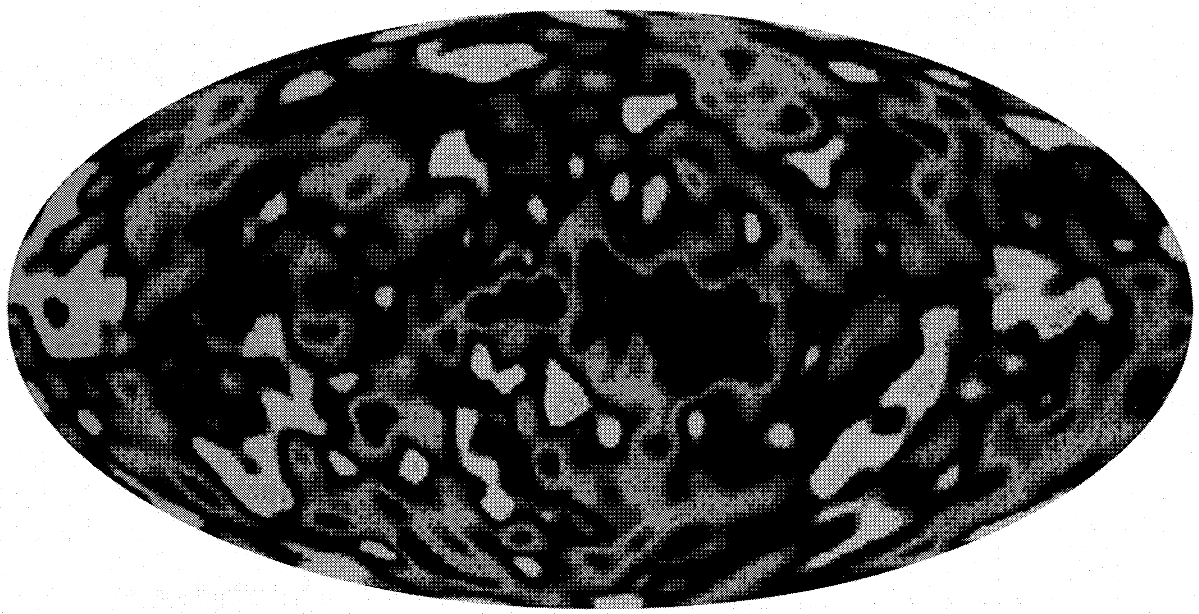
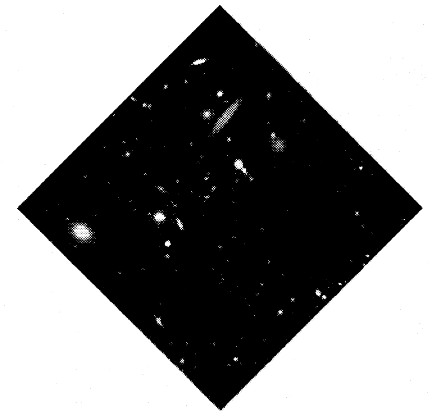
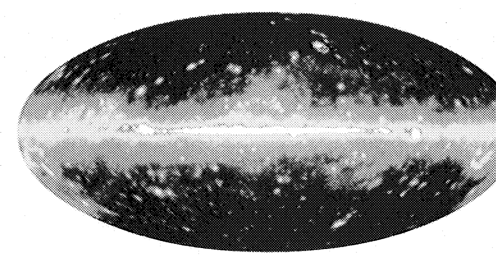
NASA/TM-97- 207049

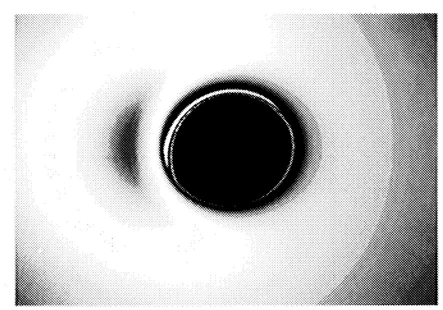
THE EVOLVING UNIVERSE
STRUCTURE AND EVOLUTION OF THE UNIVERSE ROADMAP 2000-2020

To understand the growth of Structure and the Evolution of the component parts of the Universe









SCIENCE ROADMAP

NP-1997(06)-019-GSFC

THE EVOLVING UNIVERSE

STRUCTURE AND EVOLUTION OF THE UNIVERSE ROADMAP 2000-2020

To understand the growth of Structure and the Evolution of the component parts of the Universe

STRUCTURE AND EVOLUTION OF THE UNIVERSE

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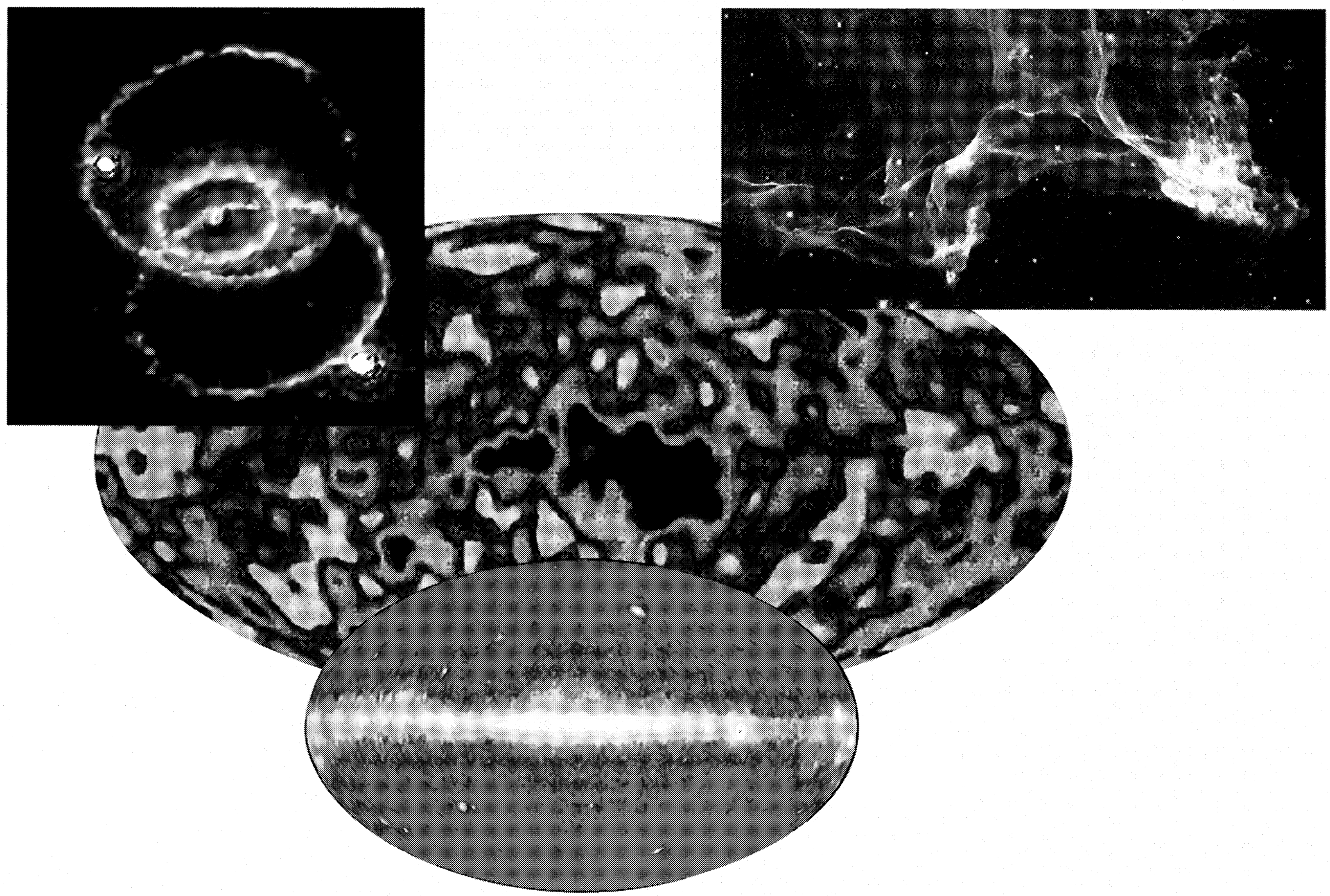
EXECUTIVE SUMMARY



EXECUTIVE SUMMARY (continued)

THE ROADMAP FOR THE STRUCTURE AND EVOLUTION of the Universe (SEU) theme embraces three fundamental, scientific quests:

- *To explain **Structure** in the Universe and forecast our cosmic destiny.*
- *To explore the cycles of matter and energy in the **Evolving** Universe.*
- *To examine the **Ultimate Limits** of gravity and energy in the Universe.*

These quests are developed into six, focused research campaigns addressing the objectives of one or more quests:

- Identify **dark matter** and learn how it shapes galaxies and systems of galaxies
- Find out where and when the chemical **elements** were made
- Understand the **cycles** in which matter, energy, and magnetic field are exchanged between stars and the gas between stars
- Discover how gas flows in **disks** and how cosmic **jets** are formed
- Identify the sources of gamma-ray bursts and **high-energy** cosmic rays
- Measure how strong **gravity** operates near black holes and how it affects the early Universe.

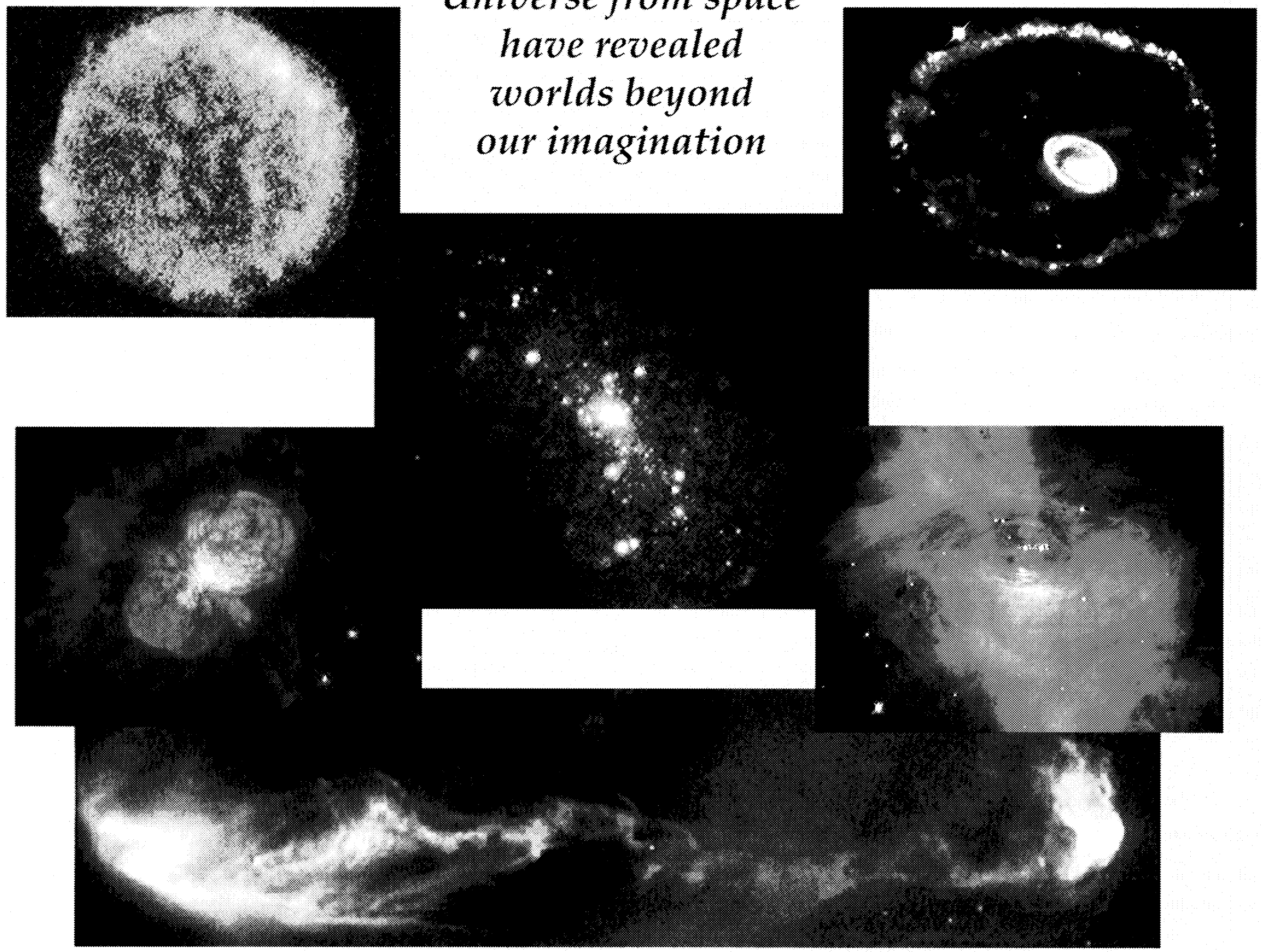
These campaigns lead to a portfolio of future major missions of strong scientific and popular appeal, strongly endorsed by the scientific community and which has undergone significant initial study. Some of these missions are in a state of readiness that makes them ideal candidates for the present Office of Space Science Strategic Plan; others may well feature in the next Strategic Plan. Each provides a golden scientific opportunity to advance our understanding of the Universe. Our highest priority science objectives are addressed by five Observatory Class Missions, unranked by science, but in approximate order of readiness:

- A high-energy gamma-ray facility that will observe relativistic jets and study the sources of cosmic gamma-ray bursts.
- An ultra-sensitive X-ray telescope, optimized for spectroscopy, to examine the hot gas linked with clusters of galaxies, the disks around black holes, and supernova explosions.
- A large, radio telescope in deep space to map central regions of distant quasars and perform astrometric investigations.
- An orbiting gravitational radiation detector able to detect coalescing, massive black holes and test how gravity waves distort spacetime.
- A pair of Earth-orbiting, optical telescopes that will detect flashes of light produced when ultra-high-energy cosmic rays impact the upper atmosphere so as to determine their arrival directions and energies.

A new program for supporting pertinent international collaboration is strongly endorsed and maintaining a strong Explorer program is important. The flexibility to exploit exceptional opportunities, such as attaching payloads to space station, should also be acquired. A strong technology development program must be initiated now to enable this mission set.

INTRODUCTION

Explorations of the Universe from space have revealed worlds beyond our imagination



INTRODUCTION (continued)

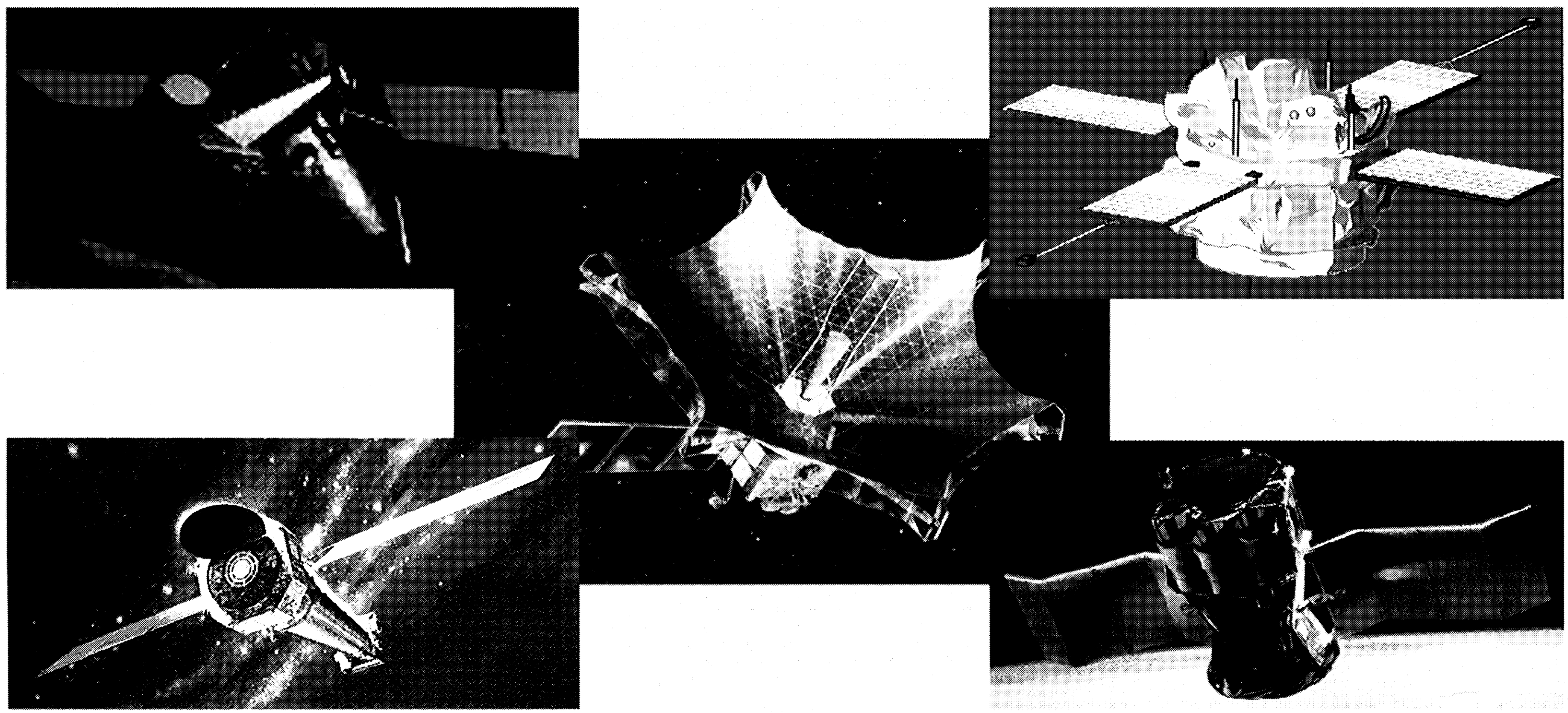
The Universe is an extraordinary, yet comprehensible, place. It is populated by billions of galaxies, scattered over vast reaches of space and time. Their tiny seeds — fluctuations in the density of matter planted soon after the big bang — are directly observable as structure in the cosmic microwave background radiation. Many galaxies congregate in giant clusters shaped largely by invisible dark matter and hot gas. Most contain giant black holes in their nuclei that can become quasars by capturing and igniting surrounding gas. Normal galaxies, like our own, are composed of billions of stars, some caught at their births in dusty clouds of molecular hydrogen, visible at infrared wavelengths. A few of them are witnessed at the ends of their lives as spectacular supernova explosions. These supernovae can leave behind neutron stars or stellar-sized black holes which, themselves, can be resurrected as powerful, pulsing radio, X-ray and gamma-ray sources. Some of these compact stars may combine to produce brief bursts of gravitational radiation, momentarily as powerful as the whole Universe. The space between the stars is a tumultuous environment, filled with hot gas from supernova explosions, cold gas which will make fresh stars and planets, cosmic rays, ultraviolet radiation, tiny grains of interstellar dust and twisting magnetic fields. This is our home.

This modern view of the Universe has a special vocabulary — black hole, cosmic microwave background radiation, quasar, dark matter and so on — that did not exist 35 years ago and much of which has now joined the general language and has enriched popular culture. It has created new paradigms for physics, chemistry and biology by showing us how Nature behaves under conditions unattainable on Earth and contributed many fascinating mysteries for all of us to ponder. This Roadmap plots a course outward into the land of the unknown.

Astronomy has been revolutionized by observing from space, away from the obscuring effects of our atmosphere. Space astronomers are opening up the entire electromagnetic spectrum, observing waves with lengths ranging from kilometers to a hundredth the size of a proton. They see how sources change on timescales from milliseconds to decades. In addition, astronomers are exploiting non-electromagnetic channels, such as cosmic rays, neutrinos, gravitational radiation and direct inspection of interstellar material. We are truly fortunate to be living at a time when our understanding of the Universe is changing from the stuff of myth and legend to a comprehensive description of its structure and evolution, together with an appreciation of its final destiny. The Cosmic Background Explorer (COBE) made the first observational link between structure in the ancient and modern Universe. The Hubble Space Telescope (HST) has found evidence that massive black holes probably exist in most galaxies. The Compton Gamma Ray Observatory (CGRO) examined the gamma-ray sky and turned a long-standing puzzle, the identity of the gamma-ray bursts, into a first rate mystery. It has also discovered powerful relativistic jets from black holes. The German-American-British Roentgen Satellite (ROSAT) has found distant, giant clusters of galaxies, through their hot X-rays. The Rossi X-ray Timing Explorer (RXTE) has discovered a rich spec-

INTRODUCTION (continued)

The current program contains a suite of missions – exciting voyages of discovery through the end of the decade. It is now time to plan for the next century.



trum of pulsations from accretion disks in binary X-ray sources that will help us explain how they work. The Japanese-US X-ray satellite, ASCA, has seen swirling disks of gas around the massive spinning black holes in active galactic nuclei. The Infra-Red Astronomy Satellite (IRAS) made an inventory of dusty star-forming regions and infrared-emitting galaxies in the nearby Universe. The Extreme Ultraviolet Explorer (EUVE) has been able to see far outside the Galaxy through clearings in the fog of interstellar hydrogen. The list goes on and is updated weekly.

The immediate future is even brighter. In a couple of years, the Advanced X-ray Astrophysics Facility (AXAF) will resolve the diffuse X-ray background to determine the dominant X-ray emitters in the Universe. It will also start to show us how gas accretes onto black holes and map, in detail, the giant clusters of galaxies to give us quantitative measurements of the extent of large scale structure. The Microwave Anisotropy Probe (MAP) will measure the fluctuations in the microwave background on angular scales much smaller than COBE to accuracies of a few percent and enable us to measure directly the size and contents of the 300,000 year old Universe, which can be compared with what we see around us now. The Advanced Composition Explorer (ACE) will make accurate determinations of the chemical and isotopic composition of low-energy cosmic rays, to show how and where they are accelerated and to address some of the outstanding puzzles in our theories of nucleosynthesis. Gravity Probe B (GP-B) will measure the Lense-Thirring dragging of inertial frames by the spinning Earth, a signature of the General Theory of Relativity. The Japanese-led very long baseline radio interferometry satellite, HALCA, has just been launched and will map cosmic radio sources in unprecedented detail, equivalent to reading this Roadmap from a thousand miles away.

These voyages of discovery are revealing what has never been seen before. However, as a science, astronomy goes beyond mere voyeurism and modern investigations are organized around key questions whose answers usually require concerted campaigns that combine telescopes in space and on the ground and that observe across the electromagnetic spectrum and beyond. The old, spectrally chauvinist view is being displaced by a modern, integrated approach. In order to foster this, the National Aeronautics and Space Administration's (NASA) space science enterprise has been reorganized around four scientific themes — Astronomical Search for Origins and Planetary Systems (ASOPS), Exploration of the Solar System (ESS), Structure and Evolution of the Universe (SEU), and Sun-Earth Connection (SEC). The SEU theme encompasses those aspects of space astronomy involving fundamental principles that govern the development of structure and the evolution of the different component parts of the Universe. It is concerned, in a quite general way, with the origin of the Universe and its components, their subsequent evolution and their eventual destiny.

The current SEU program only extends to the end of this decade. It is now time to develop the next set of mission concepts that have broad scientific and popular appeal and that strike at the big questions of the age. These will need to be studied, refined, and brought to a point of technical readiness where they can be selected for launch on the basis of scientific peer review

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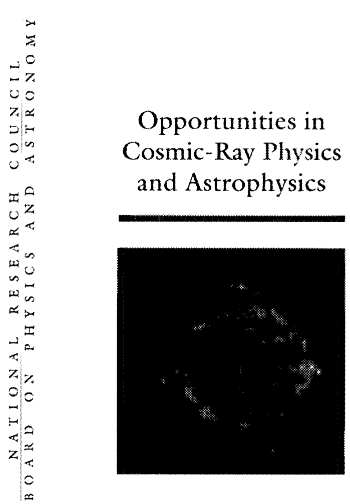
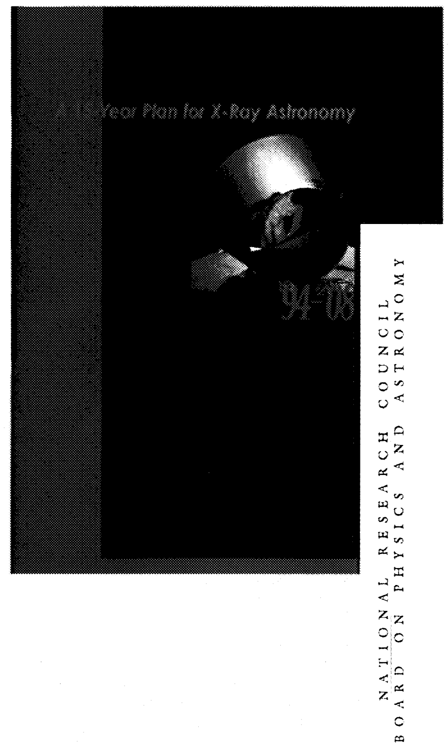
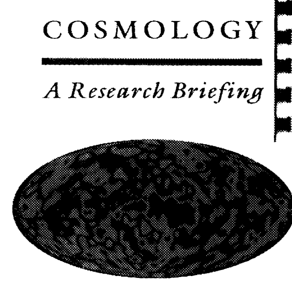
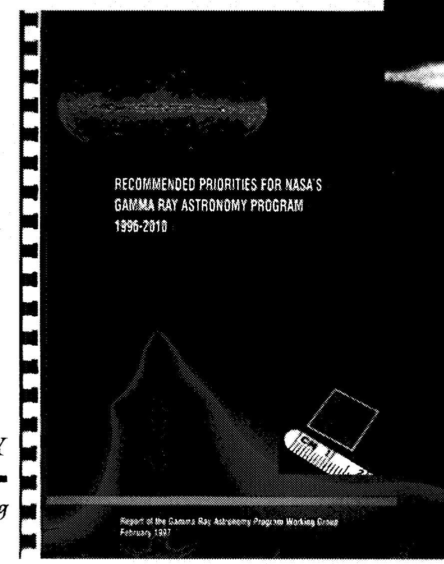
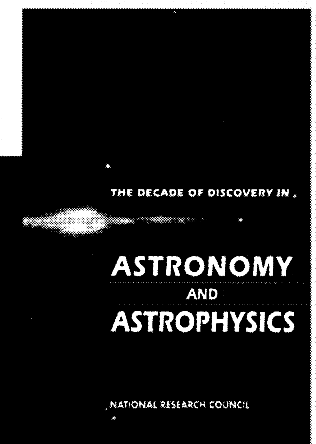
This Roadmap has an extensive heritage of prior studies on which to build





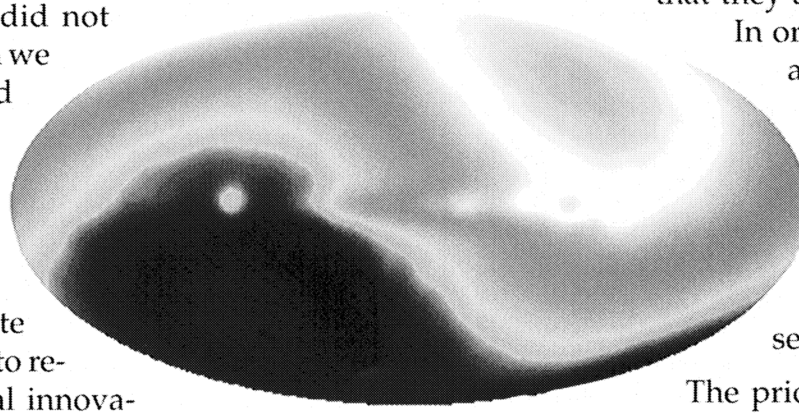






INTRODUCTION (continued)

and programmatic considerations. In order to direct this process, the Structure and Evolution of the Universe Subcommittee (SEUS) has produced a Roadmap, a long term vision of the science program encompassed by its theme, that implies a set of missions to be developed and constructed in the next century. We have tried to look forward to 2020 and to anticipate what might be possible over this epoch. At first, this exercise seems presumptuous. The world of astronomy twenty years ago was quite different from what we know now and many of our current research priorities did not even exist then. However, the reason we currently enjoy such a healthy and productive program is because our predecessors were men and women of vision who knew that the very act of exploration would lead to surprises. In formulating this Roadmap we have tried to emulate that vision and yet retain flexibility to respond to new discoveries, technical innovations and international opportunities. This Roadmap must be seen as a living document. Its successor, to be written in about three years time, ought to have significant differences from the current version — the best possible indicator of a vibrant, scientific discipline.



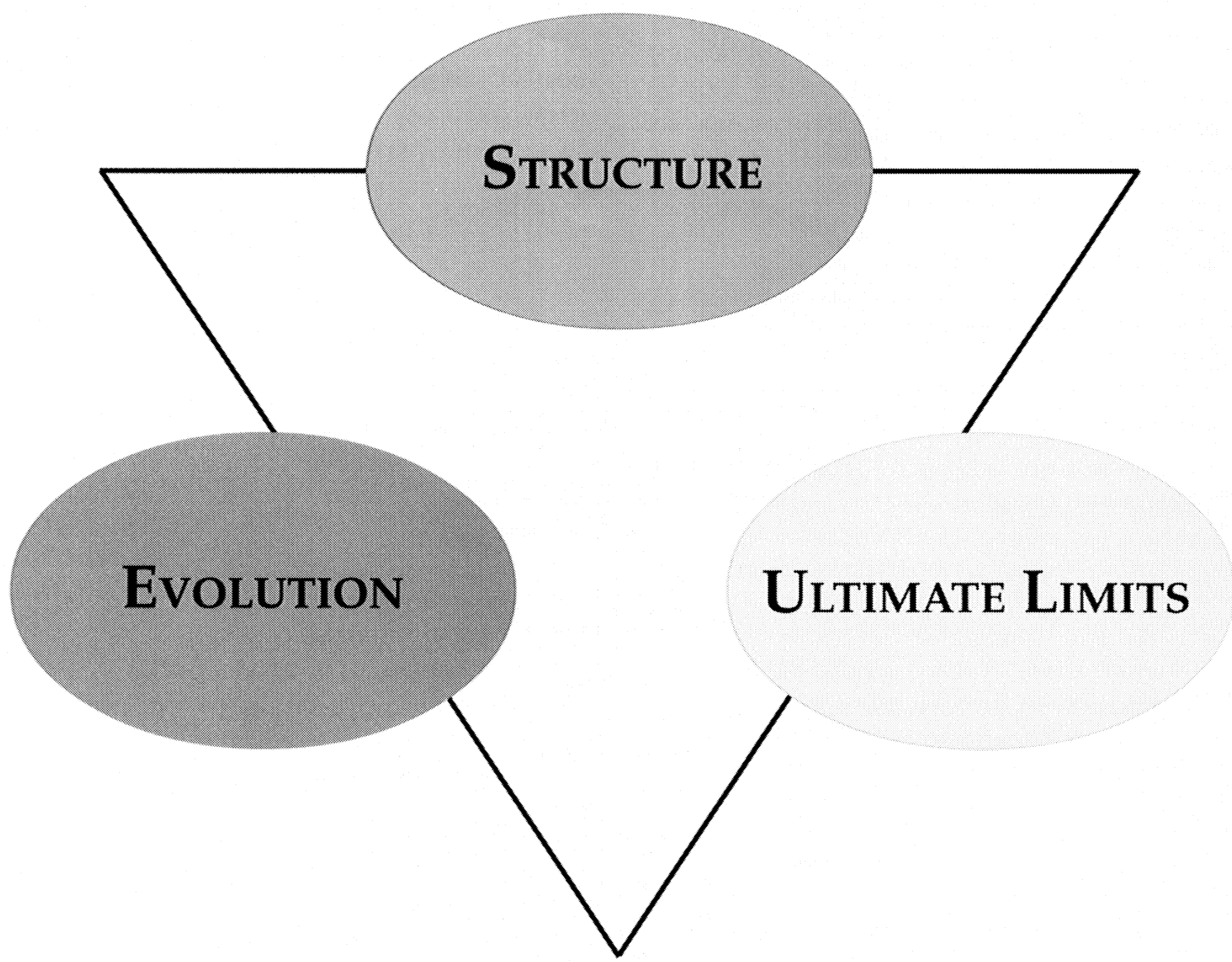
In order to organize our Roadmap, we have formulated three fundamental Quests which we present below. These are our overarching goals of broad scientific and popular appeal. However, to be more specific about our goals we have used these quests to define six more focused Campaigns that pose general questions that can be addressed over the next twenty years. We then present the mission portfolio suggested by these campaigns. This portfolio, in turn, implies technological groundwork that must be initiated now if we are not to fall behind schedule to carry out the campaigns.

One feature common to the six campaigns that we introduce is that they all represent data-rich investigations. In order to complete the science program all the way through to important and durable results, it will be necessary to maintain a strong data analysis program and to support theoretical investigations that both address campaign-specific issues and reach out to make connections to other research areas and other themes.

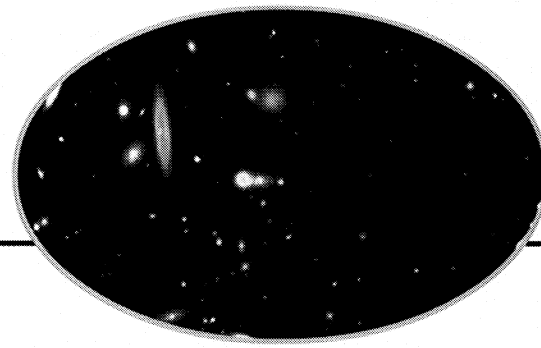
The priorities in the present Roadmap have an extensive heritage from a diverse set of prior studies. These include the Astronomy Survey Committee ("Bahcall Report"), the more recent update from the Task Group on Space Astronomy and Astrophysics ("Thaddeus Report"), the panel reports from the "Mission Concepts for Astrophysics" study, and many specialized, discipline-specific reports commissioned by NASA and the National Research Council (NRC) including those on Cosmology, Cosmic-Ray Physics, Gamma-Ray Astrophysics and Optical-Infrared Astronomy.

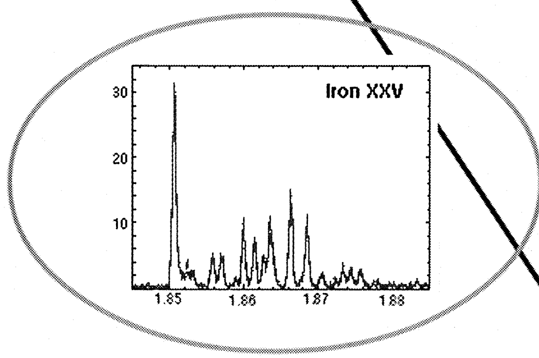
QUESTS

"The infinitude of the creation is great enough to make a world, or a Milky Way of worlds, look in comparison with it what a flower or an insect does in comparison with the Earth."
–Immanuel Kant

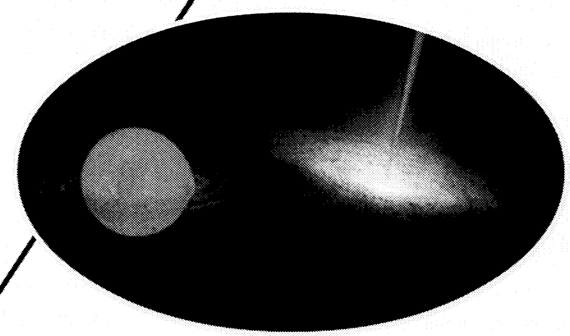


QUESTS



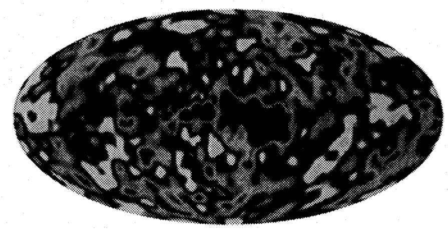


The Structure and Evolution of the Universe Roadmap derives from three fundamental QUESTS – *issues of broad scientific and popular appeal*

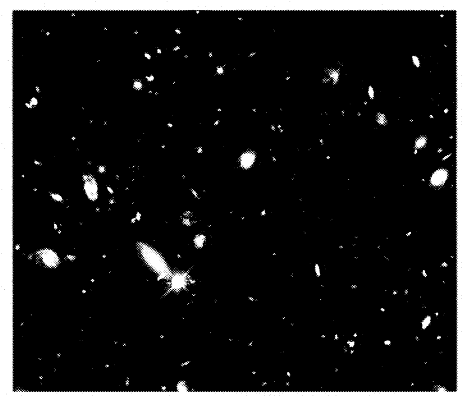


QUESTS: To Explain STRUCTURE in the Universe and Forecast Our Cosmic Destiny

Galaxies and clusters of galaxies form from tiny fluctuations in the ancient Universe. Remarkably, we can measure these fluctuations by mapping the cosmic background radiation and relate them to the structure that we observe in the modern Universe

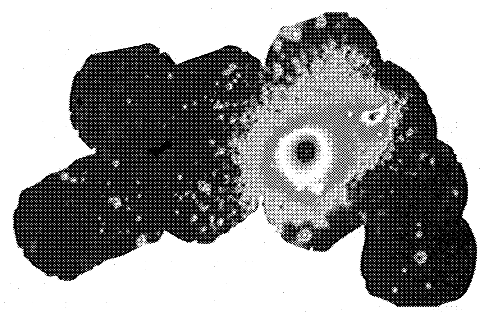


The microwave temperature of the sky measures incipient structure in the 300,000-year-old Universe



Galaxies formed when the Universe was roughly one to five billion years old

WHAT NEXT?



Giant clusters of galaxies in the present Universe, as seen in X-rays, were drawn together by gravity

QUESTS: Structure

"We now have a hasty sketch of some of the general features of the observable region..."

–Edwin Hubble

To Explain Structure in the Universe and Forecast our Cosmic Destiny.

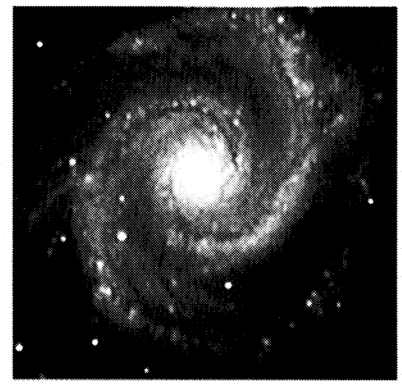
MORE THAN 70 YEARS AGO, EDWIN HUBBLE and others discovered that galaxies are receding from each other. The Universe is expanding, so it had a beginning. The first challenge is to measure its size (as quantified by the Hubble constant) and its age. Current determinations of these now have a rough uncertainty of 20 percent. However, in order to make the connection to fundamental physics and to develop a proper understanding of our cosmic history, we need to perform these measurements to accuracies of a few percent, as well as to measure directly the shape or geometry of the Universe. Is the Universe flat like a piece of paper (as theorists confidently assert), or is it curved like the surface of a sphere and, if so, by how much?

In 1964, Arno Penzias and Bob Wilson serendipitously found faint, high frequency radio emission spread isotropically over the whole sky. This cosmic background radiation is understood as a remnant of the primordial fireball, the big bang, which gave birth to our Universe roughly 12 billion years ago. Much contemporary astronomy traces the evolution of the Universe from a hot, smooth gas of matter and radiation to the highly structured entity, composed of galaxies, stars, and planets, that we see today. This structure stems from tiny departures from uniformity in the early Universe. The pull of gravity, due mostly to mysterious dark matter, causes the higher density regions to expand less rapidly and then to condense into galaxies that are themselves collected into giant clusters and groups.

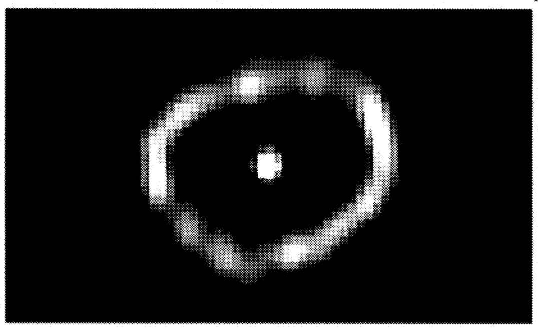
Yet we understand very little about how this evolution happened. How long after the big bang did galaxies, stars, and planets form? Was the growth bottom up with stars and star clusters forming first and then gravitating together to form galaxies and clusters of galaxies, or was it top down progressing from huge walls and filaments evident in the local distribution of galaxies, through galaxy clusters and groups to the galaxies and stars themselves? The microwave background radiation was last scattered by matter some 300,000 years after the big bang. Observations of this radiation show that the matter in the Universe was very smoothly distributed then, but more careful scrutiny by COBE discovered the tiny fluctuations out of which the giant patterns in the local distribution of galaxies formed some billions of years later. Our quest is to define the precise structure at age 300,000 years (through mapping the microwave background radiation) and then to understand how the matter became increasingly clumped until it formed the galaxies, stars and planets which characterize our Universe today.

The fate of the Universe is determined by its average density and this, in turn, is related to the geometry and the rate of expansion. If its density is low, the Universe will continue to expand forever. However, above a critical density, the inevitable pull of gravity slows the expansion and may even reverse it, causing the Universe to contract, eventually ending its life in a Big Crunch. The mass in our Universe is dominated by dark matter. To know our cosmic destiny — whether the Universe will expand forever or eventually collapse — we need to measure the mass of the dark matter and determine its nature.

QUESTS: To Explore the Cycles of Matter and Energy in the EVOLVING Universe

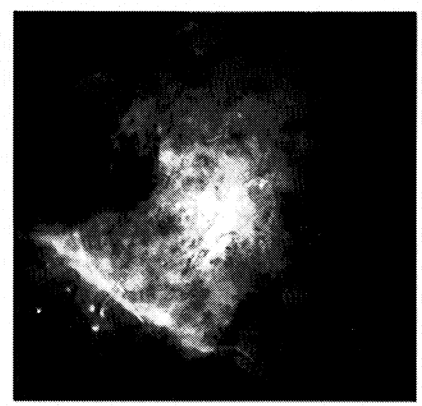


Nova Cygni



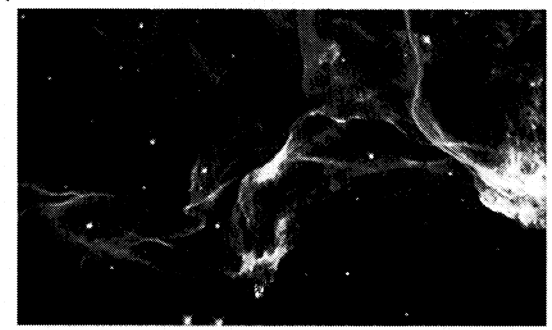
Explosions on white dwarf stars return matter to the interstellar medium

Orion Nebula



Star-forming regions remove matter

Cygnus Supernova Remnant



Supernova explosions are the main supply of energy

QUESTS: Evolution

To Explore the Cycles of Matter and Energy in the Evolving Universe.

OUR COSMIC NEIGHBORHOOD, OUR GALAXY, and the universe of galaxies have such complex webs of interactions that astronomers think of them much as biologists think of ecosystems, tracing the flow of matter and energy from one form to another. Stars have their origins in dense gas clouds, which condense and fragment to form clumps of stars with a range of masses. For a star, mass is destiny — the low mass stars slowly fuse hydrogen into helium, while massive stars burn fiercely for a brief cosmic moment. Stars of about one half the Sun's mass have a lifetime which is as long as the present age of the Universe: the oldest stars in the Milky Way Galaxy contain a sample of the Universe from 12 billion years ago. These stars show that our Galaxy was once very poor in the heavy elements out of which planets, spacecraft, and astronomers are made. More recently formed stars, like the Sun, have inherited a legacy of atoms that was created in the massive stars that lived out their short cycles more than 5 billion years ago. Massive stars make essentially all of the elements of our world–oxygen, calcium, iron–and they blast these new elements into the gas between the stars in supernova explosions. In these violent events, a single star shines as brightly as a billion Suns, while accelerating cosmic rays, forming cosmic dust, and stirring the magnetic field between the stars. This is the major source of energy for the interstellar medium. The accumulated products of all these complex events become the material for new stars which form from the densest regions of the interstellar gas. In these dusty and obscure venues, the atoms can combine into molecules, including organic molecules related to life. Understanding how these complex events are related, from nuclear reactions through the formation of stars and their planets, is a prerequisite to understanding the origin of life in the Universe.

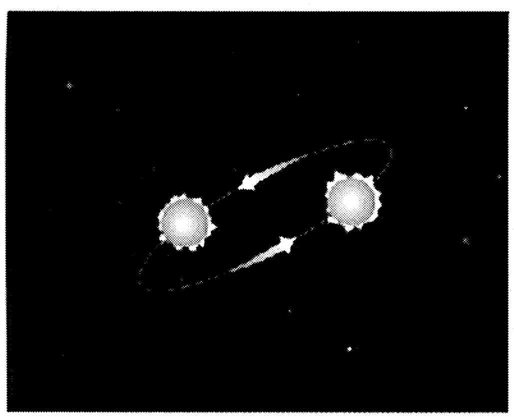
Lower mass stars evolve more sedately from a normal "main-sequence" star like the Sun, expanding to make red giants that would engulf most of our solar system, and then losing mass to leave behind hot white dwarf stars. This is the major source of matter for the interstellar medium.

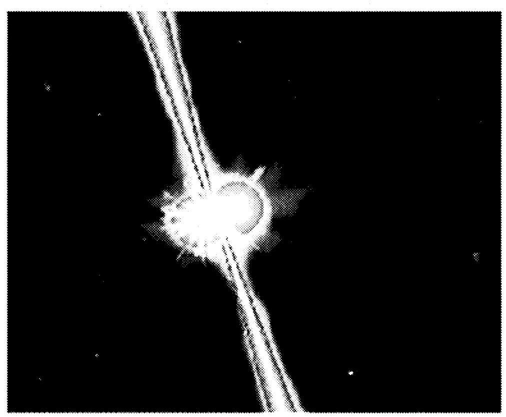
We are just beginning to learn how similar considerations apply to the larger scale phenomena of galaxy formation, and the interaction between galaxies and the intergalactic gas. Like the ancient stars that give a clue to chemical evolution in our Galaxy, quasars are ancient events that may signal the formation of galaxies when the Universe was only one fifth its present age. Quasars are probably massive black holes at the cores of nascent galaxies. They illuminate the chemistry of the intergalactic gas, heat it, and affect subsequent star formation. As stars are born and die in galaxies, and as galaxies collide, these violent events sweep the accumulated gas into the space between galaxies. Recent X-ray observations show this ancient gas and allow us to begin to trace the effects of stars on the chemistry of the Universe.

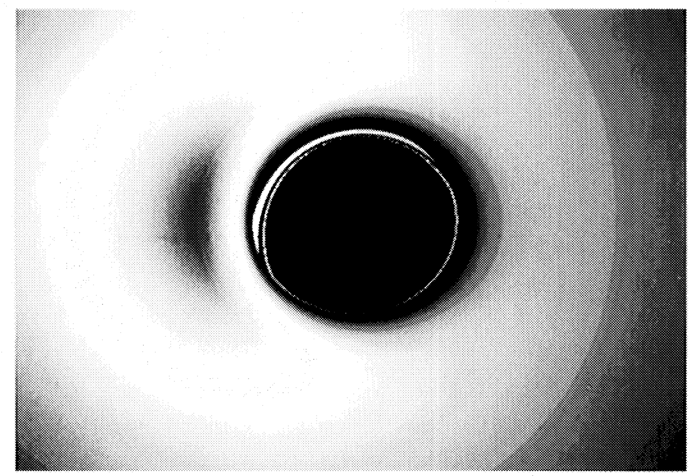
QUESTS: To Examine the ULTIMATE LIMITS of Gravity and Energy in the Universe

The Universe provides cosmic laboratories that allow us to test our physical theories by observing how matter behaves under extreme conditions

Coalescing binary neutron stars may be the source of many of the gamma ray bursts as well as the ultra high energy cosmic rays







Simulation of how a disk of accreting matter around a spinning black hole would appear to a distant observer

QUESTS: Ultimate Limits

"The relativistic theory of gravitation creates serious difficulties."
–Albert Einstein

To Examine the Ultimate Limits of Gravity and Energy in the Universe.

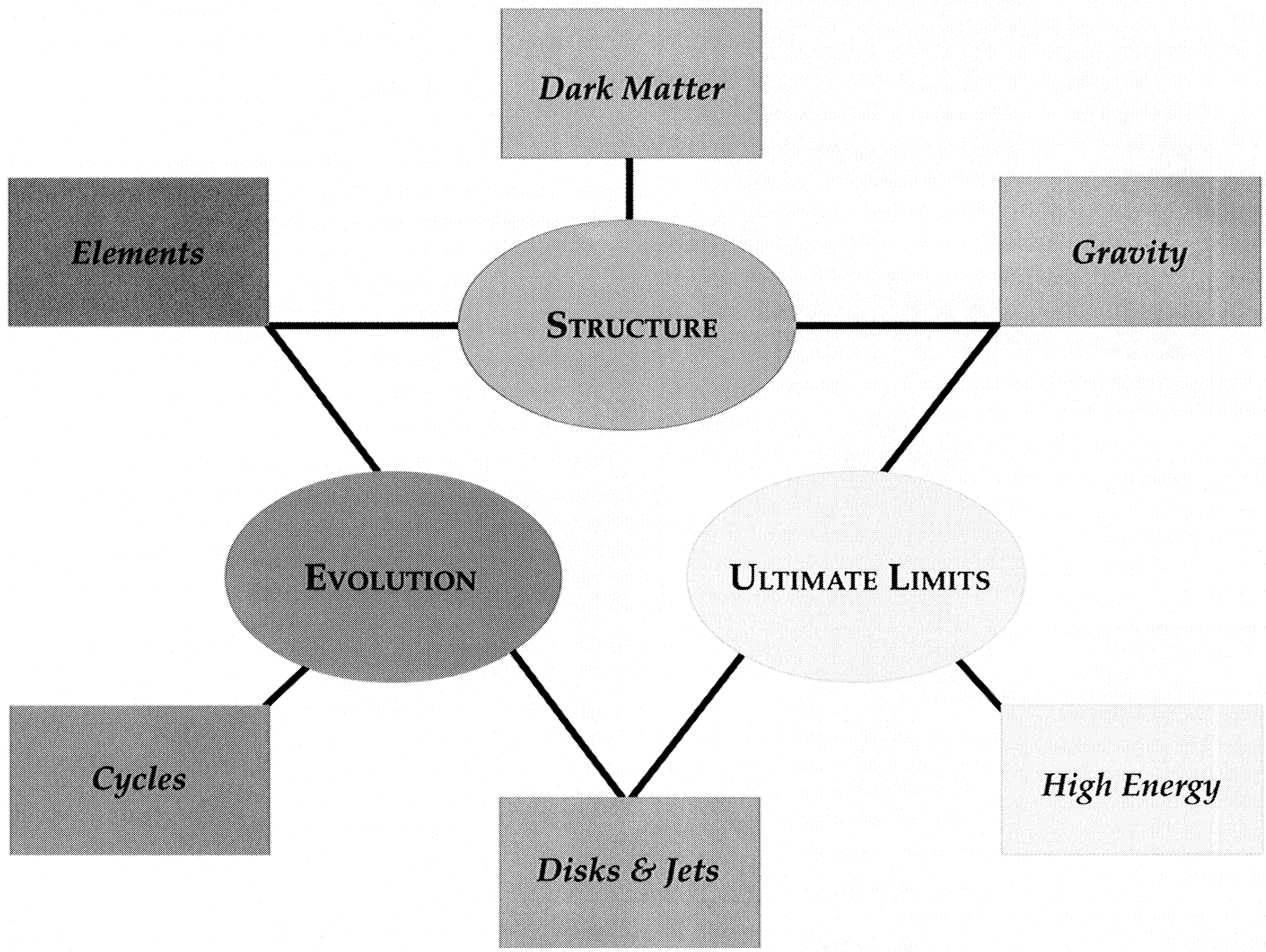
We now know that massive stars evolve relatively rapidly to form compact objects, known as white dwarfs, neutron stars and black holes. The density of matter at the center of a neutron star exceeds that of atomic nuclei and is some 45 orders of magnitude greater than that of intergalactic space, which is orders of magnitude smaller than the most tenuous vacuums that can be made on Earth. Other quantities show similarly huge ranges — the magnetic field of a neutron star may be as high as 10^{13} G, while that in intergalactic space is certainly less than 10^{-7} G. The temperature at which a neutron star is formed is about 10^{10} K, but the temperature of deep space is only 2.7 K. The kinetic energy of individual atomic or nuclear particles extends from about 10^{-3} eV for atoms in the cold, interstellar gas to over 10^{20} eV for the highest energy cosmic rays. Because of these extremes, the quest to understand the Universe is not an easy one, for we cannot create experiments in laboratories on Earth with the same conditions. Conversely, these cosmic laboratories permit astrophysicists to perform unique, passive experiments that constrain our physical theories of matter under extreme conditions.

Cosmic matter at high densities may be probed in many ways. For example, as a newly formed neutron star cools, it may be observed as a hot object in X-rays. Matter falling onto a neutron star also heats up to a high temperature and also radiates in the X-ray band. It will also spin rapidly, but then progressively slow down. This slowing causes cracking in the interior of the star, resulting in spin-ups of the rotation speed. These spin-ups can be monitored from observations of the radio and X-ray emission and tell us about the hidden interior of the star.

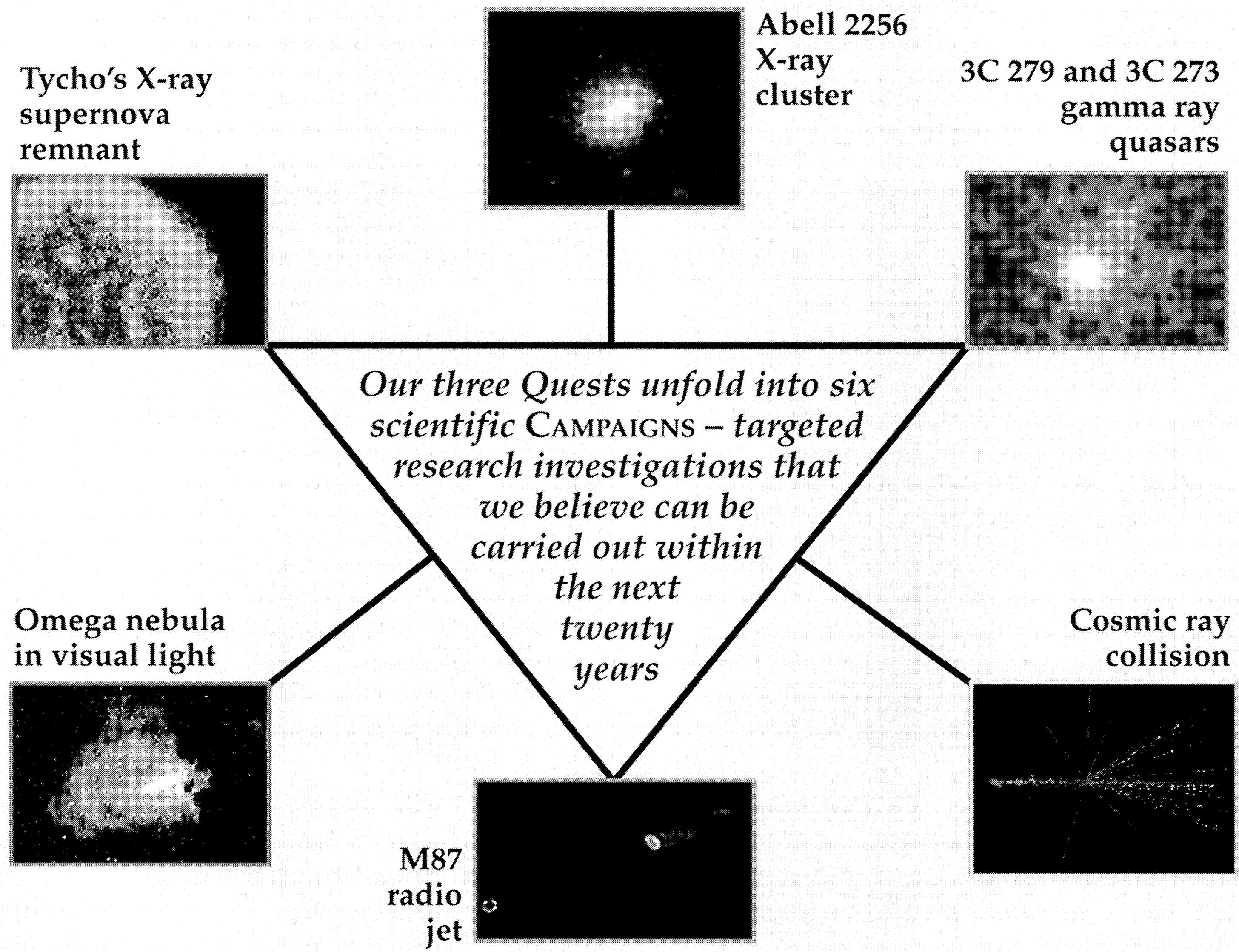
In another example, much of the focus in fundamental physics over the past 50 years has centered around observing elementary particles at the highest energies attainable by terrestrial particle accelerators. The Universe provides its own natural particle accelerators that can accelerate protons to energies over ten million times larger than those attainable on Earth. We can observe their interactions with matter as they impact our atmosphere.

There are also extremes of gravity, especially black holes, where the gravitational potential well becomes so deep that light is unable to escape. The correct description of matter under these conditions involves the general theory of relativity, which is largely untested under conditions where the gravitational forces are relatively strong. In addition, the theory of relativity predicts the existence of gravitational radiation, ripples in the fabric of spacetime itself. Observing this radiation would allow us to perform new tests of relativity theory and would also give us fundamentally new information about the high velocity, strong-gravity regions where these waves are generated.

CAMPAIGNS

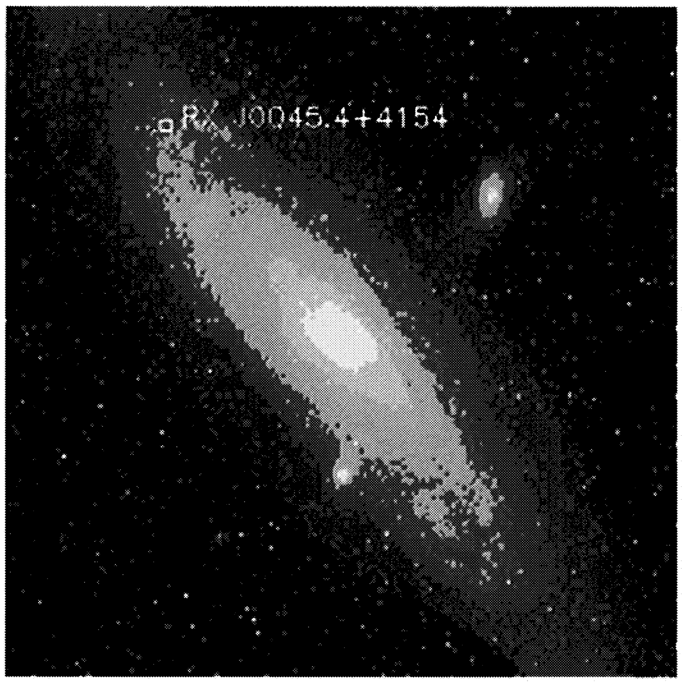

Dark Matter
Elements
Structure
Gravity
Evolution
Ultimate Limits
Cycles
Disks & Jets
High Energy

CAMPAIGNS (continued)

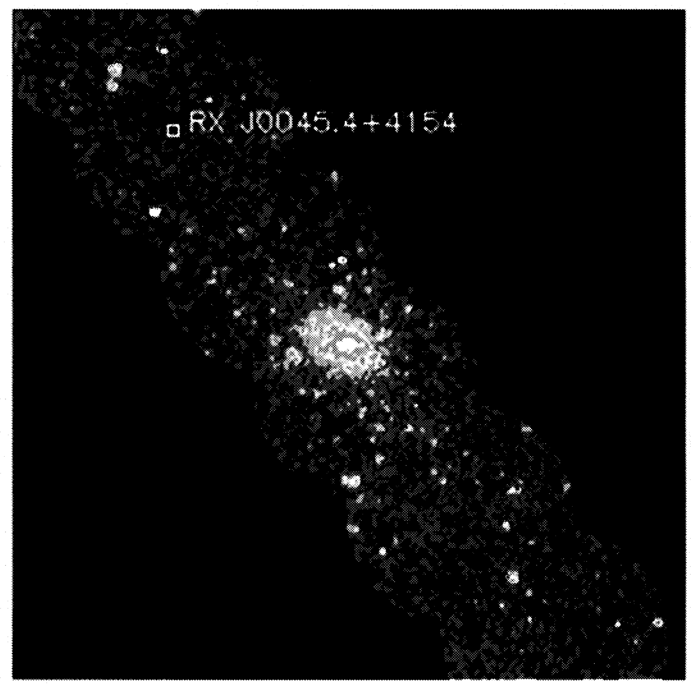


CAMPAIGNS: Identify DARK MATTER and learn how it shapes galaxies and systems of galaxies

Andromeda galaxy in the optical



Andromeda galaxy in X-rays



Galaxies form in gravitational potential wells dominated by dark matter. These dark matter halos extend well beyond the observed stellar population. They can, however, be mapped using X-ray telescopes by observing hot gas.

CAMPAIGNS: Dark Matter (continued)

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

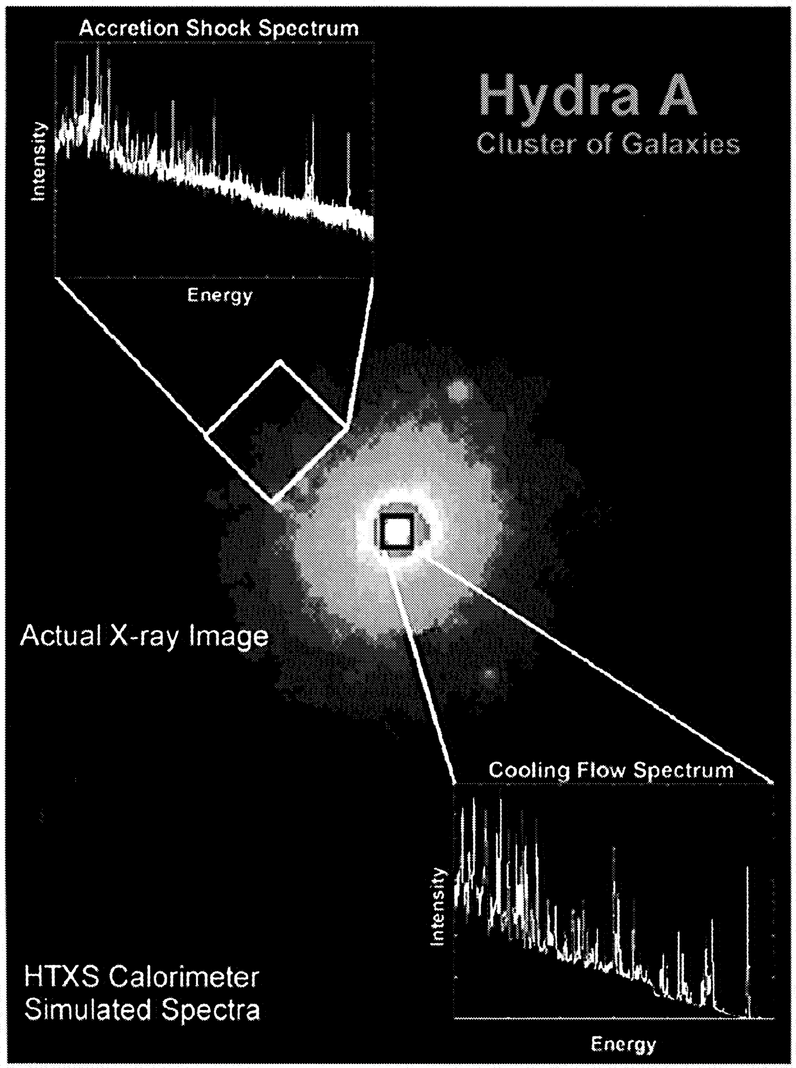
ONE OF THE MOST STRIKING DISCOVERIES of contemporary astronomy has been that most of the mass of the Universe is in a form that we cannot see. It is called dark matter and we do not know its nature. We can, however, detect it through the effects of its gravitational field and, in an indirect way, this may allow us to identify its nature. There are three distinct environments where this may be possible: individual galaxies, clusters of galaxies and the early Universe at the time of recombination.

If galaxies are dominated by dark matter, then they can be thought of as essentially invisible gravitational potential wells in which stars follow complex orbits moving with characteristic speeds of order 300 km s^{-1}. However, in the outer parts of elliptical galaxies the stars are replaced by hot, X-ray emitting gas whose density and temperature can be estimated using X-ray observations. By mapping this hot gas, one can develop a good mass model of the galaxy and trace the dark matter distribution to very large radii.

Clusters of galaxies are complex, multi-component systems with hundreds of galaxies, a hot intracluster medium, and dark matter evolving in a tightly coupled manner. As they are dynamically younger systems, their study furnishes fundamental insights into the formation of large scale structure in the Universe, especially if they can be observed at large distances when the Universe was much younger than its present age. This is because these clusters still carry the imprint of the small density fluctuations out of which they grew. In addition, as they are massive and relatively rare objects, they form only from fairly high peaks in the underlying density field. Measuring the incidence of these peaks with masses within a certain range is a powerful discriminator between different cosmological theories. Furthermore, an inventory of their mass components should be a good reflection of the primordial mix. By combining X-ray measurements with the theory of big bang nucleosynthesis, it should be possible to make rough estimates of the mean density and dark matter content of the Universe. A further cosmological clue comes from the incidence of substructure in these rich clusters. If it is low, then clusters are dynamically old and the Universe is of relatively low density. This type of investigation motivates the development of a High Resolution Imaging X-ray Telescope that would be able to see details as fine as those imaged by HST.

There also is a quite different approach to measuring the gas distribution and consequently the dark matter content of rich clusters. This involves measuring the small decrease that the hot gas produces in the apparent temperature of the microwave background radiation — the so-called Sunyaev-Zel'dovich effect. This is caused by the hot electrons in the cluster scattering the microwave photons to higher frequencies. This effect has been convincingly detected in observations from the ground. However, to measure it well in young and very distant clusters will require observations from space.

CAMPAIGNS: Dark Matter (continued)



Clusters of galaxies are also dominated by dark matter. X-ray observations have been able to measure its extent as in this example of the nearby cluster Hydra A. In the future, it is hoped to measure the temperature and the composition of the gas throughout the cluster so that we can understand the extent of the dark matter and the history of the cluster.

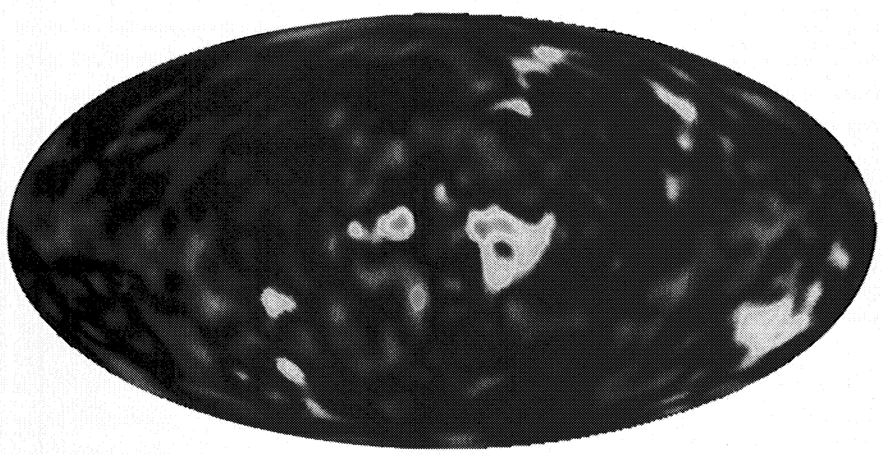
Cosmic background fluctuations have been seen by the COBE satellite coming from the epoch when ionized hydrogen changed into atomic hydrogen, when the Universe was 300,000 years old. These fluctuations can be used to obtain a quite different measurement of the matter content of the Universe. The way this works is that the fluctuations themselves are like giant sound waves which travel with a speed that depends upon how much mass is present. The observed fluctuations are larger when there is a coincidence between the period of the waves and the time it takes the photons to free themselves from their electron rich environment. This is known as the acoustic peak and ultra-sensitive measurements of the cosmic background can be used to locate it and translate its size and angular scale on the sky into a direct inventory of the contents of the ancient Universe. This can be combined with observations of the modern Universe which are directed towards a similar goal. One of the greatest hopes of contemporary astronomy is that these two, essentially independent, approaches will be found to be concordant, thereby validating our theory of cosmology. This program is one of several strong linkages between the SEU theme and the ASOPS theme and completing it will also require the full deployment of space-based infrared telescopes as well as ground-based optical telescopes.

Through approved missions including MAP, as well as investigations with HST and AXAF, we hope to have, early in the next decade, a good understanding of the primary cosmological parameters including the age and scale of the Universe and its mass density, including both the baryon fraction and the value of the cosmological constant. If this optimism is well-founded, we will have a framework with which we can work to lay out the more detailed, paleontological record of how stars, galaxies, and large scale structures form and evolve. Crucial to this endeavor will be measurements of the distribution of the mass around galaxies and clusters of galaxies and how these change with cosmic time. Since most of the matter is dark and resides in the outermost parts of these entities, it will be necessary to trace the gravitational potential wells by studying the hot X-ray emitting gas in galaxies and clusters, measuring both its distribution and its temperature in some detail. This will require the deployment of high angular resolution X-ray imaging telescopes and a high spectral resolution mission. To measure cluster evolution requires mapping the gas and dark matter in individual high redshift clusters formed when the Universe was a fraction of its present age and this imposes the additional requirement of high sensitivity.

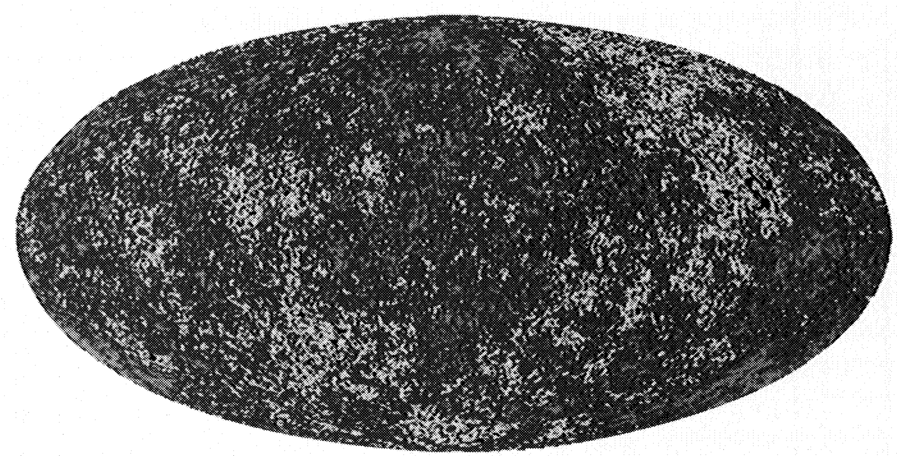
Of equal importance is direct observation of very distant galaxies which can pin down the epoch of galaxy formation. This is most naturally carried out at optical and near infrared wavelengths and this is a prime motivation for the Next Generation Space Telescope (NGST). However, it turns out that a typical spiral galaxy radiates a quarter of its bolometric luminosity in the far infrared. Indeed many galaxies emit most of their radiation in the far infrared and submillimeter and may only be observable at these wavelengths. Observations of this part of the spectrum are an excellent method for finding high redshift galaxies that complements searches that will be made in the near

CAMPAIGNS: Dark Matter (continued)

Observation of the Cosmic Microwave Background Radiation provides an independent approach to determining the amount of dark matter in the Universe. The image on the left shows the temperature of the sky in microwaves as revealed by COBE. Despite the poor angular resolution it was possible to say that the observed fluctuations had roughly the form predicted by a wide range of theories. However, in order to measure how much dark matter was present when the Universe was 300,000 years old, observations must be made with the detail exhibited by the simulation on the right.



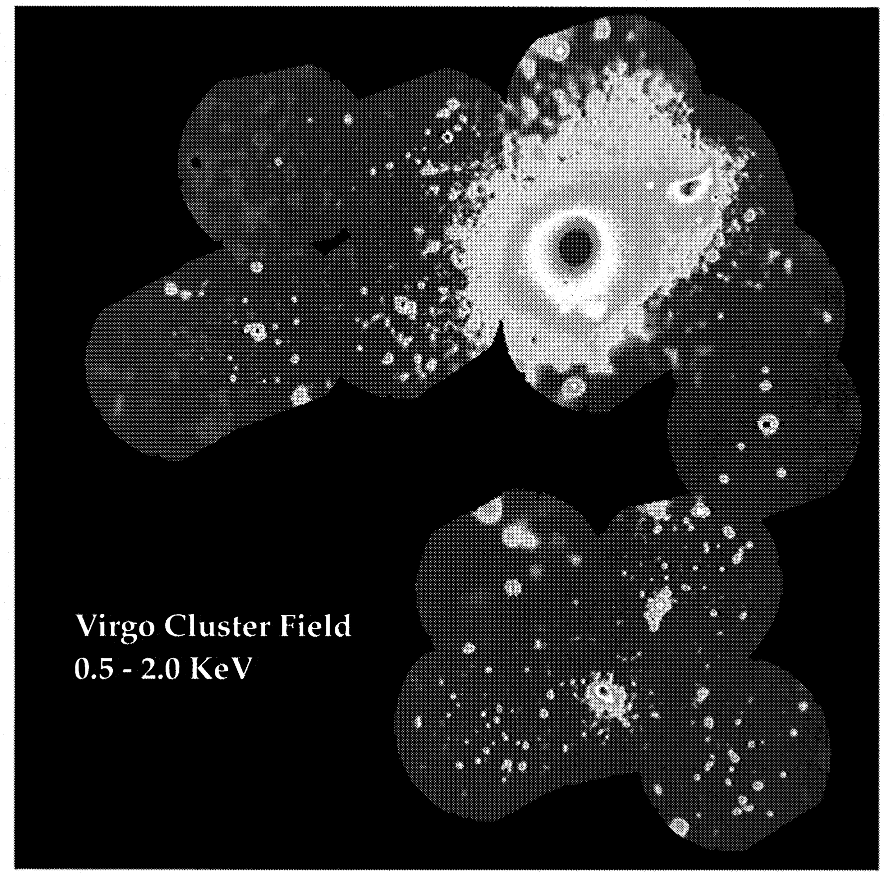
COBE DMR 4-Year Sky Map



MAP Simulated Sky Map

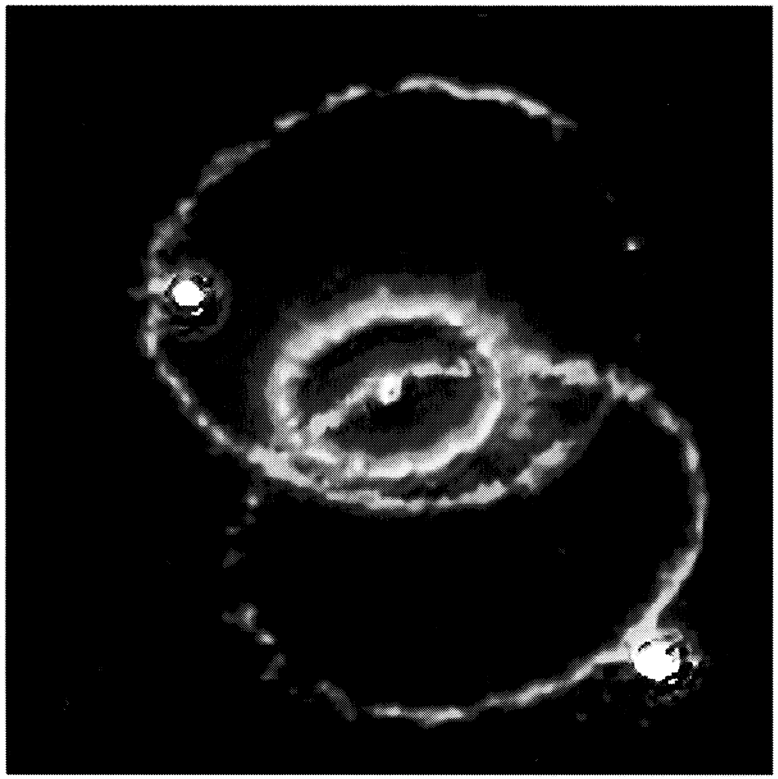
infrared using NGST. Again we see a strong connection to one of the quests of the ASOPS Roadmap.

This campaign has so far assumed a standard model of cosmology that attributes structure formation to gravitational instability in cold dark matter. There is an alternative view which would be of great interest to physicists if it turns out to be correct. This is that phase transitions in the very early Universe left it scarred with a variety of topological defects, rather like the dislocations and grain boundaries that interrupt the crystal structure of a rapidly cooled metal, and it is these that are responsible for the structure that we see. As yet we have no evidence for the existence of such defects and future microwave background observations ought to settle the matter. However, it is quite possible that they will decay into ultra-high-energy cosmic rays ($E>10^{20}$eV). Measurements of the energy spectra of these highest-energy cosmic rays would then tell us about particle physics at even higher energies.



CAMPAIGNS: Find out where and when the CHEMICAL ELEMENTS were made

The Rings of Supernova 1987A



The heavy chemical elements are manufactured through nuclear reactions occurring in stars and supernovae. These are released by stellar winds and supernova explosions throughout the interstellar medium.

CAMPAIGNS: Chemical Elements (continued)

Find out where and when the chemical elements were made.

WE HAVE KNOWN FOR NEARLY FORTY YEARS *how* the chemical elements were made. Hydrogen, helium and trace amounts of a few other light elements were made mostly in the first few minutes of the expansion of the Universe; the remainder are products of nuclear reactions occurring in stars and supernova explosions. Indeed, the theory of stellar evolution is one of the triumphs of contemporary astrophysics. With certain fascinating exceptions, we have a fairly comprehensive understanding of how a star evolves and shines as it ages from youth to senescence, all the while converting its hydrogen and helium fuel into heavy elements. These heavy elements are released by stellar winds and supernova explosions and disseminated throughout the interstellar medium where they cool and collapse under the action of gravity so that new generations of stars can form. The bulk material of our solar system — Sun, Earth, Moon, meteorites — is a sample of the local interstellar gas mix 4.6 billion years ago. By contrast, the cosmic-rays sample Galactic material that was accelerated relatively recently, about ten million years ago. We can measure the relative abundances of the different elements and their isotopes directly within our solar system, in cosmic rays, and spectroscopically in stars and elsewhere and compare with the results of detailed nuclear physics and stellar structure computations. In general such computations have successfully matched the observations — even when, as in certain cosmic-ray elements, isotopic abundances are strikingly different from those found in the bulk material of the solar system. Further important tests await isotopic measurements of rarer cosmic-ray elements, and spectroscopic observations in many parts of the electromagnetic spectrum from the submillimeter and far infrared to the X-rays and gamma rays.

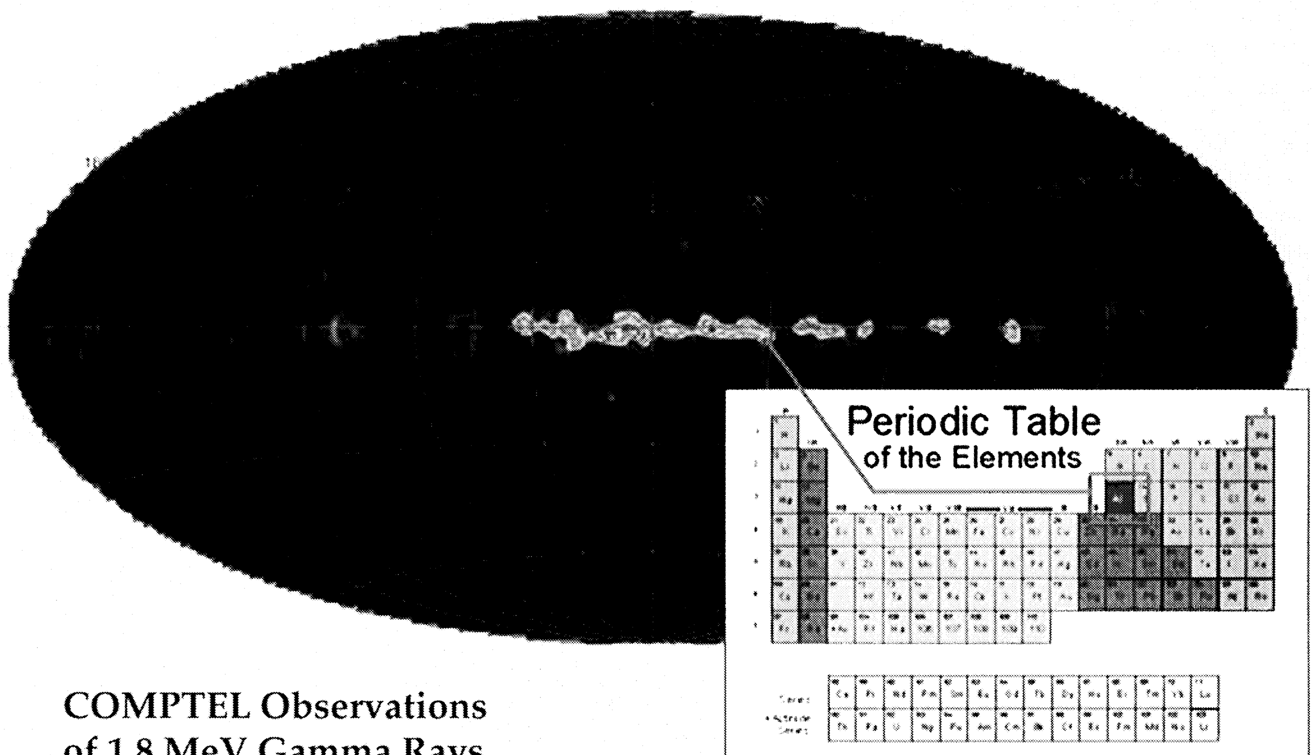
However, we also need to understand just *where* and *when* the chemical evolution happened during the lifetime of a typical galaxy like our own. One way to explore the processes of chemical evolution is to observe our galactic neighbors. The traditional method is to use stellar spectra which tell us about the composition of selected stars. We anticipate that giant ground-based optical telescopes together with complementary observations from HST will enable astronomers to perform these abundance analyses on more distant and consequently younger galaxies. However, this technique can only provide part of the information and is subject to strong biases. Several complementary approaches must be used to get the full picture.

One of these involves high resolution X-ray spectroscopy. The first X-ray images of elliptical galaxies changed the widely held view that they were gas-free. Instead they showed that hot, gaseous coronae with temperatures of 10 million K and gas masses up to 10 billion suns surround these galaxies. Since this hot gas contains the fossil record of past generations of stars, spatially resolved X-ray spectroscopy can be used to determine the earlier history of star formation and supernova activity in these galaxies.

Another approach leads us to consider the role of interstellar dust. A significant fraction of the heavy elements created by stars

CAMPAIGNS: Chemical Elements (continued)

Spectroscopic observations in many parts of the electromagnetic spectrum, including submillimeter, far infrared, X-rays and gamma rays can test theories of how the elements are made and disseminated.



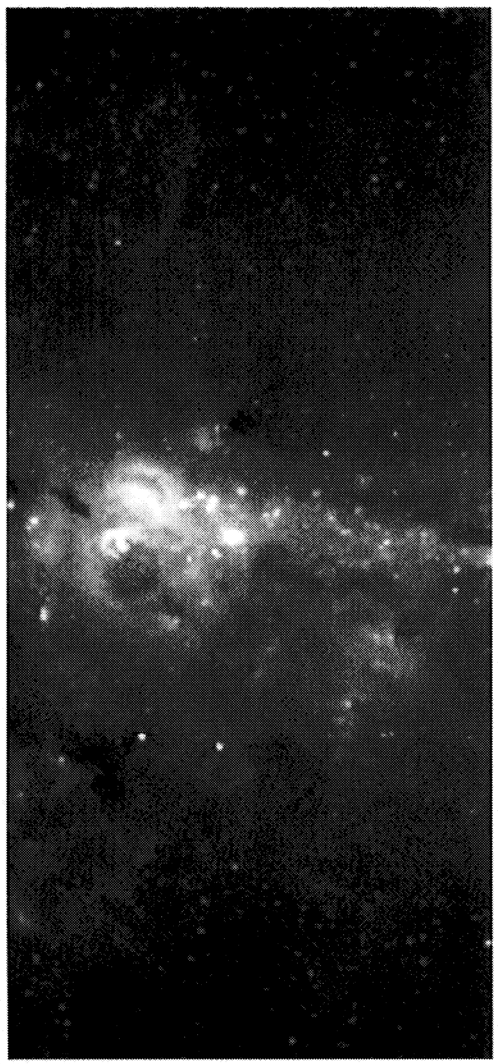
COMPTEL Observations of 1.8 MeV Gamma Rays condense into tiny grains, typically smaller than a micron, known as interstellar dust. At optical and near infrared wavelengths, this dust is an impediment to observation because it makes galaxies quite opaque, preventing us from seeing them easily and distorting their spectra in ways that are hard to quantify. However, when we look at these same galaxies at far infrared and submillimeter wavelengths, we actually see the dust as a bright source. All the optical and ultraviolet radiation absorbed by the dust causes the galaxies to glow at these wavelengths. We can then see these galaxies out to large distances and, indirectly, through measuring their dust content, understand their stellar histories.

A novel approach to interstellar dust has recently become possible in terrestrial laboratories. A small fraction of the refractory grains within meteorites have been shown to be of pre-solar origin. Tiny grains of graphite, silicon carbide, oxides of aluminum and titanium, and other refractory minerals have widely varying isotopic abundances dramatically different from those found everywhere else in the solar system. The isotopic abundances are typical of those seen spectroscopically, and predicted theoretically, around various kinds of evolved stars and supernovae. Further study of such grains will be valuable for understanding the chemical evolution of the Galaxy. These lab studies of meteorites, which are formally the province of the ESS theme, are, nonetheless, of great relevance to this campaign.

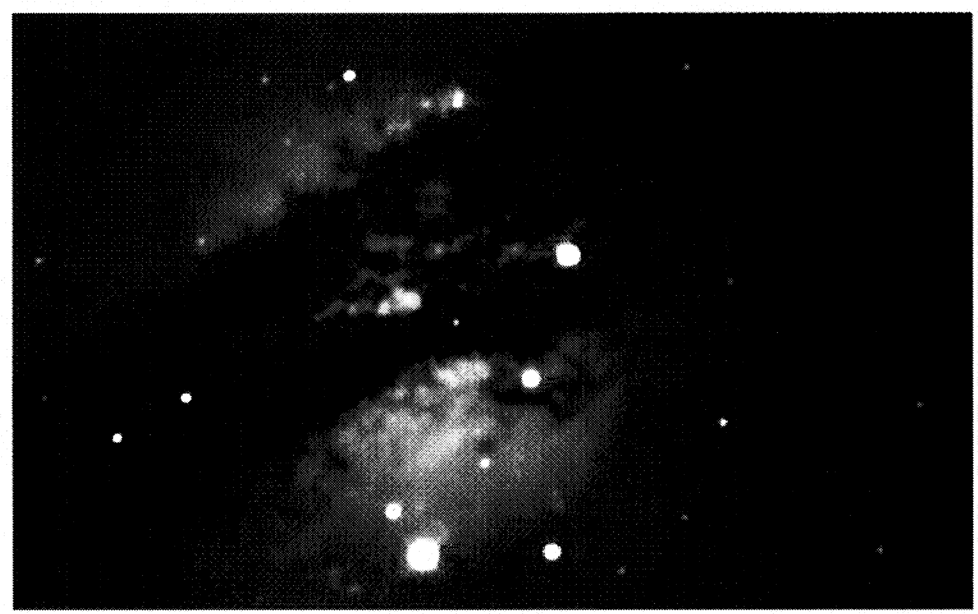
Turning to our local neighborhood, we know of several hundred individual remnants of supernova explosions that occurred over the past tens of thousands of years in our own and neighboring galaxies. These are seen as expanding spheres of hot gas. It is possible to measure the abundances of individual elements through the X-ray and gamma-ray lines that they emit before this gas gets mixed with the general interstellar medium. At present, it is only possible to detect the most common elements. However, future observations should give us a good picture of the formation of essentially all of the elements between carbon and zinc.

Another way to monitor the recent formation of elements is to observe the products of radioactive decay in our own Milky Way Galaxy and its satellites. This can be done using gamma-ray observations of the decay products of short-lived nuclei like ^{56}Co, as happened with the bright supernova in the Large Magellanic Cloud, or longer-lived species like ^{26}Al throughout the interstellar medium of our Galaxy, which measures supernova activity over the past million or so years. Observations of other long-lived radionuclei, such as ^{60}Fe, will add to the understanding of the sites of nucleosynthesis. The gamma rays provide a direct probe of the process of element formation in supernova explosions. They are also a highly penetrating radiation and therefore allow observations to be made deep into the enshrouding gas of the explosion. Observations of the 511 keV line of positron annihilation indicate large production of positrons, the antimatter counterparts to electrons, very likely from decay of radioactive nuclei, but better mapping of this line is required to understand the origin of these positrons.

CAMPAIGNS: Chemical Elements (continued)



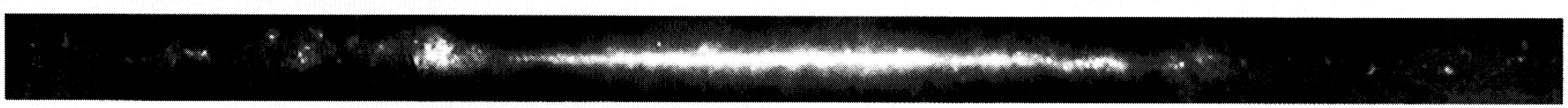
The dusty galaxy Centaurus A as seen in the optical (below). Dramatic dust lanes obscure our view. At far infrared and submillimeter wavelengths, the heavy elements that condense into dust grains become visible, as in this beautiful image of our Galactic center (left), seen in the far infrared. Observations at these wavelengths can be used to study the stellar histories in distant galaxies.



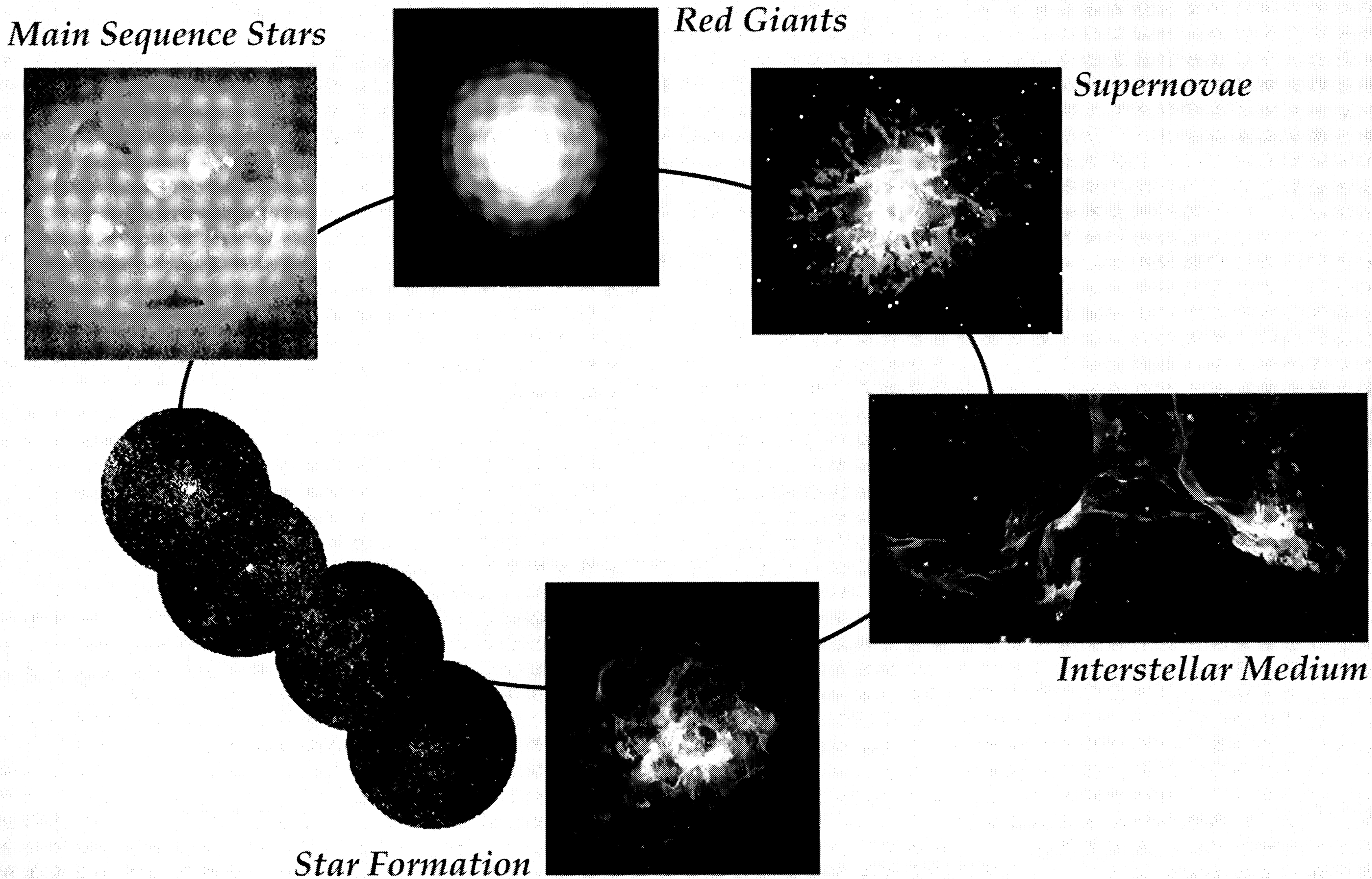
CAMPAIGNS: Chemical Elements (continued)

We have a fairly good explanation of how stars end their lives. By contrast, our understanding of how stars are formed is literally shrouded in mystery, thanks again to the effects of interstellar dust. The sites of star formation are mainly the giant molecular clouds which are dense and quite obscured at optical wavelengths. However, when we turn to the far infrared, submillimeter, and X-ray parts of the spectrum, the clouds become transparent and allow us to observe what is actually happening. We find that the gas is able to form a large variety of exotic molecules typically not found in terrestrial chemistry laboratories. By making careful spectroscopic study of all the different lines that these molecules form, it should be possible to understand where and under what conditions stars can form and what determines whether these stars are massive or small.

Although stars generate their radiation through thermonuclear reactions, protostars have not yet begun to burn hydrogen and instead derive their energy from gravity as the star contracts. Far infrared observations can detect thermal radiation from the dusty cocoons around embryonic stars. Infrared spectroscopy also will determine the density and temperature as well as the composition and size of the dust particles in the proto-planetary disks around the forming stars. Submillimeter spectroscopy can determine motions in star-forming molecular clouds. Since new stars often form in clusters, good spatial resolution also is necessary to isolate the properties of individual sources. Pre-main-sequence stars often emit X-rays, which through ionization of the gas in the cloud influences further star formation. These studies are crucial to understanding the origin of extra-solar planets, demonstrating another important connection to the ASOPS theme.



CAMPAIGNS: Understand the CYCLES in which matter, energy, and magnetic fields are exchanged between stars and the gas between stars



CAMPAIGNS: Cycles (continued)

Understand how matter, energy and magnetic field are exchanged between stars and the gas between stars.

INDIVIDUAL GALAXIES CONTAIN ABUNDANT GAS, in molecular, atomic and ionized states. This interstellar medium also contains magnetic fields, cosmic rays, dust grains and radiation and each of these components is vital to maintaining the thermal and dynamical state of the gas. The interstellar material is continually recycled as it coalesces to form new stars, and is replenished as stars evolve and die. Supernovae explosions violently disturb and heat much of the volume to million degree temperatures and expel gas from the galaxies. In order to understand galaxies and their evolution at all, it is necessary to appreciate the complex, ecological balance that operates in the interstellar medium.

The interstellar medium can be observed throughout the electromagnetic spectrum as never before and we are poised to develop a quantitative understanding of our Galactic neighborhood. The complexity and number of components in the interstellar medium require gamma-ray, X-ray, ultraviolet, infrared, submillimeter and very low radio frequency instruments with improved angular resolution and modest to high spectral resolution.

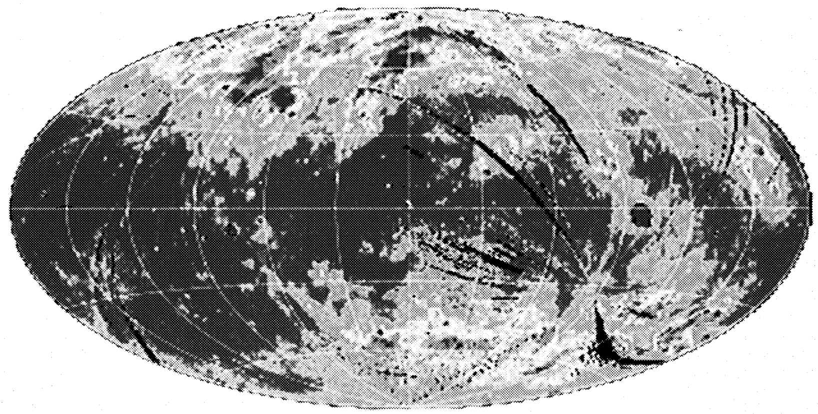
Ultraviolet (UV) absorption lines produced by interstellar material were first observed by the Copernicus satellite in the spectra of stars. This discovery led to abundance determinations for many of the heavy elements, which in turn provided new insights into the condensation of material onto dust grains. Surveys of molecular hydrogen provided accurate estimates of local temperatures, densities, and the ultraviolet fluxes from stars within molecular clouds. UV radiation from hot stars affects the energy balance and chemistry of the molecular clouds. The Space Telescope Imaging Spectrograph (STIS), a second generation HST instrument, and the Far Ultraviolet Spectroscopic Explorer (FUSE) will provide, in the near future, the high spectral resolution, sensitivity, and photometric precision necessary for forefront ultraviolet observations of the interstellar medium. Cloud structure, as well as the effects of shocks from cloud-cloud collisions or outflows from protoclusters, can be observed through far IR and submillimeter spectroscopy.

X-ray observations of our Galaxy, such as those from ROSAT, show a wealth of structure in the interstellar medium, such as deep absorption along the Galactic plane and strong emission from very ancient supernova remnants. Since it is through supernovae that both heavy elements and substantial energy are injected into the interstellar medium, studies of supernovae and their remnants are crucial for understanding these processes. X-ray observations have provided much of our current knowledge of the physical conditions of the hot gas in supernova remnants. AXAF, with its high spatial resolution, broad energy range, and excellent spectroscopy, will map the heavy element distribution in individual supernovae remnants, both in our Galaxy and in the Magellanic Clouds.

Gamma-ray observations provide a measurement of past supernova activity especially within dense clouds where supernovae are essentially invisible. Supernovae produce a number of long-

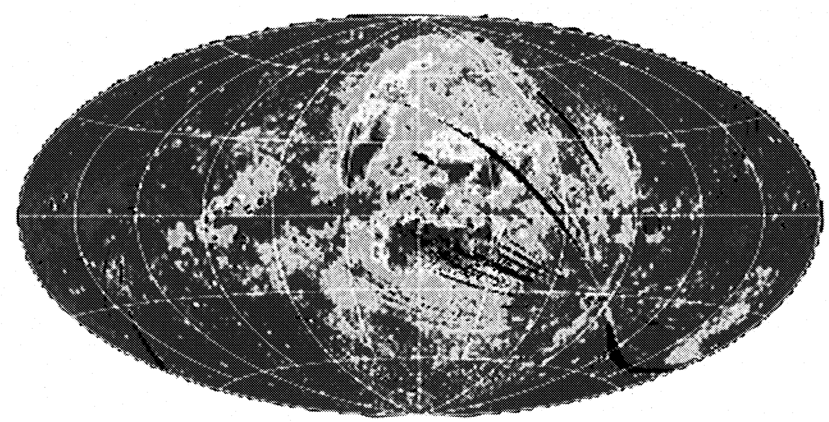
CAMPAIGNS: Cycles (continued)

The Galaxy observed at low X-ray energies.



X-ray observations of our Galaxy show a wealth of structure in the interstellar medium.

The Galaxy observed at intermediate X-ray energies.



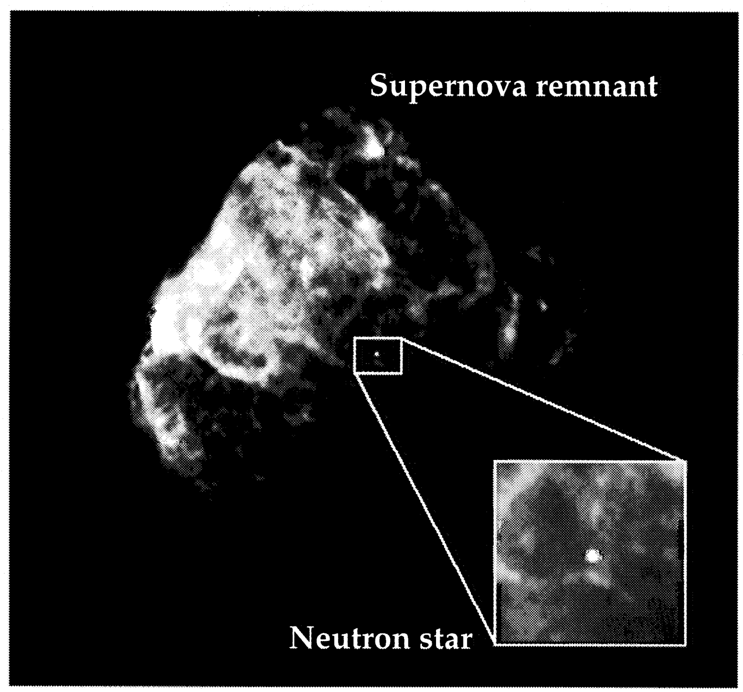
These probe the physical conditions and energy distribution in the matter between stars.

lived isotopes such as ^{26}Al and ^{60}Fe which can be used to trace out supernova activity in the Galaxy over the past few million years.

Cosmic rays, at least up to energies of order 10^{14} eV, are understood as being accelerated by shock waves created by exploding supernovae propagating into the interstellar medium. Measurement of the elemental composition of cosmic rays to these energies will test the limits of the supernova acceleration model and measurements of individual rare elements heavier than iron will distinguish between competing models of injection into these cosmic accelerators.

Direct sampling of the very local interstellar medium using a high speed probe sent outside the solar system would be particularly illuminating. Particle and field measurements on such a mission will reveal how stars and their winds contribute to the low-energy cosmic rays in the Galaxy.

Through high spatial resolution observations, we also can explore the state of the interstellar material in external galaxies. This gives a global view that is impossible to obtain directly for our own Galaxy. In some cases, particularly starburst galaxies where recent galaxy-galaxy encounters have occurred, some of the interstellar gas has been heated to temperatures of several million degrees. The X-ray radiation from this gas can be used to map the amount and distribution of heavy elements, which can tell us how uniform are the conditions within individual galaxies.

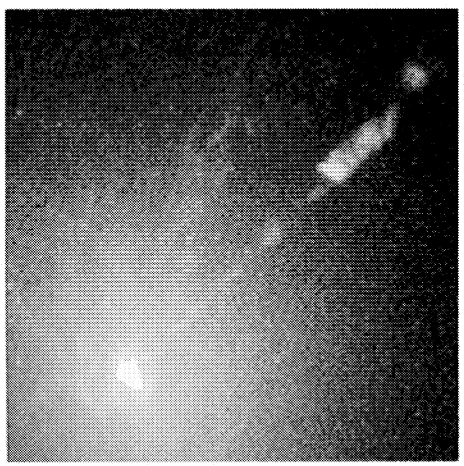


Many of the physical processes that underlie this campaign can also be observed at work in our own interplanetary medium. After all, the gas densities, temperatures, magnetic field strengths, cosmic-ray energies and so on span similar ranges. We can therefore regard the solar wind as it is launched by the Sun, as it interacts with various planetary magnetospheres, and as it encounters the interstellar medium as a sort of laboratory where we can measure these effects with a detail that would be denied to us were we restricted to observations of remote cosmic sources. For this reason, there is a strong connection between this campaign and the scientific goals of the SEC theme.

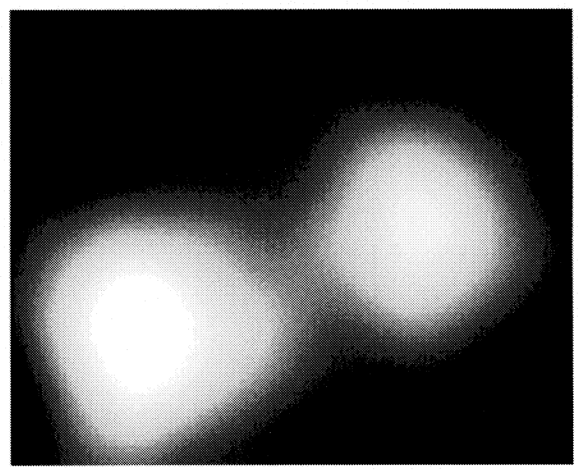
CAMPAIGNS: Discover how gas flows in DISKS and how cosmic JETS are formed

Improvements in angular resolution and sensitivity from radio to gamma-ray wavelengths will allow us to understand how jets are formed, and what role they play in the accretion process

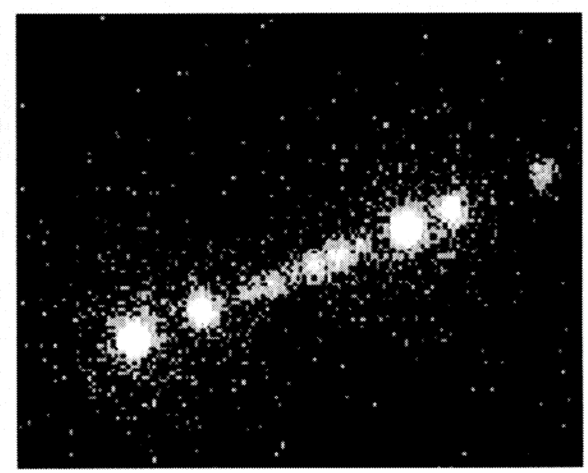
Energetic, collimated, relativistic outflows called jets can accompany accretion disks in systems containing black holes



Optical jet in Galaxy M87



X-ray image of the M87 jet



AXAF simulation

CAMPAIGNS: Disks and Jets (continued)

Discover how gas flows in disks and how cosmic jets are formed.

IN RECENT YEARS THERE HAS BEEN ABUNDANT observational evidence, much of it garnered from space by SEU missions, to support the hypothesis that gas accretes onto compact objects (black holes, neutron stars, and white dwarfs) via accretion disks. For stellar objects, the gas derives from a normal, companion star. For the massive black holes in active galactic nuclei (AGN), the gaseous fuel comes from the central star cluster and gas that simply settles into the galactic nucleus. As this gas falls deeper into the gravitational potential well of the black hole, its energy is converted into heat through dissipative stresses and then into ultraviolet, X-ray, and even gamma-ray radiation which we can observe.

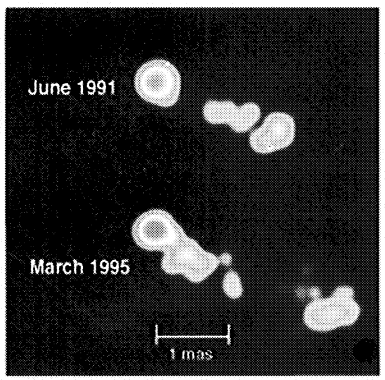
It has also been discovered that cosmic jets are often formed as a natural concomitant of accretion disks. These collimated, bipolar outflows were first observed extensively from the ground using radio telescopes. However, they are now regularly seen at optical, X-ray and gamma-ray wavelengths as well and, in particular, from space. For example, the EGRET instrument on CGRO discovered that gamma-ray jets from active galactic nuclei were far brighter and more prominent than had generally been anticipated. An important new capability is extending the technique of Very Long Baseline Interferometry (VLBI) into space using the recently-launched Japanese-US satellite HALCA. This will enable astronomers to see jets in finer detail than ever before. Understanding how these jets are made and what role they play in the accretion process is a major, unsolved problem. In particular, we hope to discover if they are launched and collimated by magnetic stresses or if the pressure of the intense radiation fields is responsible.

The most powerful active galactic nuclei are called quasars. These are so bright that they outshine the surrounding galaxy. While all galaxies may have passed through active phases, and thus may still harbor giant black holes at their centers, we know from observations that AGN were much more common at earlier epochs than at present. The high luminosities of AGN make it possible to observe these systems at very great distances, thereby providing fundamental information about the formation and early evolution of galaxies. X-ray and gamma-ray observations can probe the interior regions of accretion disks, those nearest the massive black holes. With high resolution spectral observations, X-ray emission line components have already been measured and allow us to probe the dynamics of gas flow close to black holes. A major challenge for the future is to extend this technique to many more objects and use it to measure the masses and spins of the central black holes.

Observations of lower power (but much closer) galactic nuclei are also allowing us to see the outer parts of accretion disks and to understand how gaseous fuel is supplied to the central black hole. Recent VLBI experiments from the ground have detected intense water emission lines, amplified by a natural maser process, from several of these sources. This has enabled us to measure the mass of the central black hole with unprecedented accuracy. It is intended to extend this technique to study more

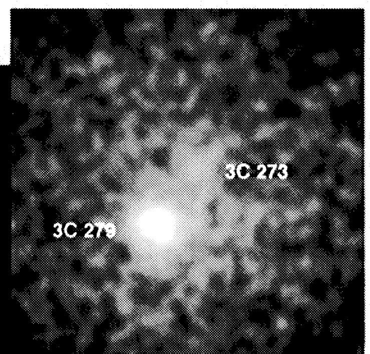
CAMPAIGNS: Disks and Jets (continued)

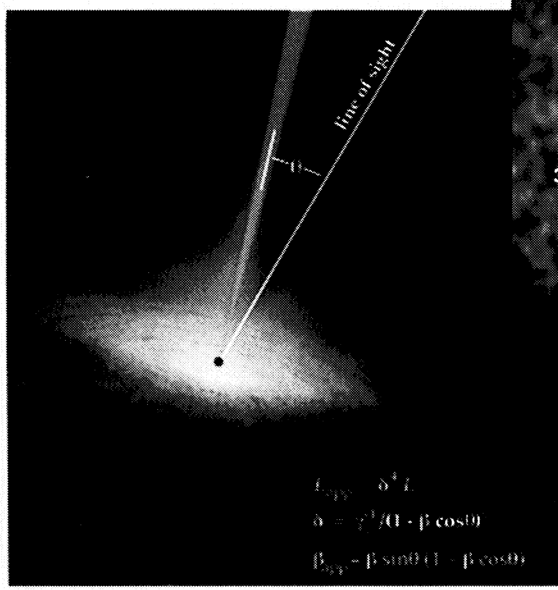
Radio



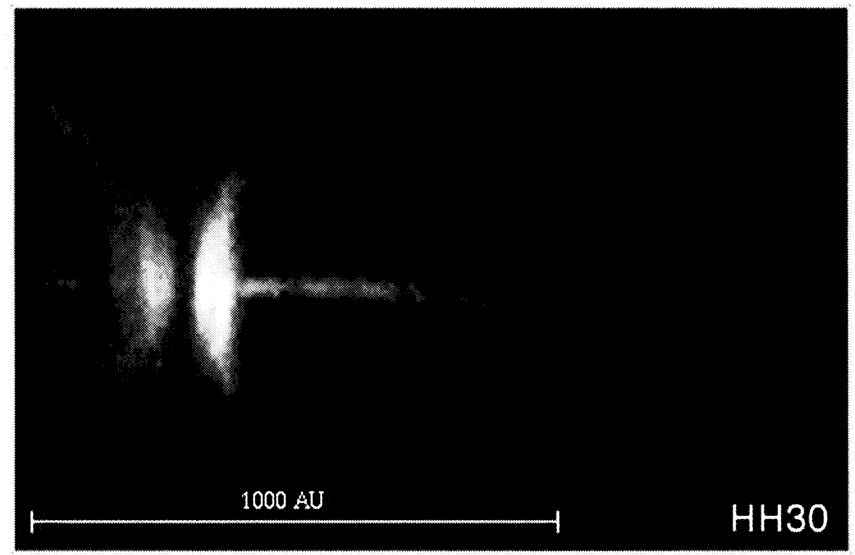
Observations of ejecta in 3C 279 in the gamma-ray and radio show apparent motions greater than the speed of light

Gamma ray





Protostellar jet



The water maser in the disk of N4258 (above) is the best evidence we have for the existence of black holes.

List of Related SEU Web Sites

SEU at NASA Office of Space Sciences	http://www.hq.nasa.gov/office/astrophysics/SEUSmain_page.html
SEU Subcommittee (Caltech)	http://www.srl.caltech.edu/seus/
SEU Technology Working Group	http://universe.gsfc.nasa.gov/SEUTWG/homepage.html
SEU Missions	http://www.srl.caltech.edu/seus/missions/index.html
ACCESS	http://hep.uchicago.edu/~swordy/access.html
ARISE	http://www.nrao.edu/~julvesta/ARISE.html
FIRST	http://astro.estec.esa.nl/SA-general/Projects/First/first.html
GLAST	http://www-glast.stanford.edu
HTXS	http://htxs.gsfc.nasa.gov/
LISA	http://jilawww.colorado.edu/~stebbins/LISA.html
OWL	http://lheawww.gsfc.nasa.gov/docs/gamcosray/hecr/owl_new.html
PLANCK	http://astro.estec.esa.nl/SA-general/Projects/Cobras/cobras.html

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Roger Blandford, Caltech
(Chair)
rdb@tapir.caltech.edu

John Armstrong, JPL
john@oberon.jpl.nasa.gov

Gordon Garmire, Penn State
ggarmire@astro.psu.edu

Neil Gehrels, GSFC
gehrels@lheavx.gsfc.nasa.gov

David Helfand, Columbia
djh@carmen.phys.columbia.edu

Martin Israel, Washington University
mhisrael@hilltop.wustl.edu

Christine Jones, CfA
cjf@cfa.harvard.edu

Steve Kahn, Columbia
skahn@carmen.phys.columbia.edu

Robert Kirshner, Harvard
kirshner@cfa.harvard.edu

Charles Lawrence, JPL
crl@jplsp.jpl.nasa.gov

Roger Malina, CEA/Berkeley
malina@cea.berkeley.edu

John Mather, GSFC
mather@stars.gsfc.nasa.gov

Peter Michelson, Stanford
pfm@egret1.stanford.edu

Dan Weedman, Penn State
weedman@astro.psu.edu

Andrew Wilson, Maryland
wilson@astro.umd.edu

Alan Bunner, NASA Headquarters
Alan.Bunner@hq.nasa.gov

Fiona Harrison, Caltech
(Commitee Secretary)
fiona@srl.caltech.edu

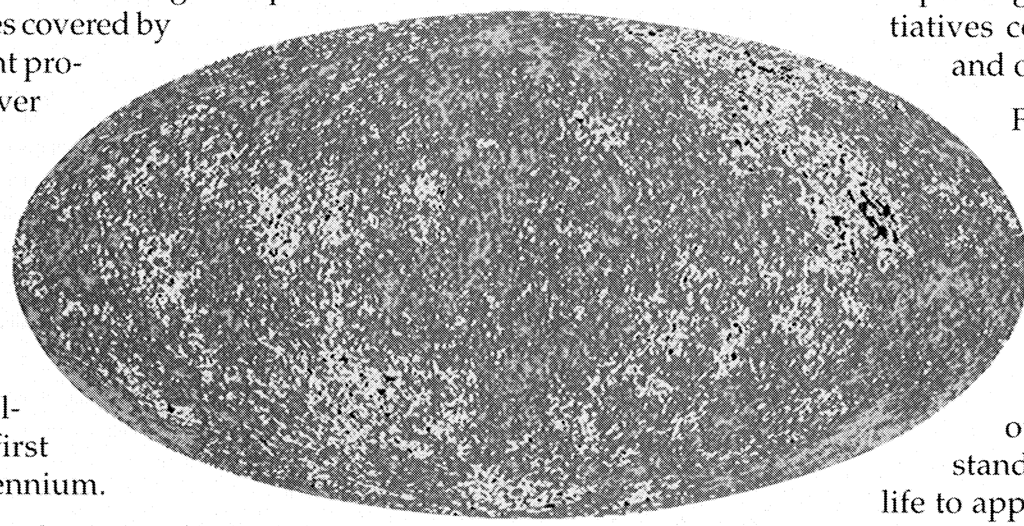
Rick Harnden, NASA Headquarters
Rick.Harnden@hq.nasa.gov

ACRONYMS

ACCESS	Advanced Cosmic-ray Composition Experiment on Space Station
ACE	Advanced Composition Explorer
AGN	Active Galactic Nuclei
ARISE	Advanced Radio Interferometry between Space and Earth
ASCA	Japanese-US X-ray Satellite
ASOPS	Astronomical Search for Origins and Planetary Systems
AXAF	Advanced X-ray Astrophysics Facility
CGRO	Compton Gamma Ray Observatory
CMB	Cosmic Microwave Background
COBE	Cosmic Background Explorer
EGRET	Energetic Gamma-Ray Experiment Telescope
ESA	European Space Agency
ESS	Exploration of the Solar System
EUV	Extreme Ultraviolet
EUVE	Extreme Ultraviolet Explorer
FIRST	Far Infrared-Submillimeter Space Telescope
FOV	Field of View
FUSE	Far Ultraviolet Spectroscopic Explorer
FUV	Far Ultraviolet
GLAST	Gamma Ray Large Area Space Telescope
GP-B	Gravity Probe B
HALCA	Japanese-led Very Long Baseline Radio Interferometry Satellite
HEMT	High Electron Mobility Transistor
HST	Hubble Space Telescope
HTXS	High Throughput X-ray Spectroscopy Mission
IR	Infrared
IRAS	Infrared Astronomical Satellite
ISM	Interstellar Medium
LIGO	Laser Interferometer Gravitational Wave Observatory
LISA	Laser Interferometer Space Antenna
MAP	Microwave Anisotropy Probe
MIDEX	Medium Explorer
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan's Space Agency)
NGST	Next Generation Space Telescope
NRA	NASA Research Announcement
NRC	National Research Council
OSS	Office of Space Science
OWL	Orbiting array of Wide angle Light detectors
ROSAT	German-American-British Roentgen Satellite
RXTE	Rossi X-ray Timing Explorer
SEC	Sun-Earth Connection
SEU	Structure and Evolution of the Universe
SEUS	Structure and Evolution of the Universe Subcommittee
SMEX	Small Explorer
STIS	Space Telescope Imaging Spectrograph
SWAS	Submillimeter Wave Astronomy Satellite
TDRSS	Tracking and Data Relay Satellite System
UV	Ultraviolet
VLBI	Very Long Baseline Interferometry
WIRE	Wide-Field Infrared Explorer

CONCLUSION (continued)

THESE ARE CHANGING TIMES IN THE NATION'S space science program. Old expectations and styles of carrying out space missions have vanished and been replaced by a leaner and swifter approach that is more responsive to scientific change, technical innovation, and a public mandate. These offer great opportunities to those disciplines covered by the SEU umbrella. The current program is healthier than it has ever been, as measured by the rate of scientific discovery, by the suite of missions that will soon be launched, and by public interest in the results. Now is the time to capitalize upon this success by planning with vision, realism and flexibility for the first two decades of the next millennium.



We have created a Roadmap that provides a framework for strategic planning and technology development. It embraces a mix of proposed missions, some in a high state of technical readiness, others with equally strong scientific motivation but which will require a decade to bring to fruition. Our Roadmap is innovative in that it has broken away from the old, wavelength-specific way of doing space astronomy. However, it is also balanced, representing all of the pressing scientific quests under the SEU theme and a mix of major and minor missions as well as exploiting the overlap with major initiatives covered under other themes and other space agencies.

From the dawn of creation in the big bang to the end of time at a black hole singularity, the Universe is source of inspiration and wonder for us all. We are on the threshold of solving the mystery of how it develops its structure, of understanding how it evolves to allow life to appear and perhaps even flourish, and of learning what will be our ultimate destiny. The Structure and Evolution of the Universe program outlined in this Roadmap presents NASA with a balanced strategy to enable it to continue its heroic voyages of discovery well into the next century.

CONCLUSION


nature
Astronomical magnetic
The subtleties of crystal close pack
agouti obesity syndrome explaine
Darwinian selection on proteins
BONUS: Your 1996 Guide to Astronomy Clubs, Planetariums, and Observatories
SKY & TELESCOPE
David Levy Profiles Sidewalk Astronomer John Dobson
What's Happening on Mars?
Backyard Astronomy: Celestial Coordina
Gamma-Ray Astronomy
Using Atmospheric Flashes to Probe the High-Energy Universe
TIME
WHEN DID THE UNIVERSE BEGIN?

TECHNOLOGICAL IMPERATIVES (cont'd.)

MUCH OF THE SUCCESS OF THE CURRENT SPACE SCIENCE program is attributable to technological innovation. The entire electromagnetic spectrum has been opened up, necessitating the fabrication of novel telescopes and detectors that can only be used above the atmosphere. Operations that may be routine at ground-based observatories acquire a whole new challenge when they have to be performed flawlessly and remotely under the hostile conditions of outer space. Equipment has to be space-qualified to withstand the rigors of launch and irradiation by ultraviolet light, cosmic rays and so on. In the past, engineers in NASA centers, the universities and private industry have combined to meet these challenges and much of what they have developed has found its way into the general technology infrastructure.

In order to advance with the SEU mission portfolio, it is necessary to continue this tradition and embark immediately upon an aggressive program to develop enabling technology that will allow the major technological hurdles to be cleared (or perhaps identified as serious obstacles) prior to starting the missions. This is the cost-effective approach that should ensure that future missions will proceed rapidly to launch after they are started. For this reason, we have developed the SEU technology program that is designed to meet these anticipated needs.

Naturally, much of the technology development that is required is quite mission-specific. However, what has been found is that a surprisingly large fraction has common elements both within and beyond the SEU theme. Examples include electronics, data-handling, and low temperature techniques. The SEU technology plan is designed to exploit these opportunities whenever appropriate and to avoid duplication.

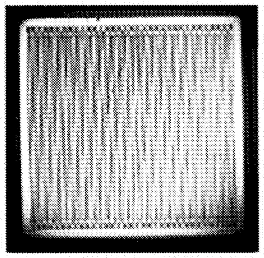
Technology development needs are not confined to identified missions. The Explorer program provides an excellent example. Here there are many generic examples of enabling technology that must be demonstrated before it makes sense to propose an Explorer mission. Looking to the more distant future there are many scientific capabilities that we suspect are attainable but we do not yet understand how to achieve. There is clearly a need to carry out this long term investment in technology research in support of the Space Science program of the future.

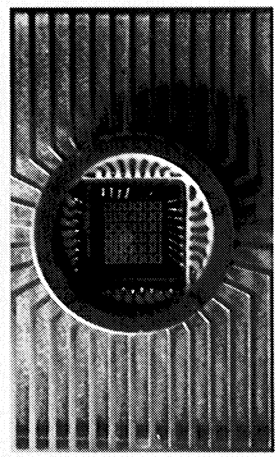
Appendix A contains the SEU Technology Roadmap with more specific discussion of technology development needs for SEU. Appendix B is the SEU Mission Portfolio with detailed mission descriptions.

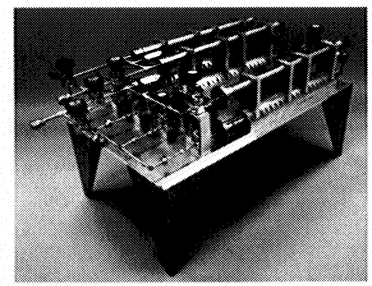
"For a successful technology, reality must take precedence over public relations, for nature cannot be fooled."

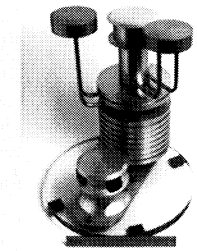
–Richard Feynmann

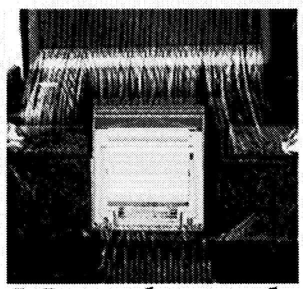
TECHNOLOGICAL IMPERATIVES

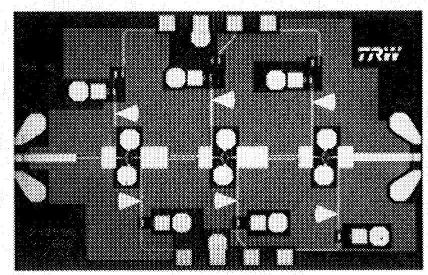

CdZnTe Array


Cryogenic X-ray Spectrometer

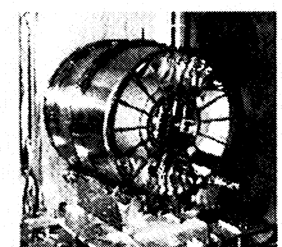

H_2 Sorption Cooler

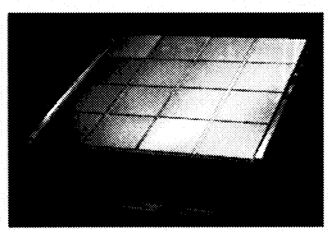

Turbo-Brayton Cooler

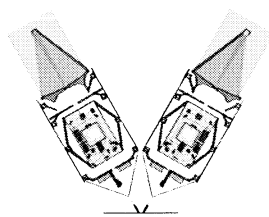

Megachannel Analog ASIC

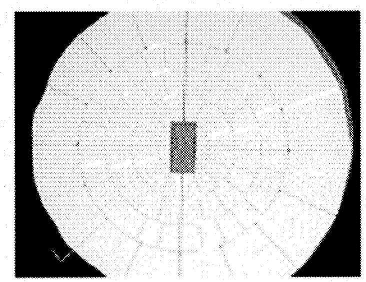


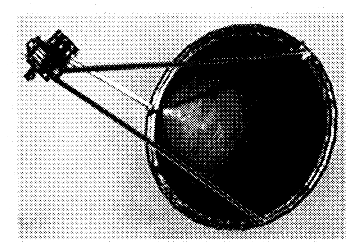
MMIC Amplifier


Grazing Incidence X-ray Optics


Si Strip Detector


Inertial Sensors


Spider Bolometer


Inflatable Optics

OUTREACH (continued)

Space Science arouses uncommonly strong public interest. This is partly because space science addresses questions that are exciting and readily communicable to a broad audience. However, it is also because it has produced a stream of fundamental and unexpected discoveries that have been widely publicized and whose implications are broadly appreciated. (No better example exists than the search for evidence of extraterrestrial life and the attention devoted to the possible discovery of bacterial fossils from Mars. This is driven not so much by the claim itself, which is quite controversial, but by the realization that we now have the capability and techniques to address some very basic philosophical questions using modern scientific analysis.)

Major space missions to address these issues are expensive. It is therefore right and proper that the ultimate sponsors (the American public) should be seen as essential partners in the nation's space science program. This, in turn, implies that space scientists have a responsibility to communicate the discoveries, aspirations and opportunities of the enterprise as assiduously as possible. The SEU theme recognizes the necessity of a strong public mandate for its enterprise and the importance of outreach to communicate the aspirations, discoveries, and opportunities of the SEU theme to a broad audience. There is strong public interest in the issues addressed within the SEU theme, most immediately those relating to cosmology and black holes but also, in practice, those involving all the scientific investigations spanned by the SEU quests. Missions under the SEU theme have always taken public outreach very seriously and have developed materials appropriate for the general public that are widely disseminated. Mission study teams routinely see it as a core part of their projects to develop this outreach.

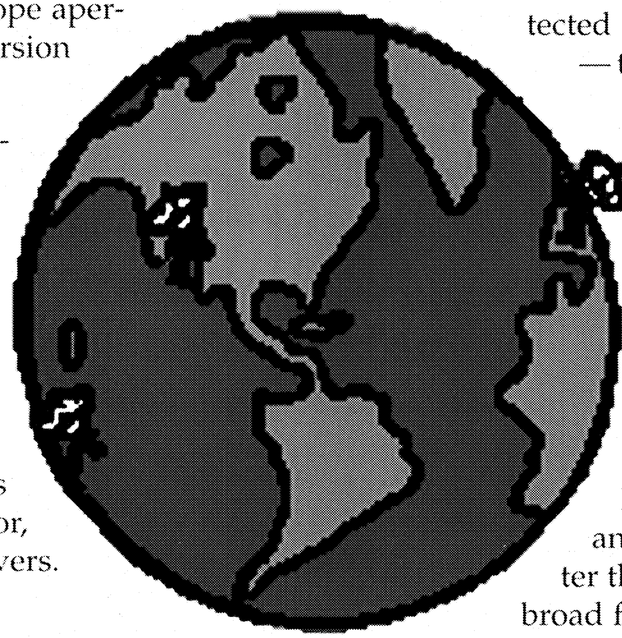
This process is now being revolutionized by changes in communication technology, and SEU-related missions make innovative and creative use of the World Wide Web. For example, the HTXS public outreach page **(http://htxs.gsfc.nasa.gov/docs/xray/htxs/home.html)**, and the MAP homepage **(http://map.gsfc.nasa.gov/)**.

Educational outreach has a different and more difficult goal, namely, raising the level of scientific literacy of the country. This is an enormous and daunting task, with primary responsibility falling on educational institutions at all levels. But space science has a special place in educational outreach. The planning and execution of space science missions provide transparent and accessible examples of the scientific process at work, addressing basic questions that can motivate and enrich curricula at all levels from kindergarten to college liberal arts programs. OSS itself has ambitious plans to strengthen its educational role and to facilitate connection with schools (see "Partners in Education: A Strategy for Integrating Education and Public Outreach Into NASA's Space Science Programs" and its companion report "Implementing the Office of Space Science Education/Public Outreach Strategy".) The SEU theme supports this OSS-wide educational outreach by providing materials that can be integrated into educational curricula. One recent and notable example is provided by the High Energy Astrophysics Learning Center **(http://heasarc.gsfc.nasa.gov/docs/learning_center).**

OUTREACH AND THE PUBLIC MANDATE

detect regular spiral galaxies like our own that are thought to radiate up to a quarter of their bolometric luminosity in the far infrared region out to intermediate redshifts. The major Galactic sources are the dense molecular gas clouds where stars may currently be formed. In order to study these sources, it is necessary to have a large, cool telescope aperture and the ability to perform high dispersion spectroscopy.

The European Space Agency (ESA) cornerstone mission, FIRST, has been planned to achieve both of these goals. It is designed to perform a giant sky survey in the far infrared with a seven arcsec angular resolution and a wide field of view and will complement the proposed Millimeter Array. In order to escape the Earth's thermal environment, it will operate at the L2 Lagrange point. Possible U.S. contributions to the FIRST mission are an enlarged mirror, lightweight coolers, bolometers and receivers. FIRST is planned for a 2006 launch.



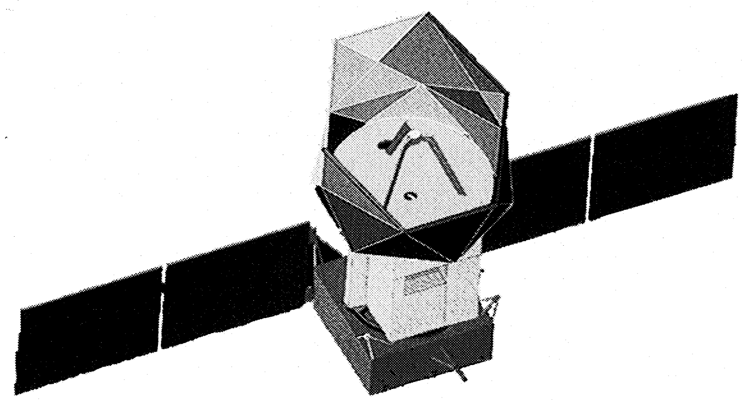
Precursors of FIRST were strongly endorsed by the Field and Bahcall decadal surveys, and a proposal to collaborate with ESA on FIRST was the top-rated IR/radio concept reviewed under the recent New Mission Concepts for Astrophysics NRA.

Planck

A major step in our goal of determining a quantitatively accurate history of the Universe was achieved by the COBE satellite which verified beyond all reasonable doubt that the cosmic microwave background had a cosmological origin and detected the expected fluctuations in its brightness — the seeds of present day structure in the Universe. The next step is to measure these fluctuations with greater sensitivity and on smaller angular scales so as to relate them to the structure we see around us. This step will be taken by the Microwave Anisotropy Probe, MAP, which will measure this structure on scales as small as 15 arc minutes. MAP is due for launch in 2000.

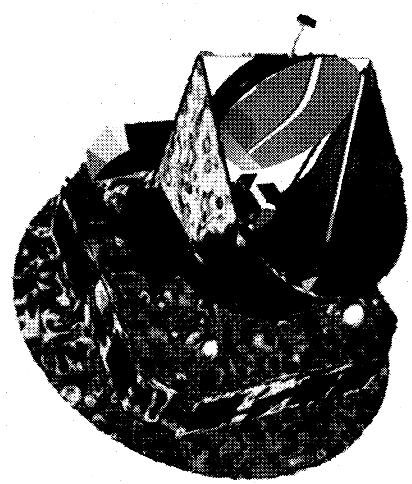
ESA's Planck mission is designed to take the third step and build upon what will be learned by MAP, with angular resolution and sensitivity factors of roughly 2 and 5 better than MAP respectively. Planck also has very broad frequency coverage for maximum discrimination between the background radiation and foreground sources. NASA's contribution to this mission will be in the areas of bolometers, HEMT amplifiers, and vibrationless cryocoolers. Planck, too, will be launched to the L2 Lagrange point and is planned for a 2004 launch.

THE INTERNATIONAL CONTEXT (continued)



FIRST:
Far InfraRed Submillimeter Telescope. ESA mission to find and study primeval galaxies and observe interstellar chemistry at work in dense, star-forming regions.

PLANCK:
ESA mission to map the cosmic microwave background radiation in unprecedented detail and to measure the far infrared background radiation.



THE INTERNATIONAL CONTEXT

From its inception, space science has been an international endeavor. This has been desirable in part because scientific programs were completed faster than if NASA had relied upon resources solely within the US. NASA's current Space Science Enterprise Strategic Plan makes clear that there is both a desire and a need, on NASA's part, to seek international cooperation on new flight programs. As NASA looks ahead, the interest and added value of international collaboration will continue to increase as a growing number of countries become involved in space science programs. This will require better coordination between national and international space agencies, and new types of agreements to ensure that programs are well matched and the approval and funding mechanisms are synchronized. For NASA to achieve the SEU goals over the next two decades, new ways of doing science business internationally must be established.

A number of motivations lead to international projects, each of which must be examined critically and then advocated in collaboration with our partners. In some cases, the basic motivation is access, and involvement of the best scientific and technical talent. Although the US remains the world leader in many fields, there are some areas where our international partners have demonstrated leadership. The high cost of some missions provides additional motivation for cost-sharing on common goals. In some cases, NASA's strategic goals encourage participation by international partners in missions that are US-led, missions that are led by other nations, and projects of a more equal, multinational character.

In the past, a significant impediment to successful collaboration has been a lack of high level synchronization between the decision making and the funding processes. If OSS is to achieve the goals of this Roadmap, it must either establish a separate, peer-reviewed international program or, at least, find ways to coordinate decision making at the highest levels.

We now describe two missions, FIRST and Planck, that exemplify the opportunities for international collaboration. Only the latter is currently approved for NASA participation, though they both have been selected as European missions and address key elements of the SEU Roadmap. In addition, LISA and ARISE are essentially multinational in character and there are several attractive possibilities for additional collaboration with Japan's NASDA.

Far Infrared-Submillimeter Space Telescope (FIRST)

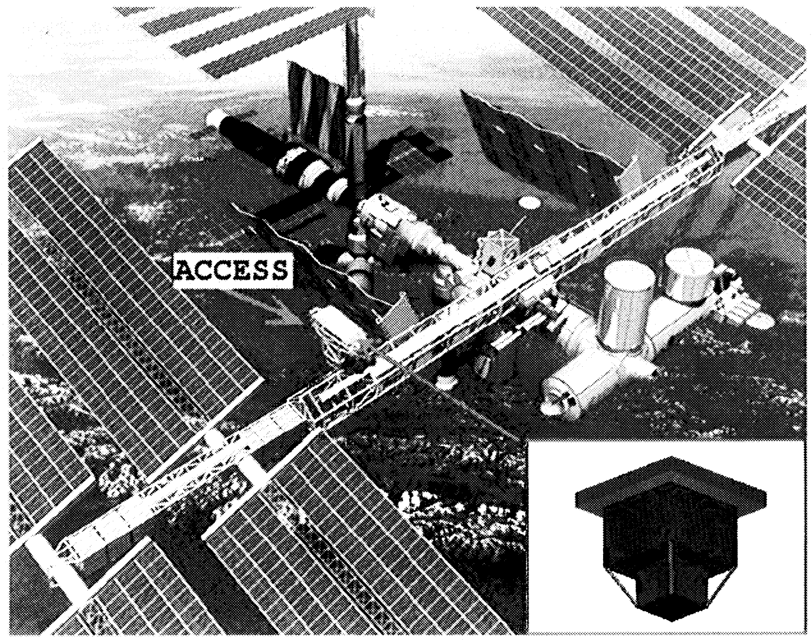
One of the last regions of the electromagnetic spectrum yet to have a major space observatory devoted to its study is the far infrared - submillimeter. The major extragalactic sources in this wavelength interval are the dusty galaxies discovered by the Infrared Astronomical Satellite (IRAS), from which visible light cannot escape. The FIRST mission is designed to detect these galaxies out to large cosmological distances when the Universe was less than a billion years old. In addition, it should be able to

EXCEPTIONAL OPPORTUNITIES

NOT INFREQUENTLY, OPPORTUNITIES ARISE for addressing science goals that do not fit into the standard program structure. We call these exceptional opportunities and they pose a particular challenge to NASA. One example which addresses a key campaign goal follows.

Advanced Cosmic-ray Composition Experiment on Space Station (ACCESS)

We have developed a reasonable understanding of the origin of low and intermediate energy cosmic rays in supernova shocks, but a key test of this model requires measuring the change in composition expected near the limiting energy of that mechanism around 10^{14} eV above which there is an observed steepening of the cosmic-ray energy spectrum. In addition, the means by which a few particles are injected into this mechanism are not well established. The material either originates from a region of temperature of order 10^4 K where the ionization potential governs the abundances, or it may come from dust grains where volatility is the parameter of interest. Distinguishing these possibilities requires measurements of abundances of rare elements heavier than iron. At energies above 10^{14} eV, some other acceleration location must be involved and composition measurements provide the best method of distinguishing various possibilities like neutron stars and a hypothetical Galactic shock front.



ACCESS

The space station attached payload proposal, ACCESS, provides an opportunity for making the key measurements required to address these questions. It should allow cosmic-ray physicists to expose large area detectors for several years to accumulate enough detections to measure the cosmic-ray abundance of every element between hydrogen and iron at energies up to 10^{15} eV. At the same time, it will be able to measure (at lower energy) the abundance of every individual element up to Uranium.

THE SUBORBITAL PROGRAM (continued)

NASA's BALLOON AND ROCKET PROGRAMS are also essential to the SEU theme. The balloon program in particular has been responsible for significant scientific discoveries. Equally important, however, is the role that both balloon and rocket experiments play in developing and demonstrating new instrumentation and technologies for space application.

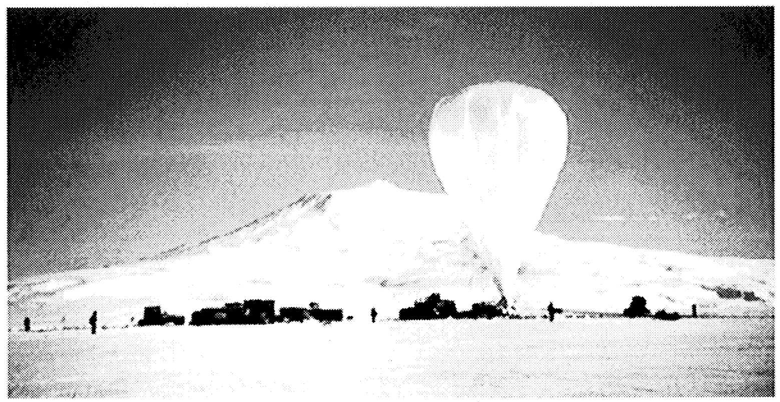
Many pioneering discoveries in astrophysics were made from balloons and rockets. For example, gamma-ray lines from radioactive elements synthesized in supernova remnants, gamma-rays from the annihilation of electrons and positrons in our Galaxy, and the sources of high-energy radiation from the center of our Galaxy were all discovered by balloon-borne instruments. Currently, balloon instruments are providing unique measurements of small scale anisotropies in the cosmic microwave background, high-energy emission from Galactic black holes, the isotopic composition of cosmic rays, and the width of the ^{26}Al gamma-ray line emission from the Galaxy with capabilities not available on any existing satellite. The observational capabilities of balloon instruments would certainly take a great leap with the development of a long-duration capability, with flights extending over periods of weeks.

The role that rocket and balloon experiments play in demonstrating instrument concepts and key technologies for space cannot be overemphasized. It is important to recognize that this is increasingly true in the new "faster, better, cheaper" era, with an aggressive Explorer program which aims to develop and construct satellite instruments in very short timeframes. To reduce the risk, ensure success of new, enabling technologies, and guarantee mission schedule, instrumentation must be prototyped and demonstrated prior to Phase A. Balloons and rocket experiments are ideal platforms for these demonstrations.

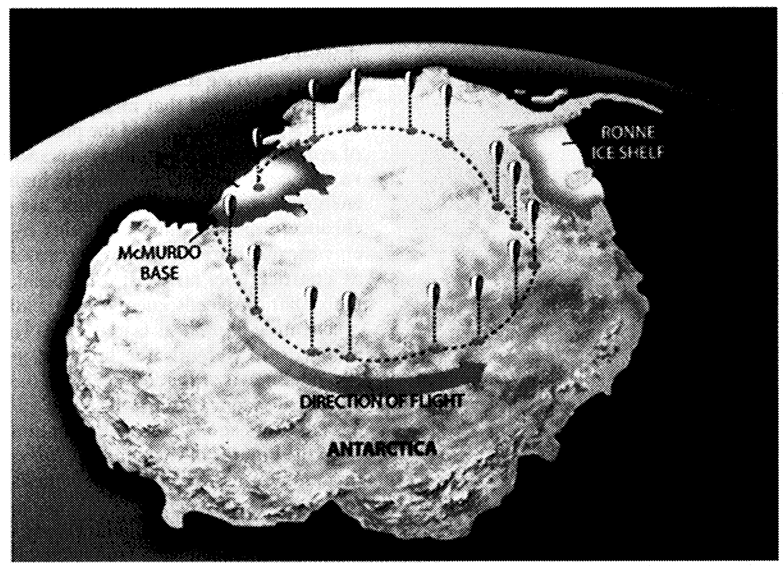
Recent advances in balloon technology, developed in connection with the Mars program, offer the strong possibility of flying one ton payloads for 100 day flights. While such balloon flights represent a more costly program than traditional flights of the order of one day, or more recent 10 day polar flights, these 100 day flights promise the ability to accomplish significant observations at a fraction of the costs of space flight in a number of areas from submillimeter and far-infrared to hard X-rays and cosmic rays.

Finally, these programs, which are based to a large extent in universities, play a crucial role in educating new generations of scientists and engineers. Since the timescale of these experiments coincides with the typical graduate student tenure, students have the opportunity to participate in all aspects of an instrument, including design, fabrication, scheduling and launch. It is not, therefore, surprising that many of the premier experimental astrophysicists in the country had their start working on rocket and balloon instruments.

THE SUBORBITAL PROGRAM



Long-duration ballooning from Antarctica promises 100-day flights of 1-ton payloads.



EXPLORER PROGRAM: Science objectives (cont'd.)

MISSION	PRIMARY SCIENCE	INSTRUMENT GOALS	SIZE	KEY TECHNOLOGY
Cycles Campaign (continued)				
UV diffuse spectral imager	Study hot ISM in our and other galaxies	Spectroscopy, 90–120 nm 120–280 nm	SMEX	Diffuse grating spectrometer
Disks and Jets Campaign				
Hard X-ray All-sky Survey	Observe hidden AGN Determine origin of the hard X-ray background	All-sky coverage 10 arcmin resolution 10–511 keV	MIDEX	Coded aperture Solid state detector
High-resolution X-ray Imager	Image jets in AGN Study nuclei of nearby galaxies	0.1" angular resolution	MIDEX	Polished spherical optics
UV Imaging Survey	Understand geometry and structure of active galactic nuclei	All sky UV coverage 90–280nm	SMEX	Channel plate detectors Normal incidence optics
High-Energy Campaign				
Arcsecond localization explorer	Provide arcsecond error boxes for deep counterpart search	1" error box for several dozen bursts	SMEX MIDEX	Coded aperture/grid or timing satellites
Rapid positioning telescope	Detection of transient counterpart at other wavelengths	Sub-degree positions within minutes	SMEX	Coded aperture telescope
High-sensitivity imager	Search for cosmological signatures, spatial anisotropy toward nearby galaxies	Factor 20 fainter than BATSE sub-degree positions	MIDEX	Coded aperture telescope
Gravity Campaign				
Polarimetric Explorer	Understanding where and how X-rays originate from around black holes and neutron stars	X-ray polarimetry of the brightest cosmic X-ray sources	SMEX	Thompson scatterer position sensitive X-ray detector
Redshift experiment	Test local position invariance by measuring gravitational redshift	Improve current accuracy by 2 orders of magnitude	SMEX	Flight-qualified precision frequency standard
Equivalence principle experiment	Test universality of free fall independent of chemical composition	Improve current accuracy by 3 orders of magnitude	SMEX	Laser interferometry
Test of relativistic gravity	Measure space curvature per unit mass	Improved accuracy by 2 orders of magnitude	SMEX MIDEX	Optical transponder drag free system
Gravitational waves	Search for low-frequency gravity waves	Sensitivity sufficient to detect galactic binaries	MIDEX	Laser interferometry; drag-free system

EXPLORER PROGRAM: Science objectives to be addressed with Explorer-class missions

MISSION	PRIMARY SCIENCE	INSTRUMENT GOALS	SIZE	KEY TECHNOLOGY
Dark Matter Campaign				
Microwave Background Spectral Mapper	Low-frequency distortions of Cosmic Microwave Background (CMB) spectrum	15 deg field of view (FOV) all-sky coverage	MIDEX	HEMT amplifiers
Deep X-ray All-sky survey	Map large sample of galaxy clusters to survey large scale structure	>20 times fainter than ROSAT	MIDEX	High-throughput grazing incidence optics
Cosmological Helium Probes	Measure $^3He/^4He$ isotope ratios in local Universe He Gunn-Peterson effect	Extreme Ultraviolet/Far Ultraviolet (EUV/FUV) spectroscopy	MIDEX	Grating spectrometer
Elements Campaign				
Cosmic-ray Trans-Iron composition explorer	Test models of galactic cosmic-rays search for freshly-synthesized supernova material	Composition for $14<Z<92$	MIDEX	Cherenkov and silicon detectors
Positron explorer	Study positron cosmic-rays especially those produced by decay of radioactive aluminum	20 MeV–2 GeV	MIDEX	Permanent magnet particle tracking
Heavy cosmic-ray composition explorer	Determine age and time of acceleration for heavy cosmic-rays	High-statistics measurements of U, Th	SMEX	Glass track Etch detectors
Far IR imager	Study cold interstellar dust	Coverage: 100–300 μm Wide FOV	MIDEX	Bolometer array
X-ray spectral line mapper	Study conditions, abundances and dynamics in supernova remnants and galaxy clusters	$\Delta E \approx 5$ eV 0.1–2 keV	MIDEX	Bragg crystals with grazing multicoated optics
Very low-frequency radio array	Study supernova remnant shock emission	Coverage: interplanetary plasma frequency to ionospheric cutoff (10 kHz–30 MHz)	MIDEX	Formation flying antenna array
UV spectroscopic survey	Survey starburst galaxies Study star formation and evolution from Z=0-2	90–120 nm 120–280 nm spectroscopy	MIDEX SMEX	Channel plate detectors Lightweight optics
Cycles Campaign				
Diffuse soft X-ray background explorer	Study the distribution, dynamics and thermal history of the hot component of the interstellar medium (ISM)	Sensitivity, resolution to detect key live emission complexes	SMEX	Wide-field telescope bolometers or tunnel junctions
Far-infrared spectroscopy mission	Understand origin of stars and recycling of interstellar gas	$\lambda / \Delta\lambda > 10^6$ sensitive in 1–3 THz	MIDEX	Hot electron bolometer mixers

EXPLORER PROGRAM (continued)

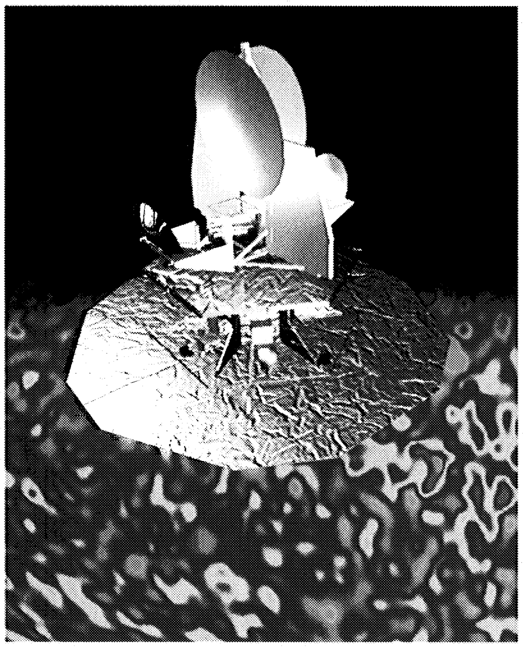
NASA's Explorer program is a vital element of the SEU science enterprise. Its importance to NASA's Space Science Program in general, and to the science encompassed by the SEU theme, has been emphasized by numerous working groups, including the Space Science Board of the National Research Council, the HST and Beyond Committee, and the Gamma-ray Program Working Group. The Explorer program offers frequent opportunities to carry out small- and intermediate-sized missions that can be completed and launched on a short (approximately four-year) timeframe.

Small and Medium Explorer (SMEX and MIDEX) missions, which are scientifically more focused than large-scale missions, can address some of the most significant scientific topics in the Structure and Evolution of the Universe theme. For example, MAP, which will be the pioneer mission in the MIDEX program, will answer fundamental questions about the age and mean matter density of the Universe, beginning a new era in cosmology and astrophysics. It will do this in a significantly shorter timeframe and for a fraction of the cost of a large Explorer or Great Observatory mission. The first astrophysics SMEX missions, SWAS and WIRE, will be launched in 1997 and 1998. These missions will advance our understanding of the processes which lead to the formation and birth of stars and young galaxies. The science which is possible with missions of this size and focus is clearly both broad and compelling.

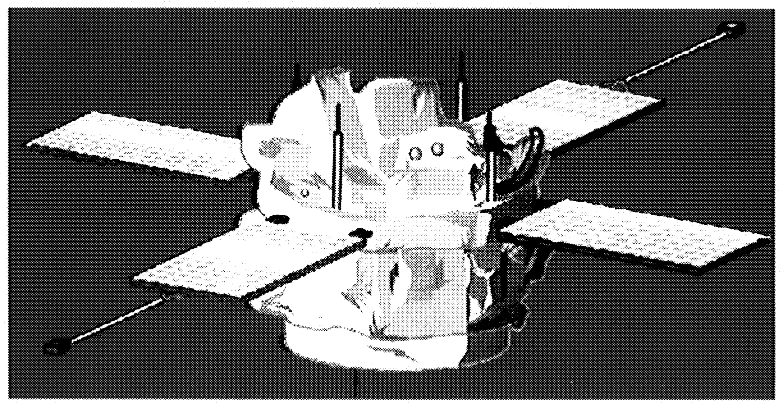
Contributions by future Explorer missions to our understanding of the structure and evolution of the Universe promise to be equally important. Each solicitation for proposals elicits many more high-quality experiments than can be implemented. Peer review, and the ability to incorporate new, creative ideas, and react quickly to recent scientific discoveries are essential elements of the "faster, better, cheaper" philosophy which lies at the heart of the new Explorer program. Suggesting a queue of future explorer missions would countermand this mandate.

To illustrate the science that is possible with Explorer class missions, we list in the table on the following page mission concepts that are mature, and that have been proposed or studied as SMEX and MIDEX experiments. This list is necessarily incomplete, and will change over time as technology matures, and new and creative ideas emerge.

EXPLORER PROGRAM

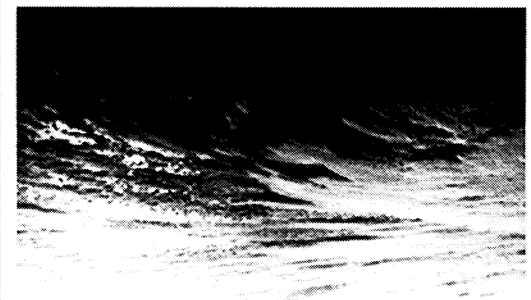


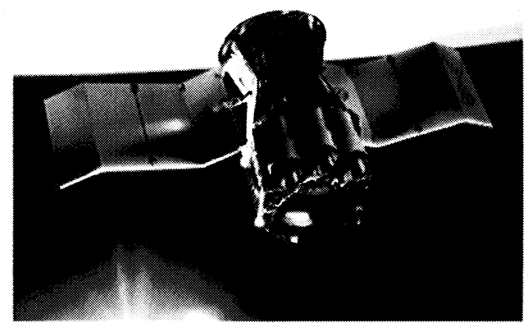
MAP



ACE

SWAS





MISSION PORTFOLIO (continued)

It is not possible to measure this long wavelength radiation from the ground; the seismic background is too great. However, a laser interferometer operating in space could monitor wave-induced changes in the separation of highly reflecting mirrors with an accuracy of about a tenth the size of a hydrogen atom over 5 million km. It is proposed to use a triangular arrangement of three spacecraft in a special librating orbit. This would enable astronomers to locate the periodic sources with an angular resolution that can be as small as one arcmin.

The LISA concept has been strongly endorsed in the 1990 NASA Report of the Ad Hoc Committee on Gravitation Physics, the joint National Academy of Sciences/National Research Council (NAS/NRC) (1981) Strategy for Space Research in Gravitation Physics, and the joint NAS/NRC (1988) report on Space Science in the Twenty First Century: Imperatives for the Decades 1995–2015.

Next Generation Space Telescope (NGST), Space Interferometry Mission (SIM)

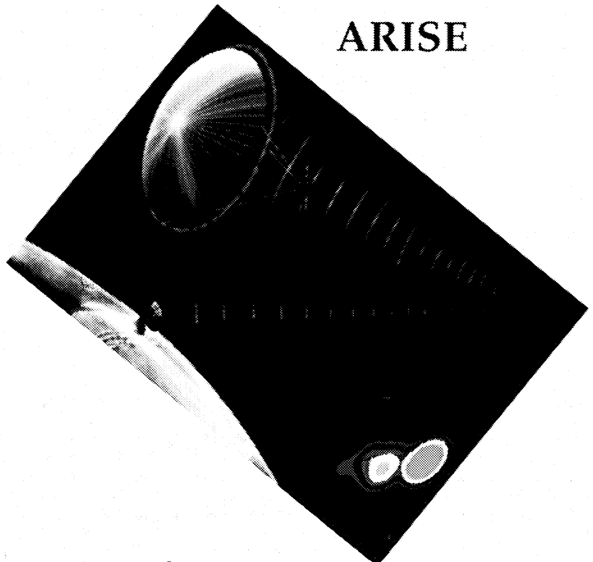
These Observatory-Class missions are described in the ASOPS Roadmap.

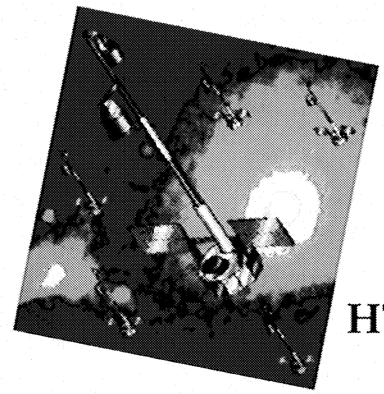
Orbiting array of Wide angle Light detectors (OWL)

We know from ground-based observations that there are a few cosmic-ray particles with surprisingly high energy, greater than 10^{20} eV. This flux is surprising because the cosmic background radiation makes the Universe opaque to protons and heavier nucleii coming to us from cosmological distances. Evidently, there must be some extremely powerful sources nearby, cosmologically speaking. We do not understand the identity of these particles — are they protons, iron nuclei or even photons? Neither do we know their sources or how they are accelerated to such high energy. It has even been suggested that these highest energy particles may come from the annihilation of topological defects formed in the early Universe. If so, there also would be an accompanying, intense flux of similarly high energy neutrinos.

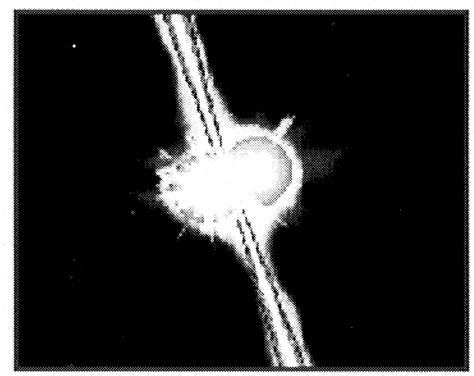
Detection of these particles requires special techniques. So far studies have been limited to ground-based telescopes that detect the shower of secondary particles they produce in the air, or atmospheric scintillation produced by those showers. Existing telescopes are so small that only a few of the very highest energy particles are ever likely to be seen this way. There is an exciting proposal called The Pierre Auger Observatory which would be a much larger array of water-Cerenkov and atmospheric scintillation detectors. Auger's two sites (one in the northern and one in the southern hemisphere) will have full sky coverage but still will be limited to a relatively modest detector area. To achieve a larger event rate, it is necessary to go to space where a much larger area of the atmosphere can be monitored. In the OWL project, it is intended to use two high altitude spacecraft to obtain a binocular view of the light flashes from these rare cosmic-ray interactions to determine their arrival directions with accuracies of about one degree.

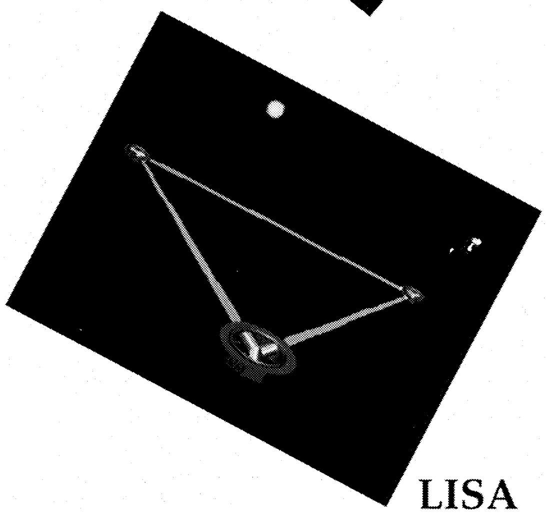
MISSION PORTFOLIO: Ultimate Limits

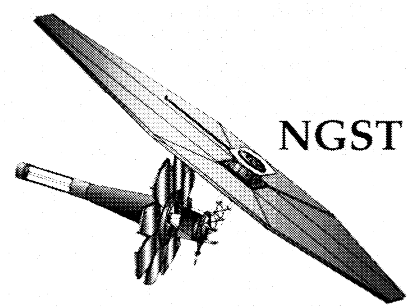

ARISE

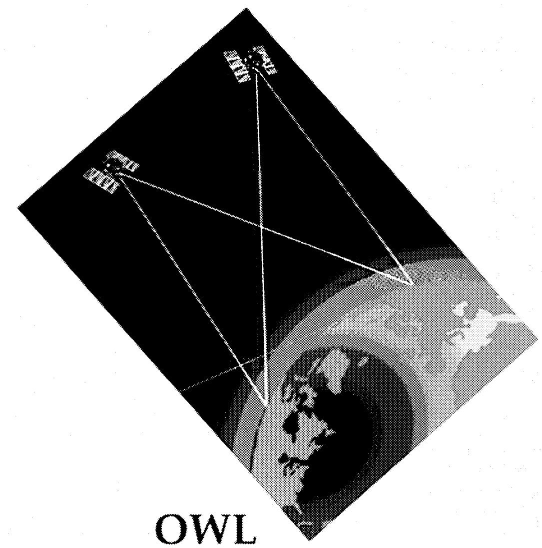

HTXS


GLAST




LISA


NGST


OWL

MISSION PORTFOLIO (continued)

High Throughput X-ray Spectroscopy Mission (HTXS)

THE NEXT MAJOR X-RAY MISSION, AXAF, due for launch in 1998, is the third "Great Observatory." Primarily a high resolution X-ray imager (though also incorporating moderate resolution spatial spectroscopy through an X-ray CCD and transmission gratings), AXAF will furnish images of cosmic sources that are the counterparts of the spectacular optical images produced by Hubble Space Telescope. However, for all its visual appeal, imaging of cosmic sources only produces a part of the scientific picture. Its complement, spectroscopy, enables astronomers to identify large numbers of spectral lines whose strengths measure the elemental composition and temperature of the emitting matter and whose wavelengths determine the object's velocity through the Doppler shift. In this way, it is possible for astronomers to determine the flow of gas in accretion disks around massive black holes in active galactic nuclei and binary X-ray sources, in supernova remnants, and in giant clusters of galaxies at great distance from us.

HTXS has been designed to perform X-ray spectroscopy with unprecedented sensitivity and spectral resolution. It is proposed to launch six identical spacecraft that will observe the same object simultaneously so that the total collecting area will be comparable to that of a 1.5 m optical telescope. It will also break new ground by working at hard X-ray energies up to 40 keV. In order to escape the Earth's radiation belts, it is necessary to launch into a high Earth orbit or to escape the Earth all together by parking at the L2 Lagrange point.

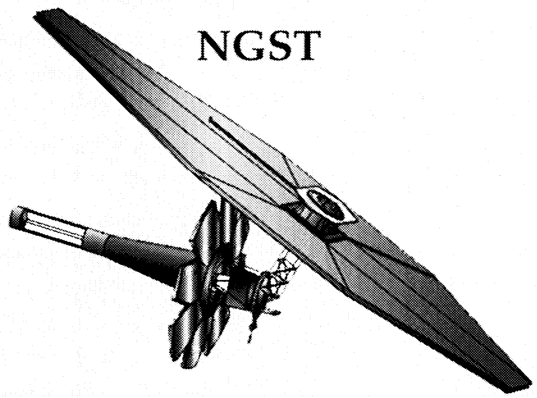
HTXS is a relatively new proposal that merges three mission concepts that were strongly endorsed under the New Mission Concepts for Astrophysics NRA. The Report of the X-ray Astronomy Working Group — A 15-Year Plan for X-ray Astronomy (1994–2008) also endorses the science goals and instrumental capabilities of HTXS as separate missions. HTXS has just received a highly favorable review by the HTXS Technology Readiness Independent Review Panel.

Laser Interferometer Space Antenna (LISA)

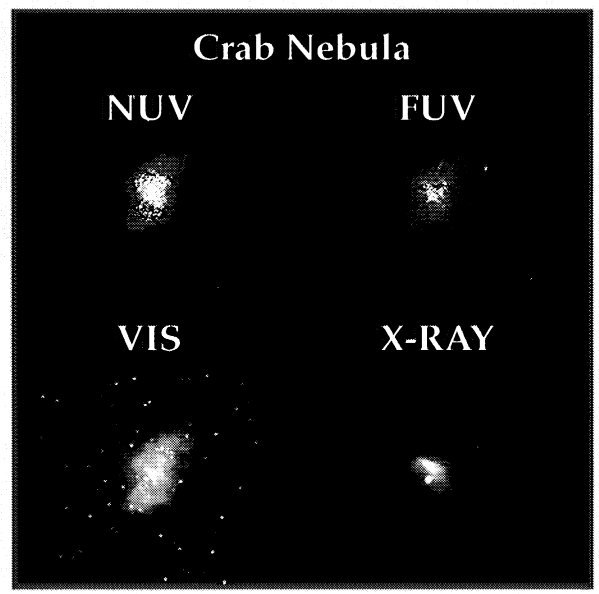
ONE OF THE LAST NON-ELECTROMAGNETIC CHANNELS to be opened up is that of gravitational radiation. There are several assured sources of cosmic gravitational radiation. However, the predicted signal strengths are very low and high precision detectors are required to observe these sources. (However, the history of astronomy does encourage optimism that there may be stronger sources than we can predict at this time.) There are several ground-based projects to detect gravitational waves, most notably the Laser Interferometer Gravitational Wave Observatory (LIGO), which is intended to be sensitive to waves with kHz frequencies produced by coalescing neutron stars and stellar mass black holes and by supernovae. An equally interesting spectral range is the mHz range (wave periods of minutes to hours). Here a prototypical source might be two coalescing, massive black holes in an AGN. Naturally, measuring the waveform from such an event gives not only astrophysical information on the sources of the radiation, but also constitutes a high order and unprecedented test of strong field general relativity theory.

MISSION PORTFOLIO: Evolution

NGST

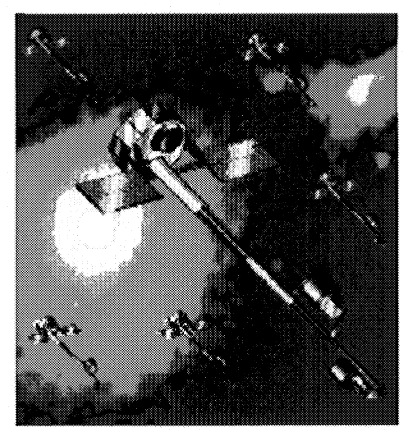


GLAST



ARISE

HTXS



MISSION PORTFOLIO (cont'd.)

"I have looked further into space than ever human did before me."
–William Herschel

Advanced Radio Interferometry between Space and Earth (ARISE)

A REQUIREMENT FOR SEVERAL SEU CAMPAIGNS is to improve the angular resolution so that we can observe cosmic objects on smaller scales and understand better how they work. This is particularly true for quasars and other forms of active galactic nuclei. The black holes in the nuclei of nearby galaxies (including our own) subtend angles of order 1-10 μarcsec. Radio astronomers have developed a ground-based technique called Very Long Baseline Interferometry (VLBI) in which the wave amplitudes at several separate telescopes are combined to obtain maps of the source structure. This achieves an angular resolution given by the quotient of the observing wavelength and the baseline of the telescopes and is limited to 300 μarcsec from the ground by the size of the Earth.

To improve on this performance requires the use of orbiting antennae. The first step involved experiments performed with the TDRSS (Tracking and Data Relay Satellite System) satellite and it was shown that quasar radio sources were smaller than had ever been measured before. The next step has just been taken with the successful launch and deployment of the Japanese/US satellite HALCA which will further increase the angular resolution by about another factor of three. The logical third phase involves launching a larger (and consequently more sensitive) antenna with a longer baseline. The ARISE concept proposes to do just this by inflating a 25 m antenna in space, so that structure can be seen on the 15 μarcsec scale. This should elucidate how jets are formed in AGN. It will also furnish accurate distances out to 100 Mpc and investigate the structure of cosmic maser sources.

Gamma Ray Large Area Space Telescope (GLAST)

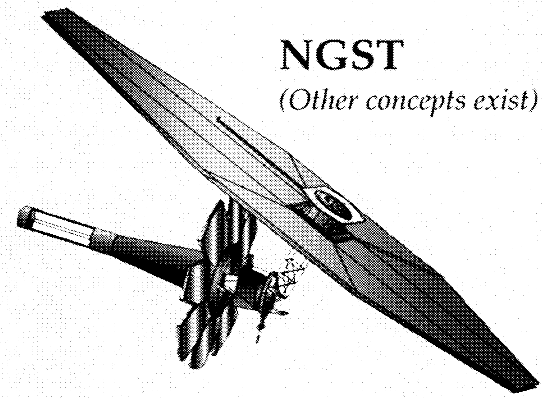
ONE OF THE MOST STRIKING AND UNEXPECTED discoveries of CGRO is that there are hundreds of sources in our Galaxy and throughout the Universe observable at energies of order 0.1 – 10 GeV. A large fraction of the extragalactic sources are identified with highly variable, relativistic jets streaming out of quasars and radio galaxies towards us. Several of the Galactic sources are found to be radio pulsars (spinning neutron stars), recognizable though their regular pulsation. This is a new field of astronomy and the sources are only beginning to be understood. The GLAST concept is the next step in exploring the mysterious gamma-ray sky at GeV energies.

The CGRO/EGRET results were achieved using a relatively old-fashioned detector and it is possible to improve the sensitivity a hundredfold using modern solid state detectors adapted from those in use at particle accelerators. Remarkably, GLAST will be able to locate the sources more accurately than before, while scanning ten percent of the sky at a time so that hundreds of sources can be monitored simultaneously. It is proposed to operate this mission, not only in collaboration with the Japanese Space Agency, but also with the Department of Energy. The science goals of this mission complement those of ARISE.

GLAST is the highest priority mission endorsed in the recent report of the Gamma-Ray Astronomy Working Group and has just received a highly favorable review by the GLAST Technology Readiness Independent Review Panel. GLAST was strongly endorsed under the New Mission Concepts for Astrophysics NRA.

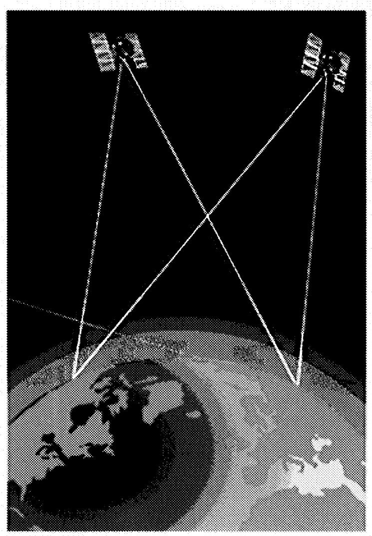
MISSION PORTFOLIO: Structure

GLAST

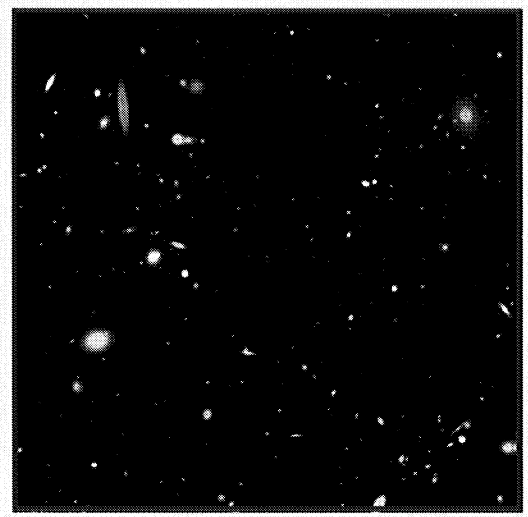


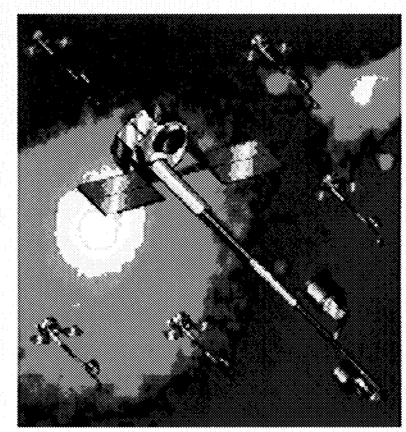
NGST

(Other concepts exist)



OWL



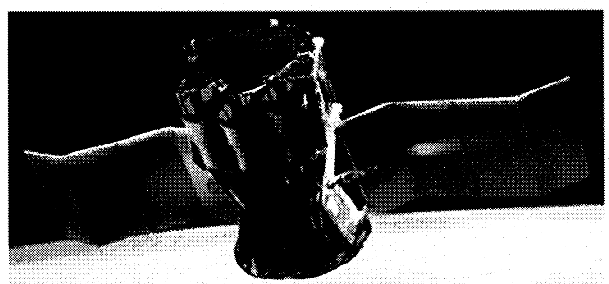


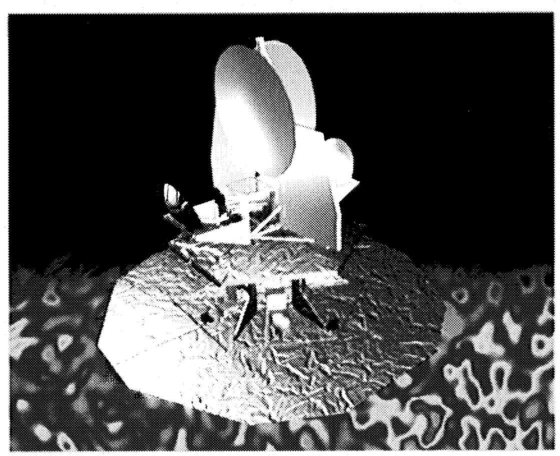
HTXS

CURRENT SEU PROGRAM (continued)

GP-B:
Will measure relativistic coordinate frame dragging.

SWAS:
Will measure distribution of water in the galaxy.

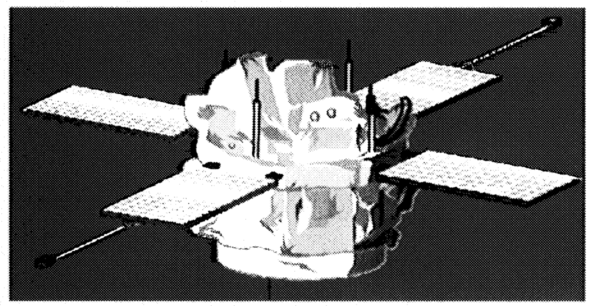




MAP:
Will measure primeval structure of the big bang.

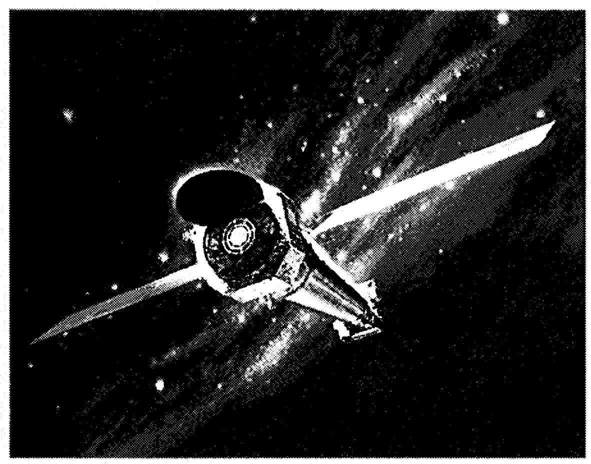
CURRENT SEU PROGRAM

THE CURRENT SEU PROGRAM IS A MIX of the currently operational missions and those awaiting completion and launch. It has been characterized by a high success rate both in terms of technical performance and in terms of fulfilling, and usually exceeding, science goals. In recent years, it has also been especially responsive to the call to make missions faster, better and cheaper. The major discoveries of the current missions have attracted unusual interest in the media and the general public.



ACE:
Will measure composition of low-energy cosmic-ray particles from the Sun and the Galaxy.

AXAF:
Will measure X-rays from galaxies, clusters of galaxies, supernova remnants, and accretion disks.



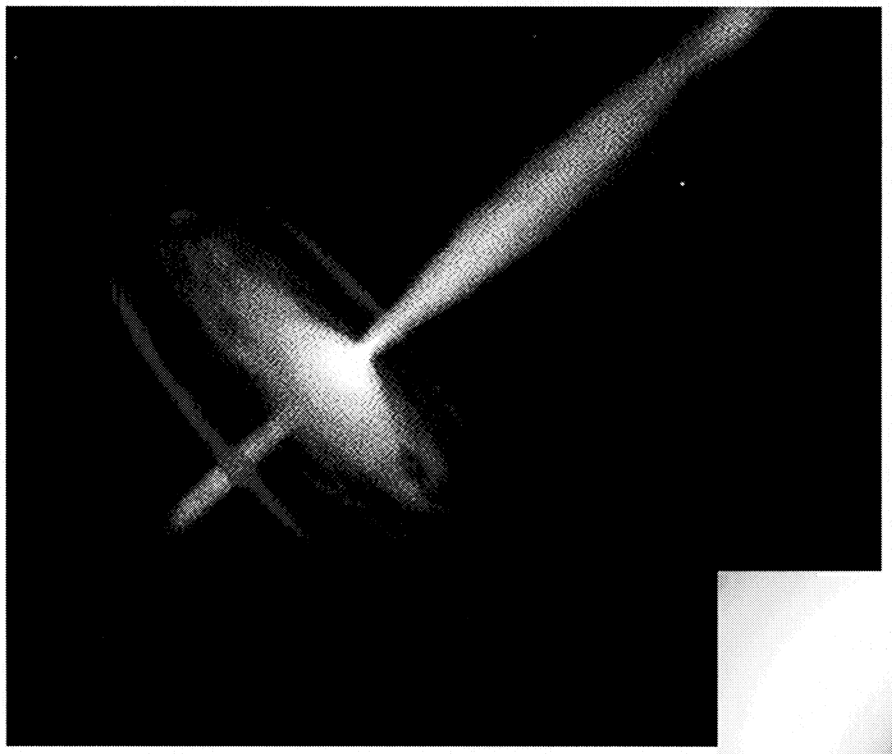
CAMPAIGNS: Strong Gravity (continued)

Gravitational waves are interesting both as probes of the fundamental nature of gravity and for the unique astronomical information encoded in their waveforms. Detailed studies of cosmic gravitational waves would provide strong-field tests of general relativity as well as astronomical information unlikely to be obtained in any other way. The most promising sources of gravitational waves observable from space are merging massive black holes in active galactic nuclei. (Somewhat weaker, but more frequent bursts are expected to be produced when individual stars are captured by massive black holes and selected Galactic binary stars should produce promising periodic sources. More speculatively, there may be a continuous background of gravitational radiation from the very early Universe.) Detection and subsequent detailed study of these gravitational waves will open a new window for observational astronomy, giving information fundamentally different from that contained in photons.

One of the most exciting long term goals of astronomical imaging is to achieve an angular resolution capable of resolving a supermassive black hole in the nucleus of a nearby galaxy, for example the famous radio galaxy Centaurus A, where an angular resolution of better than 1 μarcsec would be necessary. Unfortunately, it will not be possible to achieve this fine a resolution using radio telescopes because the interstellar medium has its own "seeing" and blurs images just like our own atmosphere at optical wavelengths. However, an array of very long baseline (more than a million km) orbiting millimeter or submillimeter telescopes might be able to achieve this goal. Achieving this imaging capability at optical wavelengths is also one of the distant goals of the ASOPS theme.

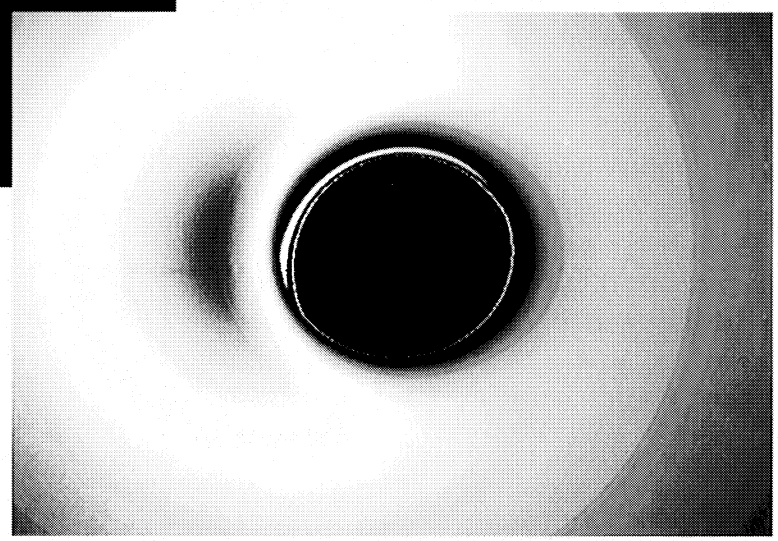
As astrophysical questions about strong gravity and black holes are answered by the SEU theme missions, they will be replaced with new and deeper questions. We can hope that, by the end of the period covered by this Roadmap, the first-generation spaceborne detector will have observed gravity waves from thousands of Galactic binaries, detected or constrained a background of low-frequency gravity waves from the big bang, and is likely to have observed low-frequency waves from massive black holes. This detector will have given the first direct observational evidence on the formation, growth, and space density of massive black holes in the mass range 100-10^6 solar masses. Thereafter, combined electromagnetic and higher sensitivity gravitational wave observations will probably be needed to give definitive information on the conditions under which massive black holes form and grow. Did they form directly from gas and dust or did they grow initially from collisions of stars? Were they present in pregalactic structures or did they form at later times? Finally, did their existence play a significant role in how galaxies formed in the first place?

CAMPAIGNS: Strong Gravity (continued)



Seeing the distortions of spacetime due to the strong gravity near a black hole, and hence checking Einstein's Theory of Relativity, requires observations that probe the regions just outside the event horizon.

X-ray spectroscopic observations with future missions can probe this region, and also measure the black hole spin, which may be responsible for powerful jets in radio galaxies.



CAMPAIGNS: Strong Gravity (continued)

Measure how strong gravity operates near black holes and how it affects the early Universe.

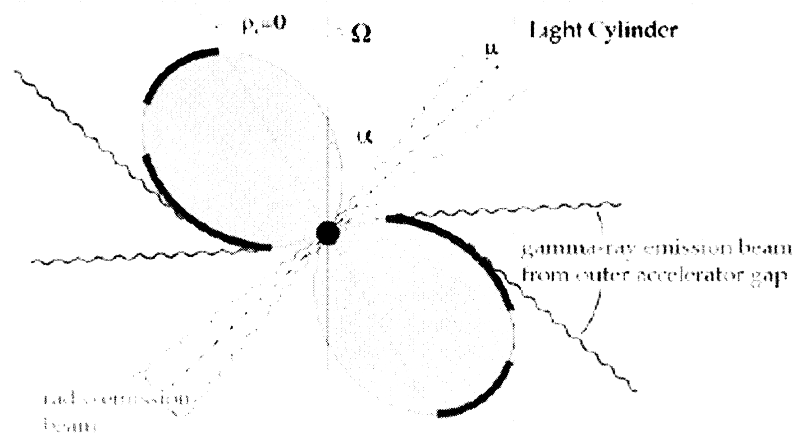
OVER THE PAST DECADE, EINSTEIN'S GENERAL THEORY of Relativity, once the exclusive property of the mathematical physicist, has been spectacularly corroborated and become the everyday tool of the astrophysicist. Black holes appear to be commonplace in active galactic nuclei and in binary stellar systems, and their properties are peculiarly relativistic. Even neutron stars exhibit special signatures of general relativistic effects.

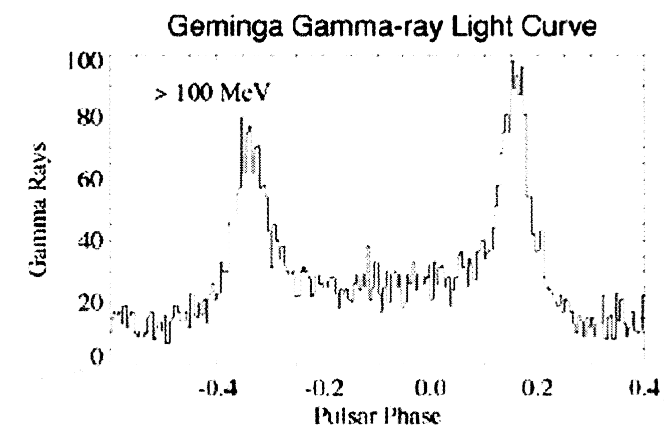
The strong gravitational fields around black holes may be probed by observing the radiation emitted by accreting gas. As we have described, this is expected to orbit in a disk before eventually being swallowed by the hole. The mass of the hole can be found if the velocity of the orbiting gas (or stars) at a known distance from the hole can be measured. Observations with the Hubble Space Telescope have allowed the masses of the supermassive black holes at the centers of galaxies to be determined using this method. However, seeing the distortions of spacetime produced by the black hole, and hence checking Einstein's General Theory of Relativity, requires observations much closer to the hole just outside its event horizon (the boundary of the region from within which light cannot escape from the hole). Emission lines from gaseous iron orbiting just outside the event horizon of supermassive black holes have recently been observed by ASCA. These lines have the widths expected for gas moving at speeds close to that of light, but the observations do not have the sensitivity to check the theory of general relativity. Better observations of these X-ray lines can confirm or refute Einstein's theory and also tell whether the black hole is spinning (the mass and spin provide a complete description of a black hole in an astrophysical setting). Although theories of black holes predict they should have spin, current telescopes are too limited to measure this vital property, which may be responsible for the powerful radio jets which propagate millions of light years from the centers of radio galaxies.

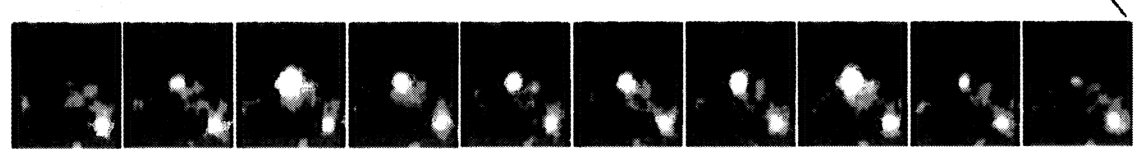
In addition to the existence of black holes, general relativity also predicts that gravitational waves, propagating ripples in the curvature of spacetime, are (like electromagnetic waves) transverse, have two independent polarization states, and propagate at the speed of light. Unlike electromagnetic waves, however, these tensor waves are extremely weak. This weakness has two consequences. First, it makes them experimentally very difficult to measure. Gravitational waves can be detected interferometrically by observing the change in distance between separated test masses. The fractional changes predicted to be observed near Earth from likely sources of gravitational waves are of the order of 10^{-20} or smaller in the low frequency (10^{-5} – 10^{-1} Hz) band accessible with space experiments. Second, once generated, gravitational waves interact so weakly with matter that they propagate with negligible scattering or absorption. This means that, unlike electromagnetic waves, gravitational waves preserve information about the strong-gravity, high-velocity regions where they are generated, unconfused by subsequent scattering or absorption in their propagation.

CAMPAIGNS: Measure how STRONG GRAVITY operates near black holes and how it affects the early universe.

Measurements of radio pulsar spin periods have been used to test the basic predictions of general relativity.



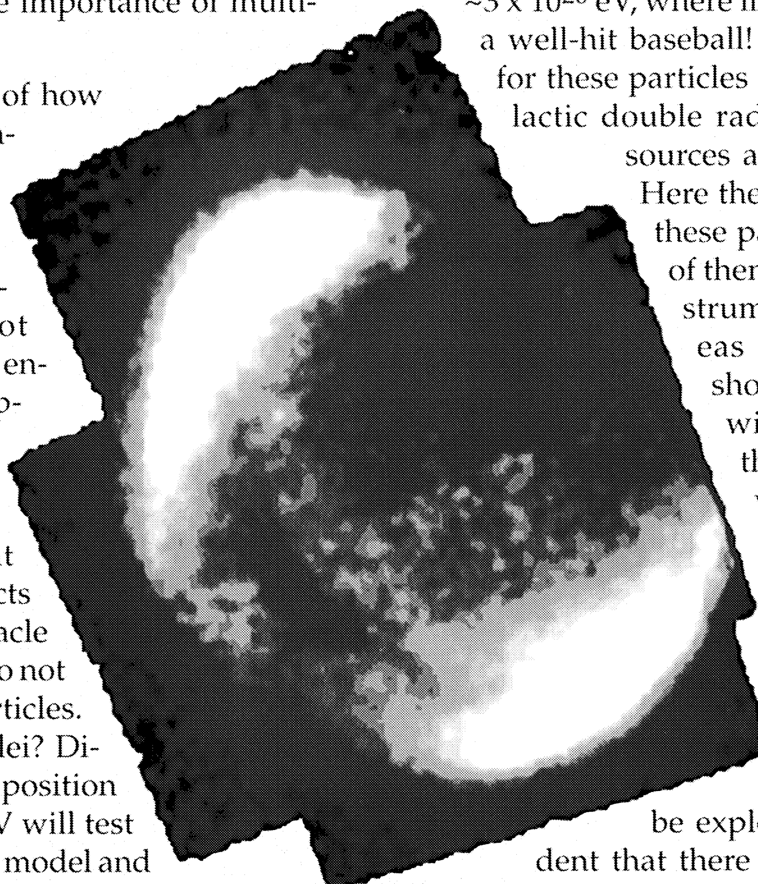




Pulsars like Geminga (right) emit radiation in the high-energy gamma-ray band.

optical source possibly associated with a distant galaxy. This is an additional tantalizing hint at an extragalactic origin of the bursts. It also clearly demonstrates the importance of multi-wavelength observations.

We have a pretty good interpretation of how cosmic rays of low and intermediate energy are accelerated at shock fronts formed by solar flares and supernova explosions propagating through the interplanetary and interstellar media respectively. However, we do not understand the origin of cosmic rays of energies more than about 10^{14} eV. It is apparent that completely new accelerators are at work. They could be the radio pulsars; alternatively they might be a hypothetical shock front formed where our Galactic wind impacts the intergalactic medium. A major obstacle to identifying these sources is that we do not understand the composition of the particles. Are they protons or are they iron nuclei? Direct observation of the elemental composition of cosmic rays at energies 100-1000 TeV will test the limits of the cosmic-ray acceleration model and locate their acceleration sites.

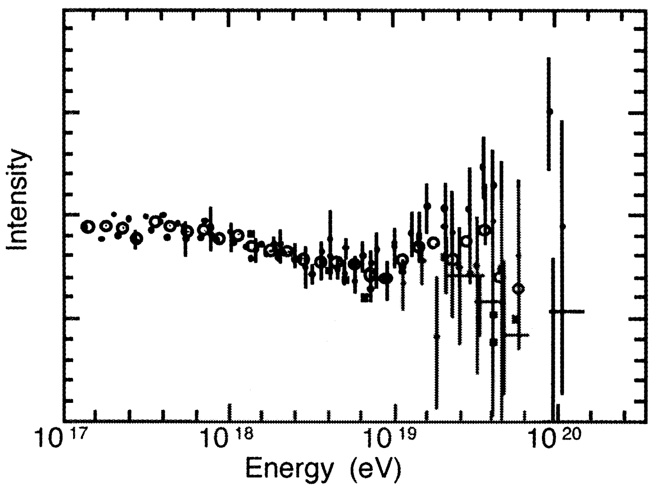


As we move to higher energies, the mystery deepens. In fact, we can measure the cosmic-ray spectrum all the way up to ~3×10^{20} eV, where individual particles have the energy of a well-hit baseball! About the only conceivable sources for these particles are galactic nuclei, the giant extragalactic double radio sources or the same mysterious sources as the gamma-ray bursts themselves. Here the problem is that the detection rate of these particles is so low that we see too few of them to describe their properties well. Instruments capable of monitoring large areas of the Earth's atmosphere for the showers that these rare particles produce will establish the energy spectrum of these highest energy cosmic rays and will determine directions to these sources.

However, this campaign is more general than these two examples that serve to illustrate that, whenever we push back the frontiers of cosmic discovery, we reveal the unexpected. As there are still extremes to be explored for the first time, we are confident that there are more surprising discoveries like these waiting to be made.

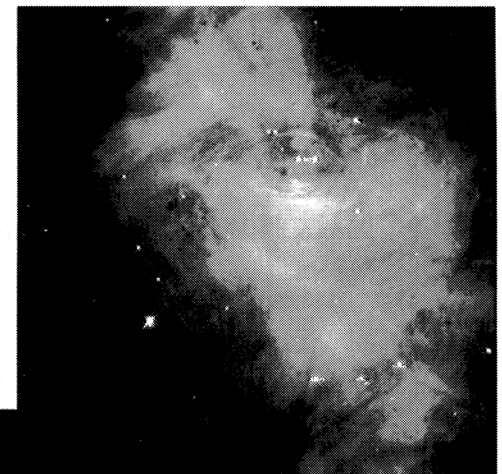
CAMPAIGNS: High Energy (continued)

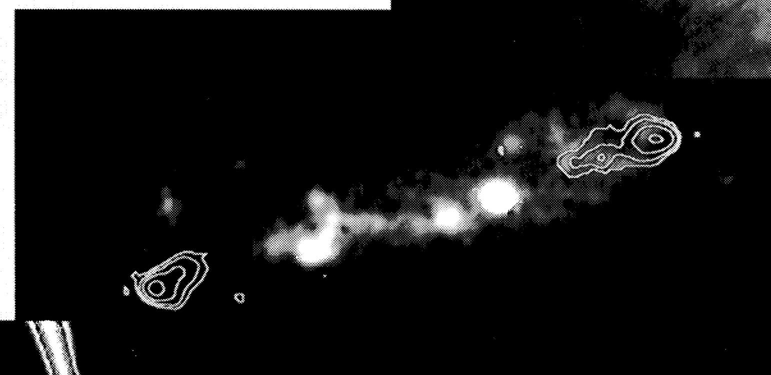
We do not understand the origin of the most energetic cosmic rays: those with energies greater than 10^{14}eV

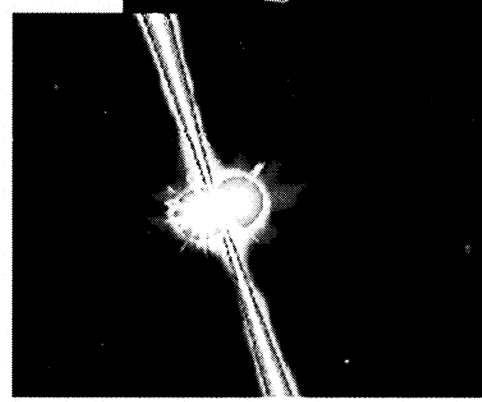


The high-energy cosmic ray spectrum

Radio pulsars, such as the one that powers the Crab nebula (right), can possibly produce some high-energy cosmic rays.







At the highest energies, above about 10^{20} eV, giant lobes in radio galaxies, or even gamma-ray bursters, could be responsible.

CAMPAIGNS: High Energy (continued)

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

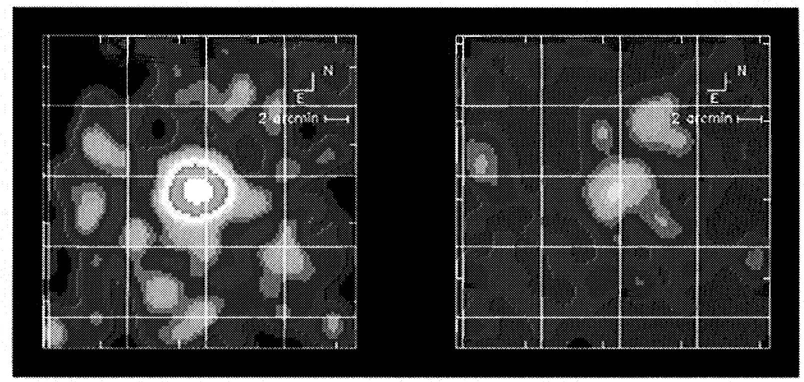
As astronomers have observed photons and particles of higher and higher energy, they have discovered that their detectors are matched by cosmic sources. Nature is able to channel enormous powers into relatively few particles so that they have huge individual energies, way out of thermodynamic equilibrium. Some of these cosmic accelerators have been identified with specific sources; AGNs and pulsars are examples. However, some of nature's most extreme accelerators are still unidentified. Two examples that stand out are the sources of cosmic gamma-ray bursts and of ultra-high-energy cosmic rays.

Cosmic gamma-ray bursts are intense flashes of gamma-rays which last from milliseconds to hundreds of seconds. They come at random times, briefly dominating the sky and then fading without a trace. CGRO has observed more than a thousand of these bizarre events and shown that they are isotropically distributed over the sky and that there are relatively fewer faint sources than would be expected from a homogeneous distribution. These observations have suggested to most astronomers that the explosions occur at cosmological distances and, consequently, each burst involves a huge amount of energy — typically as much as is produced in a single supernova, emitted as gamma radiation. An alternative hypothesis, that they are associated with the halo of our Galaxy, although less likely, cannot currently be ruled out.

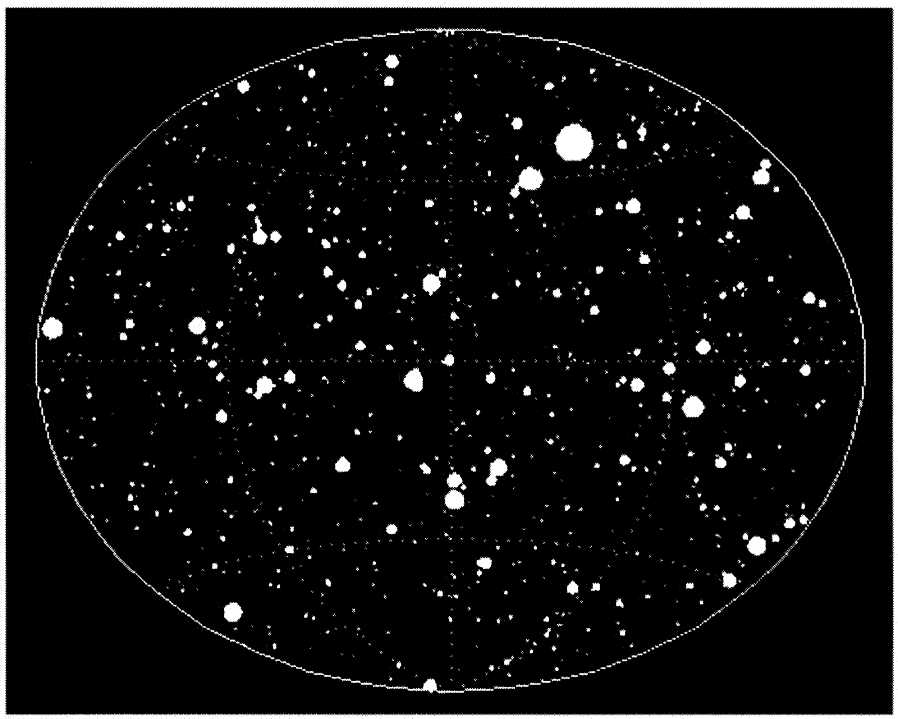
The origin of these bursts is one of astronomy's great mysteries. Assuming that they are at cosmological distances, then they are enormous explosions in which a significant fraction of the rest mass energy of an individual star would have to be released with high energies. They may involve the coalescence of pairs of neutron stars or black holes in binary systems. This comes about because, under the general theory of relativity, binary stars must radiate gravitational radiation. This, in turn, causes their gravitational energy to decrease so that they slowly spiral together; their final plunge ending with an intense, relativistic, explosion. Alternatively, they could be associated with an explosive release of energy from stellar material accelerated in the vicinity of a massive black hole, or, if the halo interpretation turns out to be correct after all, they could originate from the surfaces of neutron stars.

To solve the gamma-ray burst mystery we need to determine the distance scale to the sources (extragalactic versus galactic halo) and then determine the nature of the sources. It is important to determine if the bursts are associated with known classes of astronomical objects. As gamma-ray determined positions are relatively inaccurate, it is necessary to see the bursts at X-ray, optical, or radio wavelengths. Recently, the Italian-Dutch SAX mission detected a faint and fading X-ray source following a gamma-ray burst. Using the position of the X-ray source in the sky, astronomers were able to make deep follow-up observations with ground-based optical telescopes and found a fading

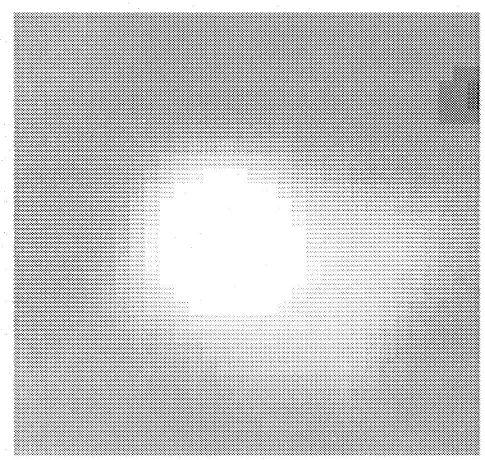
CAMPAIGNS: Identify the sources of gamma-ray bursts and HIGH-ENERGY cosmic rays



A fading X-ray counterpart for a classical gamma-ray burst has recently been detected.



The distribution of gamma-ray bursts on the sky as measured by BATSE. The size of the circle indicates the burst brightness.



The position is consistent with a fading optical source. The HST image on the left shows this possible counterpart to be extended.

distant galaxies and smaller black holes using HALCA. However, the full power of this technique will not be realized until there is a full scale space VLBI capability.

There are many similarities between the stellar mass black holes and the very massive AGN black holes, despite the fact that their characteristic scales can differ by factors of more than a million. One of the most famous of the galactic sources, SS433, has jets extending for 10^{15} km in each direction, with material being ejected from the central source and moving in collimated beams at 26 percent the speed of light. In addition, some recently discovered Galactic binary sources show jets in which the apparent motion of individual features appears to be faster than the formal speed of light. (This superluminal motion is just an optical illusion and there is no contradiction with the theory of relativity.) Similar, cosmic radio jets are often found associated with many active galaxies and trace the flow of the energy from the active galactic nucleus to the giant radio lobes observed at radii of several million light years. In many quasars, like 3C 279, these jets are aimed in our direction producing bright beams of gamma-rays overwhelmingly more powerful and more rapidly variable than the radio jets. These gamma-rays must originate from quite close to the source of the jet, almost certainly from an ultrarelativistic electron-positron plasma.

There are other approaches to understanding how accretion disks work. X-ray observations of Galactic binary X-ray sources often exhibit long trains of pulses, called quasi-periodic oscillations, with frequencies that can be larger than one kilohertz. These are telling us about the dynamics of the disk accretion process in much the same way that solar oscillations tell us about the structure of the Sun. In addition, the observed X-ray emission from these sources shows dramatic changes in intensity on time scales that can be shorter than a second and these wild variations are also reflected in the radio emission. This behavior has all the hallmarks of dynamical chaos, a generic feature of non-linear dynamical systems.

The goal of this campaign is to achieve an integrated understanding of disks and jets in all these different systems where they are found. This will require coordinated observations from radio to gamma-ray wavelengths. A VLBI network of radio/mm telescopes in space should reveal how jets are accelerated and collimated. Optical interferometric imaging, and, on larger scales, X-ray imaging, should elucidate the acceleration processes by which the relativistic electrons and positrons responsible for the non-thermal emission are created. Ultra-sensitive ultraviolet and X-ray spectroscopy is the unique tool for understanding the details of the accretion process by measuring directly the range of velocities of gas with different temperatures; the cooler gas presumably traveling more slowly, the hotter gas orbiting a central black hole with a speed approaching the speed of light. Finally, sensitive gamma-ray observations, carried out in concert with radio VLBI studies will probe both the jets and the disks closest to the central black hole.