X-Ray Astronomy

X-ray astronomy is an achievement of the space age as the Earth's atmosphere is completely opaque at photon energies beyond the ultraviolet region.

In 1949 the first X-RAYS from the solar corona were detected by a Geiger counter on a V-2 rocket. In 1962 the discovery of the first x-ray source outside the solar system followed—SCORPIUS X-1. With the same rocket experiment an apparently diffuse x-ray background was found. Since these early days x-ray astronomy has developed at an enormous pace. Today, we know more than 150 000 x-ray sources in the sky and they include almost all astrophysical species—from the nearby comets to the most distant quasars at the edge of the universe, from the tiny neutron stars to the clusters and superclusters of galaxies as the largest physical formations in the cosmos. Some species radiate most of their power in x-rays, for instance black holes or neutron stars accreting matter from a binary companion, as well as supernova remnants and single, cooling neutron stars.

Many of the known objects shine in x-rays because they are hot—having temperatures of millions to billions of kelvins. Other emission mechanisms are synchrotron radiation of extremely energetic electrons spiraling in magnetic fields or the inverse Compton effect which occurs when high-energy electrons scatter at low-energy photons, e.g. from stellar light or from the 2.7 K cosmic background radiation. In any case, the emission of x-rays points to extreme physical conditions in the source region. Also, these x-rays carry information which is not available from observations in other spectral bands. In this article we shall give a brief summary of the development of x-ray astronomy, describe the evolution of experimental techniques and x-ray space missions and highlight some of the results which have had a major impact on astrophysics.

The beginnings with sounding rockets

Like GAMMA-RAY ASTRONOMY, the field of x-ray astronomy was pioneered by physicists. Herb Friedman, who detected the first solar coronal x-rays in 1949, had been working previously in ionospheric physics; Giacconi and Rossi, who led the group discovering Scorpius X-1 and the x-ray background in 1962, were nuclear and cosmic ray physicists.

The instruments used in these pioneering experiments were rocket-borne Geiger counters and spectral discrimination was achieved by means of windows and filters. A little later proportional counters became the standard instrument, working in the 1–10 keV band and having a modest spectral resolution ($\sim$20% at 5 keV). Observations were first performed by scanning the sky by spinning or precessing the rocket. Later on more sophisticated attitude control systems allowed pointed observations to be made with greatly improved sensitivities.

The first discoveries of cosmic x-ray astronomy were totally unexpected. Sco X-1 showed a luminosity many orders of magnitude larger than that of the Sun. It soon became clear that the mechanism by which such sources are powered was the infall of matter into the deep gravitational potential well of a NEUTRON STAR (as in Sco X-1) or a BLACK HOLE. Most of the few dozen sources found during the rocket era, i.e. until the end of the 1960s, were of this kind. The other major class was SUPERNOVA REMNANTS. The identification of the CRAB NEBULA as a bright x-ray source by means of a lunar occultation was one of the early highlights. Other important discoveries of this era were the x-ray pulsations of the CRAB PULSAR and the x-ray emission from the active galaxy M87 at the center of the Virgo cluster.

After the advent of x-ray satellites rocket-borne experiments with their short observation time ($\sim$5 min) were generally not competitive any more. However, they continued to play a role as a test bed for instruments to be flown on satellites or for special observations, in particular those ones of short lead time (e.g. on the famous SUPERNOVA 1987A).

Hard x-ray balloon experiments

The rocket experiments had shown that the spectra of compact x-ray sources are quite hard, extending much beyond 10 keV. This opened up the possibility of using balloon-borne instruments as the atmosphere becomes transparent for altitudes above 40 km at high x-ray energies ($>$20 keV). Balloon flights offered the advantage of long-duration observations (up to 100 h) and the crystal scintillation counters used in these experiments allowed spectra to be taken up to $\sim$500 keV. Balloon observations were pioneered by the MIT group in the 1960s. Important results of these early years were the measurement of the Crab spectrum to high energies ($\sim$500 keV), the discovery of variability in GX1 + 4 and the detection of a 20 min flux from Sco X-1. This field of research culminated in the 1970s with experiments of the MIT–Leiden and the Tübingen–MPE groups which flew very large detectors operating in the pointing mode. Highlights of these activities were the observation of a lunar occultation of the Crab, the discovery of a spectral break in the Cyg X-1 spectrum corresponding to a temperature of about $\sim 20 \times 10^6$ K and the discovery of cyclotron lines at $\sim$40 keV in the accreting neutron star Her X-1, allowing the first direct measurement of its polar magnetic field ($\sim 5 \times 10^{12}$ G).

X-ray astronomy satellites

Most significant progress in x-ray astronomy came with the advent of satellite observatories. Their ancestor, the first satellite entirely devoted to x-ray astronomy, was UHURU. Launched in 1970 it was a spinning spacecraft with a simple, but very powerful, instrument package: an array of proportional counters of 840 cm^2 area working in the 2–20 keV band. It performed the first all-sky survey and located 339 objects, mostly X-RAY BINARIES and supernova remnants, showing a strong clustering near the galactic plane. At fainter flux levels an isotropic distribution of Seyfert galaxies and clusters of galaxies was found.

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The discovery of two pulsating and eclipsing x-ray binary systems, Cen X-3 and Her X-1, proved in an impressive way that these systems contained matter-accreting neutron stars. The discovery of short time variability of Cyg X-1 by Uhuru led to follow-up rocket experiments yielding accurate source positions which enabled the optical counter-part to be identified and the mass of the accreting compact object to be determined. This mass turned out to be larger than the limiting mass of a neutron star. Thus it had to be a black hole.

Uhuru also marked the beginning of an impressive series of satellites with ever-increasing capabilities listed in table 1. We cannot discuss them in detail here, but rather describe the main directions of developments.

Imaging x-ray telescopes

Imaging of x-rays is possible in different ways. Early solar observations used pinhole cameras and Fresnel zone plates, but the sensitivity of such devices is insufficient for studies of the rather weak cosmic x-ray sources. Therefore, the standard X-RAY TELESCOPES use Wolter optics which consist of paraboloidal–hyperboloidal mirrors reflecting x-rays under grazing incidence (see GRAZING INCIDENCE OPTICS). The first x-ray telescopes of this kind using x-ray film as a detector were used for solar observations from rockets and Skylab. The first x-ray satellite carrying a Wolter telescope was the Einstein observatory launched in 1979. It provided images with ~10 arcsec resolution and represented a real breakthrough, putting x-ray astronomy on equal footing with optical astronomy.

X-ray sky surveys

All-sky surveys have traditionally been a foundation of astrophysical research, and in the era of multiwavelength astronomy their importance has dramatically increased. Such surveys provide an unbiased view of the sky, they deliver large homogeneous samples of objects and they allow rare species to be discovered. Cross correlating the surveys from different wavelength bands—e.g. optical and x-rays—is a very effective method to select sources of a certain type, e.g. active galactic nuclei and quasars.

The Uhuru and Ariel V surveys have revealed ~350 sources in the standard x-ray band (2–6 keV). The subsequent HEAO-1 sky survey was not much more sensitive (840 sources) but widened the energy band considerably (0.1–200 keV). The limitations of all these collimated counter surveys in terms of angular resolution (<1 deg^2) and sensitivity were overcome by the German-led ROSAT which performed the first all-sky survey in soft x-rays by sweeping an imaging Wolter telescope across the whole sky. Although it took only half a year of the more than 8 yr of ROSAT's life this survey discovered 80 000 x-ray sources and located them with 25 arcsec resolution. In addition, the survey provided a complete map of the diffuse x-ray emission with 12 arcmin resolution (figure 1).

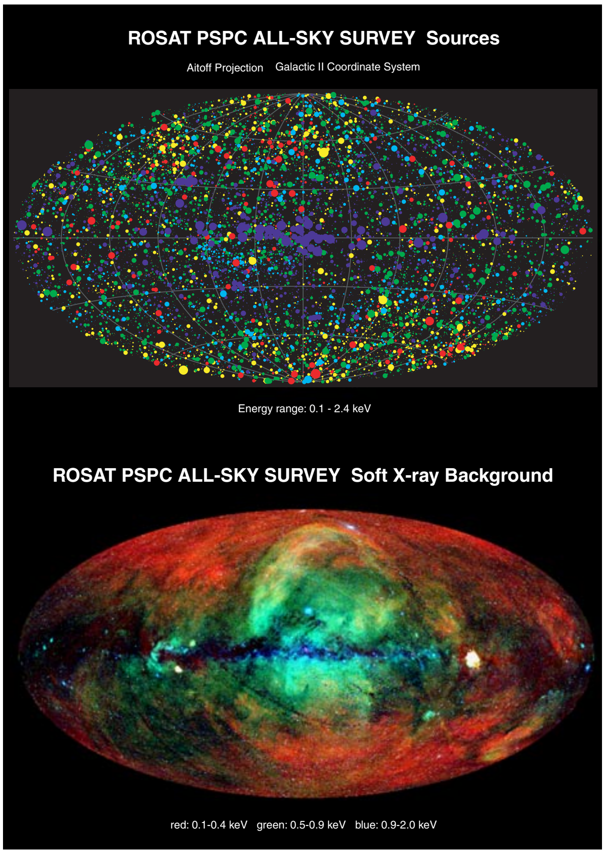

Figure 1. The x-ray sky as known at the end of the 20th century on the basis of the ROSAT All Sky Survey. Top: distribution of the ~19 000 brightest x-ray sources; Bottom: diffuse emission from hot interstellar matter heated by supernova explosions. **This figure is reproduced as Color Plate 61.**

Recent highlights of x-ray astronomy

A rather detailed account of the development of x-ray astronomy until ~1990 with a description of missions and their results can be found in Bradt *et al* (1992). Here we want to highlight the progress made in the 1990s by the powerful x-ray telescopes on ROSAT and ASCA.

In addition, there have been two very successful recent missions which must be mentioned here. The ROSSI Timing Explorer (RXTE) carrying large-area collimated counters covering a wide energy range (2–200 keV) has deepened our understanding of compact sources by high time resolution and spectral studies. One of its most exciting results was the discovery of 2.75 ms pulsations occurring during the bursts of the low-mass x-ray binary (LMXB) 4U 1728-34. The data suggest that the pulsation came from the rotation of a thermonuclear hotspot on the surface of the neutron star.

In another LMXB which had been previously identified as an X-RAY BURSTER by BEPPOSAX, RXTE found 2.5 ms pulsations in the persistent flux which must be due to the rotation of the neutron star. This is the first

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Table 1. X-ray astronomy satellites 1969–2000. Adapted from Charles and Seward (1995) updated January 2000.

Satellite	Country	Launch	Demise	Type
Vela 5 A,B	USA	May 1969	June 1979	Scanning, small scintillation counter, gamma-ray range
Uhuru	USA	December 1970	January 1975	Scanning, proportional counters
OSO-7	USA	September 1971	May 1973	Scanning, proportional counters
Copernicus	USA–UK	August 1972	February 1981	Pointed, x-ray telescope (non-imaging)
ANS	Netherlands–USA	August 1974	July1976	Pointed proportional counters, Bragg crystal spectrometer
Ariel-V	UK	October 1974	March 1980	Scanning, rotating modulation collimators (RMCs) + proportional counters
SAS-3	USA	May 1975	April 1980	Scanning, RMC
OSO-8	USA	June 1975	October 1978	Scanning, proportional and scintillation counters, Bragg crystal, polarimeter
HEAO-1	USA	August 1977	January 1979	Scanning + short pointings, proportional and scintillation counters, RMC
Einstein	USA	November 1978	April 1981	Pointed, imaging x-ray telescope, Bragg crystal, transmission gratings
Hakucho	Japan	February 1979	April 1985	Scanning, RMCs
Tenma	Japan	February 1983	~1985	Gas scintillation proportional counter (GSPC), all-sky monitor
EXOSAT	ESA	May 1983	April 1986	Pointed, imaging x-ray telescope, large proportional counters, GSPC
Ginga	Japan–UK	February 1987	October 1991	Pointed, proportional counters
Kvant	USSR–UK–Netherlands–Germany	June 1987	–	Pointed, GSPC, coded mask, scintillation counter
Granat	USSR–Russia	December 1989	August 1999	Pointed, coded masks, all-sky monitor
ROSAT	Germany–UK–USA	June 1990	December 1998	Scanning, pointed imaging x-ray and EUV telescopes
ASCA	Japan–USA	February 1993	–	Pointed, imaging x-ray telescopes, imaging GSPC
RXTE	USA	December 1995		Pointed, large proportional counters, scintillation counters, all-sky monitors
BeppoSAX	Italy–Netherlands	April 1996		Pointed imaging x-ray telescope, coded mask, scintillation counter
Chandra	USA	June 1999		Pointed imaging x-ray telescope, spectrometers
XMM-Newton	ESA	December 1999		Pointed imaging x-ray telescope, spectrometers

and so far only LMXB showing both persistent pulsations and bursts. BeppoSAX is an Italian–Dutch satellite with instruments covering a wide energy band (0.1–200 keV). By discovering the x-ray afterglows of gamma-ray bursts it pointed the way to the solution of an old puzzle, the physical nature of gamma-ray bursts.

Highlights from ROSAT and ASCA

ROSAT and ASCA have complementary properties. ROSAT carries a large x-ray telescope with a position-sensitive proportional counter (PSPC) providing moderate spectral resolution (~40%) in the 0.1–2.4 keV band. With its High Resolution Imager (HRI), a microchannel plate detector 'black-and-white' images with 5 arcsec resolution can be taken. The telescopes of ASCA cover the energy band 0.5–10 keV with CCD detectors and imaging gas scintillation proportional counters having superior energy resolution (~20%), but worse angular resolution (~3 arcmin), compared with ROSAT. Both satellites have been used by many astrophysicists to study a wide variety of problems. The numbers of scientific publications resulting from ROSAT and ASCA run to about 4000 and 1600, respectively, covering almost all fields of astrophysics. In the following a few highlights are presented.

ROSAT took the first x-ray picture ever of the MOON (figure 2(*a*)). The Sun-lit side of the Moon contains a uniform brightness distribution as in optical light. This is due to solar coronal x-rays undergoing Thomson scattering in a very thin layer of the lunar surface. The PSPC spectrum shows a broad spectral bump at 0.6 keV which is due to fluorescent resonance scattering by oxygen of the minerals of the lunar surface layers. The effective reflectivity of the Moon in the ROSAT band is only ~0.01%; this means that the Moon behaves as a black body at x-ray energies. At the same time it casts a shadow on the 'diffuse' x-ray background (see later section). The small flux of x-rays apparently coming from the dark side of the Moon is probably produced in the Earth's upper atmosphere by charge-exchange processes of solar wind ions. This is the same mechanism which is responsible for the x-ray emission from cometary comas (see below).

COMETS are cold objects that have been described as dirty snowballs. Therefore the discovery with ROSAT of x-rays from COMET HYAKUTAKE on 27 March 1996 was surprising to many scientists (figure 2(*b*)). Later, another

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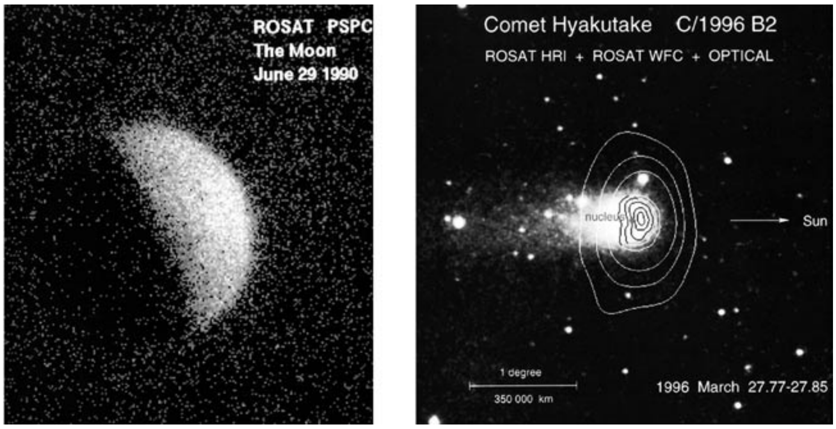

(*a*) (*b*)

Figure 2. Solar system objects in x-rays: (*a*) the Moon reflecting solar coronal x-rays and casting a shadow on the x-ray sky; (*b*) x-ray emission from comet Hyakutake superimposed on an optical amateur photograph.

four comets were found in the ROSAT All Sky Survey archive, including comet Levy. In total about a dozen comets have been detected by now in x-rays, mostly with ROSAT. Various physical processes have been proposed to explain the observed extended x-ray emission, including scattering of solar x-rays by cometary dust, x-rays produced by collisions of cometary and interplanetary dust particles and bremsstrahlung x-rays from electrons accelerated at the shock between the solar wind and the coma. However, all these mechanisms fail to explain the observed characteristics. The most successful and widely accepted model suggests that charge exchange between highly charged ions (such as C^{5+}, C^{6+}, O^{6+} and O^{7+}) in the solar wind and neutral particles (such as water) in the cometary coma is the dominant source of the observed x-ray emission.

ROSAT has given many exciting results about stars of all types. The study of a complete sample of stars of solar type has revealed the existence of a sharp lower bound to the x-ray flux, measured at the surface of the star. Interestingly, this minimum stellar x-ray flux is identical to the flux observed in the coronal holes of the Sun. This result suggests that the stars of minimal x-ray flux are completely surrounded by stellar analogs of solar coronal holes.

With ground-based optical follow-up observations of unidentified ROSAT All-Sky Survey sources, several hundred new T TAURI STARS have been identified based on Hα emission of hydrogen and lithium absorption. Surprisingly, many new T Tauri stars have been found far outside regions of ongoing star formation. Such 'off-cloud' T Tauri stars must have been either ejected from their birthplaces in the clouds with high velocities or formed in small cloudlets which have largely dispersed since then.

Recently, deep ROSAT observations have led to the discovery of young ($<10^6$ yr) brown dwarfs showing x-ray emission. The x-ray properties of these brown dwarfs, in particular their x-ray to optical light ratio, are similar to those of nuclear burning stars of low mass. This may suggest that young brown dwarfs have hot coronae responsible for the x-ray emission just like nuclear burning stars of low mass.

Early in the ROSAT mission a number of objects were discovered emitting extremely soft x-rays. They are very luminous and show temperatures of a few hundred thousand kelvins. It turned out that these sources are a species which had been predicted to exist but which had not been found before. They are WHITE DWARFS in binary systems accreting matter from their companions at a rate just sufficient to sustain steady nuclear burning on the surface of the white dwarf. Thus, they represent a unique situation in which steady nuclear burning is observed at the surface of a compact star.

Massive stars explode giving rise to a supernova when the nuclear fuel in their cores is exhausted. The core collapses to a neutron star or a black hole while the shell of the star is expelled in a giant explosion. A large fraction of the kinetic energy is converted by shocks into high-temperature x-ray emitting plasmas. Supernova 1987A was ROSAT's first-light target on 16 June 1990, but it turned out to be too faint to be seen at that time. Its remnant was first discovered in soft x-rays with ROSAT in 1992 and has steadily become brighter since then. A large increase is expected to occur in the near future when the shock reaches the high-density regions of the red giant wind. In total, some 200 supernova remnants have been found with ROSAT. Three of them are clustered in the Vela region (figure 3). One is the VELA SUPERNOVA REMNANT, which, at a distance of 1500 ly, is one of the closest supernova remnants. Its diameter is about 200 ly, its age about 20 000 yr. Protrusions discovered with ROSAT at the periphery of the shell are probably produced by fragments of the exploding star; x-ray spectroscopy with ASCA has revealed that they show different chemical compositions (figure 3(*a*)). The Puppis A remnant at the north-western rim of the Vela supernova remnant

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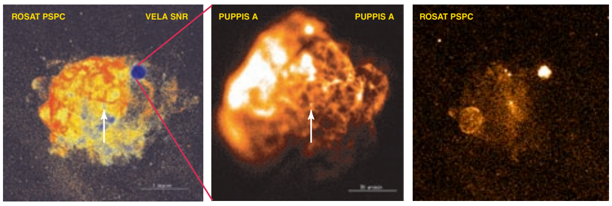

(*a*) (*b*) (*c*)

Figure 3. The Vela complex of supernova remnants: (*a*) Vela supernova remnant with the Vela pulsar and Puppis A; (*b*) Puppis A with its central source, probably the remnant neutron star; (*c*) A young, ~680 yr old supernova remnant, superimposed on Vela supernova remnant, showing titanium-44 emission. **This figure is reproduced as Color Plate 62.**

is located at a much larger distance (figure 3(*b*)). It is younger and has a much higher temperature than the Vela supernova remnant. Surprisingly, a third supernova remnant has been discovered recently in the Vela complex with ROSAT. Radioactive titanium-44 has been detected from it with the Compton Gamma-Ray Observatory (figure 3(*c*)). Titanium-44 is produced in supernova explosions and has a mean lifetime of only 90 yr, which means that the remnant is very young (~680 yr). Actually, this supernova remnant looks like a twin of SN 1006. Like the latter it must have been very bright at maximum (about a quarter of the full Moon) and it is unclear why it has not been recorded in the Chinese and Japanese annals.

Neutron stars shine in different ways. If they are highly magnetized and rapidly rotating, they appear as radio PULSARS. These objects emit beamed radiation produced by high-energy electrons (and positrons) that are accelerated in their magnetospheres. In about half a dozen young pulsars, optical and gamma-ray pulses have also been seen. With ROSAT and ASCA, 34 radio pulsars have been detected through their magnetospheric x-ray emission, including the 89 ms Vela pulsar. The characteristic features of this magnetospheric radiation are power law spectra and sharp pulses. Four of the radio pulsars seen with ROSAT, including the Vela pulsar, exhibit an additional thermal spectrum corresponding to a temperature of the order of 10^6 K, which is interpreted as the thermal radiation from the surface (photosphere) of the neutron star. A few point sources discovered near the centers of young supernova remnants also show very soft x-ray emission, which must be attributed to neutron star surface emission as well. A prominent example is the central source in Puppis A (figure 3(*b*)).

Since the ages of radio pulsars and supernova remnants can be determined quite well, one can use these observations to test cooling models of neutron stars. The result is that standard cooling models describe the observed temperatures and luminosities quite well. Rapid cooling as expected in the presence of a Bose–Einstein condensate of pions or kaons in the neutron star core can be excluded for the observed objects.

A few x-ray sources have been found in the ROSAT data showing very soft thermal spectra, (temperatures below a million kelvins) and very faint optical counterparts (25^m–26^m). These objects might be either single neutron stars accreting interstellar matter or, more likely, old (10^5–10^6 yr) cooling neutron stars whose supernova remnants have already vanished. The importance of all these observations lies in the fact that the surfaces of these tiny stars (with radii 10 km) have now become visible. Future x-ray spectroscopy should make it possible to measure their enormous gravity as well as their radii, which depend on the physical properties of matter at supranuclear densities.

The ROSAT deep survey of the Andromeda galaxy led to the discovery of 550 x-ray sources, comparable in number with the bright x-ray sources in our own galaxy found by Uhuru. As in the Milky Way, the brightest of them are young supernova remnants or binary systems with neutron stars or black holes accreting matter from a companion. These bright source populations have been studied with ROSAT in many galaxies. In addition, the hot interstellar medium, which is heated by supernova explosions, has been investigated.

A small fraction of all galaxies have an ACTIVE GALACTIC NUCLEUS (AGN) emitting huge amounts of energy in all spectral bands. The radiation is variable, indicating that it is emitted from a small region, generally not more than a few light-weeks or light-months across. Such AGNs often display jets, originating in their core. It is generally believed that the central engine is a supermassive black hole swallowing matter at a high rate. QUASARS are the most extreme representatives of the class of AGN sources. ASCA spectroscopy of the AGN MCG-6-30-15 and a few other sources has led to the discovery of iron Kα emission lines with broad and asymmetric profiles. This profile is most probably caused by gravitational and relativistic Doppler shifts of the rapidly rotating matter in the accretion disk near the central black hole. These AGNs are very bright x-ray sources, and more than 50% of all 150 000 ROSAT sources belong to this class. Because of their enormous brightness, they can be detected at large distances or redshifts. In the ROSAT Deep Surveys with a total accumulated observation time of 2 weeks, about 1000 sources are detected per square degree in the sky. Optical spectroscopy has shown that most of them are quasars and other AGNs at cosmological distances. The ROSAT Deep Surveys have also answered one of the oldest questions of x-ray astronomy, namely the origin of the extragalactic x-ray background: at least, in the soft x-ray band, around 1 keV, some 80% of the background has been resolved into discrete sources, mostly quasars. An important current question is what evolved first, the galaxies or the supermassive black holes.

Galaxies are not distributed randomly in the universe but form clusters or groups of galaxies consisting of a dozen to thousands of members which are gravitationally bound. With diameters of millions of light-years, they are the largest physical objects in the universe. As early as 1932, Fritz Zwicky found that CLUSTERS OF GALAXIES must

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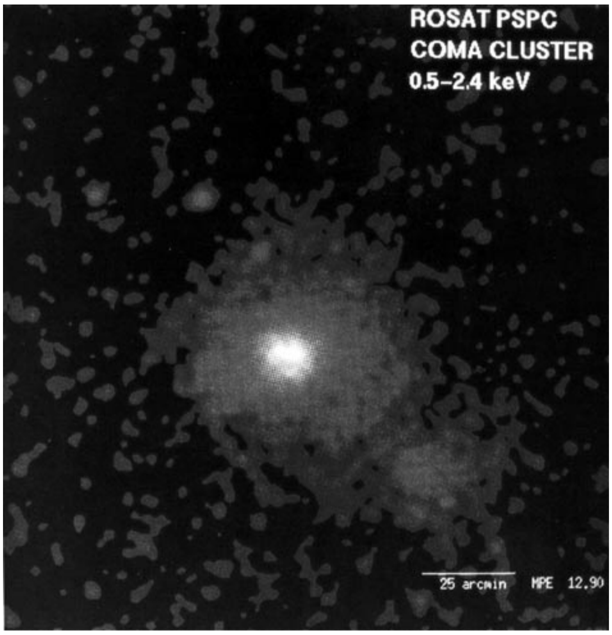

Figure 4. X-ray image of the coma cluster showing the merging with a smaller cluster of galaxies.

contain much more gravitating mass than accounted by the total visible mass of all member galaxies. Actually, the amount of 'DARK MATTER' had to be of the order of 95% of the total cluster mass.

One early surprise of x-ray astronomy was the detection by Uhuru of large quantities of hot plasma in clusters of galaxies shining in x-rays. Later Einstein and ROSAT observations showed that the mass of the hot plasma is typically a factor of 4 or 5 larger than that of the galaxies and represents some 20% of the cluster mass. In other words, a large fraction of the 'dark matter' turned out to be hot, visible only in x-rays and not in optical light. ASCA spectroscopy has allowed us to measure the heavy element (iron) abundance of the hot matter in clusters, which is typically only one-third of the so-called universal abundance. This can be explained by the infall of primordial matter onto the clusters.

Many clusters show double structures, indicating the merging of two clusters; others exhibit complicated inner structures which must be due to earlier merging processes (figure 4). Thus, the x-ray images reveal how these large objects evolve with cosmic time.

In total, several thousand clusters have been found with ROSAT. About 1500 of them have been optically identified and have known redshifts, and thus known distances. From this information one can derive the evolution of the cluster population with time. A comparison with simulations shows that the observed time dependence of the cluster population is significantly smaller than expected in a universe having the critical density. Actually the matter density inferred from cluster evolution is only about one-third of this critical density which is necessary to close the universe.

The future

During the years to come enormous progress is expected in x-ray astronomy owing to two new very powerful and complementary x-ray telescope missions: CHANDRA and XMM-NEWTON. Both satellites carry x-ray CCD detectors and dispersive spectrometers for high-resolution spectroscopy. The special strength of Chandra, launched in summer 1999, is its high angular resolution ($\sim$0.5 arcsec) which allows us to resolve fine structures such as jets and to go at least a factor of 1000 deeper than the ROSAT deep surveys did. On the other hand XMM-Newton, launched in December 1999, provides a very high collecting power ($\sim$4–10 times that of Chandra, depending on energy) at moderate angular resolution ($\sim$10 arcsec). It will be very powerful for spectroscopic and time variability studies. The first results of these two powerful missions are very tantalizing.

Plans for the future thereafter are already quite concrete. NASA is discussing a fleet of four x-ray telescope satellites called 'Constellation' to be launched in $\sim$2007. They can observe the same object with different instruments simultaneously or point to different regions of the sky. ESA's XEUS (x-ray mission for spectroscopy in an evolving universe), to be launched after 2010, foresees a giant x-ray telescope with a huge mirror system and focal instruments sitting on two separate satellites, which means that pointing requires orbital maneuvers. The collecting area of the telescope ($\sim$30 m^2) is a thousand times that of ROSAT and about a hundred times that of XMM or RXTE. It should be able to penetrate into the 'dark ages' of our universe at redshifts of 5–10, where galaxies and supermassive black holes have been formed.

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