What Causes Cosmic Inflation?



The Cosmic Microwave Background (or CMB, above). A map showing the minuscule variations in the CMB across the whole sky. The plane of our Milky Way Galaxy is the horizontal axis of the figure. All parts of the CMB correspond to an almost completely uniform temperature of about 2.7 Kelvin, which suggests that the early universe was very uniform. However, there are minute temperature variations (blue regions are cooler and red regions are warmer) of less than 1 part in 10,000. Differences in temperature reflect differences in mass density, and so although these fluctuations are tiny, they are large enough to serve as the "seeds" not only of the first galaxies, but also, ultimately, of the entire structure of the universe.

Observations over the past decade have revealed that our universe began 13.7 billion years ago in the big bang. Initially, conditions were unimaginably hot and dense. The theory of cosmic inflation proposes that the universe began to expand extraordinarily rapidly (inflate) within an infinitesimal fraction of a second after the big bang, a brief period called the *inflationary epoch*. Afterward, the universe continued to expand and cool, although much more gradually. After about 400,000 years, the temperature had dropped to about 3,000 degrees—cool enough for the first atoms to form. This phase, called the *recombination epoch*, also made the universe transparent to light for the first time. The radiation from that epoch became the faint, distant glow we detect today as *cosmic microwave background radiation*.

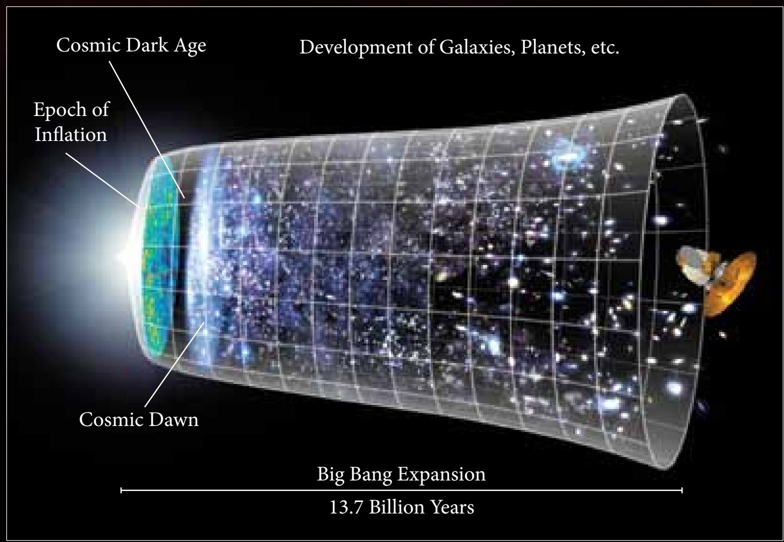
The cosmic microwave background has a surprisingly uniform temperature over the entire sky, a property that the inflation hypothesis can explain. The cause of cosmic inflation, however, remains a great mystery. The concept is central to modern astrophysics, because the small fluctuations in matter densities present during the inflationary epoch provided the "seeds" that ultimately grew into the large-scale structure of the universe we see around us today. Direct confirmation of cosmic inflation might become possible through mapping the positions of hundreds of millions of galaxies and through detecting gravitational radiation—the rippling of space and time itself—produced by objects moving through the nascent universe.

What Objects First Lit Up The Universe, and When?

Following recombination, the universe entered a cosmic dark age, during which there were no planets, stars, or galaxies, just warm hydrogen and helium gas. Over millions of years, the gas cooled and was concentrated into clumps by gravity, forming the first stars. Astronomers believe that these primordial stars were hundreds of times larger than our Sun and extraordinarily hot, bright, and short-lived. Their intense ultraviolet radiation broke apart, or ionized, neutral atoms, initiating a longer, more gradual *epoch of reionization*. As these massive stars died, their cores collapsed to form black holes. Matter falling onto the black holes emitted additional intense, penetrating radiation. The "first light" produced by these stars and black holes is sometimes referred to as the *cosmic dawn*.

We now know that supermassive black holes existed less than a billion years after the big bang. But how did they form so rapidly? We also know that they exist in the centers (nuclei) of all galaxies at least as large as our Milky Way Galaxy. But which formed first: the black hole or the galaxy around it? These questions will be addressed by careful observations of matter falling into black holes and by the gravitational radiation emitted as black holes consume infalling stars. In fact, gravitational infall onto supermassive black holes is one of the most powerful energy sources known! These active galactic nuclei power distant galaxies to luminosities so high that they can be observed across vast expanses of the universe. To us, they look almost like stars— quasi-stellar— and are called *quasars*.

One of astronomers' major science objectives is to learn about these early eras in the history of the universe. They will be able to study the formation of the first stars and black holes and the epoch of reionization with proposed new facilities operating at radio wavelengths from the ground and at x-ray and optical wavelengths from space.



The Expansion of The Universe (above): A schematic representation of the expansion of the universe from the big bang, showing the early epoch of rapid inflation, the cosmic dark ages, the first stars that lit up the universe again in a cosmic dawn, the development of galaxies, and the accelerated expansion produced by dark energy.

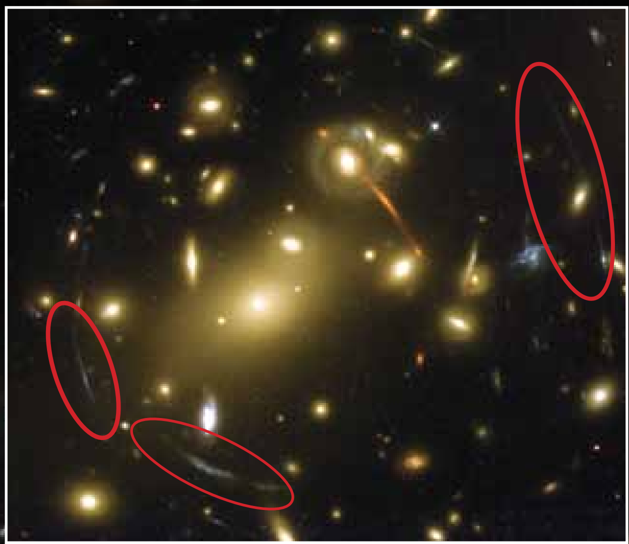
Starless Skies (background): This image of the Lagoon Nebula—with stars artificially removed—suggests the appearance of the very early universe.

How Has The Universe Evolved Over Time?

The first stars, born in clouds of primordial gas embedded in halos of dark matter, became the seeds of the first protogalaxies. Drawn together by gravity, protogalaxies became full galaxies and merged to form even larger structures, such as galaxy clusters and the wispier filaments of galaxies that connect them. This assembly of the universe's large-scale structure continues to this day.

Over the next decade, astronomers will study the evolution of such structures from the epoch of recombination through to the present day. Radio telescopes will study the cosmic microwave background intensively, detecting the minute fluctuations from which galaxies formed. They will also detect cool atomic hydrogen all the way back into the cosmic dark age, determining when and where the first stars formed.

Gravitational lensing, an effect in which a massive object bends light rays from distant sources, thereby distorting their shapes, will be used to trace the distributions of dark matter in galaxies and clusters. Matter that falls deep into the centers of galaxy clusters grows extremely hot, emitting detectable x-rays in the process. Visible and infrared investigations will search out mergers of galaxies, which are thought to be drivers of the birth of stars. And observations of the spectra of stars throughout their life cycles will determine the abundances of heavy elements in the stars and reveal how these abundances have increased during the history of the Milky Way Galaxy.



A Gravitational Lens (right). The galaxy cluster Abell 2218. A strong gravitational lens is produced by the enormous concentration of mass in this cluster. The elongated blue images tracing portions of circular arcs around the cluster are at least 22 images of 11 separate background galaxies, the images of which are distorted by this lens. Several of the blue arcs are circled in red. This gravitational lens is a "telescope" that enables astronomers to look back across cosmic time at very distant galaxies.

Galaxies In The Early Universe (background): A near-infrared image of a portion of the Hubble Ultra Deep Field, showing extremely faint and distant young galaxies in the process of forming. Very few of these irregular objects resemble galaxies near us in the universe today.

Telescopes, Instruments, and Programs

The Astro2010 decadal survey committee used input from the U.S. astronomy and astrophysics community, science priorities identified by its five Science Frontier Panels, the conclusions of its four Program Prioritization Panels, and independent evaluations of cost and technical readiness to develop the ranked priorities for large ground- and space-based activities for U.S. astronomy for the coming decade (2012-2021). The committee also ranked medium-size projects for both space and ground and identified a number of smaller projects that were deemed equally worthy and therefore left unranked. Below: The Gemini North Observatory atop Mauna Kea in Hawaii.

Selection Criteria for Telescopes, Instruments, and Programs

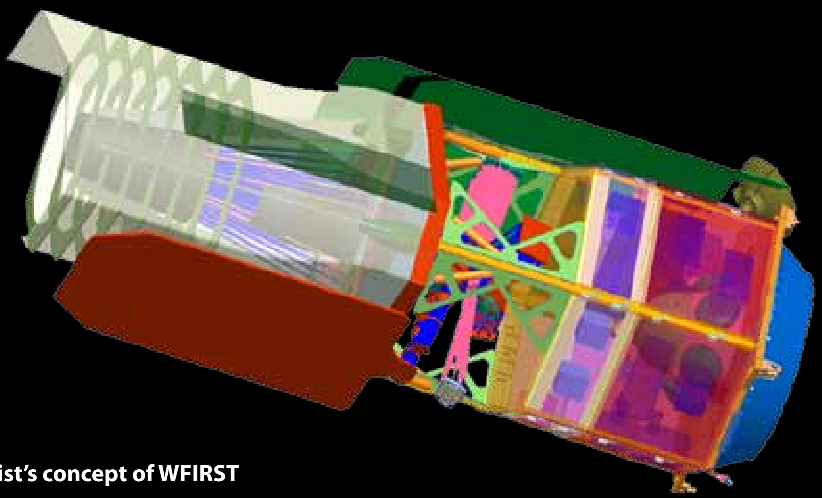
Aimed at realizing the science priorities identified by the Astro2010 survey committee, the recommended activities for the decade are rooted in existing research and also take into account the availability of new technology. The committee adopted four major criteria as the basis for prioritizing its recommendations:

- Maximizing the scientific return;
- Building upon the current base of knowledge in astronomy and astrophysics;
- Balancing activities for 2012—2021 against investments for the following decade; and
- Optimizing the science return under constrained budget guidelines by assessing for each activity its readiness; technical risk, schedule risk, cost risk; and opportunities for collaboration.

Large Space-Based Projects
Listed in Order of Priority

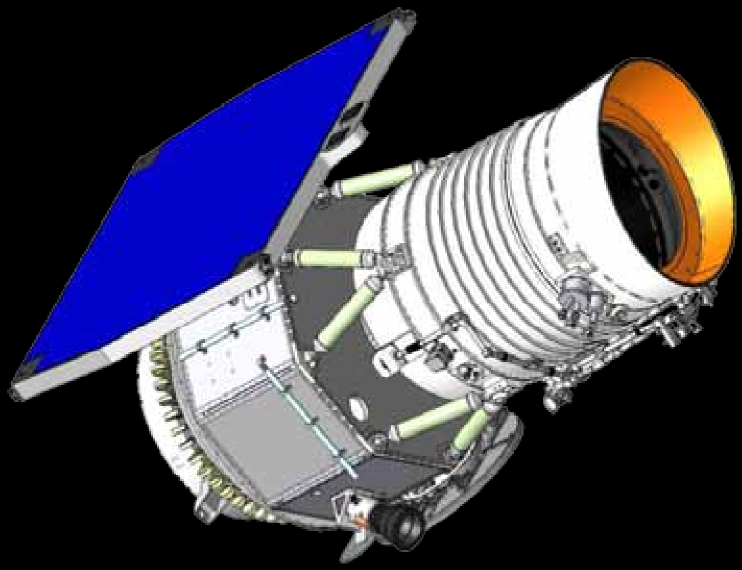
1. Wide-Field Infrared Space Telescope (WFIRST)

This 1.5-meter-diameter space observatory would have a wide field of view and be capable of low-resolution spectroscopy in the near infrared. Positioned in an Earth-following orbit beyond the Moon, WFIRST over its 5-year mission would address all three high-priority science objectives for the decade. It would map distributions of 2 billion galaxies to seek traces of structure from the earliest moments of the universe, measure 2,000 distant supernovae to map the expansion of the universe, and study dark energy by measuring the shape distortions of distant galaxies caused by gravitational lensing. It would study the formation and growth of black holes in young galaxies, help characterize how galaxies were formed, obtain spectra of 200 million galaxies, and help to determine the structure of the Milky Way Galaxy. It would also monitor the teeming stars in the central bulge of our galaxy for gravitational microlensing events—tiny deflections of light from background stars—to infer the presence of exoplanets.



Artist's concept of WFIRST

Artist's concept of WISE, the Wide-Field Infrared Survey Explorer

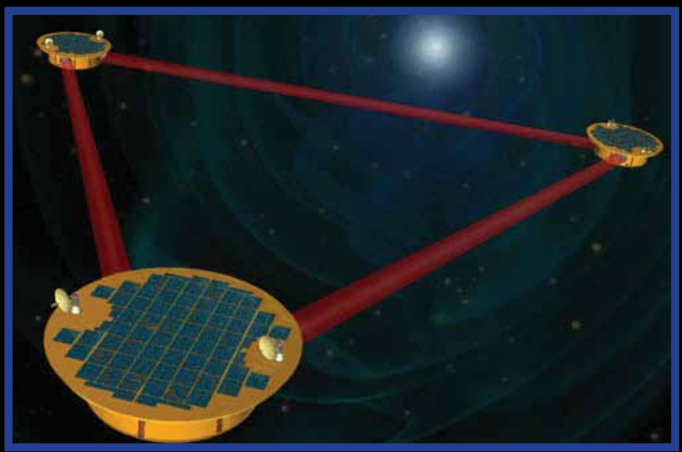


2. New Explorer Missions

Small (SMEX) and medium-size (MIDEX) Explorer missions, developed and launched on few-year timescales, allow rapid responses to new discoveries and provide versatility and high science returns. At the forefront of scientific discovery, they enable U.S. astronomers to seize promising opportunities, exploit new technologies, and involve university groups—including students and postdoctoral scholars—in significant development roles. They also offer highly leveraged Missions of Opportunity that enable U.S. scientists to participate in non-NASA missions. However, the goal of deploying a small and medium astrophysics mission every other year is not being met. Accordingly, the survey committee's second-highest priority for large space projects is the selection of two new MIDEX missions, two new SMEX missions, and at least four Missions of Opportunity over the coming decade, thereby expanding the Explorer program beyond the missions currently planned by NASA.

3. Laser Interferometer Space Antenna (LISA)

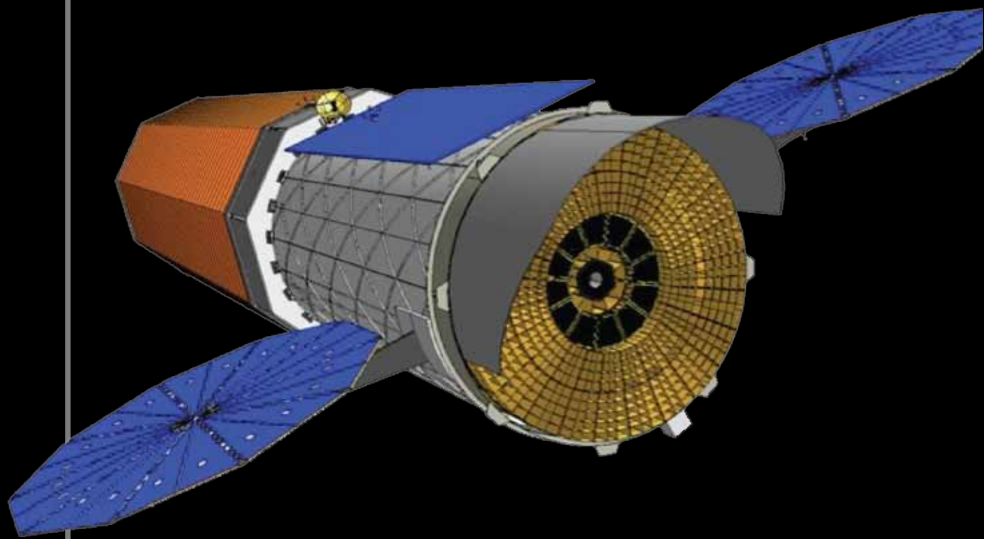
LISA is designed to sense faint ripples in the fabric of space-time caused by motions of the densest objects. This gravitational-wave observatory would open an entirely new window on the universe. Using three "laser-connected" spacecraft configured in an equilateral triangle with sides of 5 million kilometers, LISA would be placed in an Earth-trailing orbit with a planned 5-year mission. It would measure the rate at which young galaxies merge by observing bursts of gravitational radiation produced during mergers of their central black holes. It would also make a census of compact binary systems in our galaxy, help to elucidate the growth of galaxies and black holes, measure black hole masses and spins, and further test Einstein's general theory of relativity.



Artist's concept of LISA

4. International X-Ray Observatory (IXO)

IXO is proposed to be a versatile, large-area, high-spectral-resolution x-ray observatory capable of time-resolved spectroscopy. The 3-meter-aperture, lightweight, focusing x-ray mirror would have 5-arcsecond angular resolution (about the apparent size of a dime at a quarter-mile distance). Launched into an Earth-trailing orbit, IXO would probe the hottest regions of the universe. It would find and study distant clusters of galaxies to measure the rate of growth of structure in the universe, monitor the exchange of gas between galaxies and the intergalactic medium, and study the formation and growth of black holes in the nuclei of young galaxies. It would observe x-rays from gas orbiting close to black holes and neutron stars and would assess the habitability of exoplanets by studying the frequency and intensity of flares on host stars.

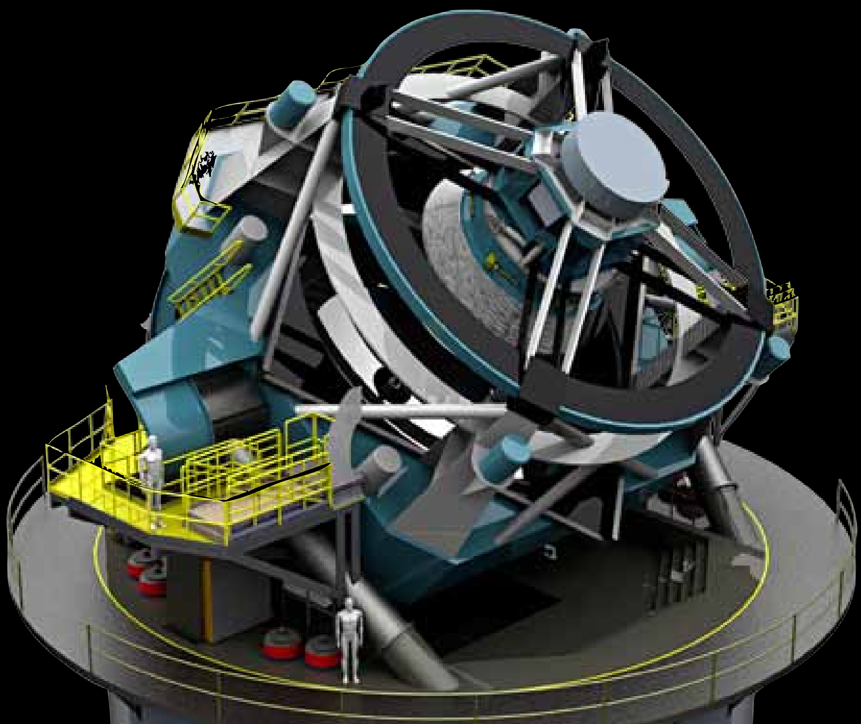


Artist's concept of IXO

Recommended Large Ground-Based Projects
Listed in Priority Order

1. Large Synoptic Survey Telescope (LSST)

Surveys are essential to astronomy: astronomers must find out "what's out there" before they can plan detailed observing programs. LSST would employ the most ambitious optical survey approach yet, creating massive databases that would be mined for decades. An 8.4-meter-diameter telescope sited in Chile with a 3.5-degree field of view (about 7 times the angular diameter of the Moon), LSST would be capable of observing in six colors. Its 10-year mission would tackle a broad range of high-priority science questions, ranging from understanding the structure of our galaxy to elucidating the physics of stars. LSST would measure distant supernova explosions and map distances to galaxies to determine the expansion rate of the universe, enabling astronomers to address the fundamental question of why the universe is accelerating. It would measure shape distortions of distant galaxies caused by weak gravitational lensing to characterize dark matter, study resolved stellar populations to determine how the Milky Way Galaxy was formed, and map near-Earth objects, supernovae, and gamma-ray bursts. Obtaining 1,000 separate images of each accessible region of the sky over its 10-year lifetime, LSST would revolutionize investigations of the time-variable universe.



Artist's concept of LSST

2. Mid-Scale Innovations Program

Modeled after NASA's highly successful Explorer program, the recommended NSF Mid-Scale Innovations program would target the design and development of instruments costing between $4 million and $135 million. It would help NSF to address the compelling number of highly promising projects with intermediate costs that the agency currently has difficulty in funding. It would enable first-class science to be accomplished at moderate cost and would train students in experiment design and instrumentation.

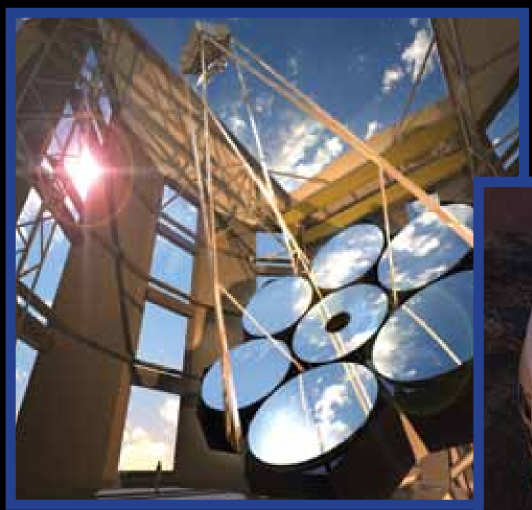
HERA (above): Prototype antennas for the Hydrogen Epoch of Reionization Array (HERA), an example of a project that could benefit from the recommended NSF Mid-Scale Innovations program. A radically new type of low-frequency radio observatory, HERA would determine how the universe was ionized by the first generations of stars.

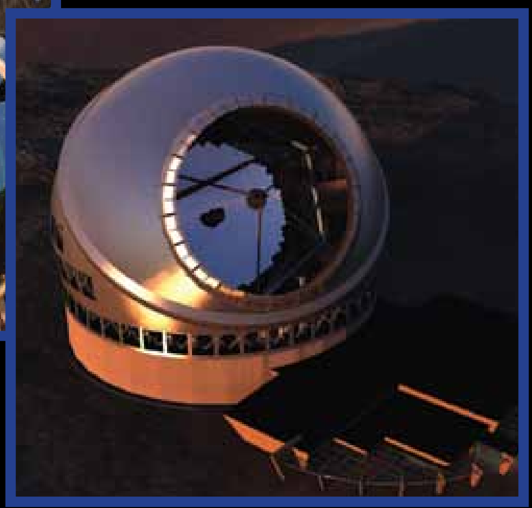
3. Giant Segmented Mirror Telescope (GSMT)

Three projects with different designs are currently underway to construct a new generation of extremely large telescopes. Collectively called the GSMT, they include two U.S-led projects, the Giant Magellan Telescope (to be sited in Chile) and the Thirty-Meter Telescope (on Mauna Kea in Hawaii). *New Worlds, New Horizons* recommends that at least one of these two should have a federal investment. Optical and infrared observations with the GSMT would study the evolution of infant galaxies, and spectroscopy of very faint galaxies would elucidate properties of dark matter. High-resolution optical spectra of gas absorption lines observed against distant quasars would monitor gas exchange between galaxies and the matter outside galaxies. Spectroscopic studies of the oldest stars in nearby galaxies would monitor the buildup of heavy elements. Measurements of distant supernova explosions would identify progenitor stars and map the expansion of the universe. Infrared surveys of clouds of gas and dust in the Milky Way and neighboring galaxies would study young stars and circumstellar disks out of which planets form and would obtain direct images of exoplanets.

4. Atmospheric Cerenkov Telescope Array (ACTA)

Very high energy gamma-ray photons from cosmic sources produce flashes of *Čerenkov light* in Earth's atmosphere that can be observed by telescopes on the ground. More than 100 sources are now known, including active galactic nuclei, pulsars, the gaseous remnants of supernovae, and binary stars. Further progress requires a large facility with new detector technology to study known sources in more detail and increase the number of sources identified. ACTA will also seek to determine whether dark matter consists of a new type of elementary particle by searching for high-energy gamma rays emitted by interactions in distant concentrations of dark matter and will advance our understanding of mechanisms for accelerating cosmic rays and amplifying magnetic fields.





Two Versions of the GSMT (left): The Giant Magellan Telescope (GMT) and an artist's concept of the Thirty Meter Telescope (TMT)

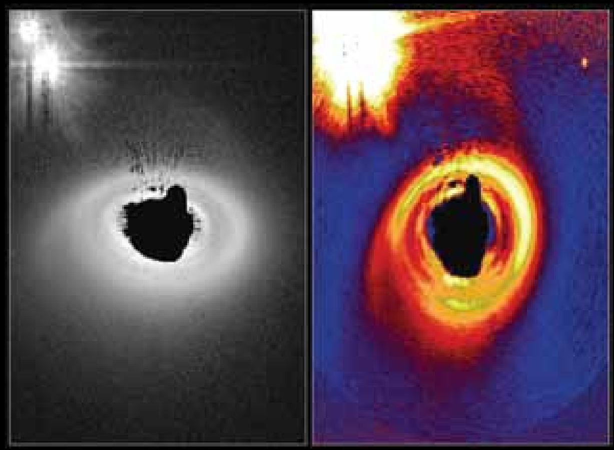
VERITAS (above): ACTA would be modeled on the existing Very Energetic Radiation Imaging Telescope Array System.

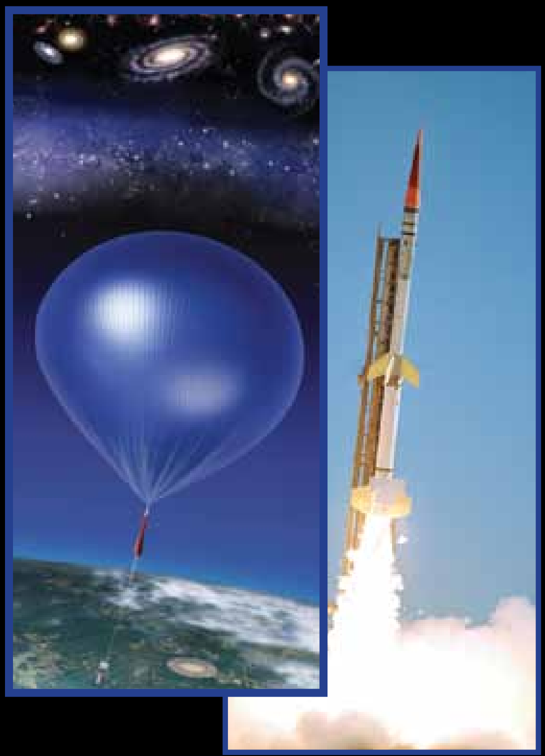
Other Recommendations

With an emphasis on a balanced portfolio of investments, New Worlds, New Horizons also recommends support for a few medium-scale space- and ground-based projects and for several unranked smaller-scale projects.

New Worlds Technology Development for a 2020 Decade Mission

Astronomers must lay the foundations in this decade for a dedicated space mission in the next to detect and characterize exoplanet atmospheres, including those palatable to biotic activity on exoplanets: What systems contain Earth-like planets in the habitable zones around their parent stars? At what level does starlight scattered from dust in exoplanet systems hamper planet detection? Starlight is many times brighter than the reflected light from companion planets, and so candidate starlight-suppression techniques must be developed for any direct detection mission. Advances in such areas would allow a space-based planet-imaging and spectroscopy mission to be defined late in the present decade.





Technology Development for a Mission to Probe the Epoch of Inflation

The theory of cosmic inflation predicts that gravitational waves produced in the early universe affect the polarization of the cosmic microwave background radiation. Detecting this effect would therefore provide strong evidence for inflationary theory and open a new window on exotic physics in the very early universe. To probe this polarization signal to faint levels, *New Worlds, New Horizons* recommends an enhanced suborbital program, Explorer missions of opportunity, and balloon experiments. If these experiments prove successful, the report recommends an enhanced program of technology development for a future dedicated space mission to study cosmic inflation.

Direct Detection of Exoplanets (above): In this Hubble Space Telescope image of the circumstellar disk around the young star HD141569, light from the central star is suppressed with a coronagraph, enabling structure in the dusty nebula to be observed.

Suborbital Experiments Probe CMB (left). Balloons and sounding rockets enable high-altitude studies of the cosmic microwave background, helping to develop technologies for future missions to study the very early Universe.

Cerro Chajnantor Atacama Telescope (CCAT)

A 25-meter telescope operating in survey mode at millimeter and submillimeter wavelengths, CCAT would perform sensitive imaging surveys of large fields in the sky, complementing the Atacama Large Millimeter Array (ALMA) currently under construction in Chile. CCAT would efficiently identify sources for detailed follow-up observations by ALMA, enabling astronomers to study the evolution of galaxies across cosmic time, the formation of clusters of galaxies, the formation of stars in the Milky Way, the formation and evolution of planets, and the nature of objects in the outer solar system.

CCAT (above). An artist's concept of the CCAT.
ALMA (below): A few of the ultimately 66 antennas for the Atacama Large Millimeter Array (ALMA) on site on the Chajnantor plain in the Chilean Andes.

Small-Scale Projects

Recommended small-scale space- and ground-based projects include core research and technology development programs (see "Keeping Science Strong" and "Technology for the Future" on page 29), suborbital flights, contributions to the SPICA mission, support for the national ground-based observatories, theory and computation networks, data handling, and laboratory astrophysics.

An Astronomer At Work. Much of an astronomer's work today is carried out in front of a computer screen. From there, she can control the largest ground-based telescope, make observations from space, analyze her data, and write scientific papers and proposals for grant support for her research.

Astronomy and the Public

Astronomy is an immensely popular science that helps to attract talented young people into careers in the sciences and engineering, provide new technologies, and develop the skills necessary to address the nation's technological challenges.

A Popular Science

Astronomy stirs the public imagination like no other science. A single astronomical image—like the Apollo 8 image of Earth-rise from the Moon or the Hubble Space Telescope image of the Eagle Nebula—can have a visceral and long-lasting impact. Astronomical themes appear in many of our most popular movies, and many terms from the field—such as quasar, pulsar, and black hole—have entered the common lexicon. Astronomy's broad public appeal helps to promote science literacy for the population as a whole, and the public reach is impressive: in 2008, 349 science centers and museums and 1,401 planetariums served 60.3 million people through onsite and online visits. An enthusiastic and vibrant amateur community helps to provide direct hands-on access to the wonders of the night sky and aids in advancing certain subfields of astronomy.

A Vibrant Training Ground

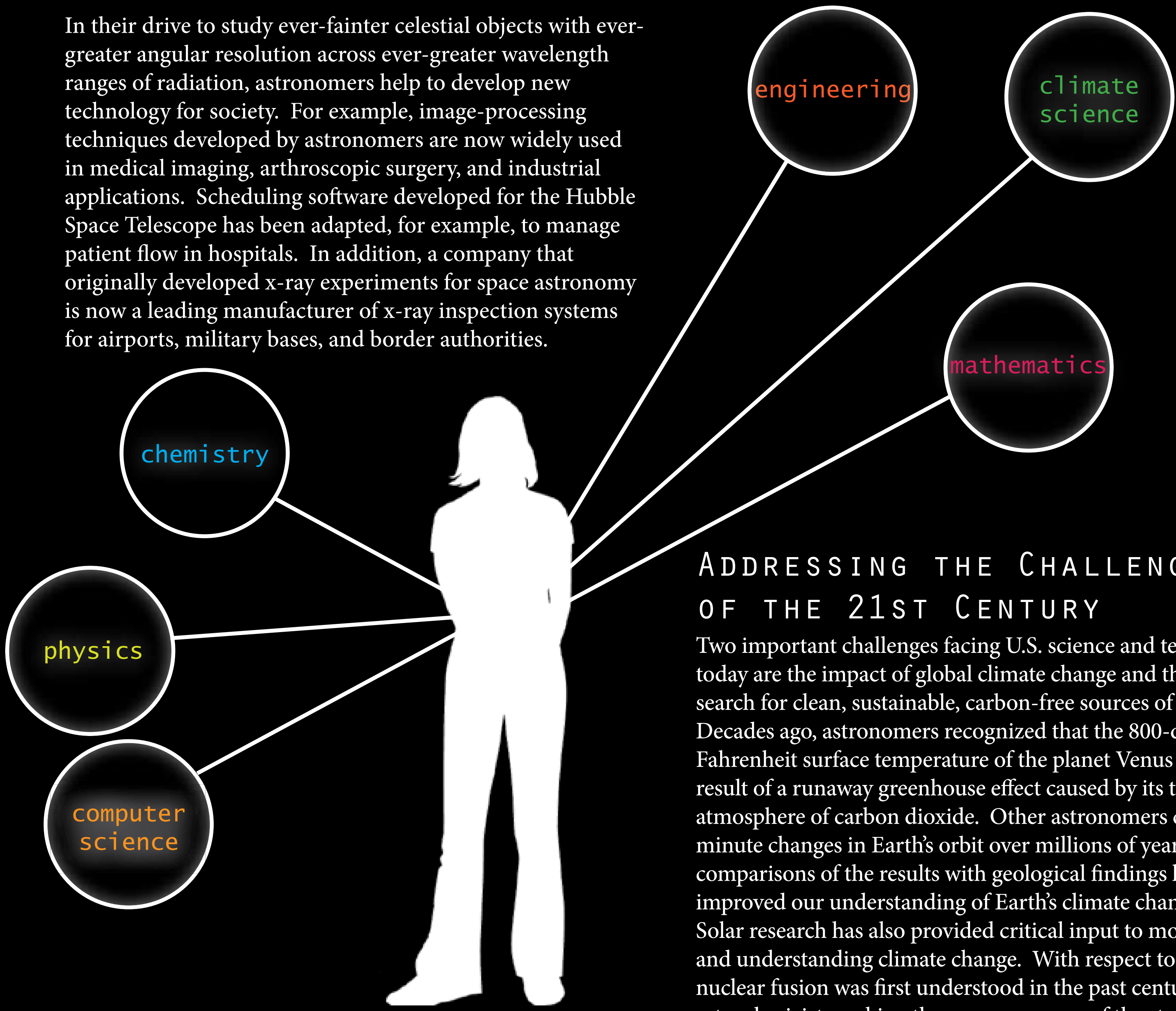
At the pre-college level, exposure to astronomy is largely through informal education and public outreach—for example, through astronomy summer camps, after-school science activities, online astronomy projects, and community K-12 programs. Because of its appeal, astronomy plays a significant role in shaping K-12 science and in postsecondary education in technology, engineering, and mathematics. In colleges and universities, astronomy courses serve 250,000 students annually, about 10 percent of all undergraduates nationwide. Introductory astronomy is often the only science course for some 15 percent of future K-12 teachers. Astronomy may also be effective in helping to attract more minorities and women into science or technology careers.

Young Discovery (above). In 2008, 14-year-old Caroline Moore became the youngest amateur astronomer to discover a supernova.

Wonders Of The Night Sky (background). The wonder of the night sky excites children and adults everywhere.

A Gateway to New Technology

In their drive to study ever-fainter celestial objects with ever-greater angular resolution across ever-greater wavelength ranges of radiation, astronomers help to develop new technology for society. For example, image-processing techniques developed by astronomers are now widely used in medical imaging, arthroscopic surgery, and industrial applications. Scheduling software developed for the Hubble Space Telescope has been adapted, for example, to manage patient flow in hospitals. In addition, a company that originally developed x-ray experiments for space astronomy is now a leading manufacturer of x-ray inspection systems for airports, military bases, and border authorities.



Addressing the Challenges of the 21st Century

Two important challenges facing U.S. science and technology today are the impact of global climate change and the search for clean, sustainable, carbon-free sources of energy. Decades ago, astronomers recognized that the 800-degree-Fahrenheit surface temperature of the planet Venus was the result of a runaway greenhouse effect caused by its thick atmosphere of carbon dioxide. Other astronomers computed minute changes in Earth's orbit over millions of years, and comparisons of the results with geological findings have improved our understanding of Earth's climate changes. Solar research has also provided critical input to modeling and understanding climate change. With respect to energy, nuclear fusion was first understood in the past century by astrophysicists seeking the energy sources of the stars, and the U.S. fusion program was actually begun by the astronomer who first proposed the space telescope. Astronomers and astrophysicists possess considerable expertise that can be tapped to help the nation meet these challenges.

The Scientific Enterprise

Astronomy is a truly international science. Maintaining the success of our nation's contributions to this field depends critically on continuing to attract talented young scientists, sustaining the support necessary for their research, and developing new, forefront technologies. Background: Earth as seen from the International Space Station illustrates the international character of science and the importance of forefront technology.

The People Who Make It Work

Astronomy attracts some of the best and brightest young people, as well as scientists from other fields (e.g., high-energy physics, computer science). Young Ph.D. astronomers and astrophysicists are broadly trained, energetic, hard-working, and highly motivated. Their ability to find innovative solutions to problems and their familiarity with cutting-edge techniques and tools have broad appeal to employers. However, African Americans, Hispanic, and Native Americans are seriously underrepresented among scientists in general and professional astronomers in particular, and the nation needs to find ways to better engage this segment of the population. As New Worlds, New Horizons emphasizes, targeted mentoring programs and partnerships between minority-serving institutions and national research centers and universities are among approaches that may help to attract and retain them. Women once were similarly underrepresented among professional astronomers, but significant progress is being made to close the gender gap.

People Of Astronomy (below). A group of professional astronomers at work in an obervatory control room.

Astronomy Around the World (below): A composite image showing some of the world's premier radio, optical, and space observatories highlights the truly international nature of astronomy and astrophysics.

A Truly International Effort

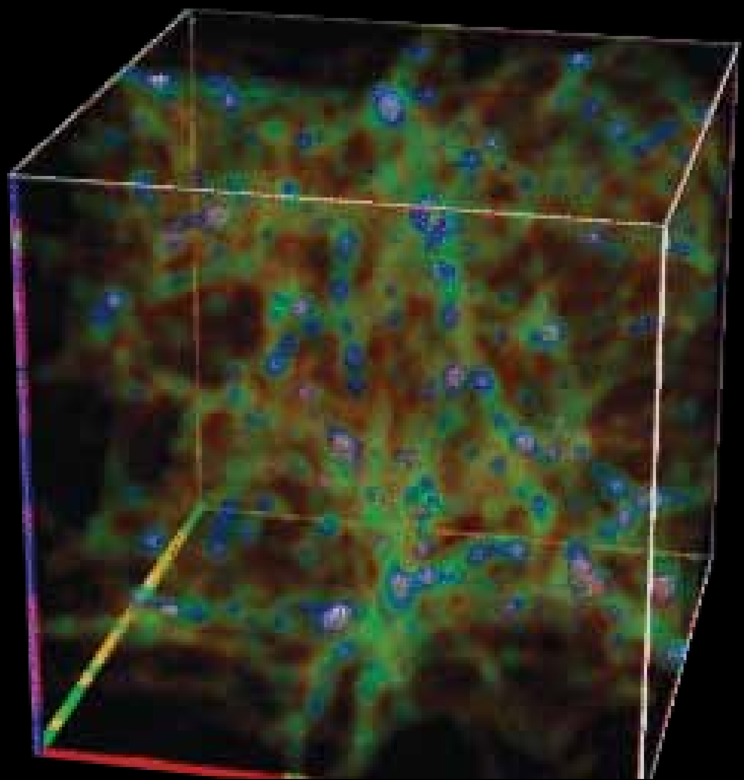
For much of the 20th century, astronomical research was dominated by the United States. However, Europe has now achieved parity with the United States in astronomical research, and Australia and South America are gaining rapidly. And the expansion underway in Asia will influence the field for the foreseeable future. In addition, because ground-based observatories view the skies through Earth's turbulent and obscuring atmosphere, large, new facilities must be built wherever in the world the best sites may be. It is thus imperative that planning for U.S. astronomy be done within the international context. All astronomers share the same sky, and significant gains can be made through international coordination and cooperation. One of many such advantages is the opportunity to construct and operate facilities that would otherwise be prohibitively expensive for any nation alone.

Keeping Science Strong

Research grants to individuals and groups are key to realizing the scientific potential of existing facilities, identifying and developing new research opportunities, and training the nation's workforce. The competitive research grants programs funded by federal funding agencies provide the primary support for these activities. However, funding for these critical programs has recently flattened or declined despite increases in, for example, the overall NSF budget. To keep astronomy and astrophysics vibrant, it is essential to increase support for individual investigators. Such support would maintain robust theory and observing programs, respond to challenges for data archiving, and sustain essential laboratory astrophysics. In addition, training the critical next generation of instrumentalists requires a steady-state hierarchy of project sizes, so that scientists and engineers can progress from relatively smaller, simpler, and faster projects to responsibilities in larger and more complex activities.

Technology for the Future

Astronomers have helped to develop some of Earth's most advanced technologies, consistently leading to dramatic advances in our understanding of the natural world. Space-based observatories have provided access to infrared and x-ray wavelengths that are blocked by Earth's atmosphere. Enhanced computing power revolutionized modern science—for example, enabling array observations in radio astronomy and *active and adaptive optics* systems that allow today's largest optical telescopes to operate at the limits of their performance and enable construction of the next generation of powerful "eyes on the sky." Astronomers also developed the computational infrastructure for large sky surveys and the dissemination of massive data sets and computed detailed simulations of, for example, star formation, galaxy evolution, and dark-matter cosmology. Technology development is truly the engine powering advances in science. Investments in this area are critical not just for astronomy and astrophysics, but also for a host of other fields that stand to benefit.



Cosmology by supercomputer. Image from a supercomputer calculation showing the origin of structure in a universe filled with ordinary matter and dark matter.

The Science and the Facilities

The table below maps the Astro2010 survey's recommended major new initiatives in astronomy and astrophysics onto priority areas of science—summarized as three science objectives articulated by the survey—to which they would be important contributors in the decade 2012-2021. Each would also contribute substantially to critical, ongoing scientific research in many other areas of astronomy and astrophysics.

- The "new worlds" priority science includes computation and theory and observations of Earth-like exoplanets, dust environments around Sun-like stars, stellar flares, and biogenic molecules.

- The "fundamental physics" priority science includes theoretical investigations; observations of distant supernovae, the distribution of galaxies, the expansion of the universe, the epoch of inflation, and black holes; and studies to determine the properties of dark matter and dark energy.

- The "cosmic dawn" priority science includes theory and simulations and observations of the epoch of reionization, young galaxies, star formation, galactic life cycles, black holes, gravitational radiation, and the oldest stars.

		New Worlds	Fundamental Physics	Cosmic Dawn
Large Space-Based Facilities	WFIRST	✓	✓	✓
	SM.MIDEX*		✓	✓
	LISA		✓	✓
	IXO	✓	✓	✓
Large Ground-Based Facilities	LSST		✓	
	MSI**	✓	✓	✓
	GSMT	✓	✓	✓
	ACTA		✓	✓
	CCAT			✓
Existing Facilities	ALMA	✓		✓
	JWST	✓		✓

*Additional, new SMEX, MIDEX, and Missions of Opportunity beyond those currently in the NASA pipeline.
** New Mid-Scale Innovations program recommended for NSF.

Glossary

Active galactic nucleus: The central region of a galaxy containing a supermassive black hole that produces intense radio emission, jets of ionized plasma moving at velocities near the speed of light, or other indications of energetic activity

Black hole: An object so massive and dense that its gravity prevents light from escaping. Supermassive black holes have masses millions to billions of times the mass of our Sun.

CCAT: A 25-meter radio telescope to operate at millimeter and submillimeter wavelengths.

Čerenkov light: Light emitted when an elementary particle enters a medium with a speed faster than the speed of light in that medium (which is less than the speed of light in free space).

Circumstellar disk: A disk of matter in orbit around a star.

Core-collapse supernova: A Type II supernova, caused when core pressure can no longer withstand the gravitational weight of the rest of the star.

Cosmic dark age: The period between the recombination epoch and the epoch of reionization, before the first stars and galaxies formed.

Cosmic dawn: The beginning of the epoch of reionization when the first stars began to shine.

Cosmic microwave background (CMB) radiation: Faint radio noise with a temperature of about 2.7 Kelvin that still remains from the epoch of recombination.

Dark energy: A mysterious substance that accounts for more than 70 percent of the energy content of the universe and that produces a gradual acceleration of the expansion of the universe.

Dark matter: An invisible substance that contributes most of the mass of a galaxy or cluster of galaxies.

Epoch of reionization: The point in time at which the first stars formed, emitting intense ultraviolet radiation that broke apart (ionized) the primordial hydrogen and helium atoms.

Exoplanet: A planet outside our solar system.

Gamma-ray burst: A cosmic source, believed to be a type of supernova, that emits a burst of very high energy gamma rays.

General theory of relativity: Einstein's theory of gravitation.

Gravitational lens: A mass, such as a galaxy or cluster of galaxies that bends light rays from distant sources, refocusing them as a lens would do.

Gravitational microlensing: A tiny deflection of light from a background star produced by the mass of an exoplanet.

Gravitational waves: Ripples in the fabric of space-time produced by the motions of massive bodies.

Halo: An extended region of material around a galaxy.

Hubble Ultra Deep Field: A very-long-exposure image of a region of the sky taken by the Hubble Space Telescope and revealing very faint and distant sources.

Inflationary epoch: A brief period near the very beginning of the universe during which the size of the universe expanded extraordinarily rapidly (inflated) within an infinitesimal fraction of a second.

Milky Way: The galaxy within which we exist. It is a disk-shaped spiral galaxy some 100,000 light-years in diameter, and the Sun is located in a spiral arm about 26,000 light-years from the center. From Earth, we see the disk as a starry band across the night sky.

Nebula: A cloud of gas in space that emits or reflects light.

Neutrino: A ghostly particle with almost no mass that interacts very weakly with ordinary matter.

Neutron star: An incredibly dense object with about the mass of our Sun packed into the size of a city.

Plasma: An ionized gas consisting of negatively charged electrons and positively charged ions (atoms with one or more electrons removed).

Polarization: A property of waves, such as electromagnetic and gravitational waves, that describes their orientation

Protogalaxy: A newly forming galaxy.

Protostar: A newly forming star that derives its energy from the contraction of a gas and dust cloud, converting gravitational energy into kinetic energy. The young star continues to contract until its central density and temperature become high enough to ignite nuclear burning in the core.

Pulsar: A rotating neutron star that emits intense, narrow beams of radio waves.

Quasar: A very distant galaxy harboring a supermassive black hole that emits such powerful radiation that it can be seen across vast expanses of the universe. Quasars are so distant that the galaxies appear to be star-like or quasi-stellar.

Recombination epoch: A point in time after the big bang when the universe first became cool enough for electrons and ions to combine into neutral atoms.

Space-time: The three ordinary spatial dimensions plus time, which must be considered together according to Einstein's special theory of relativity.

Suborbital: A description for an aerial or space project that reaches space but does not achieve sufficient velocity to remain in orbit around Earth.

Type Ia supernova: A violent explosion in a binary system produced when sufficient matter is accreted from a companion to cause a white dwarf star to collapse to the density of an atomic nucleus.

Type II supernova: A violent explosion of a massive star produced when the core exhausts nuclear energy sources and collapses into a neutron star or black hole, blowing off the outer layers.

Weak gravitational lensing: Slight distortions in the apparent shapes of galaxies caused by the bending of light due to intervening matter.

White dwarf star: A star with about the mass of our Sun packed into the size of Earth.

Wide-field survey: A survey of large areas of sky conducted with a telescope having a wide angular field of view.

Acronyms

ACS: Advanced Camera for Surveys
ACTA: Atmospheric Cerenkov Telescope Array
ALMA: Atacama Large Millimeter Array
CXC: Chandra X-ray Observatory Center
ESA: European Space Agency
ESO: European Southern Observatory
GMT: Giant Magellan telescope
GSFC: NASA's Goddard Space Flight Center
GSMT: Giant Segmented Mirror Telescope
HERA: Hydrogen Epoch of Reionization Array
HST: Hubble Space Telescope
IXO: International X-ray Observatory
JDEM: Joint Dark Energy Mission
JHU: Johns Hopkins University
JPL: NASA's Jet Propulsion Laboratory
JWST: James Webb Space Telescope
LISA: Laser Interferometer Space Antenna
LSST: Large Synoptic Survey Telescope
MIDEX: Mid-sized Explorer space missions
MIT: Massachusetts Institute of Technology
NAOJ: National Astronomical Observatory of Japan
NASA: National Aeronautics and Space Administration
NRAO: National Radio Astronomy Observatory
NSF: National Science Foundation
SAO: Smithsonian Astrophysical Observatory
SMEX: Small-sized Explorer space missions
SPICA: Space Infrared Telescope for Cosmology and Astrophysics
STScI: Space Telescope Science Institute
TMT: Thirty-Meter Telescope
UCO: University of California Observatories
WFPC2: Wide Field Planetary Camera 2 on HST
VERITAS: Very Energetic Radiation Imaging Telescope
WFIRST: Wide-Field Infrared Space Telescope

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ABOUT THIS BOOKLET

This booklet summarizes the scientific program recommended in the astronomy and astrophysics decadal survey, *New Worlds, New Horizons*, which has the potential to revolutionize our understanding of the Universe in the coming decade. It presents the recommendations for new space- and ground-based facilities and notes the investments needed to maintain and strengthen America's role in the field of astronomy in the 21st century. It also outlines the capabilities astronomers can bring to bear toward solving the nation's challenges.