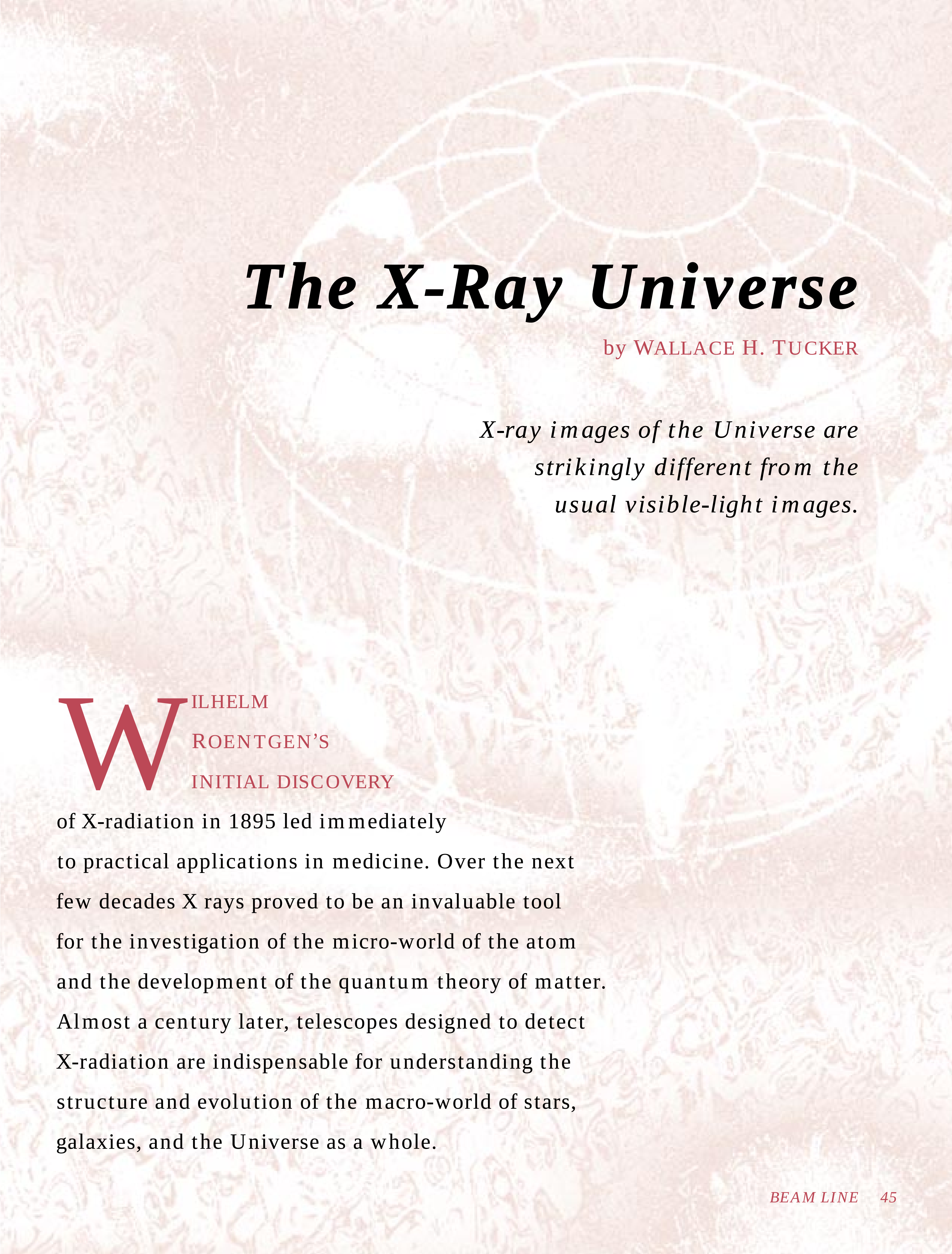


The X-Ray Universe

by WALLACE H. TUCKER

X-ray images of the Universe are strikingly different from the usual visible-light images.

WILHELM ROENTGEN'S INITIAL DISCOVERY of X-radiation in 1895 led immediately to practical applications in medicine. Over the next few decades X rays proved to be an invaluable tool for the investigation of the micro-world of the atom and the development of the quantum theory of matter. Almost a century later, telescopes designed to detect X-radiation are indispensable for understanding the structure and evolution of the macro-world of stars, galaxies, and the Universe as a whole.

THE BIRTH OF THE FIELD

X-ray astronomy emerged with the space age, because X-ray observatories could now be positioned above earth's X-ray-absorbing atmosphere. This may seem strange, since X rays pass right through our flesh, which is much denser than the atmosphere. Even though the atoms in the atmosphere are widely spaced, the total thickness of the atmosphere is so great that an X ray has a negligible chance of getting to the ground. (The lower-energy visible-light photons interact weakly with the atmospheric atoms and pass through with little absorption.)

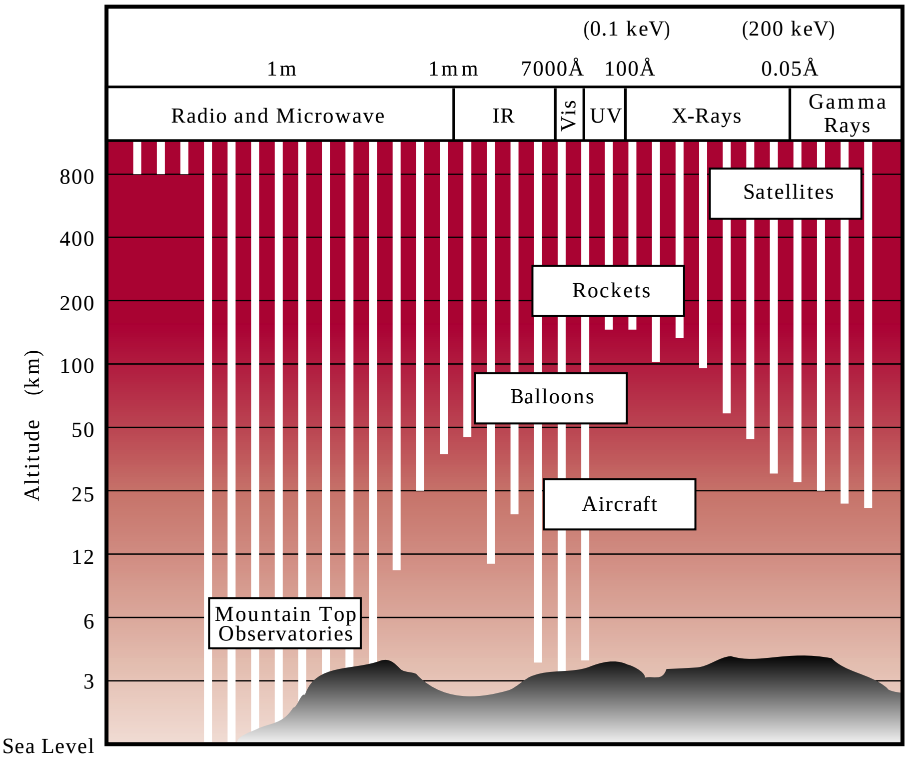
In September 1949 a team led by Herbert Friedman of the Naval Research Laboratory was the first to detect X-ray emission from the solar corona, the hot outer layers of the sun's atmosphere. Their experiment consisted of a collection of small Geiger counters aboard a captured German V-2 rocket. The observed X-ray emission was weak, amounting to only one millionth of the total energy radiated at all wavelengths by the sun.

The low X-ray output from the sun led many astronomers and astrophysicists in the late 1950s and early 1960s to think that efforts to build larger detectors and telescopes to observe X rays from sources outside the solar system would be fruitless. Fortunately, a group led by Riccardo Giacconi at American Science & Engineering (AS&E) did not listen to the pundits. Instead they followed the example set by Roentgen, who when asked what he thought when he first observed X rays in his laboratory, replied, "I did not think: I investigated." Undeterred by NASA's rejection of a proposal to search for cosmic X-radiation, Giacconi persuaded the Air Force to fund the project with the understanding that its primary goal was to look for X rays from the moon.

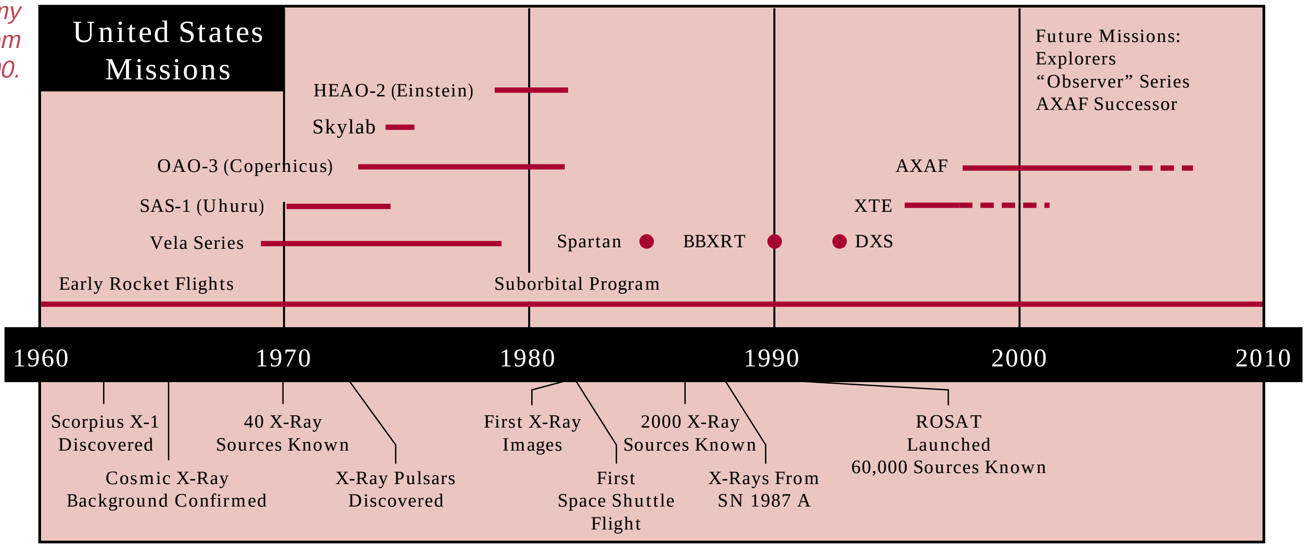
The AS&E team's first two X-ray astronomy rocket flights failed. The third try, in June 1962, was a success. During an observation period that lasted just over five minutes, Geiger counters a hundred times more sensitive than any used before detected a strong source in the constellation of Scorpius, as well as a smooth background glow. Within a year these results were verified by the AS&E group and confirmed by Friedman's group at the Naval Research Laboratory. A new field of astronomy had been born. As a historical footnote, X-ray emission from the moon was not detected until 1990 by the Roentgen Satellite X-ray observatory (ROSAT).

THE X-RAY SATELLITES

By 1967 there were a dozen or more groups involved in X-ray astronomy, and more than thirty sources had been found. Major advances in the field began in the 1970s with the use of satellites



The absorption of X rays by the earth's atmosphere restricts ground-based observations to radio, near infrared, and visible wavelengths. X rays are absorbed high above the earth.



X-ray astronomy missions, from 1960–2000.

equipped with X-ray detectors. The first of these, Uhuru, was launched in 1970. In 1978, NASA's Einstein X-ray observatory was the first large focusing X-ray telescope to be placed in orbit. The Einstein X-ray telescope produced high-resolution images and accurate locations for thousands of cosmic X-ray sources. This and later missions have observed X rays from ordinary stars, white dwarf stars, neutron stars, black holes, interstellar shock waves produced by stellar explosions, the nuclei of galaxies, and hot gas in intergalactic space.

The X rays detected by X-ray astronomers, like those put to use in industry, medicine, and laboratory research, must be produced by high-energy particles. It is not surprising, then, that an X-ray image of the sky can look markedly different from an optical image. In essence, X-ray images reveal hot spots in the universe: regions where particles have been energized or raised to very high temperatures by phenomena such as strong magnetic fields, violent explosions, or intense gravitational forces. The temperatures inferred are typically several orders of magnitude higher than those on the surfaces of stars. Where do such conditions exist? In an astonishing variety of places, ranging from the vast spaces between galaxies to the bizarre warped space around neutron stars and black holes.

The ROSAT mission, an international collaboration involving Germany, the United Kingdom, and the United States, launched in 1990, has the most sensitive detector so far for low-energy X rays of the type emitted by stars similar to the sun. The source of X rays from these stars is a hot gaseous upper atmosphere, or corona, that has been heated to temperatures of millions of degrees Celsius.

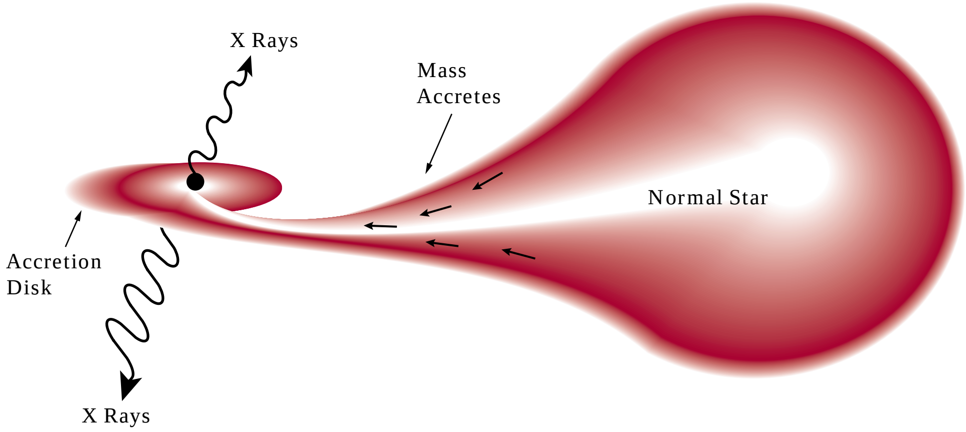
Young stars less than a hundred million years old are observed to have an X-ray output a thousand times more than that of the sun. This suggests that the X-radiation from the young sun could have been much stronger than it is today. How did this enhanced radiation affect the evolution and chemistry of the primordial atmosphere of the earth? X-ray observations should help to answer this vital question.

THE STRONGEST X-RAY SOURCES

The brightest X-ray sources in the sky are associated with the end phases of stellar evolution: the remnants of supernova explosions as well as neutron stars and black holes formed in the violent final seconds of a massive star's normal existence. The X-ray emission from these collapsed stars is billions of times greater than that from the sun.

The launch in 1970 of the Uhuru X-ray satellite by NASA made it possible to monitor X-ray stars for prolonged periods of time. It was discovered that the X-ray emission from these stars undergoes rapid, intense, and sometimes periodic variations. Combined observations with optical and X-ray telescopes have demonstrated that these X-ray sources are members of binary systems in which matter streams from a normal star onto a nearby collapsed star with an intense gravitational field.

In most X-ray binary star systems, the collapsed star is a neutron star. Neutron stars are the end products of the evolution of stars approximately ten times more massive than the sun. These stars undergo a supernova explosion in which most of the star is expelled into space at very high speeds. A shock wave analogous to a immense sonic boom spreads through space, heating interstellar gas to temperatures of millions of degrees. X-ray observations study these shock waves for clues about the origin of all of the heavy elements from carbon on up.



Cross section of an accretion disk of a neutron star.

Left behind is the rapidly spinning, highly magnetized, compressed core of the star—a core so dense that the electrons have combined with the protons to form an object composed mostly of neutrons. A sample of neutron star material the size of a sugar cube would weigh one billion tons. Most neutron stars appear to have a mass about equal to that of the sun compressed into a ball about twenty kilometers in diameter. The strong magnetic field on the surface of the star can funnel the infalling matter, resulting in a hot spot which manifests itself as a regularly pulsing X-ray source.

BLACK HOLES

For a few binary X-ray star systems, the mass of the collapsed object is deduced to be greater than three times the mass of the sun. These objects are presumably the end products of stars even more massive than those that produce neutron stars. The theory of dense matter and Einstein's theory of general relativity require that such an object would collapse in on itself to form a warp in space called a black hole. A black hole does not have a surface in the normal sense of the word. It is more like a whirlpool with a critical range of influence. The critical distance from a black hole is called the gravitational horizon. Anything that falls within the horizon—matter, light, X rays or other forms of electromagnetic radiation—is pulled inexorably inward by the gravity of the black hole and cannot escape.

No unique X-ray signature of a black hole has yet been discovered. In general, successful black hole candidates meet two requirements: (i) they are luminous X-ray sources that exhibit large, rapid, and sometimes quasi-periodic (a stable period would indicate a neutron star) fluctuations on a time scale of milliseconds; and (ii) optical observations of the primary star indicate that it has an invisible companion with a mass greater than three times the mass of the sun, the theoretical upper limit for the mass of a neutron star.

To date, a half dozen such systems have been discovered. The best estimates of the black holes in these systems are about 10 solar masses. Observations by future missions such as the X-ray Timing Explorer, scheduled to be launched by NASA in August of 1995, are expected to expand this list.

GALACTIC BLACK HOLES

Black holes of much larger mass are thought to lie at the center of many and perhaps all galaxies. These supermassive black holes, which could contain the mass of as many as a billion suns, are thought to form when a stellar-mass black hole swallows enormous quantities of interstellar gas that has accumulated in the central regions of galaxies. As gas falls inward, it is accelerated to high energies. This energized matter produces copious amounts of electromagnetic radiation over a wide range of wavelengths.

If the black hole is extremely massive and the rate at which it is pulling in matter is large, the energy release can be stupendous. This is apparently what is happening in quasars. They radiate as much energy per second as a thousand or more normal galaxies from a region about the size of our solar system. It is as if a small flashlight produced as much light as all the houses and businesses in the entire Los Angeles basin.

In black hole models for quasars, matter approaching the gravitational horizon radiates predominantly energetic X-ray and gamma-ray photons. A study of the intensity and variability of the X- and gamma-radiation from quasars can then provide information on the size of the black hole, the rate at which it is accreting matter, and other factors that are crucial to understanding the inner workings of these violent maelstroms.

INTERGALACTIC GAS AND DARK MATTER

The matter around black holes radiates intense X-radiation because it is highly compressed and exceedingly hot. Extreme temperatures can also be found in the near vacuum of intergalactic space. In contrast to the gas spiraling into black holes, the intergalactic gas is hot because it is spread out. Its low density makes it easy to heat and difficult to cool. Ordinarily this would also preclude it from producing any appreciable X-ray emission. However, in certain regions of space thousands of galaxies have clustered together. The amount of gas associated with these clusters of galaxies may have a mass equivalent to a hundred trillion suns. The only direct way to study this gas is through the X-radiation it emits. X-ray observations have shown that the mass of the gas in clusters of galaxies is considerable—comparable to the mass of all the stars in all the galaxies.

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Unless we are seeing a cluster of galaxies at a very special time when gas is exploding out of the cluster, the pressure of the hot gas must be balanced by the gravity of the cluster. X-ray observations indicate that the hot gas in clusters cannot be confined by the combined gravitational force of gas and galaxies. An additional, as yet unobserved form of matter, called dark matter, must be postulated. The implied amount of dark matter is enormous, about three to ten times as much as that of the observed gas and galaxies.

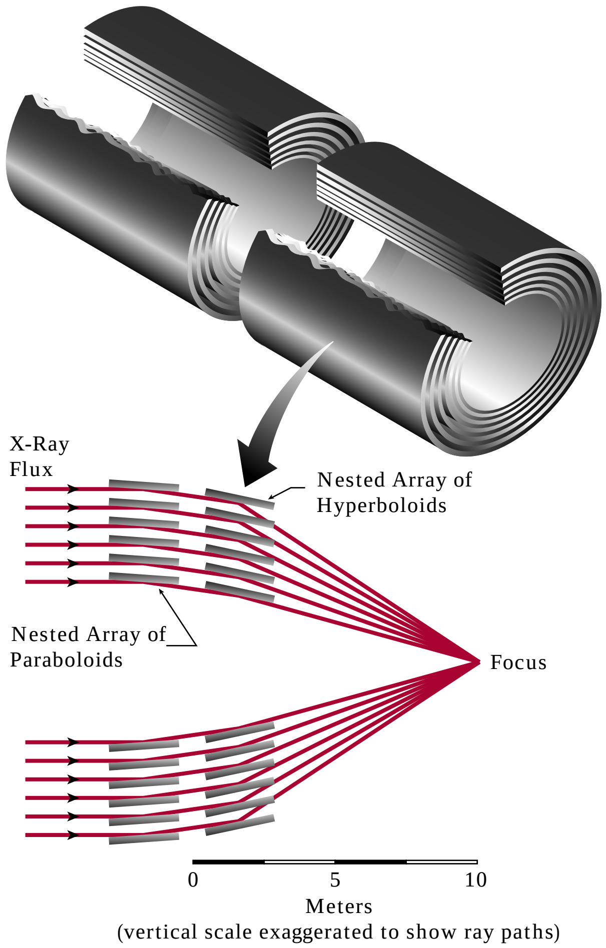
If the conclusions drawn from observation of clusters of galaxies so far can be generalized to the universe as a whole, then dark matter is the predominant component of our Universe.

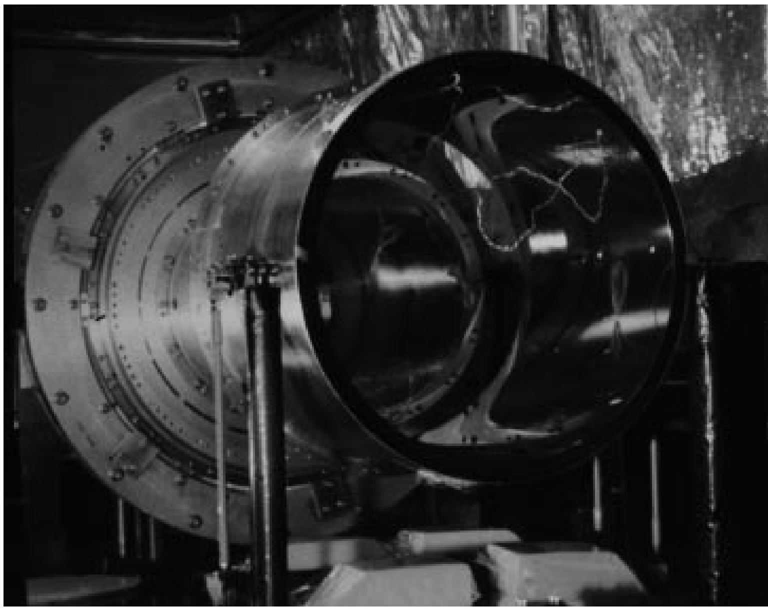
Is the dark matter composed of dim stars, planets, or black holes? Or does it consist of subatomic particles that interact with ordinary matter only through gravity? We do not know. But it seems certain that an understanding of the nature of dark matter could change our theories of the formation of stars and galaxies, the nature of subatomic particles, and the evolution of the Universe.

X-RAY BACKGROUND RADIATION

Other important clues to the evolution of the universe are found in the X-ray background radiation. One of the first discoveries of X-ray astronomy was an unexpectedly strong and uniform background glow of X-radiation. The uniformity of the radiation suggests that it is not coming from nearby galaxies, but from a distance so great that all the individual sources merge into a smooth background, just as the lights of a distant city appear as a uniform glow.

The current opinion is that the X-ray background radiation must have been produced about ten billion years ago. Sometime between a million and a few billion years after the hot Big Bang phase from which our Universe is thought to have evolved, the universe made a dramatic transition from a smooth, featureless state to clumps of galaxies. The X-ray background radiation must have been produced during this transitional period. Radiation from quasars and the bright nuclei of galaxies appear to be capable of producing a significant portion of the





Above right: Photograph of the largest AXAF mirror.
Above: Schematic of nested pairs of grazing-incidence mirrors which permit the precise focusing of X rays. (Courtesy Harvard-Smithsonian Center for Astrophysics, Marshall Space Flight Center, Hughes Optical Systems, and Eastman Kodak).

X-ray background, but it is still unclear if they can produce all of it.

THE FUTURE

What is clear is that future X-ray missions will probe ever more deeply into space with ever more sensitive and versatile instruments. The most important X-ray astronomy mission of the coming decade will be NASA's Advanced X-ray Astrophysics Facility (AXAF), which is scheduled for launch in 1998. This observatory, with its four sets of nested mirrors, will be the X-ray equivalent of the Hubble Space Telescope. AXAF and other future missions will provide scientists with opportunities for deeper insight into black holes, dark matter, the X-ray background, and the events that led to the formation of the elegant galaxies and colossal clusters and superclusters of galaxies that constitute our Universe.