THE GREAT OBSERVATORIES
FOR SPACE ASTROPHYSICS

ORIGINAL PAGE
COLOR PHOTOGRAPH

THE GREAT OBSERVATORIES

FOR SPACE ASTROPHYSICS

☆

The origin of the universe

☆

The fundamental laws of physics

☆

The birth of stars, planets, and life

☆

NASA
National Aeronautics and
Space Administration

Astrophysics Division

NP-128

Fundamental Questions in Astrophysics

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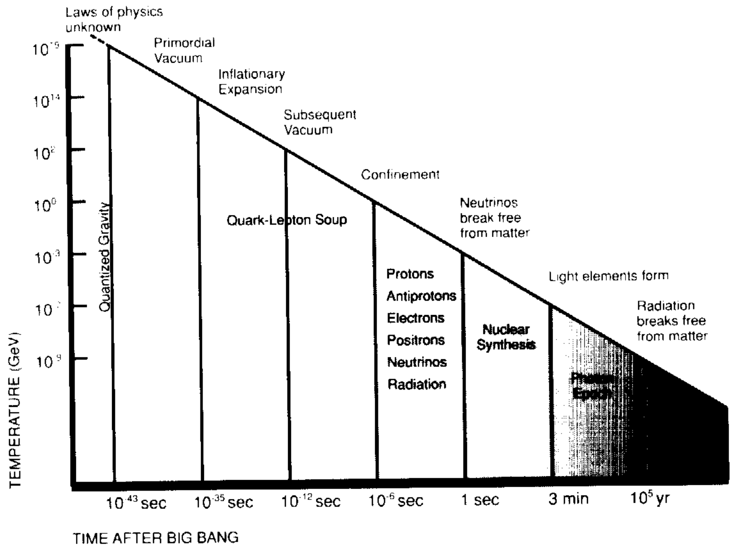
We ask fundamental questions about the nature of the cosmos, not in idle curiosity but of necessity. The long-term future of our world is linked to answers to questions about the past and future of the whole universe, its governing physical laws, and its potential for hospitable planetary systems.

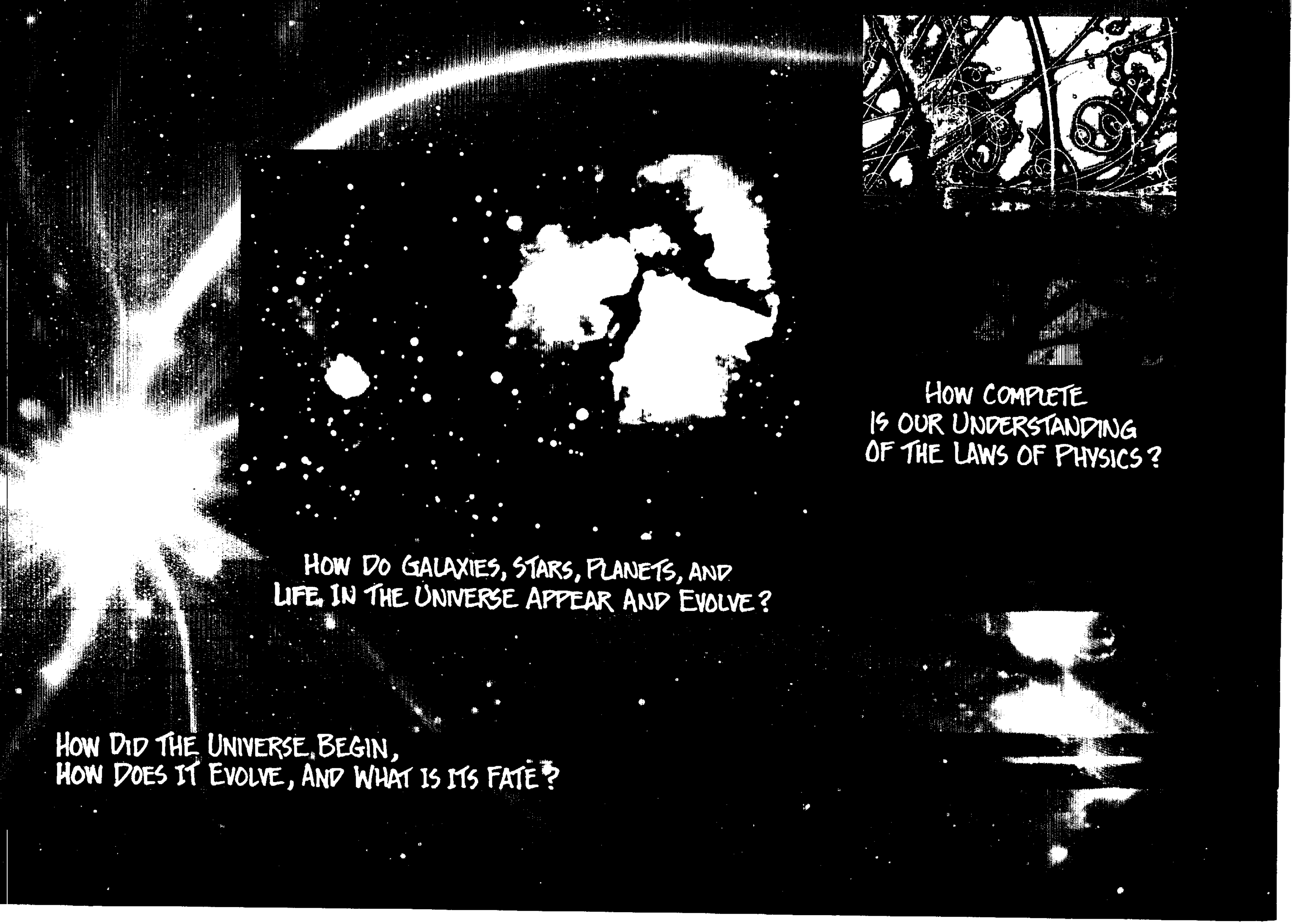
As we study the heavens with the best instruments and methods we can devise, we organize our research around intriguing questions in cosmology, basic physics, and astronomy. We seek to know the origin and fate of the universe; to learn in the vast laboratory of space, where extreme temperatures and pressures prevail that are impossible to create on Earth; and to understand how galaxies, stars, and planets evolve over the course of eons far beyond human history.

- How did the universe form and evolve in the first few seconds? Can we learn more about the basic laws of physics from the effects they have had on the structure of the universe?
- Do we need new laws of physics to describe observed phenomena? Must the Law of Gravitation be modified? Will new fundamental particles be found to play a central role in structuring the cosmos?
- How did galaxies and clusters of galaxies initially form, and how have they evolved?
- Can massive stars or galaxy-size aggregates collapse to form black holes, liberating enormous amounts of energy? Are such black holes the energy sources of quasars and active galactic nuclei? How do these powerful sources affect the galaxies in which they reside?
- How do stars and star clusters form and die, and how do they interact with interstellar matter? Do shock waves from stars dying in supernova explosions induce star formation? How do magnetic fields arise in interstellar matter and in stars?
- How are planetary systems formed? How many stars have planets and how many might be habitable? Where and how did life start? Can we remotely observe other life forms? Are there intelligent civilizations elsewhere in the universe?



What happened in the very beginning, when the universe was less than a second old? Recent research to trace the origin of the universe has focused on the fundamental forces governing the structure of matter at the earliest instants.

FUNDAMENTAL QUESTIONS IN COSMOLOGY, ASTRONOMY, AND PHYSICS



HOW COMPLETE
IS OUR UNDERSTANDING
OF THE LAWS OF PHYSICS?

HOW DO GALAXIES, STARS, PLANETS, AND
LIFE IN THE UNIVERSE APPEAR AND EVOLVE?

HOW DID THE UNIVERSE BEGIN,
HOW DOES IT EVOLVE, AND WHAT IS ITS FATE?

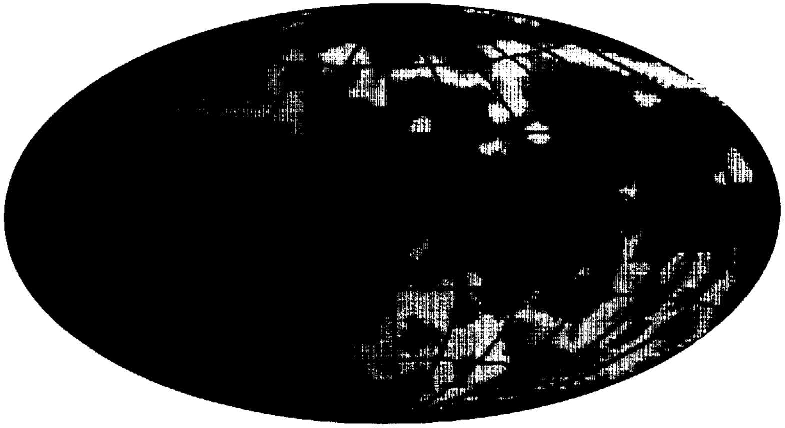
NASA's Role in Space Astronomy

2

Astronomical observations from Earth's surface, even from the highest mountain peaks, are plagued by clouds and poor visibility and by the fact that most radiation from celestial objects never penetrates the atmosphere. Thus, much information about the universe cannot be obtained from the ground, and what is available is degraded by atmospheric conditions. Above the atmosphere, however, the view is spectacular.

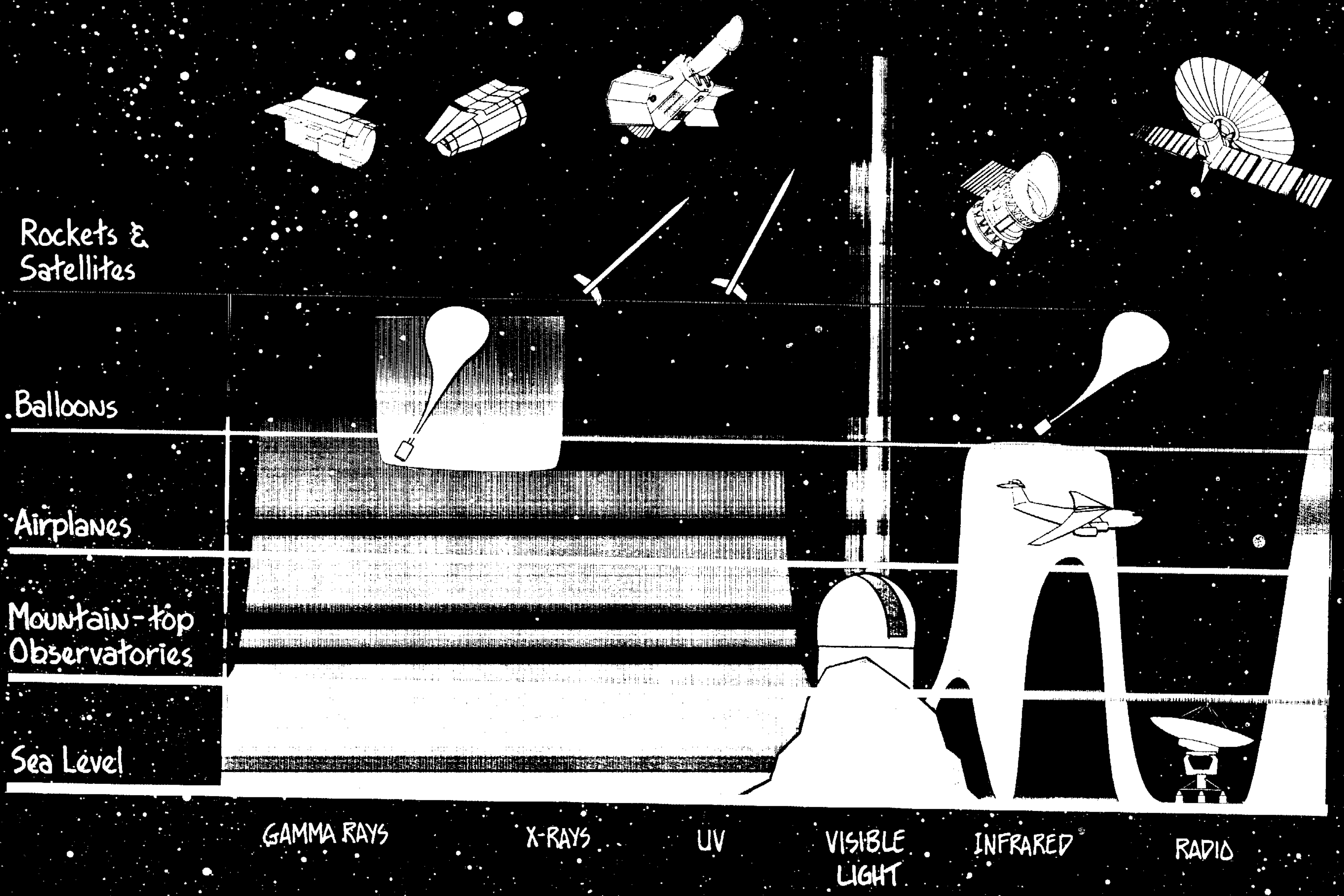
NASA's major contribution to modern astrophysics has been to place powerful new telescopes in orbit. From their vantage point in space, these observatories can sense gamma rays, X-rays, ultraviolet, optical, and infrared radiation undisturbed by the distorting, absorbing atmosphere. Some of these wavelengths would otherwise be blocked and inaccessible to astronomers. The agency also has vastly improved the ability to operate orbital telescopes and receive information rapidly.

Observations from space can take the form of high-resolution images or color-discriminating measurements across the electromagnetic spectrum. Ultra-hot gas in clusters of galaxies, background gamma radiation from the universe, and galaxies that emit virtually all their energy in infrared have been discovered through this ability to use telescopes in space. Observations in each wavelength band reveal a new universe.



Observed at soft X-ray energies (160 eV to 284 eV) where quanta of radiation are up to 50 times more energetic than visible light, the Milky Way has a novel appearance, different from that observed in visible light, infrared radiation, or radio waves. It is impossible to see the galaxy thus from the ground.

Observatories in space, high above Earth's absorbing atmosphere, provide new vistas on the universe. NASA has long been the leading architect of space observatories.



Looking at the Universe through the Great Observatories

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The nation's strategy for astrophysics research during the rest of this century and into the next is a coordinated, multispectral examination of the universe. NASA plans to launch a family of large orbital observatories, each tuned to a different part of the electromagnetic spectrum.

- The GAMMA-RAY OBSERVATORY (GRO) will explore the most energetic part of the spectrum across a much greater wavelength range than its predecessors, searching for evidence of anti-matter present in the universe and probing the mysteries of distant explosive galaxies and quasars.
- The ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF) will cover the X-ray portion of the spectrum with a hundred-fold improvement in sensitivity, attempting to identify dark matter, believed to be the most massive component of the universe.
- The HUBBLE SPACE TELESCOPE (HST) will penetrate far into the universe in visible and ultraviolet light, expanding the volume of observable space several hundred times to answer the question, "How large and how old is the universe?"
- The SPACE INFRARED TELESCOPE FACILITY (SIRTF) will span the infrared part of the spectrum with a thousand-fold increase in sensitivity to discover how and where galaxies, stars, and planetary systems are formed.

To complement these sensitive space telescopes, a powerful new radio observatory system is envisioned: the Very Long Baseline Array (VLBA), an intercontinental network of radio telescopes, working with radio observatories in space to perform orbiting very long baseline interferometry (OVLBI).

Observing the universe across the spectrum requires different kinds of telescopes based on quite different techniques of detection. An optical telescope has little in common with a gamma-ray detector; they do not look alike, nor do they operate on the same principles. No single telescope can answer all the questions or make all the discoveries that await us.

Each of the new observatories was designed to be the best of its kind and to operate for many years. With improvements in sensitivity and resolution much beyond their predecessors, the Great Observatories will enable us to see farther into the universe, and in more detail, than we ever have.

WHAT ARE THE GREAT OBSERVATORIES LOOKING FOR?

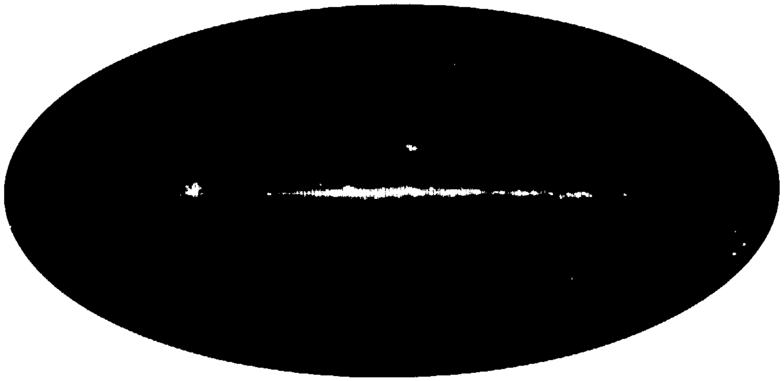
Perspectives on The Milky Way

4

Our galaxy, the Milky Way, is populated by star clusters, dusty clouds of turbulent gas, exploding or collapsing stellar masses, and gradually evolving systems of stars—phenomena that are revealed by observations at widely differing wavelengths. Through the use of several telescopes, each sensitive to radiation from matter at a different temperature, we hope to observe and comprehend the processes that govern our galaxy.

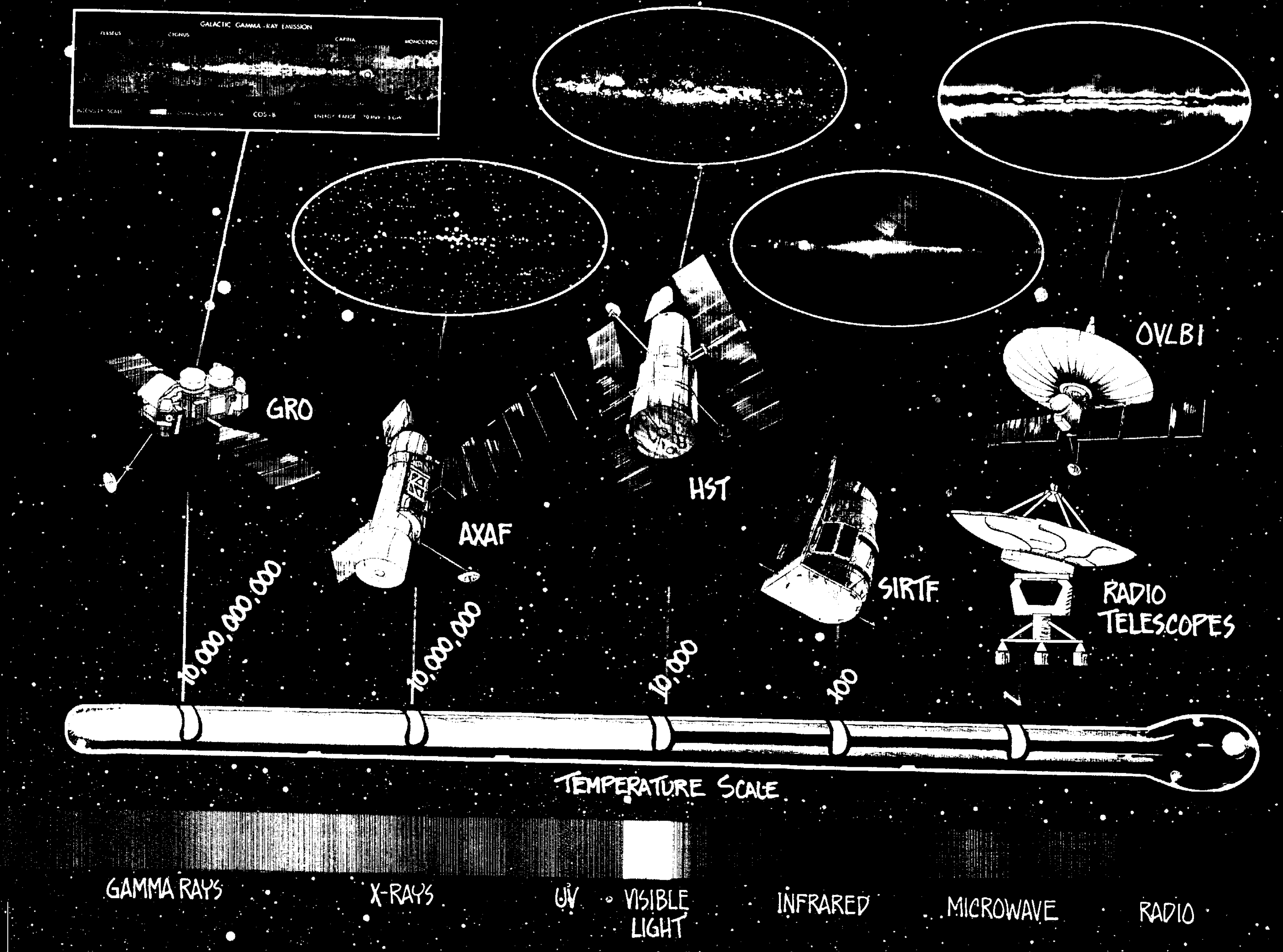
- At radio wavelengths, we detect cool clouds in space; some are destined to contract to form new stars, while others are ejected at high speeds, emitting radio waves characteristic of water vapor masers.
- At infrared wavelengths, we see matter at room temperature, such as dusty regions warmed by stars that have formed, or currently are forming, within them; we also register dying stars discarding shells of matter.
- At visible and ultraviolet wavelengths, we see matter at the temperature of the sun's surface or of the filament in an incandescent light bulb. In this temperature range are millions of ordinary stars and galaxies like our own; we can study their evolution as they consume their nuclear energy.
- At X-ray wavelengths, we see matter at about 1 million degrees C. One way matter becomes so hot is by falling from the extended atmospheres of giant stars onto the compact remains of more massive dead stars.
- At gamma-ray wavelengths, we see matter-antimatter annihilation and nucleosynthesis. We also detect sudden bursts of intense emission from sources not yet understood, and we observe the radioactive debris of novæ and supernovæ.

By combining these different pictures of our galaxy, we gain physical understanding, while any one of these observations alone might leave us puzzled.



The Infrared Astronomy Satellite (IRAS) mapped the Milky Way at four different wavelengths. This composite map clearly shows the dusty regions in which stars have formed and the center of our galaxy where vast outflows of energy occur. What is the nature of this powerful energy source?

PERSPECTIVES ON THE MILKY WAY



Radiative Processes

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Photons in each wavelength region arise from different physical processes and different characteristic temperatures. For example, gamma rays arise when electrons and their anti-particles (positrons) meet and annihilate. Gamma rays of higher energies are emitted when protons, the nuclei of hydrogen atoms, meet their anti-particles (anti-protons). Nuclear reactions, such as those which power stars, emit radiation in the gamma-ray band.

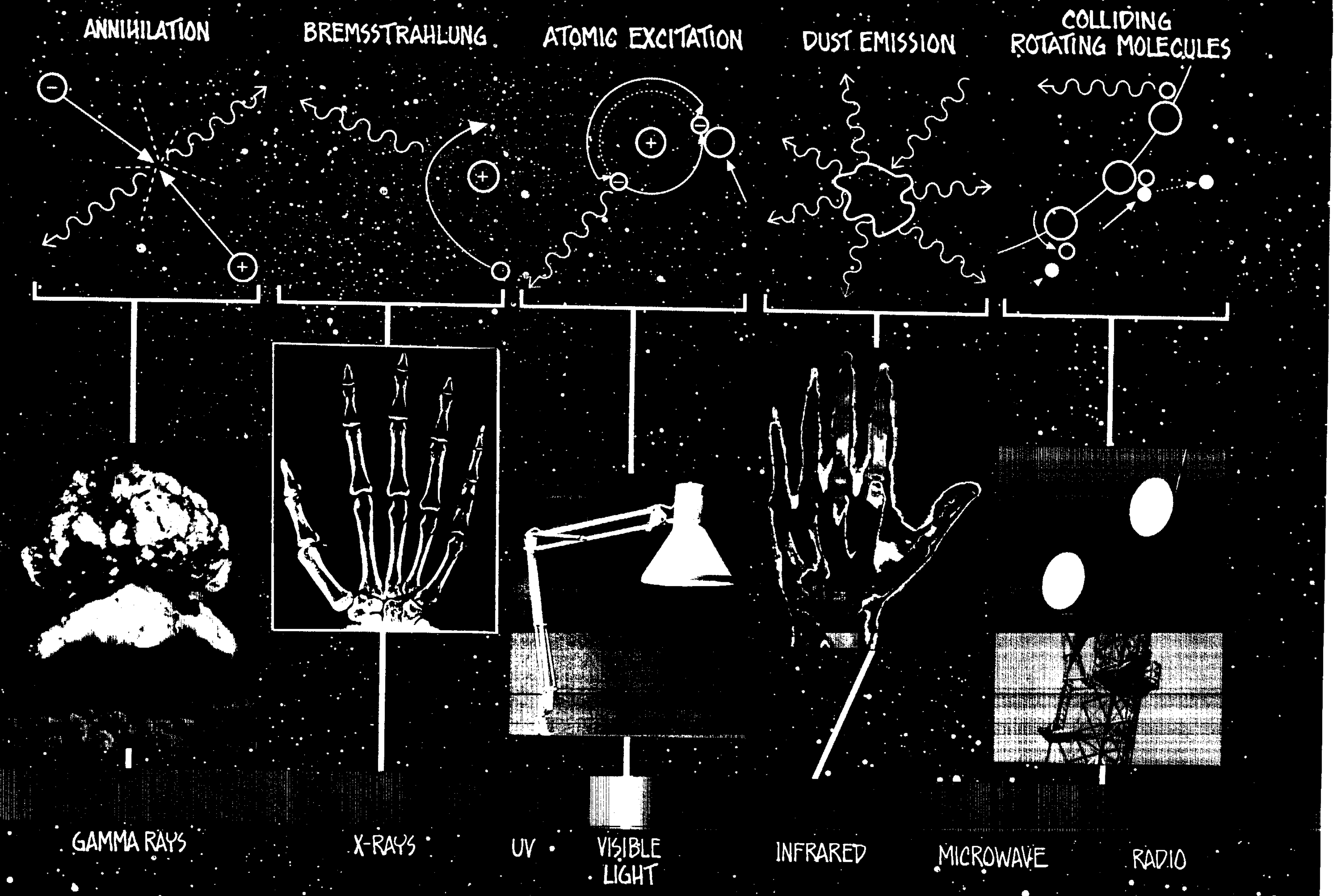
X-rays, likewise, are emitted by various processes. In the spaces between stars and galaxies, X-rays can be produced by the close passage of an energetic electron past a proton. The electron's path is altered in that interaction, and an X-ray is emitted. We encounter X-rays on Earth in hospitals, where they are useful in diagnosis of injuries.

Visible light can be emitted from atoms that have been energized through a collision with another atom. An electron bound to the atomic nucleus is imparted greater energy through such a collision; that energy subsequently is emitted as visible light when the electron gives up the energy and reverts to its normal state in the atom. Sodium or mercury vapor lamps (yellow or purplish street lights, respectively) emit visible light this way.

Infrared emission from interstellar dust is given off when a submicroscopic dust grain absorbs a single photon of visible or ultraviolet radiation and then cools by emitting a large number of less energetic infrared photons. Infrared radiation is emitted by any material in the temperature range naturally found on Earth. Infrared aerial photography or satellite imagery is often used on Earth to differentiate types of vegetation or indicate areas of pollution.

Radio waves are emitted by various processes, too. One astrophysically important way is through a two-step process in which a molecule is set rotating through collision with another molecule or atom. After a while, the molecule emits a radio wave, and the loss of that energy slows down its rotation. In dense interstellar clouds where molecules often collide, this loss mechanism can radiate away a great deal of energy and cool the whole cloud. Radio waves, of course, are important in daily life; they carry the information broadcast in all radio and television programs.

RADIATIVE PROCESSES AND FAMILIAR EXAMPLES



Detection Techniques

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No single method suffices to capture all types of radiation for analysis. Mirrors from conventional optical telescopes, for example, are useless for X-ray astronomy, because the shorter- wavelength, higher-energy X-rays are absorbed by the mirrors instead of being reflected. Each of the Great Observatories depends on a different technique of detection.

Gamma rays cannot be observed directly, but the effects of their passage through a detector can be recorded and measured by several techniques. When a gamma ray interacts with matter, it can expel one or more energetic electrons by the production of an electron and positron pair or by kicking out an orbiting electron (Compton scattering). These electrons can excite certain crystals and liquids to produce a faint flash of light, which can be recorded by very sensitive detectors. Alternatively, the path of an electron can be visualized by the spark produced when high voltage is applied to a gas in which it is moving. The Gamma-Ray Observatory includes spark chambers, scintillators, and Compton scattering detectors. It is very difficult to record individual gamma rays because they are relatively rare compared to the much more numerous cosmic rays (charged particles) that also enter detectors.

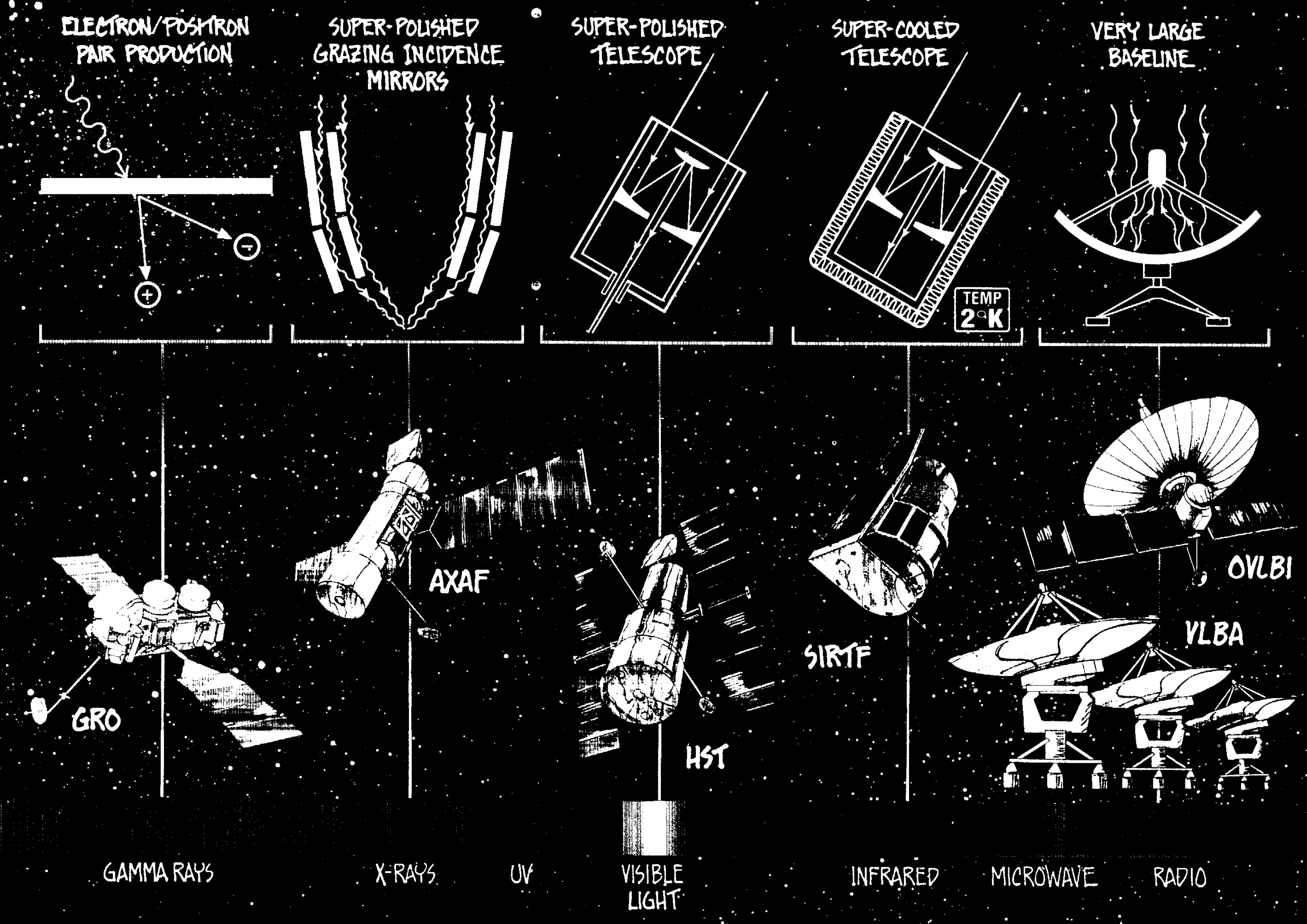
X-rays are absorbed or scattered by matter, so it is a challenge to bring them to a focus within a telescope. However, X-rays can be reflected from highly-polished surfaces if they only graze the surface at shallow angles. The Advanced X-Ray Astrophysics Facility uses a nested set of six super-polished cylindrical glass mirrors coated with gold to bring X-rays to a focus so detectors can record their spectral signature or make an image of the source of the radiation.

The Hubble Space Telescope uses a standard technique of reflection by two mirrors to detectors at the focal plane. Its design is a variation of a Cassegrain reflecting telescope. To achieve the desired performance, the primary mirror had to be extremely precise and smooth. It is large but lightweight and reflects not only visible light but also a portion of the ultraviolet band.

The Space Infrared Telescope Facility uses a reflecting mirror configuration like the Hubble Space Telescope with one major difference: the infrared telescope is contained within a dewar or “thermos bottle” chilled almost to absolute zero. This telescope requires cryogenic cooling with superfluid helium; otherwise the warmth from the instrumentation itself and the ambient environment would interfere with the detection of infrared radiation from astronomical sources.

Radio telescopes use large reflector dishes to focus radio waves into an antenna suspended above the reflector. Because radio waves are much longer than light waves, even large radio reflections cannot provide angular resolution comparable to traditional optical telescopes. Fortunately, a technique called aperture synthesis can be used to combine the signals from an array of telescopes for enhanced angular resolution. This technique is being extended into space with orbiting radio telescopes.

DIFFERENT TECHNIQUES OF DETECTION



History of a Supernova

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The radiation emitted by astronomical objects may change over time, as their ongoing physical and chemical processes evolve. Observations with only one type of telescope would offer only a “snapshot” of a moment in the life of an object, whereas observations across the spectrum enable us to track all phases of its evolution.

A prime candidate for multispectral observation is a supernova, an exploding star, which evolves rapidly through various phases marked by changes in its radiant output. The supernova that appeared in the Large Magellanic Cloud in 1987, the nearest and brightest such occurrence since 1604, is a good case study. A suite of telescopes like the Great Observatories would be ideal for studying in detail the nuances of the supernova process.

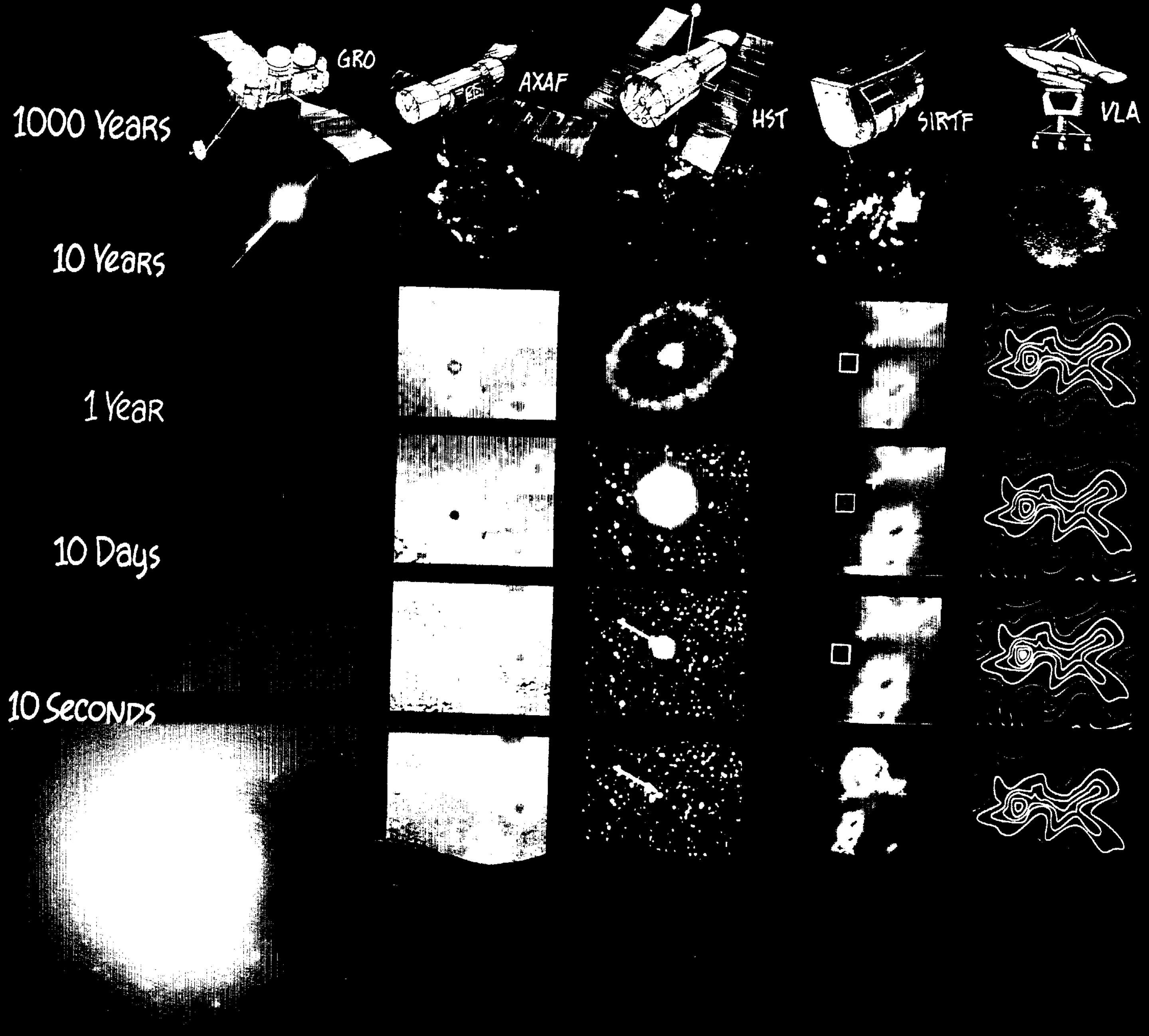
Because a supernova shines about 1,000 times brighter than the original star, it is observed first in visible light. This dramatic brightening happens overnight and may progress over a year’s time, before fading into a series of light “echoes” and eventually a wispy haze that remains visible for centuries. The initial, enormous burst of energy results from the collapse of a star, which generates a shock wave that blows the star apart. A burst of neutrino particles that travel unhindered at the speed of light precedes the visible brightening; when they arrive at Earth, however, they may not be recognized as evidence of a supernova explosion until the visible brightening has been noticed.

Sometime within a few months, the supernova remnant begins to radiate gamma rays and X-rays as it is heated by the decay of radioactive material produced in the explosion. These emissions are intense for perhaps a year as radioactive elements such as cobalt are spewed out from the explosion. The supernova star may ultimately become a pulsar, emitting gamma rays and X-rays for centuries, or the only lasting remnant may be a shell of gas and matter that remains a strong source of high-energy radiation as these heavy elements undergo radioactive decay.

Infrared radiation characteristic of radioactive elements deep in the core of the supernova passes unhindered through the outer, gaseous envelope and provides direct knowledge about the formation of heavy elements. As the supernova expands and cools, infrared and radio images show a lingering glow; pulsars, however, continue to be strong radio emitters.

Since different elements radiate at different energies, the complex chemistry and physics of a supernova cannot be understood by observations in any one wavelength band. Studying supernovae across the spectrum reveals inter-related processes and changes from the first seconds until centuries later. This multispectral coverage is important for the study of other astronomical phenomena as well.

Observations across the spectrum can trace the whole story of an astronomical event over time.



Advances in Instrumentation and in Understanding Nature

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When we look at the Orion constellation in the sky with our bare eyes, we note a pink-appearing star at the center of Orion's sword. With a large telescope, that star can be resolved and turns out not to be a star at all but an extended nebula of roiling gas and dust clouds. What we gain through increased angular resolution is a sharper image with increased detail and, therefore, more information.

Similarly, when radio astronomy was still a young science, astronomers thought all celestial sources shined steadily. When a capability to sense changes faster than the blink of an eye became available in the mid-1960s, rapidly pulsating neutron stars (pulsars) were soon discovered. The pulsar in the Crab Nebula, flashes 30 times each second. Its discovery became possible only through the increased time resolution that permitted such short intervals to be differentiated. Just as a precise stop watch provides 100th-second resolution while a poorer one only ticks off seconds, today's astronomical instruments can detect emission changes in microseconds whereas the earliest radio telescopes barely deteced changes over hours.

Two different colors, both of which appear to be the same red, actually may be produced through the emission of quite different atoms or molecules. A spectrometer capable of resolving these colors better than our eyes can not only distinguish these differences but also identify the atoms and molecules that emitted the radiation. In astronomy, spectral analysis helps us to distinguish the chemical nature of emitting matter at great distances across the universe. With increased spectral resolution, we can sometimes identify not only the chemical elements but also the isotopes that are emitting. A simple detection system might only distinguish visible light from ultraviolet or infrared radiation; a high-resolution spectrometer will divide the seven-color visible band ranging from violet to red into as many as a million distinguishable parts.[1]

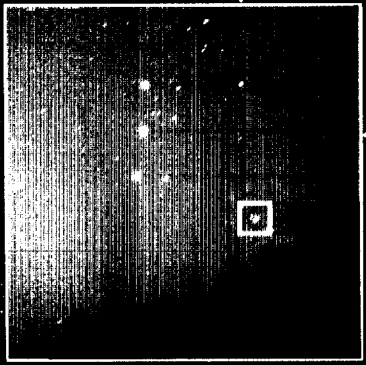
Sensitivity is the ability of an instrument to sense weak signals or to distinguish small differences in the intensity of two signals that, on first look, might appear equally bright. When we first enter a dark room from daylight, we may see nothing. As our eyes become dark adapted, they become more sensitive and begin to distinguish shapes and perhaps even colors. Similarly, a highly sensitive charge coupled device (CCD) can record faint images of the sky that never could be visible, even with the best dark-adapted human vision or the best photographic plate. In this fashion, we are able to obtain images of faint regions far across the universe and to observe objects hundreds of millions times fainter than anything our eyes could see.

These five capabilities—access to different wavelength regimes (gamma-ray, X-ray, visible, infrared, and radio), angular resolution, time resolution, spectral resolution, and sensitivity—provide us with the means for discovery. As our detection techniques improve, we are better able to study nature and gain increased knowledge of the universe. Improvements in any of these capabilities can produce gains; however, improvements in all of them combined are our best hope for ultimate understanding.

IMPROVED MEASUREMENTS—
ADVANCES IN INSTRUMENT CAPABILITIES

GAMMA RAYS X-RAYS UV VISIBLE INFRARED RADIO

WAVELENGTH COVERAGE

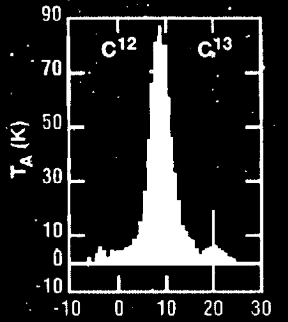


ANGULAR RESOLUTION

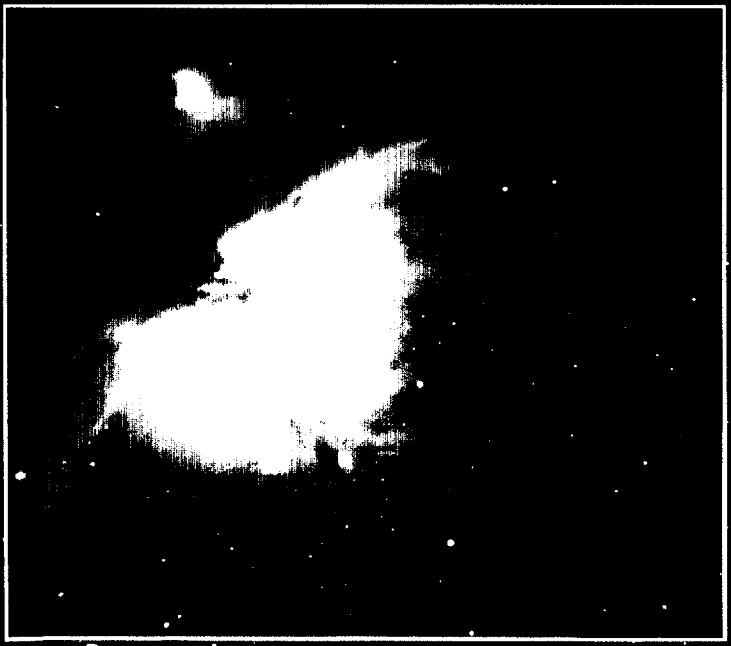
SENSITIVITY

SPECTRAL RESOLUTION

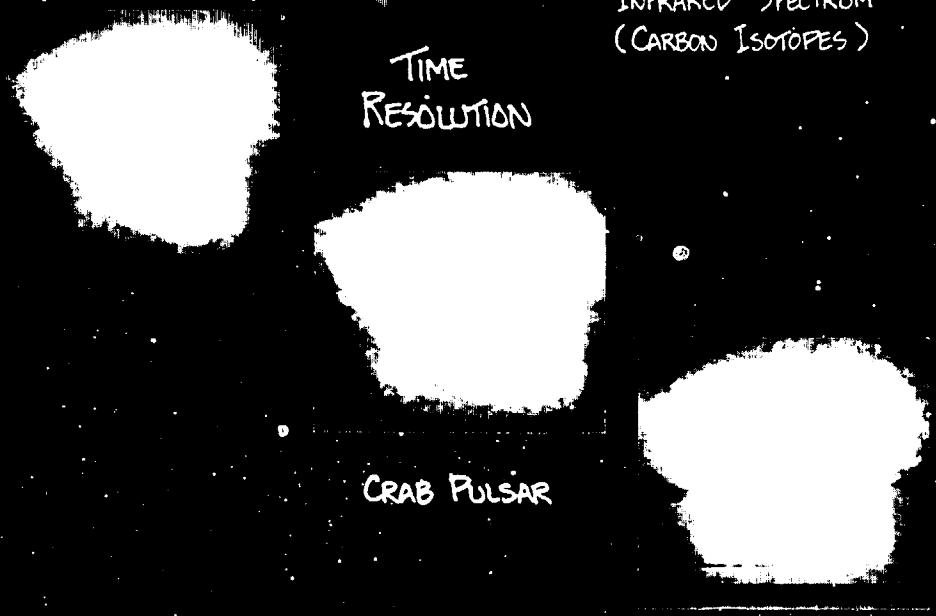
TIME RESOLUTION



ORION NEBULA INFRARED SPECTRUM (CARBON ISOTOPES)



ORION NEBULA



CRAB PULSAR

Hubble Space Telescope (HST)

9

The Hubble Space Telescope for visible light and ultraviolet astronomy is the first member of the Great Observatories family to enter service. Housing a 2.4-meter (8-foot) mirror and five sophisticated cameras and detectors, the telescope is the largest optical astronomy observatory ever placed in space.

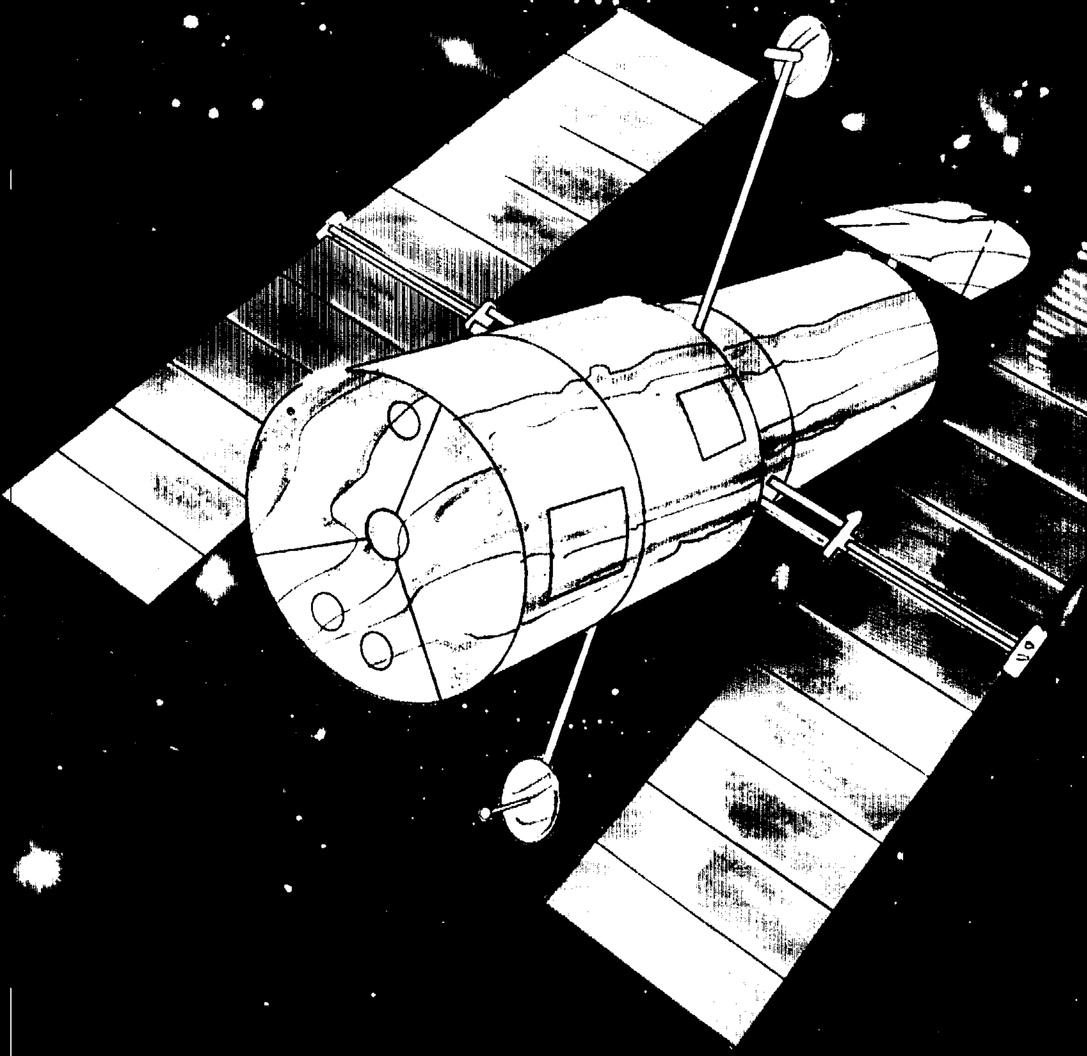
For optical astronomy, the greatest technical challenge is to collect as much light as possible, with as little distortion as possible, and bring it into very sharp focus where it can be recorded by sensitive detectors. The Hubble Space Telescope forced advances in mirror design, polishing, and coating; in telescope pointing and control devices; and in lightweight construction. (Unfortunately, an error in manufacture of the telescope optics affects image quality and requires correction in orbit.)

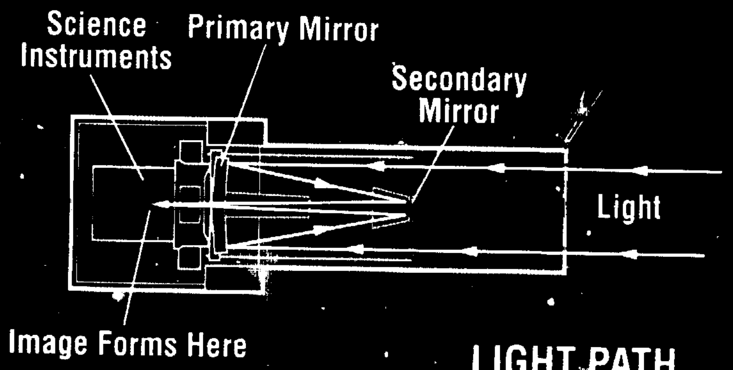
Focal plane instruments include two cameras, two spectrographs, and a photometer: the Wide Field/Planetary Camera, Faint Object Camera, Faint Object Spectrograph, High Resolution Spectrograph, and High Speed Photometer. In addition, the Fine Guidance Sensors are used for precise position measurements.

The Hubble Space Telescope is the first observatory designed for extensive maintenance and repair in orbit. Servicing in the Space Shuttle or Space Station will guarantee a long and productive operational lifetime as astronauts replace batteries and other elements and eventually upgrade the observatory with newer technology for enhanced scientific return.

Because of its extremely precise pointing stability and corrected optics, the Hubble Space Telescope images will then be 10 to 30 times sharper than our best images to date. Its sensitivity and resolution will be so fine that the telescope will be able to observe faint objects some 12 to 14 billion light years away as clearly as the best ground observatories can see objects at a range of 1 to 2 billion light years. In addition, distances between celestial objects can be measured 7 to 10 times more precisely with the aid of this telescope.

HST: THE UNIVERSE IN SHARPER FOCUS





LIGHT PATH

Opportunities for the Hubble Space Telescope

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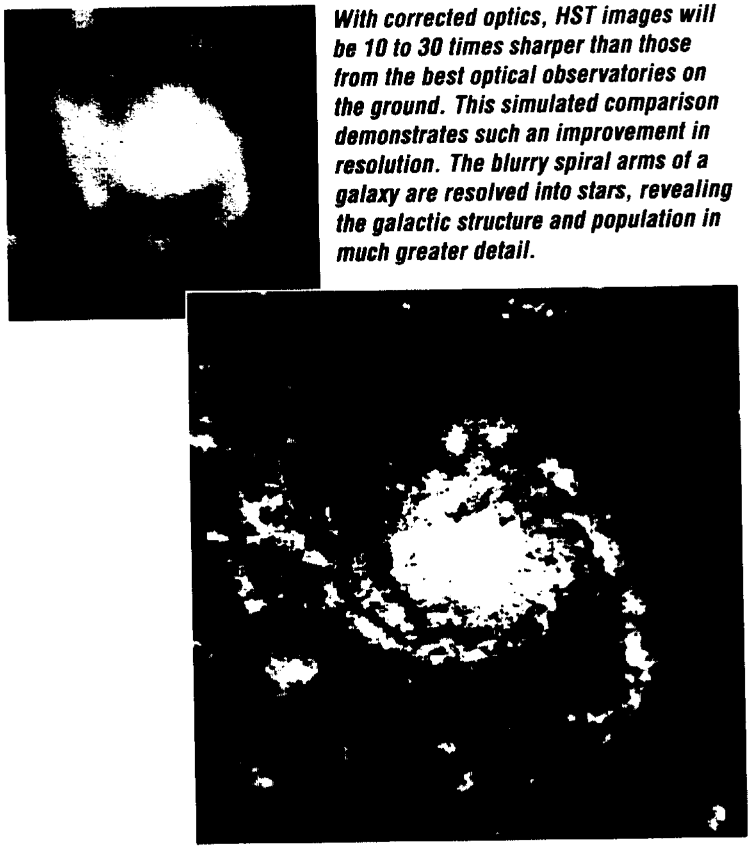
There are an estimated 100 billion galaxies in the universe, and we know only one reasonably well: our own, the Milky Way. Galaxies are evidence of the origin of the universe, for it is thought that they were the first objects to form after the cosmic "Big Bang." They seem to be the basic building blocks that give structure to the universe. The vast majority of galaxies must have formed long ago, for there is no clear evidence that new ones are forming today.

Astronomers are eager to see the farthest (youngest) galaxies at distances approaching 14 billion light years, for these should reveal the conditions under which the universe began to take shape. To understand how the universe evolved, we need to study as many galaxies of as many types and ages as possible. Today, only the 20 nearest galaxies have been studied in great detail; these are similar in form and content to the Milky Way and may have originated at the same time. A more thorough census is required.

With the very sensitive Hubble Space Telescope, astronomers will be looking much farther back in time and increasing the number of galaxies available for study. In addition, they will get a clearer look at some puzzling phenomena, such as active galactic nuclei that produce extraordinary energy compared to typical galaxies. It is thought that the centers of such galaxies may harbor quasars, which are not yet understood. With the improved resolution of the Hubble observatory, astronomers will be able to peer into the crowded centers of galaxies to see what lies hidden there.

Another high-priority project is to use the Hubble Space Telescope to determine the distance scale of the universe and an accurate value of the Hubble constant, a measure of the rate of expansion of the universe. Precise determination of this number has eluded astronomers despite decades of concerted effort. Current values differ by a factor of two, which causes uncertainty in almost every extragalactic astrophysical problem.

An exciting use of the Hubble Space Telescope is to focus on the planets and moons in our own solar system, giving us a front row view of these fascinating worlds almost comparable to photos from the Voyager spacecraft. Whereas the exploratory Voyagers had only a fleeting glance at Jupiter, Saturn, Uranus, and Neptune, the Hubble telescope can study them whenever we desire, repeatedly and in finer detail than observations from the ground. Thus, the telescope complements the discovery missions by providing for longer-term study.



With corrected optics, HST images will be 10 to 30 times sharper than those from the best optical observatories on the ground. This simulated comparison demonstrates such an improvement in resolution. The blurry spiral arms of a galaxy are resolved into stars, revealing the galactic structure and population in much greater detail.

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Gamma-Ray Observatory (GRO)

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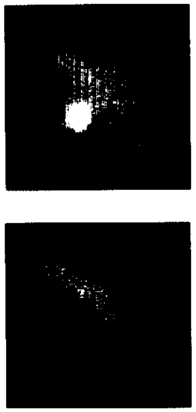
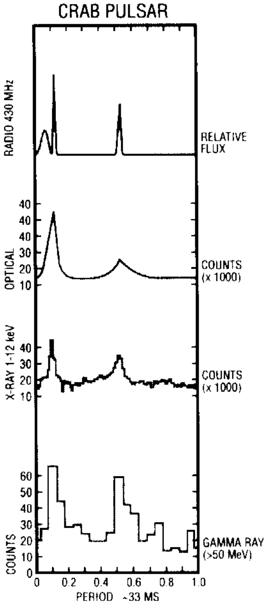
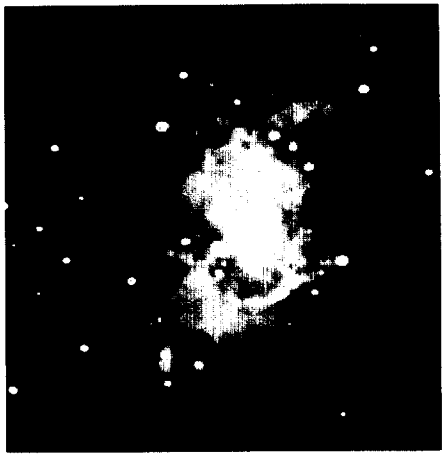


An X-ray image of the Crab Nebula shows the surviving core of an exploded star, now a spinning neutron star that emits regular pulses of energy. The Crab Nebula pulsar blinks on and off 33 times per second. The pulses are prominent in all wavelength bands, especially in the gamma-ray spectrum.





The Gamma-Ray Observatory will probe the high-energy universe, where processes abound that are invisible to ordinary telescopes and yet are crucial for understanding the basic physics of matter and radiation under extreme conditions. This observatory will be launched from the Shuttle several months after the Hubble Space Telescope. It provides the first opportunity since the highly successful European satellite, COS-B launched in 1975, to study the gamma-ray emission from cosmic sources; sensitivity and resolution are improved by more than an order of magnitude.

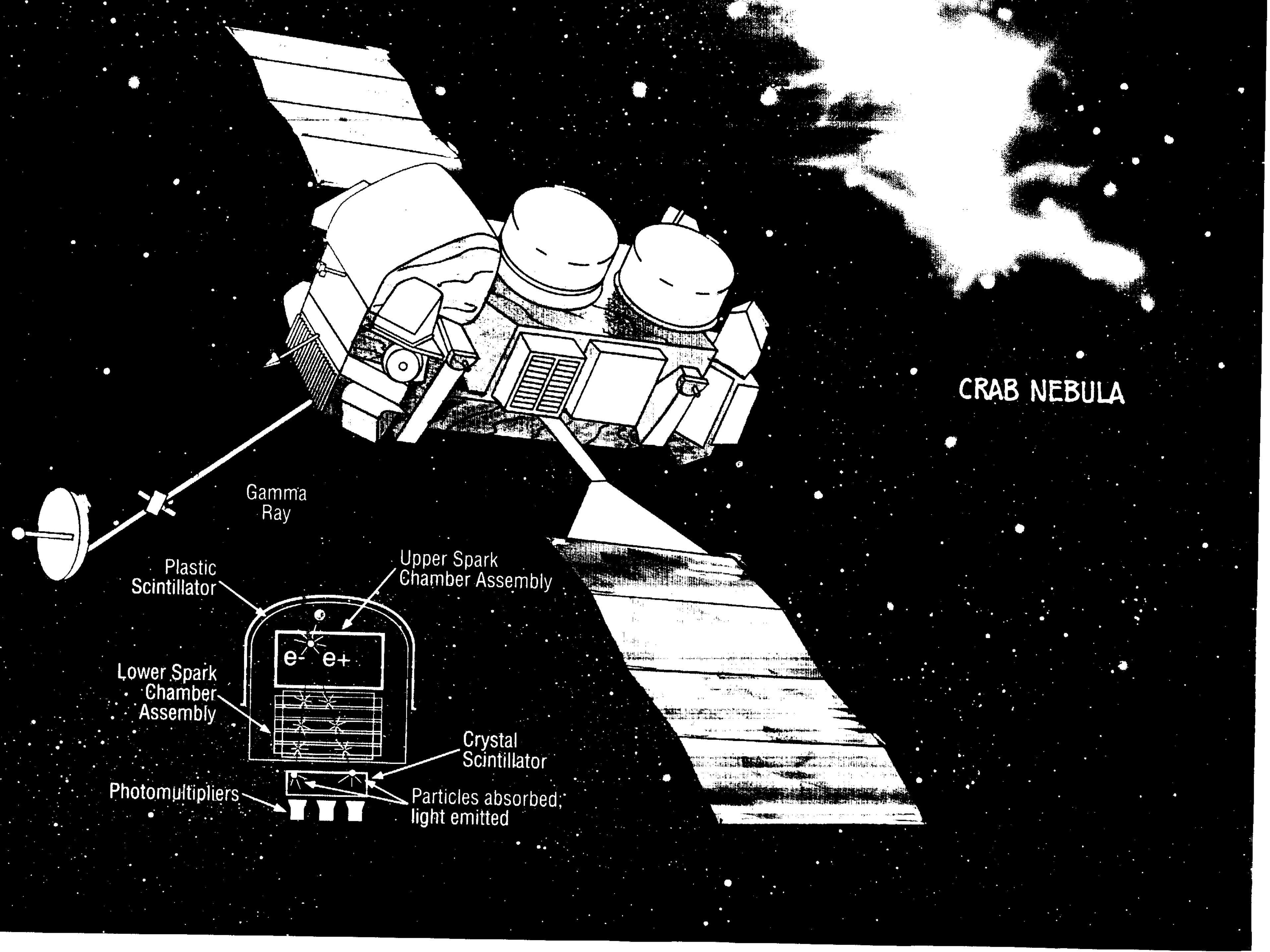
Objects that emit gamma rays cannot be photographed, but images can be derived through painstaking reconstruction of detector data. Gamma rays are difficult to detect because each photon must actually pass through the detector and be identified against a cosmic ray background that is a thousand times stronger. Spark chambers and scintillation detectors are used to record the passage, arrival time, trajectory, and energy level of gamma rays; a penetrating gamma-ray photon interacts with the detector material and causes a spark or glow that can be analyzed. Since gamma rays are too penetrating to be focused by conventional telescope techniques, the technical challenge is to capture individual gamma ray photons and gain as much information as possible from each one.

GRO consists of four major instruments mounted on a common platform: an Energetic Gamma Ray Experiment Telescope (EGRET) to study faint point sources and diffuse emission, an Imaging Compton Telescope (COMPTEL) for sensitive wide-field surveys, an Oriented Scintillation Spectrometer Experiment (OSSE) for spectral analysis, and a set of monitors for sudden gamma-ray emissions (Burst and Transient Source Experiment, BATSE). This suite of instruments will cover a wider energy range with much greater sensitivity than any previous gamma-ray astronomy facility.

These instruments span an enormous energy range—a factor of 100,000 in wavelength or energy—from the energetic X-ray to the high-energy gamma-ray bands. Designed both to survey large areas of sky and to study individual sources in detail, GRO should be able finally to resolve the nature of the many localized sources of gamma rays discovered along the plane of our galaxy by the COS-B mission. With this powerful new observatory, the relatively young field of gamma-ray astronomy enters maturity.

GRO includes onboard thruster rockets and propellant tanks for occasional adjustments in altitude. The observatory can be refueled in the Shuttle or Space Station.

GRO: THE HIGH-ENERGY UNIVERSE



Opportunities for the Gamma-Ray Observatory

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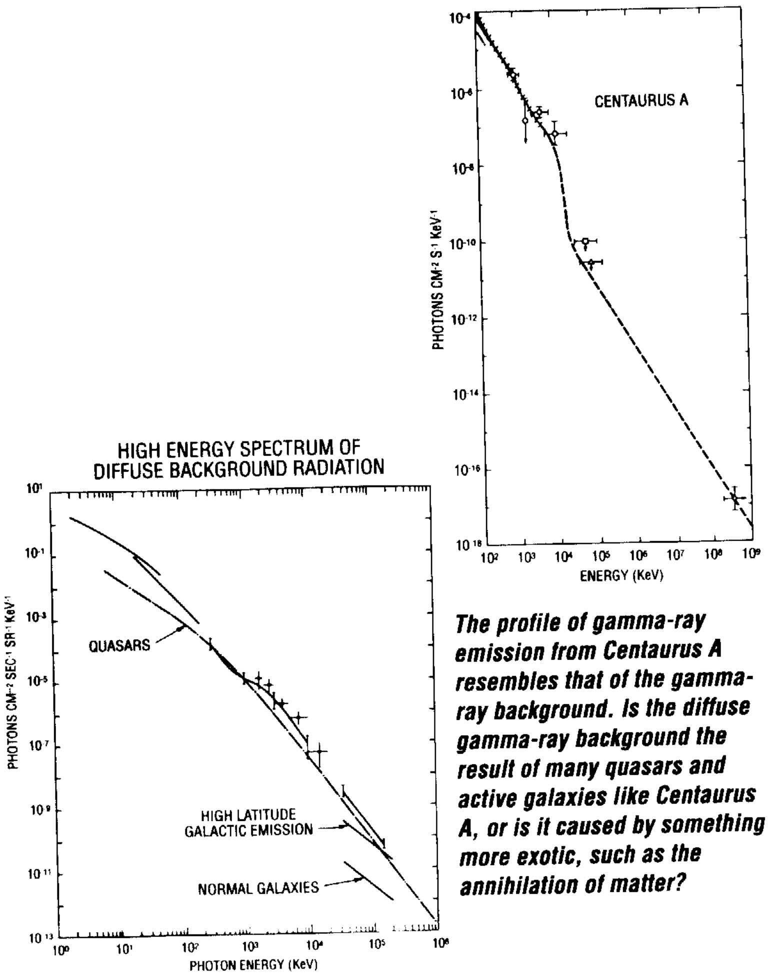
Gamma rays arise in our galaxy from localized sources and from the interaction of cosmic ray particles with diffuse gas clouds. The greatly enhanced GRO sensitivity and resolution will allow this emission to be mapped in far greater detail than previously possible and its correspondence with individual features such as giant molecular clouds, now only hinted at, to be studied in detail.

The bright localized sources along the galactic plane may be young pulsars or compact cores of giant molecular clouds. At present, only two pulsars (the Crab and Vela) are known as gamma-ray emitters. Only by studying many more pulsars can the general nature of pulsed gamma-ray emission be understood; it is already suspected that gamma rays may hold the key to the pulsed emission from pulsars in general.

The most extreme examples of active galaxies—the radio galaxy Centaurus A and the bright quasar 3C273—are powerful sources of cosmic gamma rays. Indeed, 3C273 emits a substantial portion of its total energy output in the gamma-ray band. The intensity of gamma rays compared to other emissions (from radio through X-rays) is the key to their origin. Gamma-ray emission from the giant galaxy Centaurus A reveals the physical conditions in the nucleus of this bizarre galaxy and the origin of its energetic powerhouse. GRO spectra over a broad energy range may allow the fundamental radiation mechanisms to be disentangled and then applied to comparable but far more distant sources.

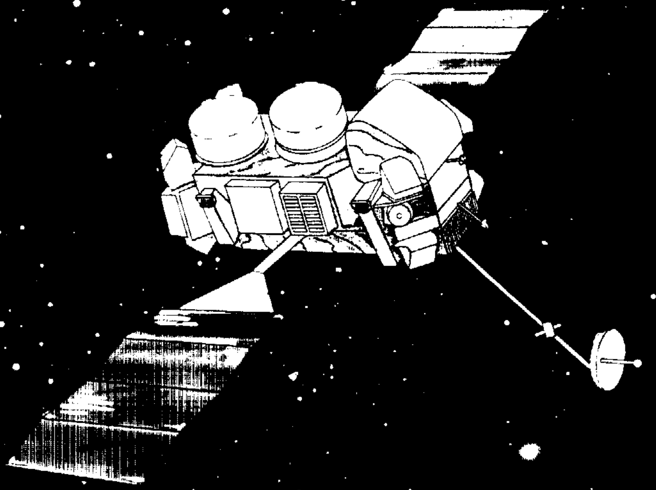
The sky is glowing in gamma rays, just as it is in radio and X-rays, in a diffuse background radiation whose origin remains enigmatic. Does this diffuse background arise from the emission of many quasars and active galaxies? Detailed GRO spectra of active galaxies as well as the diffuse spectrum will isolate this contribution and, hence, the importance of quasar gamma-ray emission in the early universe. It is also possible that this diffuse radiation is the product of the annihilation of matter and anti-matter in the universe on larger scales; confirmation would have the profound consequence that an anti-matter universe is awaiting to be explored.

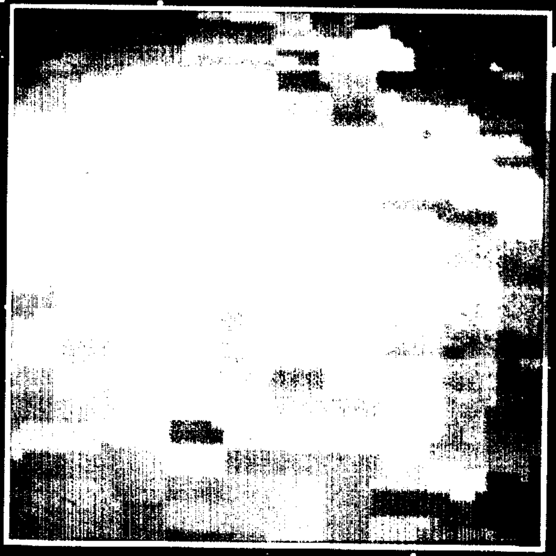


The profile of gamma-ray emission from Centaurus A resembles that of the gamma-ray background. Is the diffuse gamma-ray background the result of many quasars and active galaxies like Centaurus A, or is it caused by something more exotic, such as the annihilation of matter?

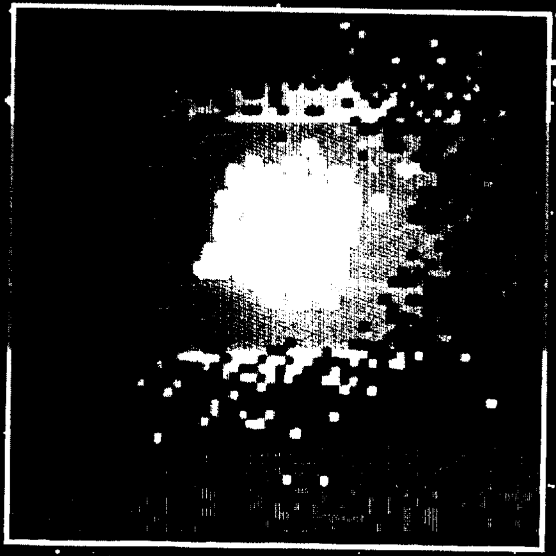
Where do gamma rays originate?
GRO will find and map this high-energy radiation.

CENTAURUS A

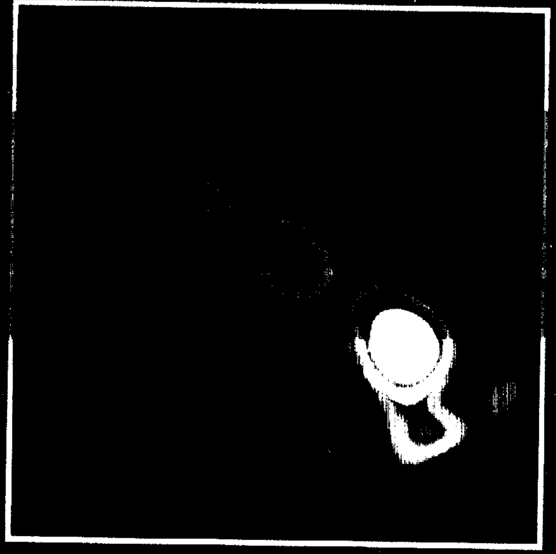




GAMMA-RAY IMAGE



X-RAY IMAGE



RADIO IMAGE

Advanced X-Ray Astrophysics Facility (AXAF)

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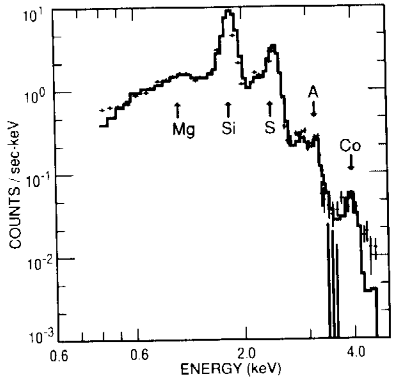


AXAF will obtain spatially resolved spectra of the shell of Tycho and other supernova remnants to study, for the first time, the onion-skin-like structure of the original star. Supernova explosions enrich the universe with the heavy chemical elements whose signatures can be read in high-energy radiation. Only AXAF can search for the expected iron emission between 6 and 7 keV to confirm this theory.

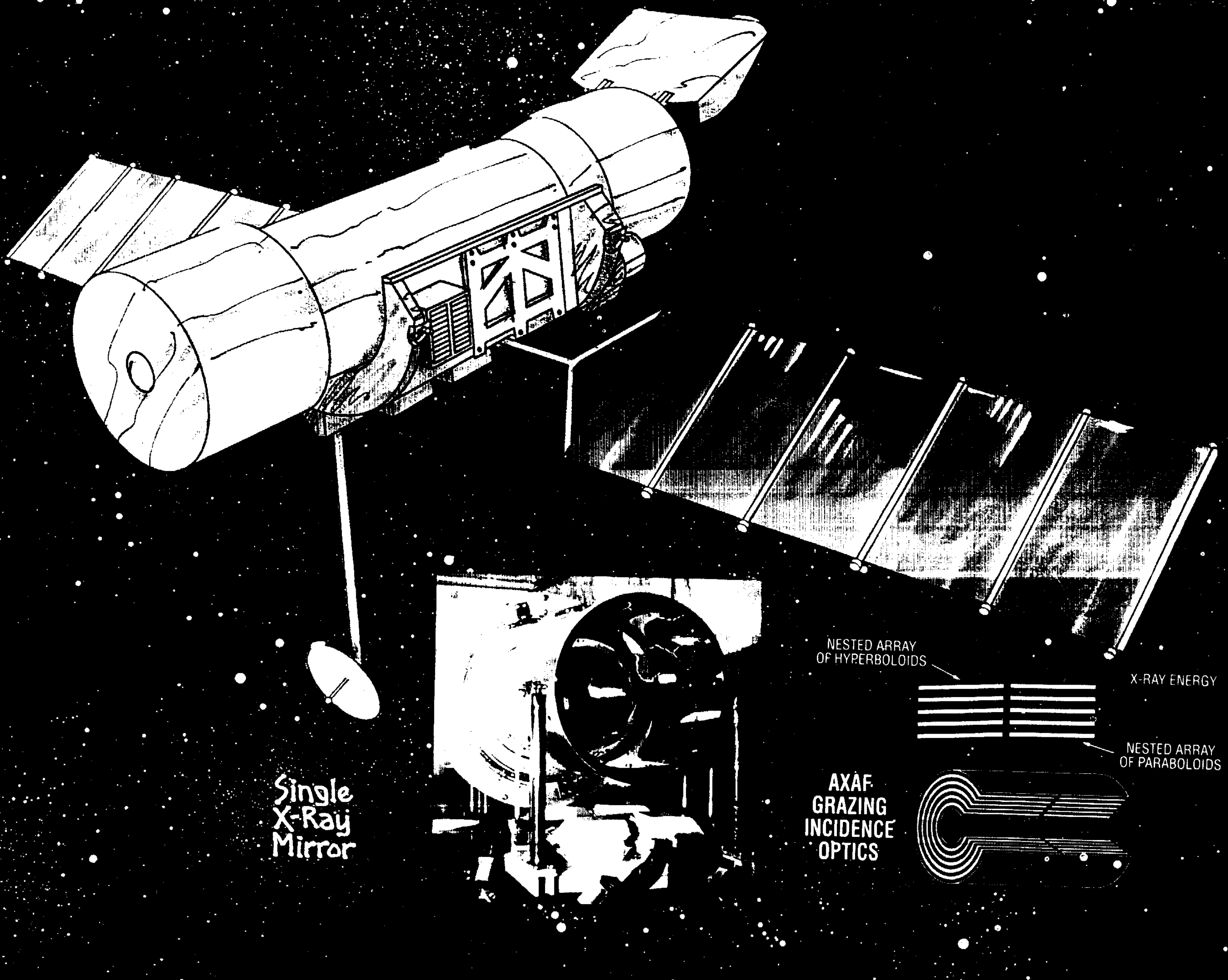
The Advanced X-Ray Astrophysics Facility (AXAF) will unlock the mysteries of the X-ray sky which were hinted at in earlier satellite-borne X-ray observatories, notably the Einstein (HEAO-2) Observatory (1978-1981). AXAF is the same enormous leap in capabilities for X-ray and high-energy studies of the universe that the Hubble Space Telescope is in optical and ultraviolet astronomy. Long-term studies with these observatories will produce answers to some of the most fundamental questions about the structure and evolution of the universe.

X-rays are produced in settings where temperatures reach millions of degrees, where particles can be accelerated by gravity to nearly the speed of light, and where magnetic fields are more than a trillion times stronger than the Earth's. Cosmic X-ray sources are studied in three ways: by obtaining images with special optics and detectors, by measuring the X-ray spectrum (the number of X-rays produced at each energy), and by monitoring changes in X-ray brightness over time. These methods combined yield information about the structure and dynamics of X-ray sources among stars, galaxies, and quasars.

X-rays pass through an ordinary telescope mirror but they can be reflected from highly polished surfaces if they only graze the mirror at a slight angle; two reflections are necessary to focus all X-rays within the field of view. AXAF is a high-resolution telescope in which cosmic X-rays are focused by nested sets of state-of-the-art mirrors onto either imaging detectors or spectrometers. AXAF will incorporate the largest total surface area of highly polished mirror yet achieved and put into space. Its sensitivity is more than 100 times greater than the highly successful Einstein Observatory, and its images will be almost 10 times sharper. This Great Observatory extends the power of direct imaging and spectroscopy to the highest X-ray energies practicable, to energies significantly higher than those reached with the Einstein Observatory. AXAF will allow the worlds of both extremely high temperatures and extremely high particle energies to be explored in detail, with resolution comparable to the best optical observations.

Like the other Great Observatories, AXAF is designed for servicing in space, either in the Shuttle or at the Space Station. Spacecraft systems and observatory instruments are accessible for in-orbit maintenance, repair, or replacement to ensure a long operational life.

AXAF: THE UNIVERSE IN X-RAYS



Single X-Ray Mirror

AXAF GRAZING INCIDENCE OPTICS

Opportunities for the Advanced X-Ray Astrophysics Facility

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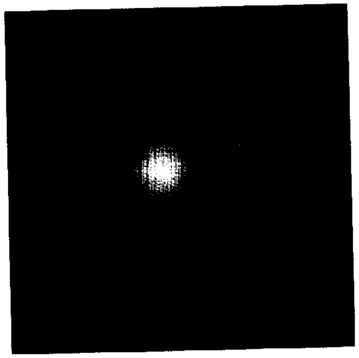
With its great sensitivity and resolution, AXAF can be used to examine the structure and evolution of virtually all classes of astronomical objects—from young stars in the process of formation in their parent molecular clouds to the most distant quasars and the earliest generations of galaxies. Even the large-scale structure of the entire universe will be probed by AXAF studies of distant galaxy clusters, combined with high-resolution radio images.

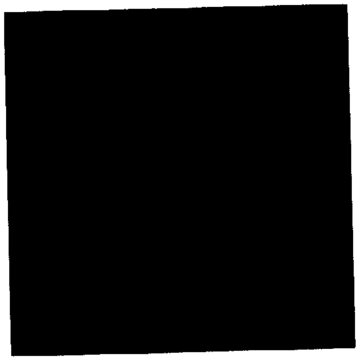
Of special interest are jets of outflowing matter observed near certain stars, galaxies, and quasars. In the case of the giant radio galaxy M87 in the Virgo cluster of galaxies, AXAF will be able to observe the jet itself, which has been detected at radio and visible energies as well as X-rays. AXAF also will observe both the galactic nucleus where the jet seems to originate and the galactic halo of glowing, hot gas in which the jet is embedded. High-resolution observations of the entire jet system may reveal what causes and confines these unusual features.

The halos around M87 and other galaxies are also of interest as possible hiding places of invisible mass, or dark matter, in the universe. The hot X-ray emitting gas of a halo must be confined to the host galaxy by at least 10 times more mass than can be seen or accounted for by optical observations. X-ray observations reveal otherwise invisible halos and trace them out to great distances around visible galaxies. AXAF may help to explain how a halo merges into the X-ray emitting gas that pervades a cluster of galaxies.

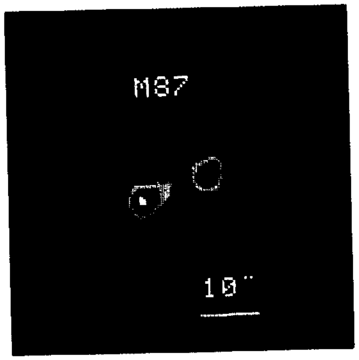
AXAF will image and study objects at the extreme distances accessible to the largest telescopes on the ground and may well extend our view beyond that of the HST to the very earliest phases of galaxy formation. The Einstein Observatory showed that the X-ray sky is peppered with faint point sources, primarily quasars but many sources still not identified, which together must account for at least a third of the mysterious cosmic background of diffuse X-ray emission. Very deep survey observations with AXAF, with total exposure times measured in days on a given region of sky, will bring these faint distant objects into view for detailed study and reveal many more of them, if they are indeed the origin of the X-ray background.



Optical Image



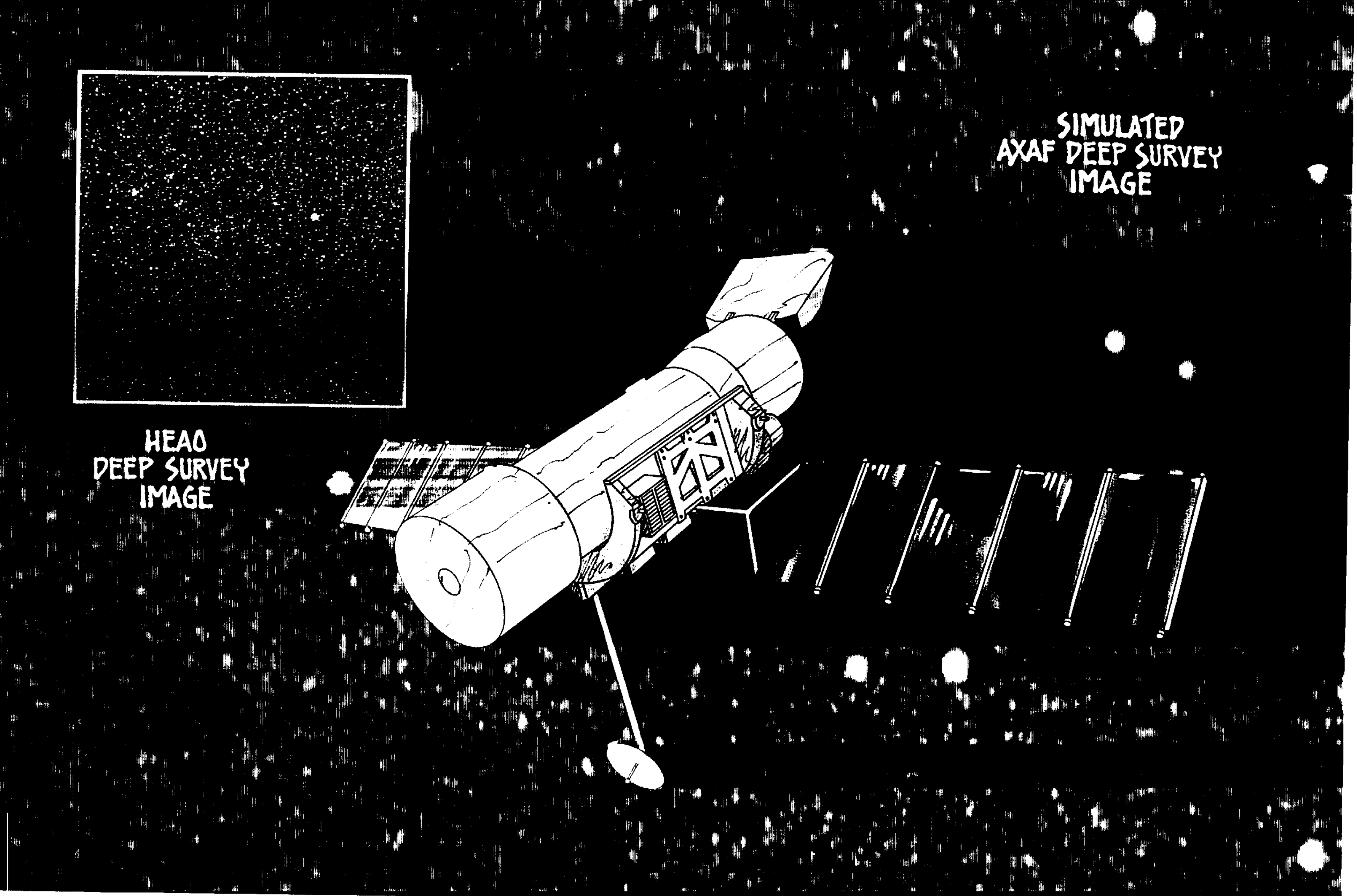
Radio Image



X-Ray Image

Jets of material ejected from stars, galaxies, and quasars are targets of study by all of the Great Observatories. The jet from the giant radio galaxy M87 in the Virgo cluster of galaxies is familiar across the spectrum. High-resolution study with AXAF may reveal what generates and channels such outflowing streams.

AXAF will extend our view to great distances, to pick out and study quasars and the earliest generations of galaxies that may be the origin of the diffuse X-ray background.



Space Infrared Telescope Facility (SIRTF)

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Simulated IRAS Image

Corresponding Simulated SIRTF Image

Infrared detector technology has progressed dramatically since IRAS was launched in 1983, yielding not only more sensitive detectors but also much larger detector arrays. SIRTF has a larger and better mirror, more detector elements, greater resolution, and longer observing times than IRAS; it will make observations in a few seconds or minutes that could have taken a few years on IRAS and would be altogether impossible from Earth-based telescopes. Whereas IRAS surveyed the entire sky, SIRTF will investigate individual sources in detail and will be able to detect infrared sources several thousand times fainter.

Everything emits heat. Our bodies, our equipment, and our atmosphere are strong sources of infrared radiation. This background radiation can be a million times more intense than the radiation from an astronomical object. The difficulty in making infrared astronomical observations is that the atmosphere and the telescope itself emit so much heat that celestial sources cannot be seen through the glow.

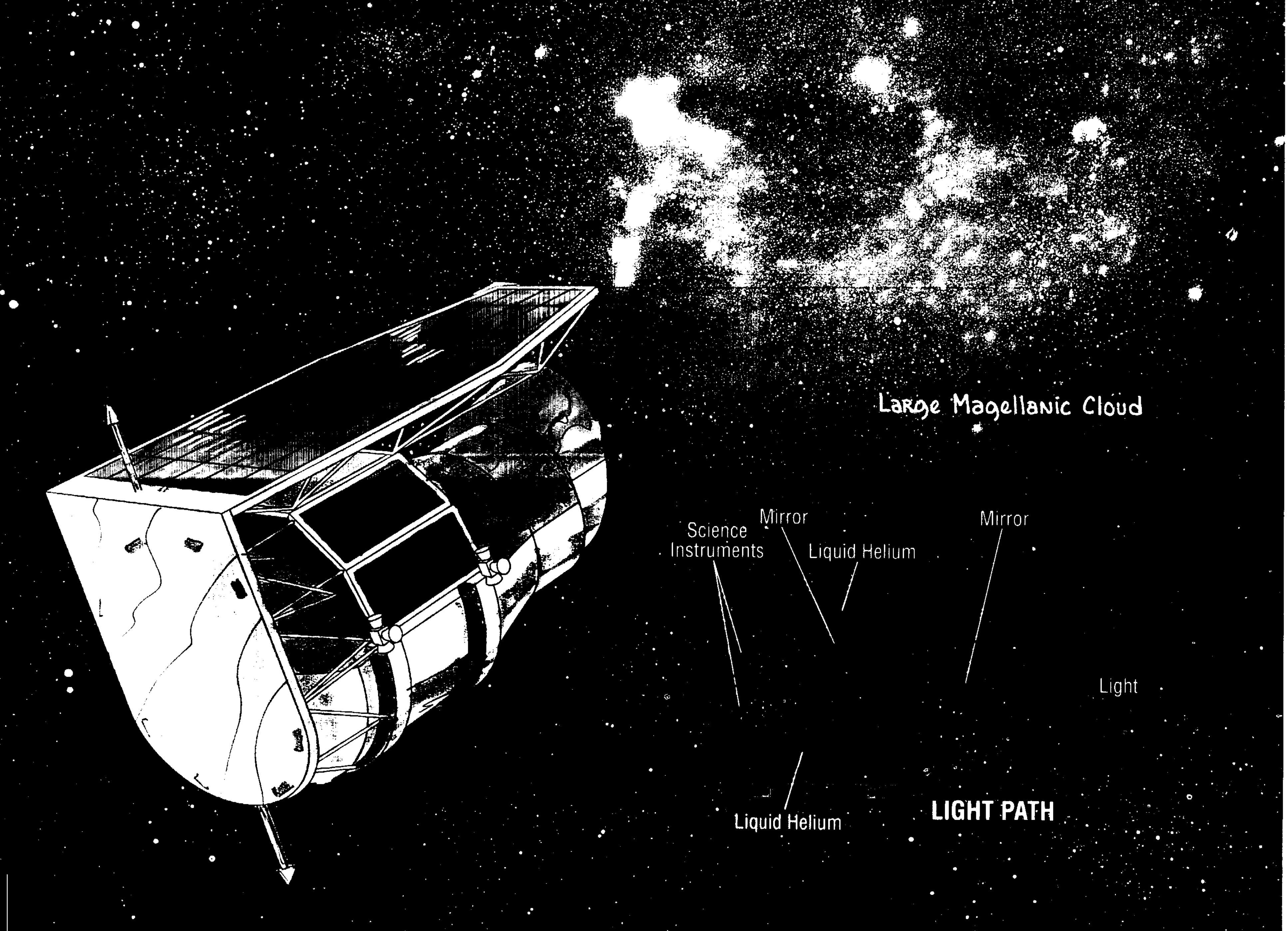
Sensitivity can be greatly improved by placing an infrared telescope in space, above the Earth's emitting atmosphere, and by refrigerating the telescope. If the temperature of the optics, internal structure, and detectors can be kept low enough that they do not emit any heat, a cold telescope can detect infrared radiation from very weak sources in space. The Space Infrared Telescope Facility overcomes the problem of internal heat and background infrared radiation.

SIRTF's optical system and infrared instruments will reside within a donut-shaped tank of superfluid helium, a very effective cryogen that will cool them to a temperature a few degrees above absolute zero (-441°F) so they will not radiate. To prevent heat from the sun, Earth, and moon from entering the telescope, the entrance will be protected by a sunshade. Air and other contaminants will be excluded by a large vacuum cover that will be opened only in space. Because of the unique problems associated with operating a cryogenically-cooled telescope in space, SIRTF, unlike the other Great Observatories, will be placed into an extremely high (100,000 km) orbit.

SIRTF's 85-centimeter (34-inch) mirror will collect infrared radiation from astronomical objects and focus it on several instruments for analysis. The Multiband Imaging Photometer will measure the intensity of radiation at all infrared wavelengths. The photometer and the Infrared Array Camera will provide astronomers with infrared images in much greater detail than ever achieved before. The Infrared Spectrograph will divide the incoming radiation into its various wavelength components, providing information on the composition, temperature, and motions of many infrared sources.

SIRTF's long lifetime in space, with virtually continuous observations in a low background environment, will allow it to investigate a wide variety of important astronomical problems with a sensitivity 1,000 times greater than observations to date.

SIRTF: THE INFRARED UNIVERSE



Opportunities for the Space Infrared Telescope Facility

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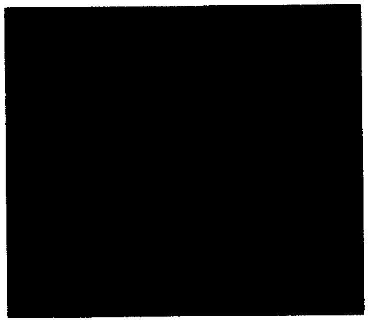
From our own solar system to the fringes of the universe, SIRTF, with its great sensitivity, offers a view unobtainable at other wavelengths. Infrared observations by SIRTF provide a unique opportunity to discover and examine the embryonic stages of astronomical objects over an enormous scale: the origin of our solar system as revealed in the study of planetary atmospheres, asteroids, moons, comets and the zodiacal dust distribution; the formation and distribution of planetary systems around nearby stars; the birth and evolution of stars in the spiral arms of our galaxy and other galaxies; the origin of primordial galaxies and the early evolution of the universe.

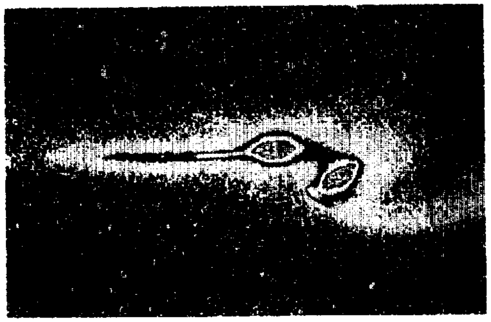
In addition, SIRTF provides an opportunity to investigate objects that emit most of their radiation at infrared wavelengths. SIRTF can be engaged in a deep survey to search for the dark matter—possibly failed stars called brown dwarfs—that must exist to explain the motions of galaxies. SIRTF's spectrometers will yield a new understanding of the chemistry of atoms and complex molecules in interstellar space and will provide information on chemical composition, density, temperature, pressure, and velocity within the source of this radiation.

SIRTF's ability to see into the core of our own Milky Way galaxy can help us determine whether a massive black hole exists there. Ultraluminous galaxies were discovered by IRAS to emit most of their radiation at infrared wavelengths; these objects may be galaxies in collision, generating intense, short bursts of star formation as the galaxies merge. Quasars also produce large amounts of infrared radiation. SIRTF will be able to investigate a number of these objects at great distances and determine their role in the birth and evolution of galaxies.

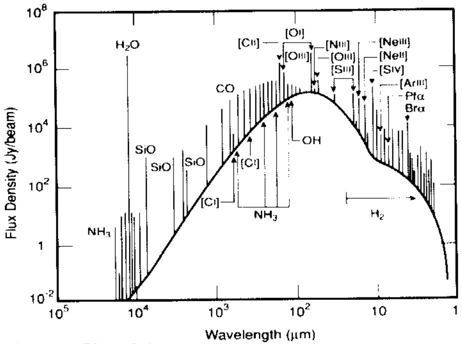
Formation of Planets



Dark Matter

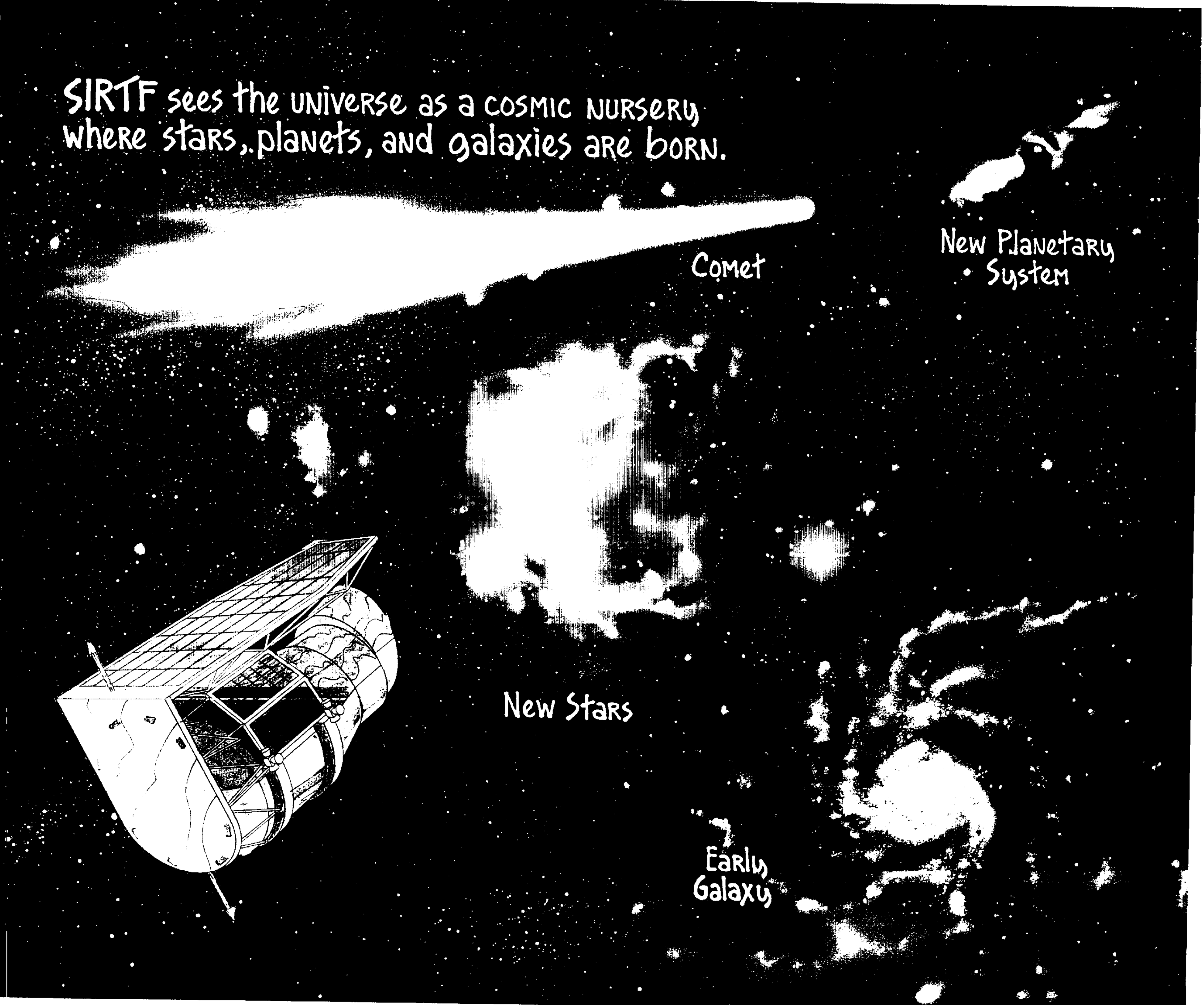


Colliding Galaxies



Cosmic Chemistry

Infrared radiation reveals a variety of processes, such as the birth of stars and planets, the dark corpses of burned-out stars, galaxies in collision, and cosmic chemistry.



SIRTF sees the universe as a cosmic nursery where stars, planets, and galaxies are born.

Complementary Observations

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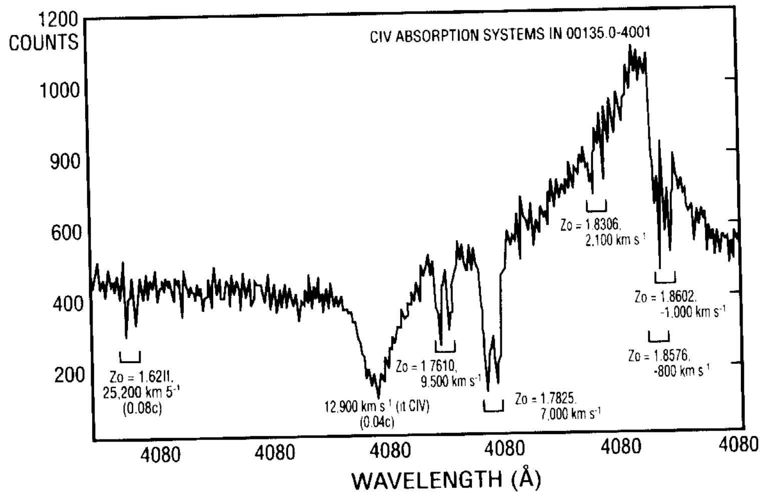
Telescopes on the ground or in high-altitude aircraft complement the Great Observatories. Certain types of investigations require the best features of both orbital and terrestrial observatories. An example of this complementary relationship is found in infrared astronomy. The SIRTF observatory has exquisite sensitivity for detecting the faint universe, but its relatively small aperture (1 meter) makes it less effective for spectroscopy. A proposed airborne infrared telescope, the Stratospheric Observatory for Infrared Astronomy (SOFIA), has a much larger aperture and collecting area (2.5 meters, comparable to Hubble Space Telescope's) suitable for high-resolution spectroscopy of the brighter, nearer universe. SOFIA will be able to study with great precision the dynamical motions in regions of star formation, in colliding galaxies, and in the center of the Milky Way galaxy.

Using both SIRTF and SOFIA for infrared astronomical observations enhances the Great Observatories strategy. This type of mobile observatory is particularly useful for targets of opportunity, such as planetary occultations, eclipses, comet and supernova observations, and other fleeting events when a telescope must be in the right place at the right time. SOFIA's frequent flights also would provide many opportunities for technology development and hands-on training for a new generation of astronomers.

The atmosphere does not absorb all radiation from space; it is transparent for visible light and radio wavelengths. For observations in these spectral bands, large ground-based telescopes capable of collecting radiation from faint sources can be constructed at relatively low cost. Telescopes on the ground do not have the size and mass restrictions of orbital telescopes; with their larger apertures and collecting areas, they can be used for spectroscopic investigations in conjunction with observations from space.

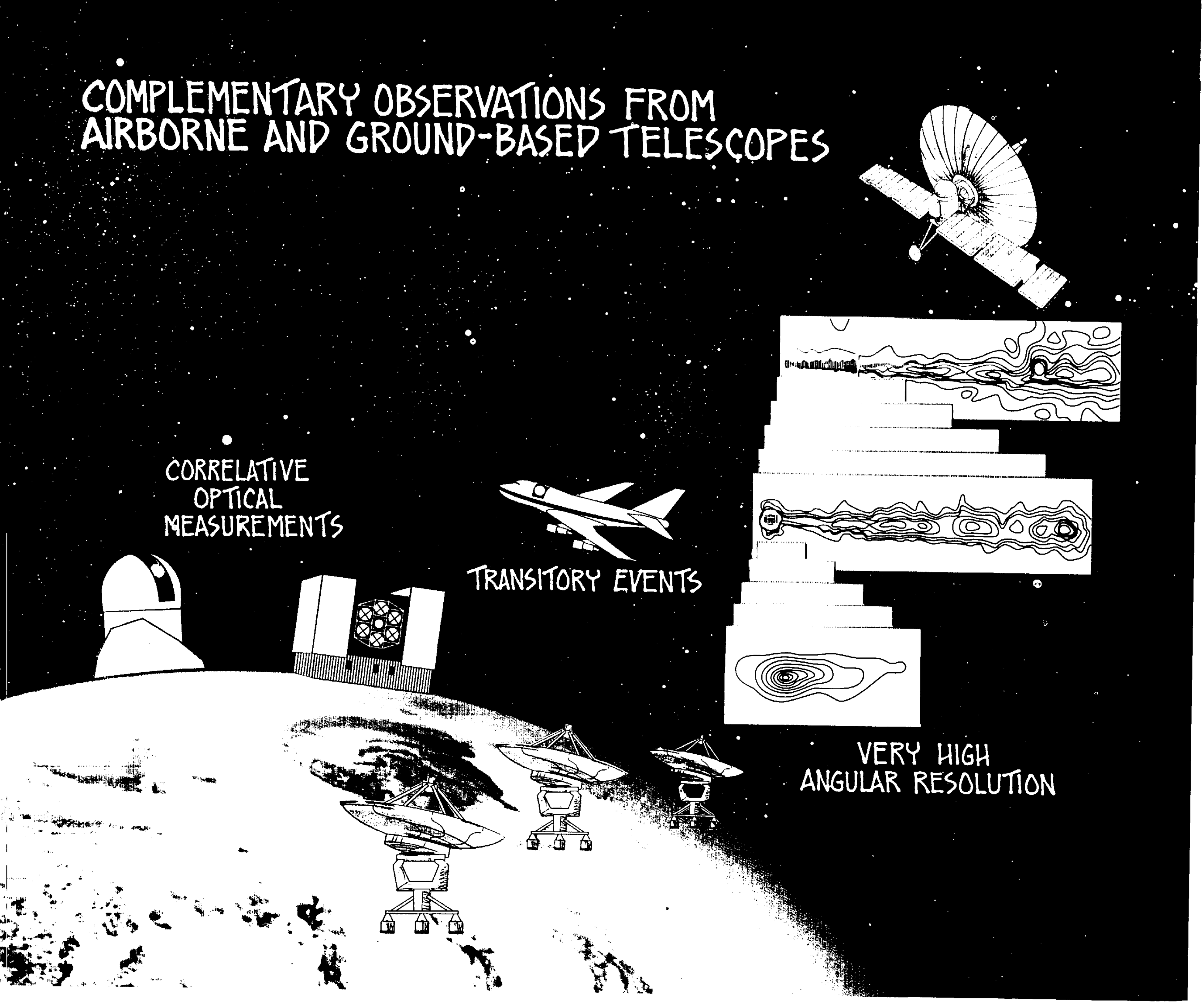
Large telescopes on the ground can complement the Great Observatories in space by providing information on some of the most distant sources ever observed. For example, at optical wavelengths, a large number of gaseous clouds can be detected stretching out to the greatest distances known, each cloud making its presence known through its characteristic absorption of light by hydrogen. Since the distance of such a cloud changes the speed at which it recedes, the hydrogen absorption in each cloud takes place at a slightly different wavelength. Optical observatories on the ground also can monitor, for longer periods, variable sources such as supernovae detected by the Great Observatories.

At radio wavelengths, arrays of telescopes spanning the globe now are able to provide picture resolution unmatched even by optical telescopes. Clouds of material shot out of distant quasars at velocities appearing to exceed the speed of light have been detected, even though the angle traversed by these clouds in a year is less than one millionth of a degree. With long-baseline arrays of telescopes on the ground and a triangulation technique called interferometry, such extended features can be observed in their entirety with "close-up" detail.



The dips in the curve of this ionized carbon spectrum from the quasar 0135.0-4001 correspond to individual clouds receding from us at the velocities shown.

COMPLEMENTARY OBSERVATIONS FROM AIRBORNE AND GROUND-BASED TELESCOPES



Astrophysics Data System

Observations in space are just the beginning of the process of scientific investigation. The data derived from a few minutes or hours on a target may well occupy data analysts for years after the actual observation has been completed. A user-friendly system for data archival and dissemination is an essential component in the Great Observatories program.

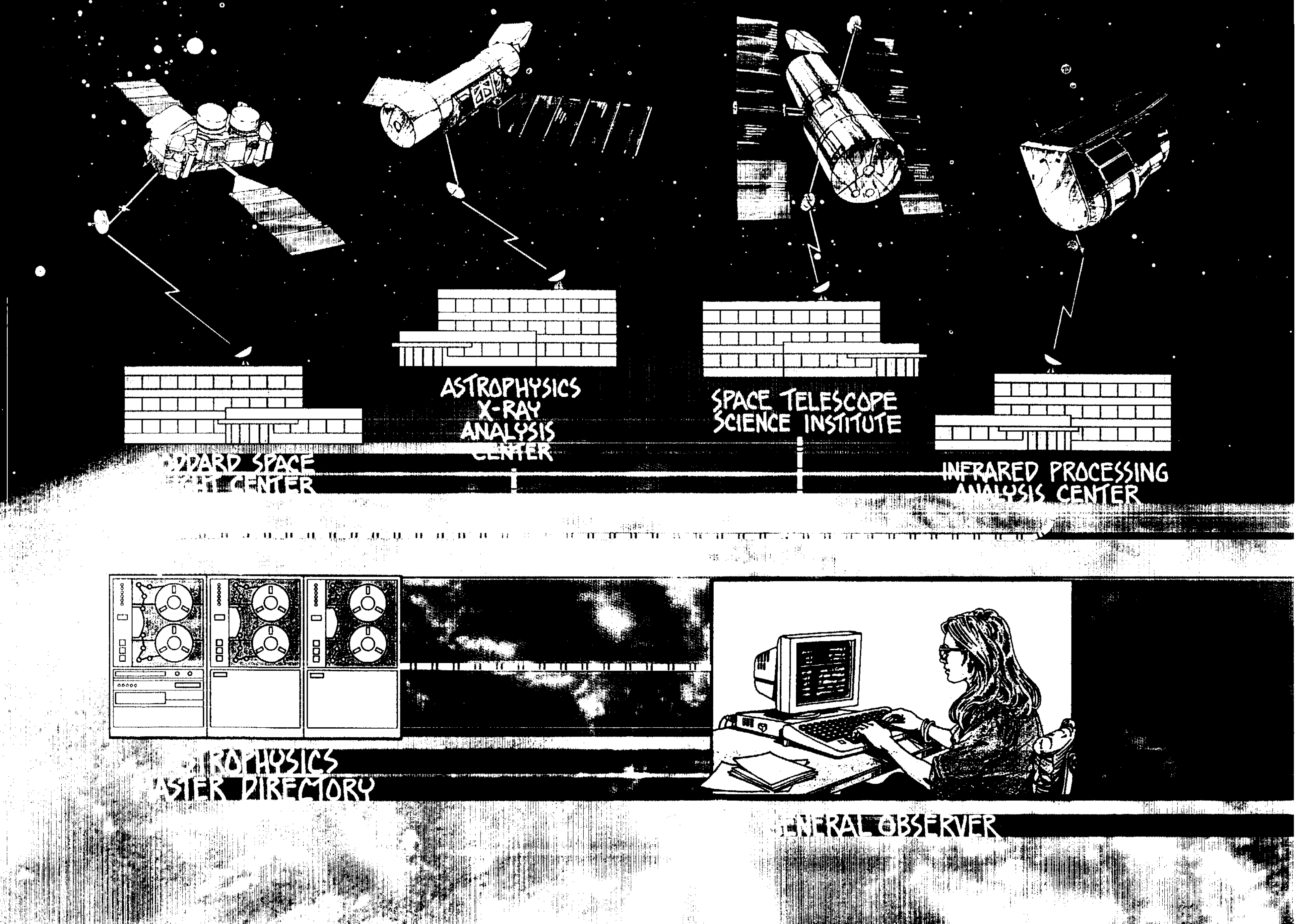
During a mission, observational data are transmitted to a science data center affiliated with each space telescope. There, a team of scientists prepares the data and forwards data sets first to the principal investigators for initial analysis and later makes them available to the astronomical community at large. The observational data also are maintained in archives at each center for further research. These data have standardized formats and portable analysis software to facilitate analysis at other locations and on different types of computers.

During data analysis, astronomers almost certainly will want to examine other data for the same astronomical object, to compare how it appears at other wavelengths, for example. The Astrophysics Data System is designed to enable and assist such research. Data from all of the Great Observatories, as well as other astronomical missions, can be accessed electronically through this system. Scientists around the world can search and sample the data bases through a directory service or master catalog from their home institutions via standard electronic networks.

In a typical on-line session, an astronomer would request information on all observations of a particular object or region of the sky, perhaps limiting by wavelength, search radius, or observing time. In response to the query, the directory provides a table of observations and offers detailed information on the particular observatory and instruments involved. The astronomer then has the option to request small data sets for on-line transmission or larger sets by mail. Analysis software from the observatory data centers is available through the data system.

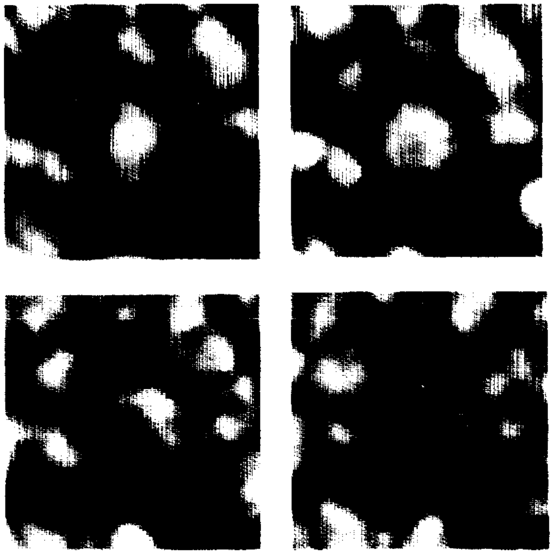
Thus, the Great Observatories strategy of multispectral observation is carried into the data analysis phase in the Astrophysics Data System, through which astronomers have access to all available information across the spectrum. This system is an efficient way to involve the worldwide research community in reaping the harvest of the Great Observatories and to ensure the greatest scientific yield. The data system will contain ample material for decades of investigation and discovery.

ACCESS TO DATA FROM THE GREAT OBSERVATORIES



The Solar-Stellar Connection

19



These images of an exploding solar granule show changes occurring within minutes in a small region of the sun's surface. While the granule in the center swells and bursts, the surrounding cells also move about. These observations are the most detailed record of small-scale solar turbulence ever made; the view is virtually microscopic.

The sun is our best laboratory for studying many processes that are important both to astrophysics and to physics in general. Because the sun is the only star we can see in detail, solar observations are directly relevant to many remote stars and other celestial objects, such as active galactic nuclei, jets, pulsars and accretion disks. Solar observations also reveal extreme conditions that cannot be duplicated within the confines of laboratories on Earth.

Viewed in sharp focus, the sun resembles a boiling cauldron of gases that bubble and explode in an ever-changing commotion of magnetic fields. We cannot see directly into the core of the sun where energy is generated, but turbulent surface features, such as pockets of gas called granules and wave-like oscillations, suggest complex patterns of energy transport through the sun's magnetic fields. Granules seem to be the fundamental building blocks or cells of solar structure.

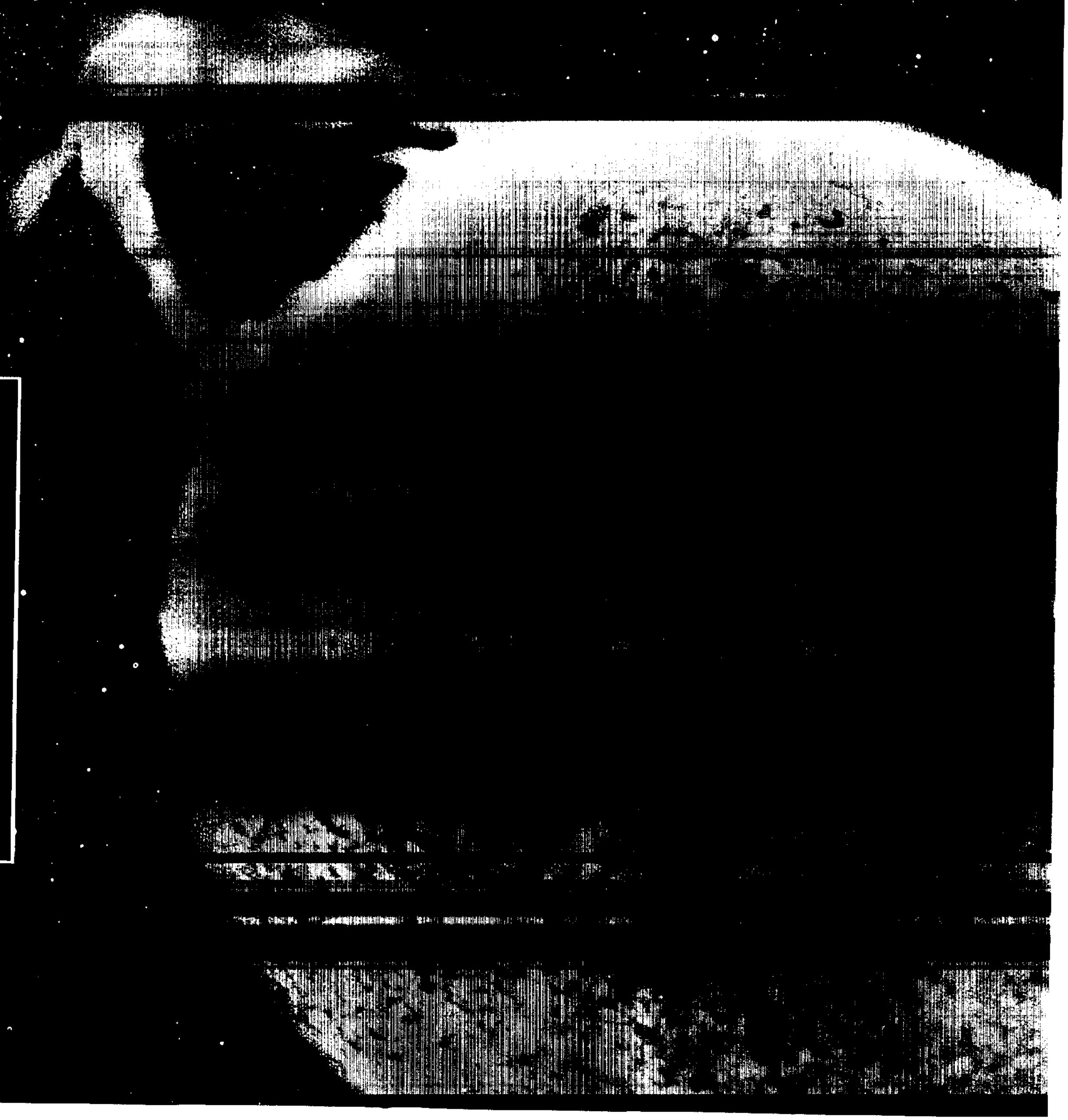
Most of this activity cannot be discerned from observatories on the ground because the solar features are small and their radiation is distorted or blocked by Earth's atmosphere. An orbiting high-resolution solar telescope could complement the Great Observatories by examining the nearest star in detail, measuring temperatures, magnetic fields, and flow patterns over a long time. Just as we could not understand blood until microscopes enabled us to see cells and watch them function, a high-resolution telescope would permit microscopic study of the sun. Such an observatory would help us understand the sun's behavior and use it as a model for other physical and astrophysical processes.

Areas of less than 100 km (granules, cells, kernels, and pores) are crucial to the development of enormous solar features, such as sunspots and tremendous explosions called solar flares. Examination of small features in minute detail will reveal the causes and progressive course of much broader processes on the sun and other stars and will shed light on a number of problems: How do fluids mix and flow in rotating bodies such as stars and planets? How is energy radiated through dense matter? What are the physical mechanisms of sunspots and starspots?

Magnetic fields are responsible for many events on the sun. A puzzling issue in modern physics is the interaction of magnetic fields with ionized gas, called plasma. In plasma physics laboratories on the ground, scientists are trying to confine and accelerate extremely hot gases within strong magnetic fields to produce energy. Observations of solar activity will help them understand how magnetic fields form, evolve, dissipate, and annihilate and what laws govern magnetohydrodynamic stability and turbulence. These matters are of great importance to particle physics and fusion research.

The sun's features offer clues to test and refine our theories about other processes hidden from view. Thus, the sun is a Rosetta Stone for deciphering some of the secrets of astrophysics and plasma physics.

The sun is a laboratory for studying other astrophysical phenomena and the basic physics of matter in magnetic fields.



Solar Prominence

Prominence in
Center of Galaxy

Life Cycles of Stars

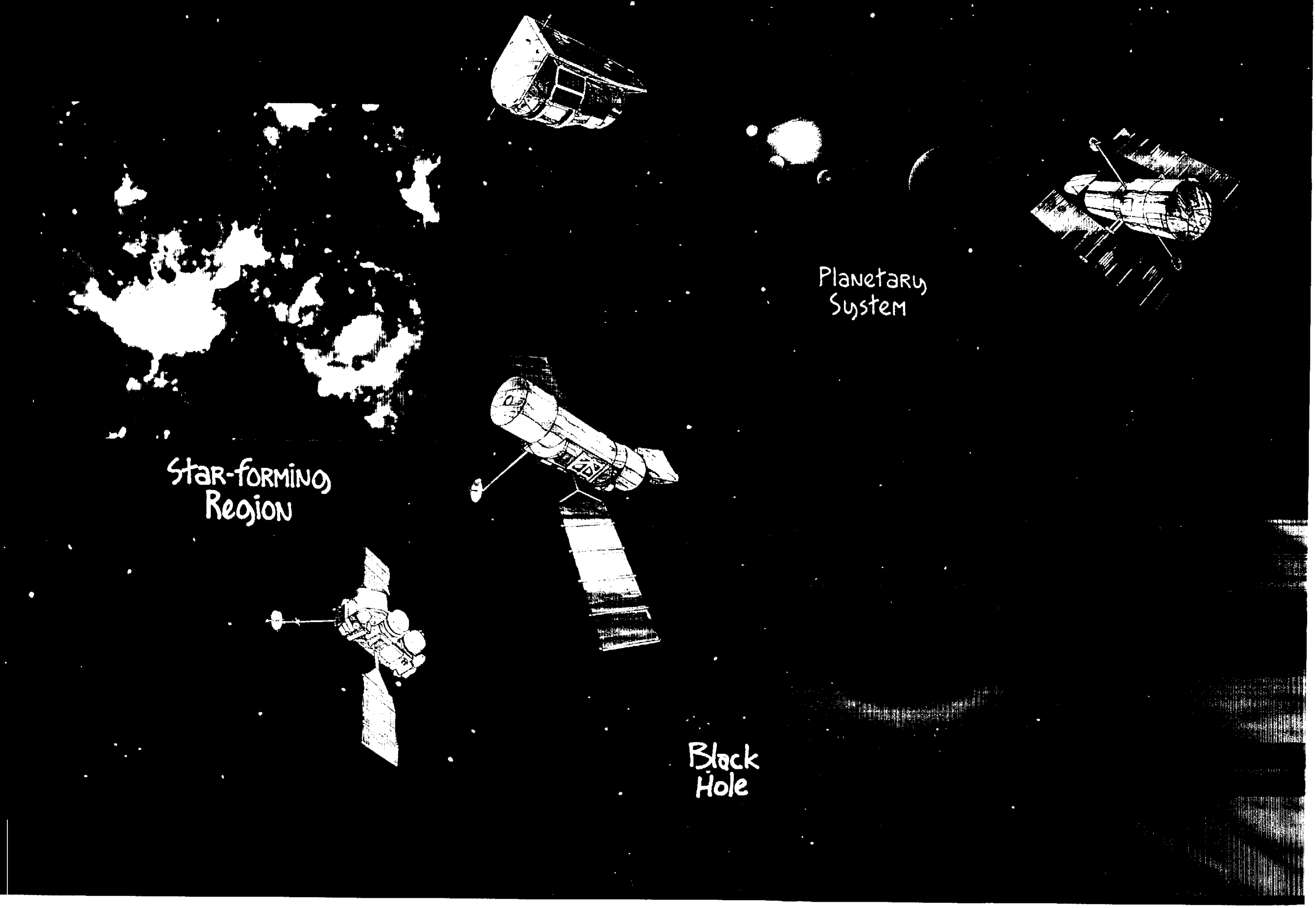
The birth of stars may be triggered by the explosion of a supernova that compresses a nearby dusty cloud of gas, which then collapses to form a new group of stars. Some of these are more massive than others and begin to shine thousands of times more brightly than the sun. Such stars consume their supply of nuclear fuel in a few million years and collapse to form a neutron star or possibly a black hole. In this collapse, enormous amounts of energy are suddenly liberated, and the outer shell of the star is hurled into space in another supernova explosion. X-ray observations of the remains of such explosions can tell us much about the original star as well as the exploding shell.

Less massive stars, like our sun, never explode as supernovae. Instead, they shine steadily, at a far more subdued rate, for ten billion years before continuing their lives, briefly as red giant stars and finally as faint white dwarfs. Some of these stars may originally be enveloped by a disk of matter, which may condense into a system of planets.

Currently we have no way of knowing how many stars are orbited by planets or how many stars are encircled by disks. We hope to answer these questions by making optical observations with HST and infrared observations with SIRTF.

Beta Pictoris, a nearby star embedded in a disk of dust and possibly larger chunks of matter, emits infrared radiation and scatters visible light, seen in this IRAS image as a faint two-lobed glow centered on the star. Might some planets be hidden in this debris?

The Great Observatories can reveal the life cycle of stars, which may evolve into planetary systems or erupt as supernovae.



Quasars and Active Galactic Nuclei

21

Quasars are distant, massive bodies no larger than the solar system but so luminous that they outshine surrounding galaxies a hundred times. We do not know how to explain this immense power. One possible model of a quasar is an intensely hot central source emitting gamma rays and embedded in X-ray-emitting plasma. Enveloping dust clouds absorb much of the emitted energy, re-radiating it at far-infrared wavelengths. An outermost, unobscured layer also radiates at ultraviolet and visible wavelengths. Plasma beams ejected from the central source at nearly the speed of light power distant radio lobes.

Quasars challenge our current understanding of astrophysics. How can so much energy be radiated from so compact a source? What causes the rapid variations in luminosity, from month to month, sometimes even from one hour to the next? Are quasars powered by a rapid succession of supernova outbursts in a central core, or by matter falling onto a central black hole, or by something yet to be discovered?

To clear up many of these questions, we need the full complement of our most powerful observatories, often working together to trace quasars as they evolve—sometimes emitting successively in different wavelength bands, sometimes simultaneously varying across the entire spectrum. These detailed observations may reveal the nature of the central engines powering quasars and explain the structure of ambient regions.

We know little about when in the history of the universe quasars formed and how they evolved over time. As the Great Observatories probe deeper into the universe, they should discover many new quasars. Observations of very young quasars will document the origin and progress of quasar formation. Comparison of older, nearer quasars with younger, more distant ones may indicate their evolution. Quasars may be markers for the history of the universe in general.

IRAS discovered a large class of infrared-luminous galaxies that probably are related to quasars. Many of these seem to be galaxies in collision. Their luminosity could be caused by a sudden burst of star formation (starburst), or by matter swept up in collisions being fed into central black holes, or by both processes. SIRTF, in particular, will study this phenomenon in great detail at vast distances.

The quasar 3C48 in the Hercules cluster of galaxies is a strong radio source. One of the first two quasars discovered in 1960, 3C48 had an unrecognizable spectral signature. Study of 3C48 and another similar object, 3C273 (left), led astronomers to understand redshift as an indicator of a quasar's velocity and extreme distance.

Quasars are the most powerful known energy sources in the universe.
How do they generate so much energy?

Invisible Mass

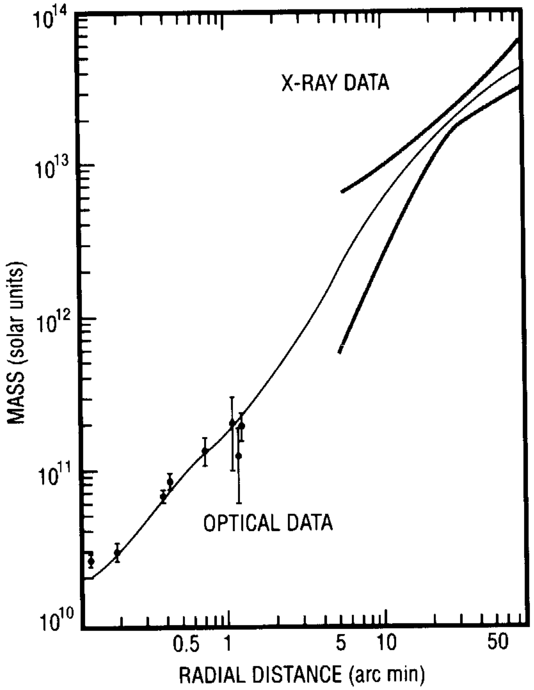
22

Most of the matter in the universe is known to us only through the gravitational forces it exerts on stars, galaxies, and other visible sources, whose orbital motions we can follow. We have no adequate explanation for this invisible mass, which gives rise to one of the most troubling questions in astrophysics: what is it?

One suggestion is that most galaxies may have a faint halo of low-luminosity stars. These could be traced with an optical telescope like HST placed above the Earth's atmosphere and therefore capable of seeing fainter diffuse distributions of stars. The matter might also be distributed in galactic halos in the form of brown dwarfs, bodies intermediate in mass between Jupiter-sized objects and the least massive stars known to emit visible light. Brown dwarfs would emit primarily at infrared wavelengths and be observed with SIRTF. A further possibility is a halo of black holes or of low-mass stars. In either case, a faint diffuse glow of X-rays would emanate from the halos of galaxies, a glow that AXAF would permit us to detect.

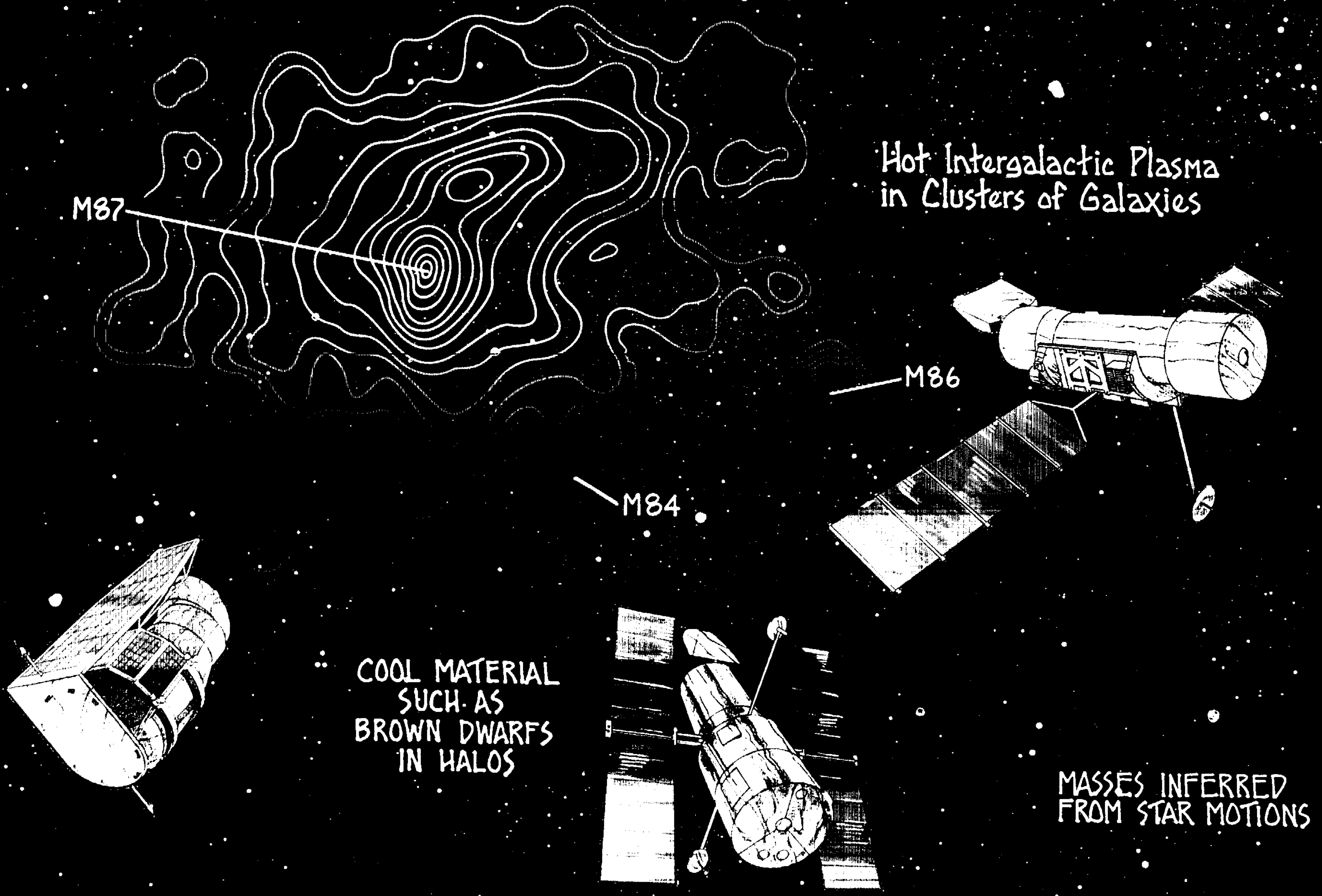
An entirely different tracer of invisible mass in clusters of galaxies is intensely hot intergalactic plasma. X-ray emission from this plasma is brightest in the innermost portions of the cluster where most of the mass is concentrated. The distribution of X-ray brightness across the cluster provides us with a measure of total mass. Using this measure, AXAF would permit us to search for invisible mass in clusters at extreme distances across the universe.

Finally, families of new, exotic particles, like axions or gravitinos, or else networks of massive cosmic strings required by some elementary particle theories, could be responsible for this invisible mass. Further study may enable us to distinguish among these different kinds of particles and provide insight into fundamental forces that govern their interactions.



Optical data on arbitrary stars (shown by error bars) and X-ray data on hot gases surrounding the galaxy M87 (shown by the two curves) indicate the mass contained within increasingly large distances, out to a span amounting to 100 arc minutes. Most of that mass appears to be dark, non-atomic matter of a puzzling variety.

90% of the matter in the universe is invisible. What is it?



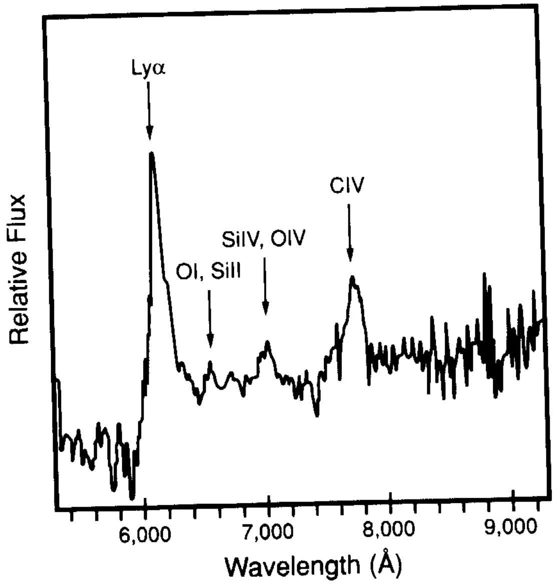
Hot Intergalactic Plasma
in Clusters of Galaxies

COOL MATERIAL
SUCH AS
BROWN DWARFS
IN HALOS

MASSES INFERRED
FROM STAR MOTIONS

Looking Back in Time

23



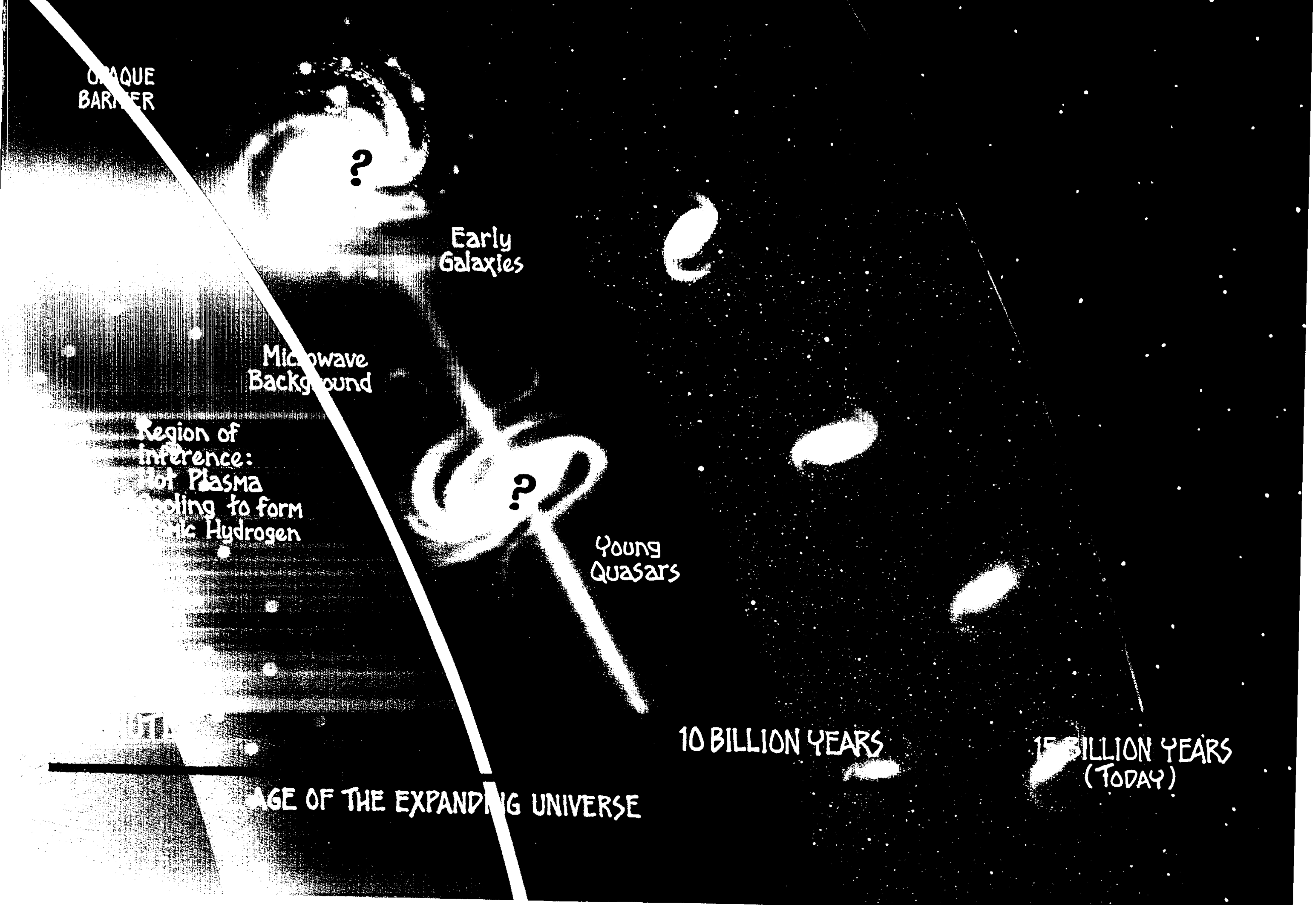
The quasar 0046-293 is one of the most distant (and thus earliest) sources ever identified. The wavelength of light we detect is more than five times longer than it was when the light was emitted. The Lyman-line of hydrogen, here seen at a wavelength longer than 6000 Angstroms, normally is seen at 1216 Angstroms. The quasar is receding from us at more than 90% of the speed of light, roughly at 277,000 kilometers (170,000 miles) per second.

The universe is so large that signals travelling at the greatest speed that can be attained—the speed of light—require billions of years to cross major portions of the tracts we can survey. This long delay in the arrival of radiation can work to our advantage.

To understand how galaxies or quasars originated in a rapidly expanding universe, we can look back in time to observe the contraction of proto-galactic clouds, expected to emit far-infrared radiation, and young galaxies emitting radiation at visible as well as infrared wavelengths. Young quasars also should be powerful sources of X-rays and radio waves.

These sources are beyond the range of present instruments, but those limits will be surpassed with the next generation of space observatories capable of surveying the sky out toward the moment when galaxies began to form, and beyond, to the impenetrable barrier that lies at a distance and time when electrons and protons were combining to form atoms of hydrogen. Currently, only radio telescopes can look back at that barrier from which the cosmic microwave background radiation emanates. Some day we may devise ways of looking even further back, but that may have to await the construction of gravitational wave detectors or neutrino observatories.

To understand how quasars and galaxies formed, we need to look further out into the universe and observe earlier epochs.



The Search for Other Planetary Systems

Data from the Infrared Astronomical Satellite (IRAS) show disks of warm rocks and pebbles orbiting several stars. Such a disk could be a precursor of a planetary system or could co-exist with a system of planets like ours. By studying the planets of our own solar system, we should gain insight into how planets elsewhere might be formed and how we may best search for planets around other stars.

Distant planets will be detected most readily through infrared radiation, since planets are too cool to emit visible light and the visible light they reflect is lost in the glare of starlight. Stars are often less bright at infrared than at visible wavelengths. A visible spectrum of a planetary system mainly will register stellar emission and reflect the chemical composition of the star. An infrared spectrum will show planetary contributions to the system's emission and could provide evidence for molecules, like methane and carbon dioxide, found on planets in our solar system but destroyed on the hot surface of a star like the sun.

SIRTF will be able to search for planets around the hundred nearest stars. Spectra for any planets detected could tell us the chemical composition of the atmosphere and help us determine whether it might sustain life similar to that on Earth. Once planets are detected, heroic efforts at optical wavelengths might detect primitive life and a Search for Extraterrestrial Intelligence (SETI) could become more focused.

The search for other planets may help us locate other solar systems in which we could pursue our quest for extraterrestrial life. Primitive life forms are likely to remain undetectable for a long time to come; but technologically advanced civilizations could be identified by artificial signals they generate.

We know that stray television and FM broadcast signals radiated into space from Earth could be picked up by powerful radio observatories if they exist in the vicinity of nearby stars. Similarly, highly sensitive receivers on Earth might detect signs of technological expertise around other stars in nearby parts of the Milky Way. The only question then remaining is how we could be sure that such signals were generated by an extraterrestrial technology rather than by some previously unidentified natural phenomenon or by interference from our own technology.

We have some evidence that planets exist around other stars.
How common are planetary systems in our galaxy?
Are any inhabited?

Mutual Advances in Astronomy and Technology

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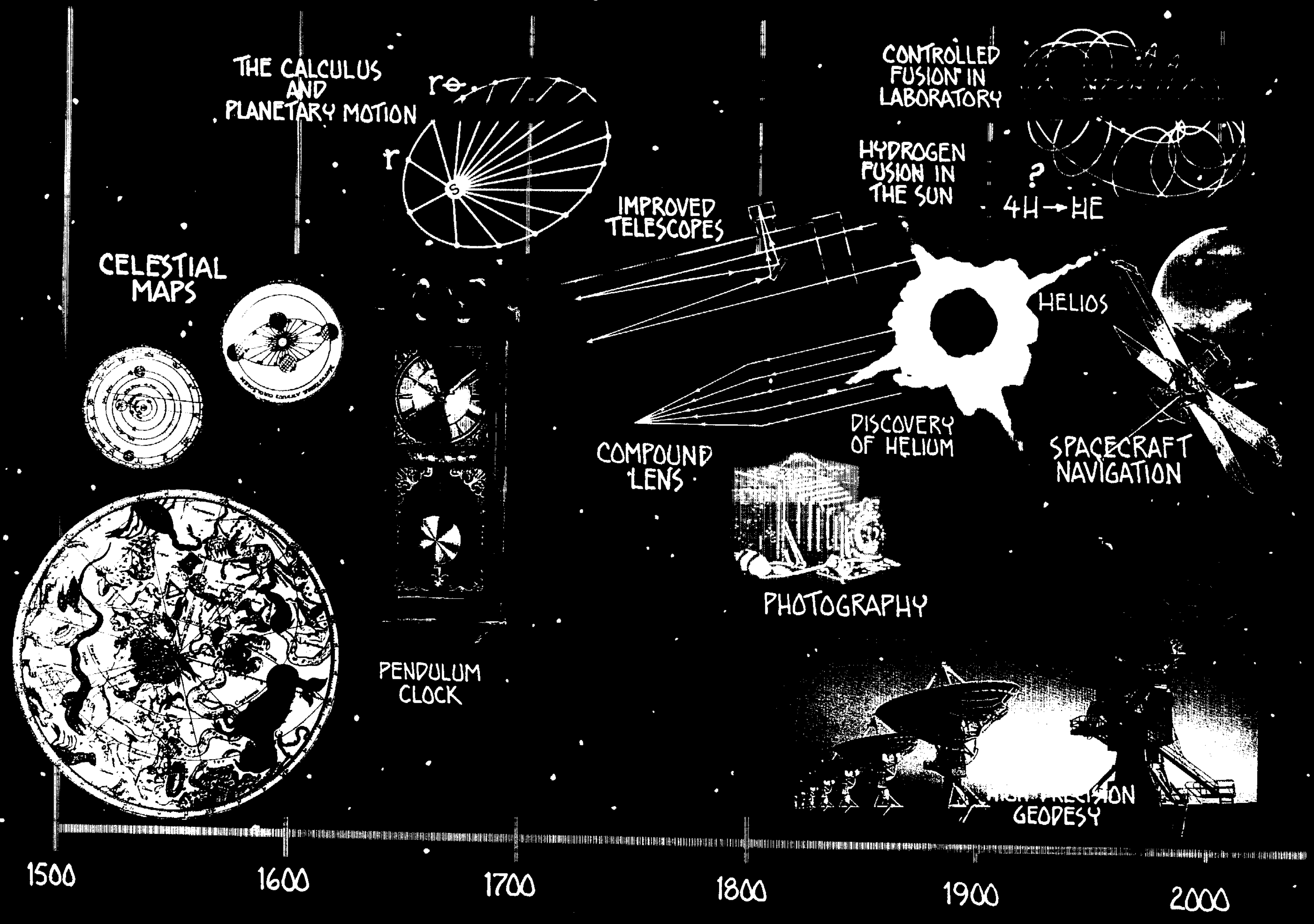
Over the centuries, astronomy and technology have progressed hand in hand. The study of the universe has benefited from improved observational devices and techniques. By the same token, developments in astronomy have led to practical applications in other disciplines.

1500-1600	■ Increasingly accurate maps of the sky for navigation
1600-1700	■ Invention and use of the telescope
	■ Christian Huygens' invention of the pendulum clock for navigational time keeping
	■ Newton's development of the calculus, the laws of motion and the law of universal gravitation to explain the motions of planets and comets
1700-1900	■ Increasingly sophisticated optical innovations by astronomers (William Herschel, Fraunhofer, Lord Rosse, Alvan Clark, and many others)
	■ Development of increasingly sensitive photographic techniques
	■ Lockyer's discovery of a new chemical element, helium, on the sun before it was known on Earth
1900-NOW	■ Hans Bethe's theoretical prediction of hydrogen fusion at the center of the sun, a precursor for all modern fusion efforts
	■ Lyman Spitzer's development of astrophysical plasma theory, the basis of present devices for releasing energy from controlled fusion
	■ Very long baseline radio interferometry techniques used in high-precision geodesy to monitor the motion of the Earth and its crust
	■ Techniques of celestial mechanics, precursors to the development of accurate spacecraft navigation.

The mutually beneficial interaction between astrophysics and technology continues today. The advanced mirror and detector technologies incorporated in the Great Observatories will doubtless account for many discoveries.

ASTRONOMY AND TECHNOLOGY



Progress in Astronomy and Astrophysics

Historically, leadership in science and astronomy has passed from culture to culture, often moving where curiosity and the will to excel prevail. Astronomy seems to have flourished independently in Mesopotamia and in China as early as 1000 BC. Chinese astronomy was independent of Europe and the Middle East, migrating only to Korea and then to Japan, until about 1644 AD, when European influences arrived. However, from ancient Mesopotamia scientific influences spread from culture to culture between 150 BC and 1000 AD, arising among the Greeks, then spreading from the Aegean Sea and Alexandria on the Northern shores of Africa, where Hipparchus and Ptolemy worked, to India and then back to the Arab world.

Around 1100 AD the works of Aristotle became known in Spain from an Arab translation of the original Greek texts, and from Spain the long-lost Greek traditions spread throughout Europe to the English and French Scholastics around 1200 and into Germany and Italy.

By the times of Tycho, Kepler, and Galileo, all Western Europe was caught up in the spirit and practice of astronomy. German science perhaps reached its peak in the era from 1900 to 1930, but with the rise of Nazi power, much of Europe's talent moved to the United States and joined the burgeoning community of American scientists. For the past half-century, the United States has led scientific progress on many fronts. Rapid advances in American technology have opened new fields of inquiry and analysis.

Will this leadership role held by the United States persist, or will it pass, as it has historically in other places and other times? The role our nation chooses to play may well determine whether we maintain our leadership in astrophysics or surrender it to more aggressive proponents of scientific research. Preeminence can be maintained only through investment. The United States gained early leadership in astronomy through the creation of new astronomical observatories and in science as a whole through the investment in scientists.

Technological advances inevitably lead to discoveries in astronomy; discovery and understanding, in turn, stimulate new technologies, often spawning new industrial opportunities. Because of the close connection between astronomical and technological advances, leadership in astrophysics and space is an important goal for our nation. The Great Observatories program represents American leadership in scientific research and technology.

THE SHIFT OF SCIENTIFIC EXCELLENCE

1700 BC Babylonian mathematics
585 BC Thales
350 BC Aristotle
150 BC Hipparchus

1000 BC
1600 AD
Chinese, Korean,
Japanese astronomy

1900s AD
German physics (1900-1930)
United States astrophysics (1910-present)

150 AD Ptolemy
500 AD Aryabhata
1000 AD al-Biruni
1100 AD Aristotle introduced to Europe through Spain
1200 AD English and French Scholastics
1500 AD Copernicus
1600 AD Kepler, Galileo
1700 AD Newton

21st Century ?

A Unique Opportunity

The United States is poised at a unique moment in history, when the compelling questions in modern astronomy and astrophysics can be answered. Pioneering research in the various disciplines over the past three decades has brought the questions into focus and refined the techniques for reaching credible answers. At the same time, the developments in crucial technologies—detectors, mirrors, spacecraft systems, computers and data analysis—enable us to seek those answers with confidence, to cross physical and technical barriers that have delayed our quest for knowledge.

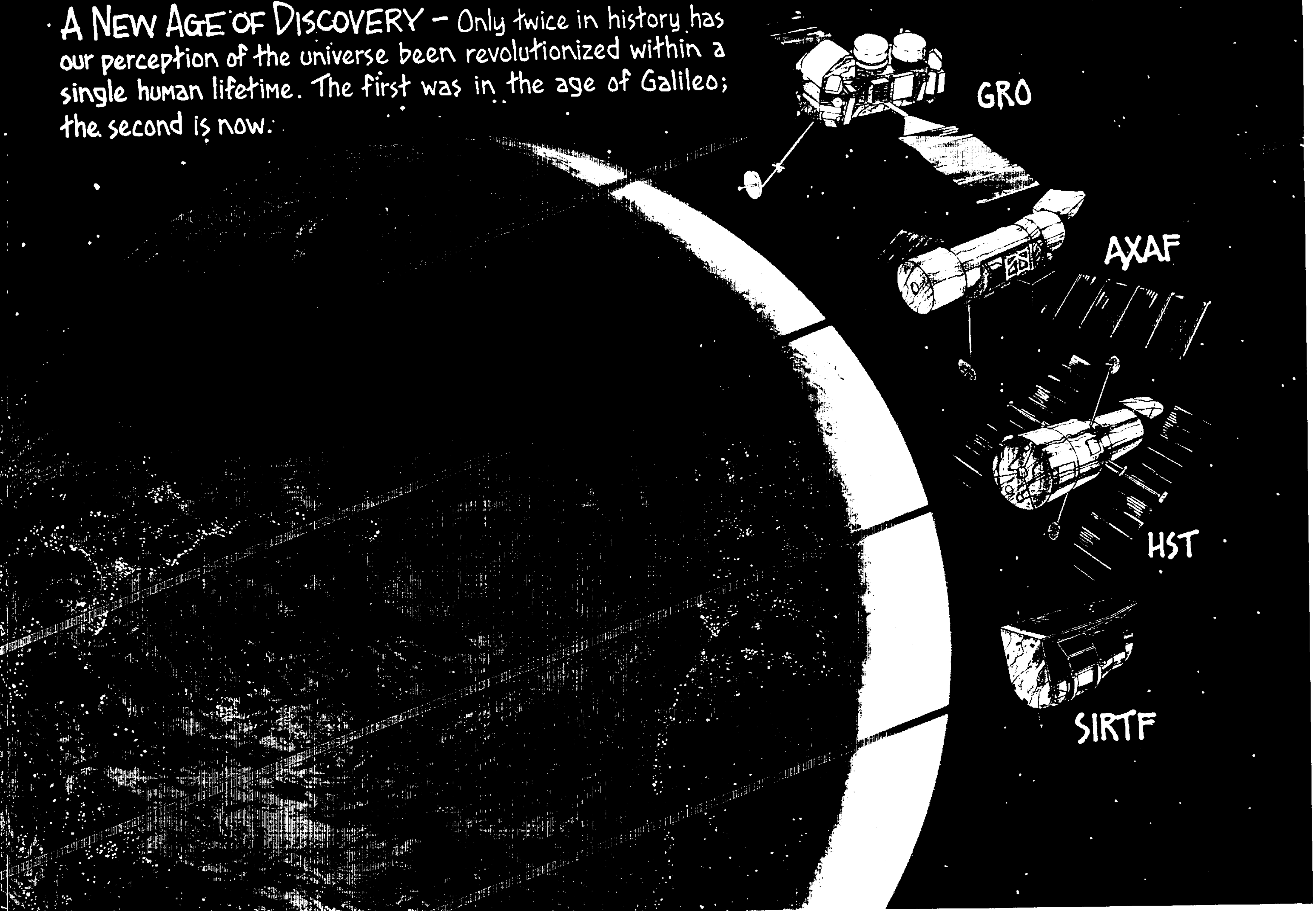
Simultaneously, progress in theoretical physics is moving toward a Grand Unified Theory, anticipated since Einstein's time and advanced by knowledge gained through increasingly powerful observational and experimental techniques. Physics and astrophysics are parallel paths of inquiry that may lead to the same ultimate explanation of the natural forces that govern the universe from the smallest to the grandest scale, from fragments of subatomic particles to the total fabric of space-time in the cosmos.

The incentive to answer fundamental questions is strong across the sciences; the technology is ready and improving daily; the momentum of space science and exploration is spreading around the world. As the international scientific community becomes increasingly active in space, the United States has new opportunities for partnership to hasten research.

America's will and resources always have been dedicated to challenges. We are lured to frontiers, whether they are geographic, political, technological, or intellectual. The space frontier is not merely a place to be; it is a place to know—a venture of the mind and spirit. We can search that realm now with the Great Observatories, and we will find answers that have intrigued, and eluded, us for centuries.

THE GREAT OBSERVATORIES

A NEW AGE OF DISCOVERY – Only twice in history has our perception of the universe been revolutionized within a single human lifetime. The first was in the age of Galileo; the second is now.



Acknowledgements

Astronomical images supplied by the Smithsonian Astrophysical Observatory, Kitt Peak National Observatory, and Hansen Planetarium

Data and images from other sources:

1 (left)	D. Schramm, Physics Today (April 1983)
3 (right)	(particle tracks) Brookhaven National Laboratory
5 (r)	(atomic explosion) Los Alamos National Laboratory; (X-ray) Academy of Orthopædic Surgeons
7 (r)	(infrared image of supernova, neutrino detection chart) D. Helfand, Columbia University
10 (l)	NASA
16 (l)	(planet formation) Seth Shostak, artist
17 (l)	Weyman et al., Annual Review of Astronomy and Astrophysics, 19 (1981)
19 (l)	Lockheed Palo Alto Research Laboratory & Solar Observatory
21 (l)	National Radio Astronomy Observatory
22 (l)	Sargent et al., (1978)
23 (l)	Warren et al., Nature, 325 (1987)

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