tidal forces is thought to be incredibly short by astronomical standards (less than 10^5 years), so the the system is either being observed at a very unique time or some mechanism that is not well understood may be stablizing the double nucleus against orbital decay. This image of the closest spiral galaxy serves as a reminder that even so-called normal galaxies are not yet well understood.

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Recent Advances of X-ray Astronomy

Yasuo Tanaka

Among the great astronomical discoveries of the 1960s was the totally unexpected finding by Giacconi *et al.* (*1*) of a bright x-ray star, now known as Scorpio X-1. Because cosmic x-rays are absorbed by the Earth's atmosphere, astronomers were effectively blind in the x-ray wavelength band until they were able to send instruments into space. The discovery of Sco X-1 was truly surprising because no bright x-ray sources other than the sun were considered to exist. Since then, x-ray astronomy has developed very rapidly, especially in the last 20 years, after satellite observations became possible.

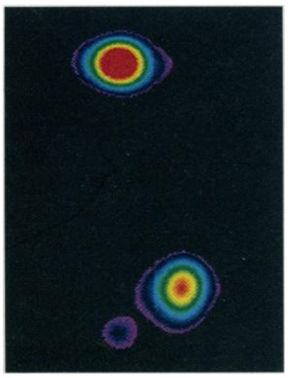

Fig. 1. X-ray image of M81 obtained with ASCA on 7 April 1993. The source near the top (north) is the nucleus. The bright source below is SN 1993J (3 arc min from the nucleus). Another source adjacent to the supernova is a probable x-ray binary in M81.

X-rays are emitted either thermally, from hot plasmas with temperatures of millions to tens of millions of kelvins, or nonthermally through relativistic processes involving high-energy electrons. Therefore, many high-energy astrophysical processes are manifested most directly in the x-ray and gamma ray bands, and x-ray observations have become indispensable for the studies of high-energy astrophysics. At present, every class of astronomical object, from nearby stars through quasars at cosmological distances, is the subject of x-ray astronomy investigations.

The first x-ray astronomy satellite, UHURU (1970), revealed a great many x-ray sources, galactic as well as extragalactic. One of UHURU's most important discoveries was that the brightest galactic x-ray sources were close binaries of which one member was a gravitationally collapsed, compact object—usually a neutron star, but possibly a black hole (*2*). The intense x-ray emission arises as matter dragged from the normal companion star falls into the extremely deep potential well of the compact object, releasing 100 MeV per nucleon of gravitational energy in the form of heat. This process, called mass accretion, produces a variety of phenomena in the x-ray band, allowing detailed investigation of the nature of these compact objects.

The richness of the x-ray sky was further disclosed as exploration progressed with succeeding x-ray satellites. The Einstein Observatory (1978) carried the first focusing x-ray telescope and had a sensitivity that was improved by several orders of magnitude over previous experiments. This enormously expanded the horizon of the x-ray sky and made x-ray studies of extragalactic sources an important branch of astronomy.

The Einstein Observatory revealed that many active galaxies, including quasars, were strong x-ray emitters (*3*). An active galaxy emits an immense quantity of electromagnetic radiation from a tiny region at the center of the host galaxy, called an active galactic nucleus (AGN). The emission is clearly of nonthermal origin, and the spectrum extends up to the gamma ray regime, indicating that complex relativistic processes are involved. From various arguments, an AGN is suspected to be a supermassive black hole, but the mechanism of the "central engine" of the AGNs still remains enigmatic.

Observations at x-ray wavelengths revealed that clusters of galaxies contain a large amount of hot (several tens of millions of kelvins) plasma (*4*). The mass of this intracluster gas is comparable with or more than the total mass of the constituent galaxies and accounts for a substantial fraction of the baryonic matter in the universe. The formation and evolution of clusters of galaxies have become increasingly important topics of x-ray astronomy.

More recently, the German x-ray satellite, the Roentgen Satellite (ROSAT), was launched in 1990. It was equipped with a larger x-ray telescope than that of the Einstein Observatory and, in the limited soft x-ray band of 0.3 to 2 keV, has the highest sensitivity of any soft x-ray telescope flown to date. Naturally, many discoveries are being made with ROSAT. The ROSAT all-sky survey vastly expanded the previous catalog to include nearly 100,000 x-ray sources.

In the past, despite great scientific need, high-energy astronomy satellites have been scarce, too few compared to the ground-based observatories. Today, fortunately, several x-ray and gamma ray satellites with unique capabilities are simultaneously in operation: ROSAT (Germany), GRANAT (Russia), the Compton Gamma-Ray Observatory (CGRO) (United States), and the most recently launched Japanese satellite, ASCA. Significant advances in high-energy astrophysics can be expected.

In the remainder of this article, I shall focus on several topics in x- ray astronomy, using recent results obtained mainly with Ginga and ASCA. Ginga (1987–1991), the Japanese x-ray satellite before ASCA, had an x-ray collecting area of 4000 cm^2, the largest of its kind, covering a wide energy range between 1 and 40 keV. Launched in February 1993, ASCA is the first x-ray observatory capable of simultaneous imaging and spectroscopic observations over the range 0.5 to 10 keV. Although the angular resolution is modest (1 arc min), the x-ray charge-coupled device (CCD) cameras provide spectra of an unprecedented energy resolution.

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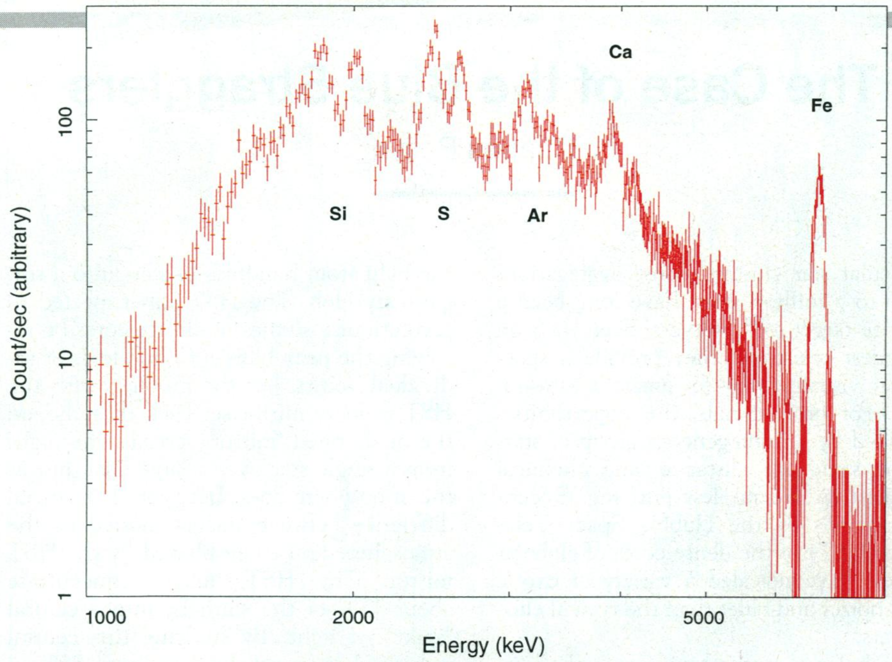

Fig. 2. The energy spectrum of the supernova remnant W49B obtained with the x-ray CCD camera of ASCA. Characteristic lines from silicon, sulfur, argon, calcium, and iron are clearly resolved.

There are about 200 x-ray binaries in our galaxy. About 30 of them include a strongly magnetized neutron star and appear as x-ray pulsars. Ginga observed the spectra of many binary x-ray pulsars and found cyclotron resonance features in 10 of them, which allows the direct measurement of the surface magnetic field of the neutron stars. These measured field strengths fall within a narrow range, 1×10^{12} to 4×10^{12} G (*5*), which casts doubt on the hypothesis that the magnetic field of neutron stars decays on a time scale of millions of years.

Most x-ray binaries, however, do not pulsate because the neutron stars in them have a much weaker magnetic field than those in the x-ray pulsars. Their companions are almost always low-mass stars, so the systems are called low-mass x-ray binaries. Sco X-1 is this kind of x-ray binary. How these low-mass x-ray binaries are formed is still an unresolved problem. The spectrum of a typical bright low-mass x-ray binary actually consists of two components: a soft component from the accretion disk formed around the compact object by the infalling matter, and a harder blackbody component from the neutron star surface.

About 20 bright x-ray binaries have been observed whose spectra are distinctly different from either the x-ray pulsars or the low-mass x-ray binaries (*6*). One group has a soft component characteristic of an accretion disk and is accompanied by a hard tail; the other group has a spectrum approximated by a single power law. The blackbody component expected from the neutron star surface is absent in both types of spectra. Optical observations of binary orbital motions allow us to estimate the mass of the compact object. For five of these binaries (Cygnus X-1 is a well-known example) for which such optical observations were made, the lower limit to the mass was found to exceed three solar masses. According to standard theory, a neutron star with a mass greater than three solar masses is unstable and collapses into a black hole, so the compact objects in these systems are most probably black holes. Even if optical measurements, and hence mass estimates, are not available, sources with similar x-ray spectra are also considered to be good candidates for black holes because of the unique spectral forms.

For some unknown reason, most of the candidate black hole binaries are transients. The records of previous observations and observations from Ginga, GRANAT, and CGRO indicate an occurrence rate for such transients of roughly one per year. These statistics lead to an estimate of more than several hundred black hole binaries in our galaxy (*6*).

Interestingly, the Ginga results show that there are striking similarities in the behavior of galactic black hole binaries and AGNs (*6*). Both systems exhibit rapid intensity fluctuations. This leads us to suspect that the fundamental physical processes are common to both systems, despite the difference of many orders of magnitude in the system scale and mass. However, the nature of such processes is not well understood at present. Multiwavelength studies of AGNs from radio waves through gamma rays are considered crucial for a better understanding of AGNs.

A supernova is a violent outburst of a massive star at the end of its evolution. Three weeks after Ginga was launched, a supernova (SN 1987A) occurred in the Large Magellanic Cloud. It did not emit x-rays at first, but after 5 months, Ginga and the Russian Mir-Kvant instrument detected x-rays from the radioactive decay of ^{56}Ni, synthesized during the supernova explosion and emerging from the expanding debris (*7*, *8*). Five weeks after ASCA was launched, a supernova (SN 1993J) occurred in M81 (a nearby galaxy about 10 million light years away). This supernova emitted intense x-rays, which ROSAT and ASCA detected (Fig. 1) (*9*, *10*). This was the first time that x-rays were observed from a supernova so soon (within 10 days) after outburst. The spectrum obtained by ASCA indicated that the temperature of the shock-heated plasma was initially greater than 10^8 K.

More than a hundred galactic supernova remnants (SNR) are known, and many are strong x-ray emitters. The best known is the Crab Nebula (SN 1054), which emits synchrotron radiation from radio through gamma rays generated by the neutron star. However, synchrotron nebulae are rather rare, and most SNRs emit thermal radiation from shock-heated plasmas. X-ray spectroscopy of SNRs, combined with detailed plasma diagnostics, enable us to study chemical abundances and dynamics of SNRs. This information is very important because all elements heavier than helium in the galaxy were synthesized in the interior of stars and spread over the interstellar space by supernovae. Spectra of SNR of unprecedented quality are being obtained with the ASCA x-ray CCD cameras, as the spectrum of the SNR W49B shows (Fig. 2). Individual characteristic lines from various elements up to iron are clearly resolved. A major advance in SNR physics is expected.

The interstellar space of our galaxy is complex. Most interstellar matter is in a cool phase, consisting of 100 K atomic hydrogen clouds and even colder molecular clouds and dust. However, x-ray observations have revealed that a large fraction of interstellar space is occupied by hot plasma at millions to tens of millions of kelvins. In fact, the solar system is within a huge volume filled with a tenuous 10^6 K plasma. The Ginga survey of the galactic plane showed that there exist regions that are much hotter, around several 10^7 K as characterized by emission lines from highly ionized iron, which are distributed all along the galactic plane (*11*). The origin of these hot plasmas is yet unknown. If they were of supernova origin, it would require a supernova rate of one in 10 years, 10 times higher than currently believed.

In addition, there is a strong peak of emission toward the galactic center (*11*). The amount of plasma responsible for this peak corresponds to thousands of supernovae. The center of our galaxy is not a bright x-ray source. Yet, this huge amount of hot plasma may indicate intermittent activity in the galactic nucleus. There is other observational evidence for a large mass concentration at the galactic center, suggestive of a massive black hole. Observations with ASCA have also revealed x-ray luminous nuclei in several spiral galaxies like ours (the nucleus of M81 in Fig. 1 is an example), indicating an activity similar to that in AGNs even in normal galaxies. These nuclei are less luminous than the previously known AGNs and hence may be called "mini AGNs."

ASCA is the first x-ray observatory able to provide spatially resolved spectra of the hot gas in clusters of galaxies. The results of such studies are important as they have significant implications for the cosmological evolution and the problem of dark matter which determines the gravitational potential of clusters of galaxies. Investigations of clusters of galaxies with ASCA have just started, and we anticipate significant advances.

Finally, the origin of the intense cosmic x-ray background (CXB), whose existence has been known since the birth of x-ray astronomy, is an important but still unresolved issue. As the sensitivity of observations has improved, the CXB has been increasingly resolved into discrete sources. The ROSAT deep survey has resolved more than 70% of the CXB below 2 keV into discrete sources, of which the majority are found to be AGNs, but there remains the puzzling "spectral paradox": The CXB has a slope (the exponent of a power law) of –1.4 in the photon number spectrum, whereas most AGNs have softer spectra, with an average slope of –1.7. Known AGNs therefore cannot account for the entire CXB, and a significant fraction of the CXB must be due to galaxies with flatter (harder) spectrum in order to account for the CXB spectrum. Capable of determining the spectral shape with its wide-band coverage, ASCA will be able to find the yet unidentified contributors to the CXB.

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The Case of the Blue Stragglers

Charles Bailyn

Globular star clusters, dense aggregations of up to a million stars, have long been a favorite target for observers. Seen through a modest telescope, they provide a spectacular visual display for amateur astronomers. For professionals, the opportunities provided by a homogeneous group of stars of the same age, distance, and chemical composition are no less enticing. Recent observations by the Hubble Space Telescope (HST) of the dense cores of globular clusters have revealed a variety of exotic stars, hotter and bluer than the typical cluster stars.

Globular clusters provide crucial observational tests of theories of stellar evolution. Theoretical models that predict the properties of a population of stars of uniform age, distance, and chemical composition can be compared with the observations. Such a comparison not only tests the stellar models, but also provides estimates for the physical parameters of the cluster as a whole. In addition, the clusters are almost perfect manifestations of the classic "gravitational *N*-body problem," in which one wishes to solve the equations of motion for a large collection of objects interacting solely through gravity.

The advent of large computers and efficient programs has led to great progress in the *N*-body problem (*1*). Numerical studies show that the density of stars at the core of a globular cluster increases with time, leading in principle to a central "cusp" of infinite density. Such an endpoint is clearly unphysical, and when the core density becomes high, close encounters between stars and binary star systems begin to radically alter the stellar velocity distribution. Energy can be added to the motions of stars in the core, halting core collapse in much the same way that the initiation of nuclear fusion prevents the collapse of the gas in the center of an individual star. These collisions and near collisions control the overall evolution of the cluster but may also do drastic damage to individual stars and may provide an explanation for the existence of certain stars whose presence in globular clusters has long baffled students of stellar evolution.

It is almost impossible to observe individual stars in globular cluster cores from ground-based telescopes. The Earth's atmosphere blurs the stellar images, combining the light from hundreds of stars into a single fuzzy blob. The HST was expected to revolutionize studies of cluster cores by resolving the fuzzy blurs into hundreds of individual points, but the problem with the HST primary mirror set back these hopes; the malformed mirror spreads the light from a single star over a large area, just as the atmosphere does. But there is a crucial difference between images blurred by the atmosphere and those blurred by the HST mirror. The HST images concentrate about 15% of the starlight into a central "spike" of light. By studying this central spike and ignoring the remaining 85% of the light, astronomers have been able to distinguish the individual stars in the centers of several globular clusters despite the HST's optical flaw.

There are limitations to what can be done with HST. Accurate measurements of the brightness of the stars are impossible because the fraction of light in the central spike varies with time, the position of the star within the image, and the wavelength of the light in ways that are difficult to calibrate. Exposure times have to be increased because only 15% of the light is being used: Faint stars are often lost in the blur from their brighter neighbors and cannot be measured at all. Nevertheless, the positions and approximate fluxes of stars in crowded cluster cores can be determined with HST far better than has ever been done from the ground.

The advantages of HST are particularly acute for blue stars because it can observe ultraviolet (UV) photons, which are blocked by the Earth's atmosphere. In the UV, blue stars stand out against the background of generally red globular-cluster stars, which obliterate them in images at optical wavelengths. Standard models of stellar evolution predict that there should be no blue stars in globular clusters; as in all old stellar systems, the blue (brighter and more massive) stars should long ago have evolved through the red giant stage and then died. The only blue stars expected in globular clusters are exotic objects created by stellar collisions and interactions. The HST is therefore particularly well suited to identify stars that have undergone such cataclysms. In particular, HST has broken new ground in the study of two kinds of blue cluster stars: blue stragglers and x-ray–emitting binary systems.

Blue stragglers have been a thorn in the side of students of stellar evolution since

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