INVITED DISCOURSES

https://doi.org/10.1017/S1539299600010327 Published online by Cambridge University Press

Recent Advances in X-Ray Astronomy

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1 Introduction

X-ray astronomy was born in June 1962 with a totally unexpected discovery of a bright X-ray source (presently known as Sco X-1) in a historic rocket flight conducted by Riccardo Giacconi, Herb Gursky, Frank Paolini and late Bruno Rossi. In the last 30 years, astronomy through the newly opened window has made a dramatic expansion.

The universe contains enormously rich varieties which had been left unexplored until recent times. From 40's through 60's, new wavelength windows, radio, infrared and X-rays successively opened. As a result, the presence of objects and regions distributed over an extremely wide temperature range from a few Kelvin through hundreds of millions of Kelvin were discovered. A burst of surprising discoveries made in 60's marked the opening of a whole new era of multi-wavelength astronomy.

Of these varieties, X-ray observations selectively find objects of millions to hundreds of millions Kelvin, and also the places where non-thermal, often relativistic processes are taking place. This is unique to X-ray astronomy.

In this talk, I shall attempt to highlight some selected topics with my own bias from the advances made in the last several years, in order to illustrate the richness and uniqueness of information available in this particular wavelength range. I shall not cover the gamma-ray regime above 100 keV which has its own right for a separate review. I also apologise that I admittedly omit references and names of people who deserve credit.

X-ray astronomy has developed with rapid advances of space technology as well as laboratory X-ray technology. Every field of astronomy is constructed on the basis of four different kinds of measurement: photometry imagery, spectroscopy and polarimetry. As in other wavelength bands, X-ray astronomy has first developed with photometry: measurements of broad-band flux and its time variations with low spectroscopic resolution. The first X-ray satellite *UHURU* of this kind made an epoch-making jump in the history of X-ray astronomy. The *UHURU* catalogue contains about

I. Appenzeller (ed.), Highlights of Astronomy, Vol. 10, 3–16.

200 galactic and extragalactic X-ray sources. The later satellites with improved capabilities such as *SAS-3, HEAO-1, EXOSAT, Ginga*, and soon to be launched *XTE* are of this kind.

Imagery came next. Utilization of focusing X-ray optics improves not only the accuracy of source positions but also the sensitivity by orders of magnitude. *The Einstein Observatory* launched in 1978 dramatically opened a new X-ray horizon. *ROSAT* launched in 1990 has further explored the X-ray sky with a higher sensitivity. As shown in Fig. 1, the *ROSAT* all sky survey has enormously expanded the catalogue with some 60,000 X-ray sources, compared to the previous number of 840 in the *HEAO-1* catalogue. *AXAF* is anticipated to make another major step by achieving sub-arcsecond resolution.

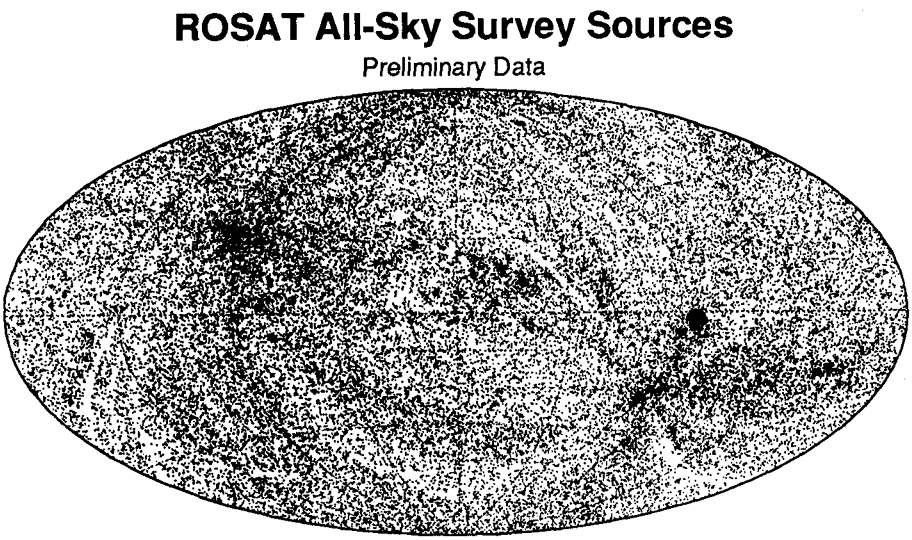

Fig. 1. The *ROSAT* all-sky X-ray sources in the band 0.1-2.4 keV.

Spectroscopy is the third to come. While some precursory attempts have been made, the first marked progress in X-ray spectroscopy is currently being made with *ASCA*. X-ray spectroscopy with still higher resolution of *XMM* and *Astro-E* is expected to make another jump towards the end of this century. Polarimetry in X-ray astronomy is yet to come.

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2 X-ray binaries

The brightest objects in the X-ray sky are accreting neutron stars and black holes in close binaries. More than 200 X-ray binaries containing either a neutron star or a black hole have been found in our galaxy. In the early days, these objects with luminosities of 10^{37-38} erg/s, emitting most of the energy in the X-ray band, were enigmatic. Owing to many pioneering studies, we know that mass accretion onto a compact object in a binary system is the answer. This mechanism allows to liberate a large amount of gravitational energy.

Although the neutron star masses have been best determined for some binary radio pulsars to a high degree of accuracy, many other important properties of neutron stars can be studied from various phenomena that mass accretion manifests in X-ray binaries. As a result, our understanding of neutron stars has much advanced.

At present, there is little doubt that black holes exist in some X-ray binaries. As listed in Table 1, we have six X-ray binaries of which the mass lower limits of the compact objects estimated from the optically-determined mass functions exceed $3M_\odot$, a firm upper limit for a stable neutron star. In addition, there are about twenty good black hole candidates, most of which are transients. Current statistics indicate that there exist more than several hundred binaries involving a black hole in our galaxy.

Table 1. Black-hole binaries established from mass functions.

Source	Cyg X-1	LMC X-3	LMC X-1	A0620-00 V616 Mon	GS2023+33 V404 Cyg	GS1124-68 Nova Mus
Transient	No	No	No	Yes	Yes	Yes
D(kpc)	2.5	55	55	0.9	~ 3.5	~ 3
Period(d)	5.6	1.7	4.2(?)	0.32	6.47	0.43
Companion	O9.7Iab	B3V	O7-9III(?)	K5V	G9V/K0III	K0V-K4V
$f(M)(M_\odot)$	0.25	2.3	0.14(?)	2.91	6.26	3.1
BH Mass($M_\odot$)	$\sim 16(>7)$	>7	~ 6(?)	>7.3	8-12	~ 6

There still remain many problems and puzzles about X-ray binaries. However, I will not discuss X-ray binaries further, since these problems are being discussed comprehensively in the IAU Symposium 165 organized by

Ed van den Heuvel. I will pick up two main subjects here: (a) extended hot plasmas of various scales, i.e., supernova remnants, hot plasmas in galaxies and clusters of galaxies, and (b) active galactic nuclei.

3 Supernovae and supernova remnants

X-ray observations of supernovae provide direct information on the shock heating by the collision of the expanding ejecta with pre-existing circumstellar matter due to a stellar wind from the progenitor. For instance, *ROSAT* and *ASCA* observed SN1993J in M81 within a week after the outburst, and detected intense X-rays. In contrast, in the case of SN1987A, *Ginga* did not see an initial X-ray outburst, clearly indicating devoid of circumstellar gas near the progenitor star. This was because the progenitor was a blue supergiant which produced a fast, low-density wind. However, in the near future, still expanding ejecta of SN1987A is expected to hit a dense circumstellar zone produced by a slow wind during the red supergiant phase of the progenitor. By that time, a bright X-ray outburst will be seen.

Concerning supernova remnants (SNRs), some hundred new SNRs were discovered in the*ROSAT* all sky survey, more than twice the SNRs seen in X-rays before. New results are obtained from detailed morphological studies of individual SNRs. For example, a very interesting features are found in the Vela SNR with *ROSAT* (Fig. 2), which is interpreted as the supersonic wakes due to protruding pieces of ejecta.

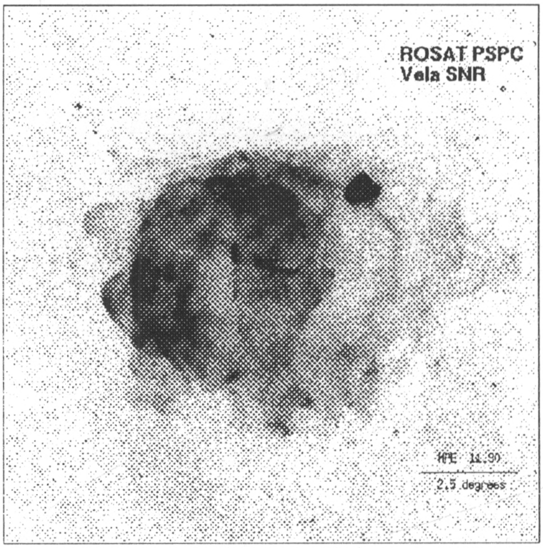

Fig. 2. X-ray image of the Vela SNR taken with *ROSAT*.

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Supernova remnants are among the best objects for X-ray spectroscopy. *ASCA*, the first X-ray satellite that combines imaging with spectroscopy, can individually resolve all major lines up to the K-lines of iron and nickel. For an example, the spectrum of a young supernova remnant, W49B, is shown in Fig. 3. The K-emission lines from Si through Fe (from helium-like as well as hydrogen-like ions) are clearly resolved. An energy spectrum of this quality allows good plasma diagnostics. This remnant has a rather rare center-filled X-ray morphology as opposed to a more common shell-type morphology (although these shells are often deformed and inhomogeneous). Separate images produced with the line photons of different elements (Si, S, and Fe) clearly show that the Fe line dominates inside, and the lines of Si and S form an outer shell. This result may be interpreted to reflect a stratified elemental distribution inside the progenitor star of a type II supernova.

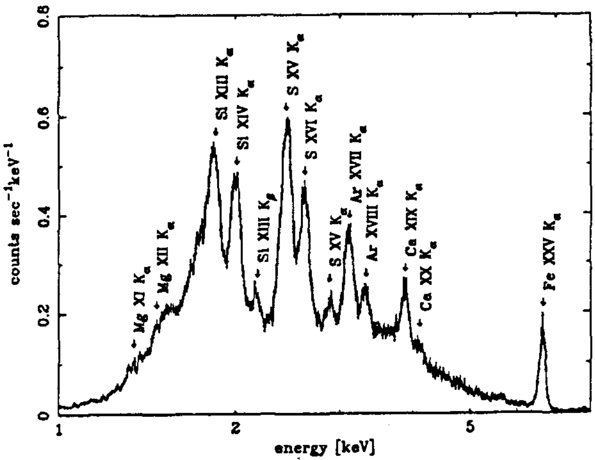

Fig. 3. X-ray spectrum of the SNR W49B measured with *ASCA*.

Several young SNRs of age ~1000 years in the LMC and SMC have been observed by Jack Hughes, Katsuji Koyama and their collaborators with *ASCA*. The distinction between type Ia and type II SNRs is pretty clear with respect to the line intensities of Si through Fe relative to those of O, Ne and Mg.

The spectra in the upper panel in Fig. 4 show prominent K-lines of Si through Ca and an intense L-line complex of Fe. These elements are the dominant products of type Ia supernovae. Whereas, the spectra in the lower panel show that the lines of Si through Fe are less intense, and O, Ne and Mg lines are clearly visible. This is consistent with what is expected for type II supernovae which are the core collapse of massive stars. These stars produce large amount of O, Ne and Mg which will be ejected during the explosion.

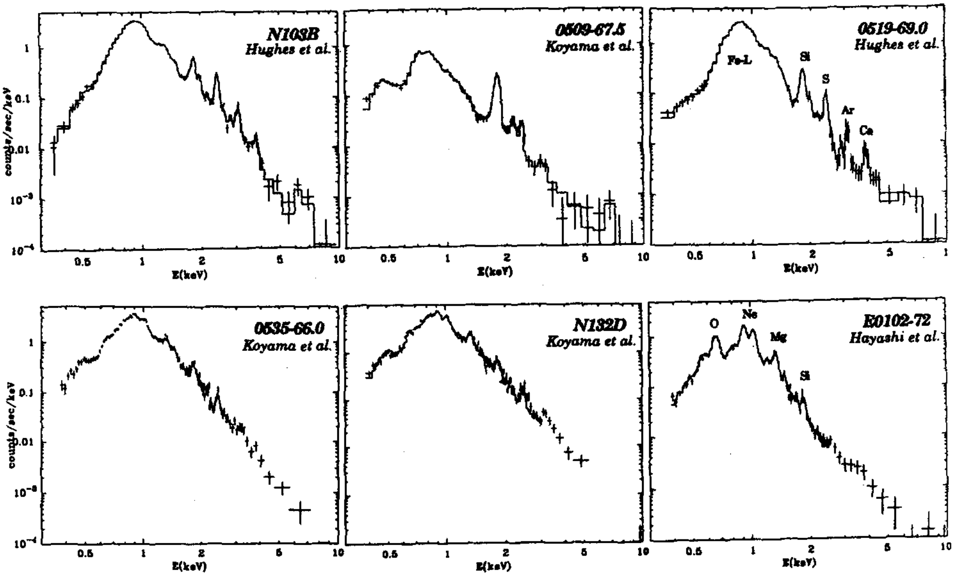

Fig. 4. X-ray spectra of young SNRs in the LMC and SMC.

4 Normal galaxies

A great amount of work has been made on normal galaxies with *the Einstein Observatory* (among the pioneers are Peppi Fabbiano, Ginevra Trinchieri, Bill forman, Claude Canizares et al.). From these X-ray studies, many galaxies, in particular the star-burst galaxies and elliptical galaxies, are known to have hot interstellar medium and an extended halo such as seen in the *ROSAT* image of the star-burst galaxy NGC253 (Fig. 5). Our galaxy also contains hot plasmas of 30 million to 100 million Kelvin, somewhat extended (scale height of a few degrees) out of the galactic plane as seen from *HEAO-1, Tenma, and Ginga.*

The elemental abundances of the plasma of these galaxies are of particular interest in relation to the galaxy evolution. This is also important for understanding the heavy elements in the plasma of clusters of galaxies, since heavy elements in clusters of galaxies are considered to be supplied predominantly by elliptical galaxies. Direct abundance measurement has become possible for the first time by spectroscopic observations with *ASCA.*

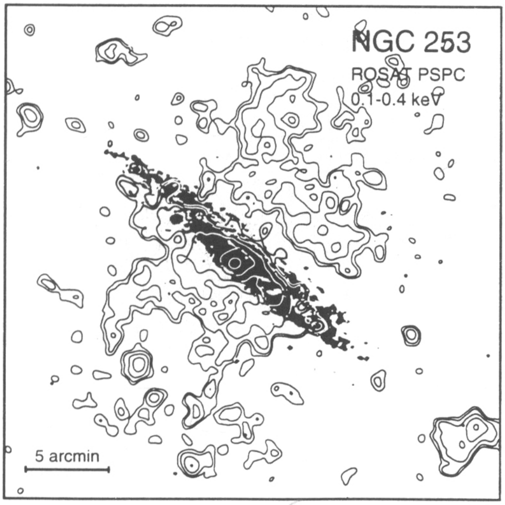

Fig. 5. *ROSAT* X-ray contour map of NGC253 on the optical image.

Three nearby bright ellipticals, NGC4472, NGC4406, and NGC4636, show a similar thermal spectra with temperatures ~8 million K. These spectra are somewhat reminiscent of type Ia supernova remnants in that the Si, and S lines as well as the Fe L-complex are prominent but the O, Ne and Mg lines are insignificant. Probably, type Ia supernovae are the main origin of the metallic elements in these ellipticals. On the other hand, their abundances in these ellipticals are only about one third the solar abundances. Particularly, the abundance of iron could hardly exceed half the solar abundance, though somewhat dependent on the plasma model used. This is in contradiction to a high iron abundance predicted from optical studies. This fact will have an important implication regarding the iron abundance of the hot plasma in clusters of galaxies.

5 Clusters of galaxies

Much attention has been focused recently on clusters of galaxies in relation to cosmology, as they are the tracers of large-scale sturctures in the universe. Systematic X-ray study of clusters of galaxies started with *the Einstein Observatory* (involving many people, among others Bill Forman, Christine Jones, and Craig Sarazin). As a result, the common presence of a large amount of hot plasma was established. In rich clusters, the mass of the intracluster plasma dominates that of the galaxies. Direct observations of such a hot plasma is only possible through the X-ray window.

The intracluster plasma temperature spans the range from ~10 million to 100 million K, and is strongly correlated positively with luminosity. Recent spectroscopic measurements provide us with accurate plasma temperatures of many more clusters than previously available. The X-ray surface brightness and temperature distribution of the plasma allow estimates of plasma mass and the total gravitaitonal mass of which the largest is so-called dark matter. These estimates yield the baryonic mass fraction which is a crucial quantity for cosmology. Dark matter concentration in clusters also causes gravitational lensing. Clusters of galaxies display a rapid evolution even in the redshift range $z < 0.3$. Also, morphological studies in X-rays reveal various substructures and mergers.

Following a major step with *the Einstein Observatory*, the next big progress is currently being made with *ROSAT*. The *ROSAT* all sky survey has provided a complete sample of clusters, containing ~5000 clusters over a distance range to z~0.5. Based on this cluster sample, systematic studies are in progress.

The iron K-line is commonly found in the spectrum of the intracluster plasma. Since iron is most probably a supernova product, the iron abundance is a good indicator of the activities of the member galaxies. In most clusters, the iron abundance determined from the observed K-line is approximately 0.3 solar, with little dependence on luminosity. A problem is that, as mentioned earlier, the observed iron abundance of ellipticals which are the main donors of iron is about 0.3 solar. Since primordial matter must be dominating the intracluster medium, this falls too short to explain the observed iron abundance. It might suggest that the rate of type Ia SN was much higher in an early phase of galaxy formation.

Another topic is an attempt to determine the Hubble constant from radio and X-ray observations of clusters. Intracluster plasma causes a "microwave decrement" of the 3K background radiation as a result of inverse Compton scattering of the 3K blackbody photons with hot electrons. This is known as Sunyaev-Zeldovich effect. The microwave decrement is proportional to the Compton depth times the electron temperature of intracluster plasma. X-ray data give the angular diameter, the electron temperature and density. The radio and X-ray data, combined with the cluster redshift, yield the Hubble constant. This method is straightforward, and needs not climb the "distance ladder". A caveat, however, is that the three-dimensional density and thermal structure must be known for this method to give the right answer. Non-sphericity will cause an error. Therefore, enough samples are required to obtain a reliable average. So far, the Hubble constant has been estimated with this method for three clusters (A665, A2218 and CL0016+16). Interestingly, all three give the values around 50 km/s.Mpc. Ovbiously, more samples are needed, and will become available in the near future.

6 Active galactic nuclei (AGNs)

6.1 Low-luminosity AGNs

Active galactic nuclei are the most energetic objects in the universe. Typically, they show a fairly flat power-law spectrum in the X-ray range above 2 keV with a slope of ~ -0.7, often extending to 100 keV and beyond. Therefore, most of the radiated energy falls in the X-ray and gamma-ray bands. The observations from *the Einstein Observatory* achieved a tremendous advance in the study of AGNs. Following this success, *ROSAT* is making a further big step forward. According to the *ROSAT* all sky survey data containing more than 25,000 AGNs, AGNs comprise the largest population among X-ray sources in the sky. Instead of reviewing the previous results, I shall pick up some recent results on two topics here.

The first topic is low-luminosity AGNs. *The Einstein Observatory* and *ROSAT* have observed a number of normal galaxies. It was noticed that some of them have an X-ray luminous galactic center in the luminosity range 10^{40-41} erg/s, which were suspected to be low-luminosity AGNs (eg. from time variations). Recent *ASCA* observations over a wider energy range 0.5-10 keV find that they often show a featureless power-law spectrum characteristic of AGNs. The center of M81, a nearby spiral galaxy, known to show the optical properties of Seyfert 1 (Fillipenko & Sargent) is a good example. Except for their lower luminosities, other properties are essentially the same as those of Seyfert 1 galaxies.

6.2 The center of our galaxy

With respect to the activities of galactic nucleus, our galactic center has also drawn much attention in connection with suspected presence of a massive black hole. The galactic center region is very complex as revealed from the radio and infrared observations.

Following the previous result from *the Einstein Observatory*, recent observations with *ROSAT* below 2.5 keV resolved several weak sources within 10 arcmin of the galactic center, one of which is found within 10″ coincident with Sgr A* (Predehl & Trümper).

One the other hand, the recent *ASCA* observation revealed that this region shows a remarkably different picture at higher energy range 2 - 10 keV, where diffuse emission dominates (Fig. 6). A central oval-shaped region of 4 $\sim$ 6 pc across is distinctly bright, the brightest part of wihich forms a narrow ridge appearing like a jet. The X-ray emitting region extends along the galactic plane as far as 70 pc on both sides of the cnter, but at much reduced brightness. The structure of the X-ray emitting region is found to be strikingly well correlated with that of the radio continuum image. A distinct radio shell of Sgr A encircles the oval-shaped X-ray bright region. Also, the outer boundary of the enhanced X-ray emission coincides with that of the radio emission. A prominent radio feature in the north-east, called Radio Arc, is apparently not associated with X-ray features, however.

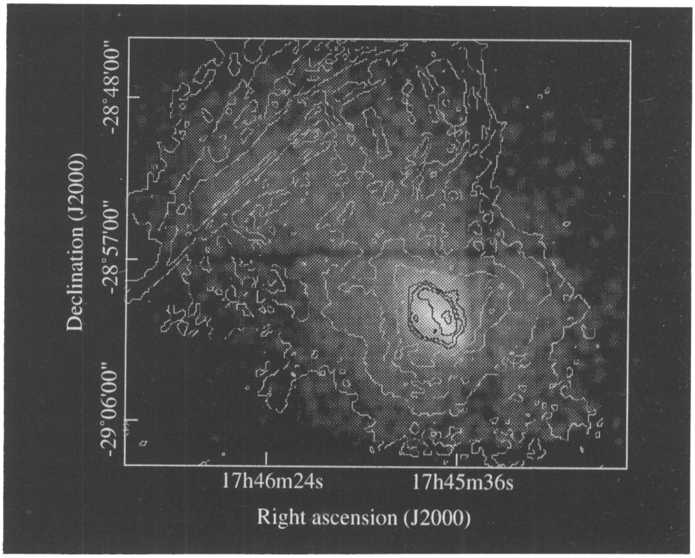

Fig. 6. X-ray image of the galactic center region in 2-10 keV (*ASCA*), overlaid with the radio contour.

The observed X-ray spectra of the Sgr A region and of the surrounding fields exhibit a number of emission lines from highly-ionized ions of various elements, characteristic of thermal emission from hot plasma of $\sim$10 keV (Fig. 7). Remarkabley, the shape of the spectra at different places are strikingly similar to each other, except for different amounts of low-energy absorption. This would be hard to explain if the extended plasma were an integral of individual SNRs along the plane. This might suggest the same origin for the whole plasma: possibly the galactic center.

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The spectra in some regions show a strong 6.4-keV iron k-emission line, most probably the fluorescent line from neutral iron atoms. One of the regions coincides with a dense molecular cloud, Sgr B2, which indicates that the cloud is being irradiated by intense X-rays. On the other hand, we do not find strong enough X-ray source(s) in the galactic center region to explain the observed 6.4-keV line.

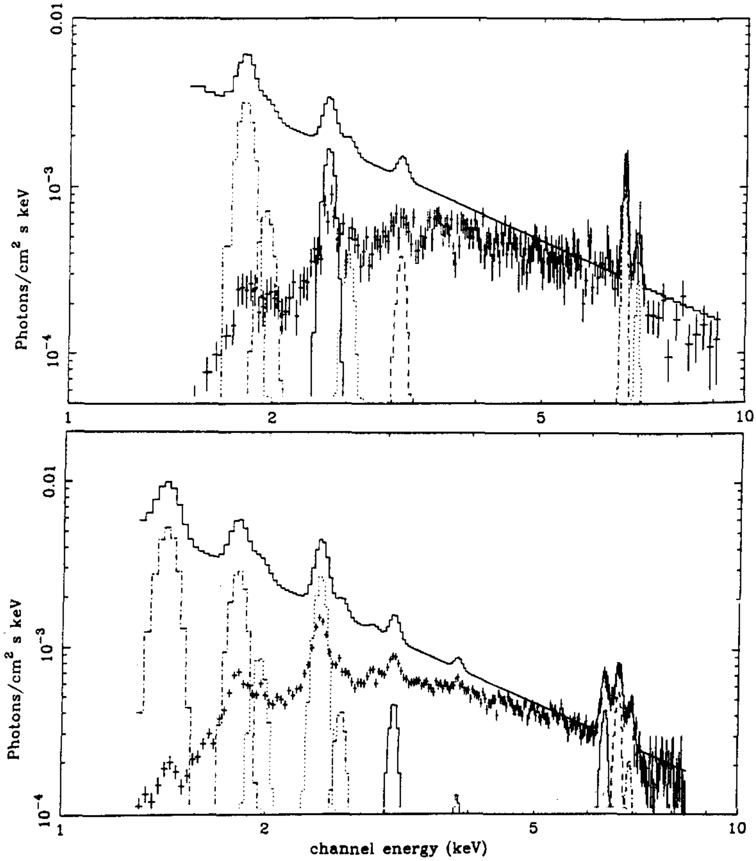

Fig. 7. X-ray spectra inside (top) and outside Sgr A (bottom), together with the best-fit models after correction for absorption.

These facts make us speculate the presence of a hidden X-ray source in the galactic center, or that the galactic center was much brighter in the recent past. In this connection, it is interesting to note that the spectrum of a bright Seyfert 2 galaxy, NGC1068, shows a similar thermal component to that observed here (see Fig. 9). Anyway, the whole X-ray feature is probably related to the activity of our galactic center.

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6.3 Seyfert 2 type AGNs

Another topic concerns Seyfert 2 galaxies. The distinction of Seyfert 2 from Seyfert 1 is the absence of a broad emission line region (BLR). This is interpreted as due to heavy obscuration of the central nucleus by a thick material (e.g., torus). A unified model (brought forward by Antonucci and others) explains the difference between Seyfert 1s and Seyfert 2s as due to different orientation of the torus with respect to the line of sight. In support of this model, the previous observations from *Ginga* show that many Seyfert 2s have a power-law continuum similar to Seyfert 1s but their low-energy X-rays are indeed heavily absorbed. An iron K-line with a large equivalent width (several hundred eV and above), often 6.4 keV fluorescent line, is also a common feature of Seyfert 2s.

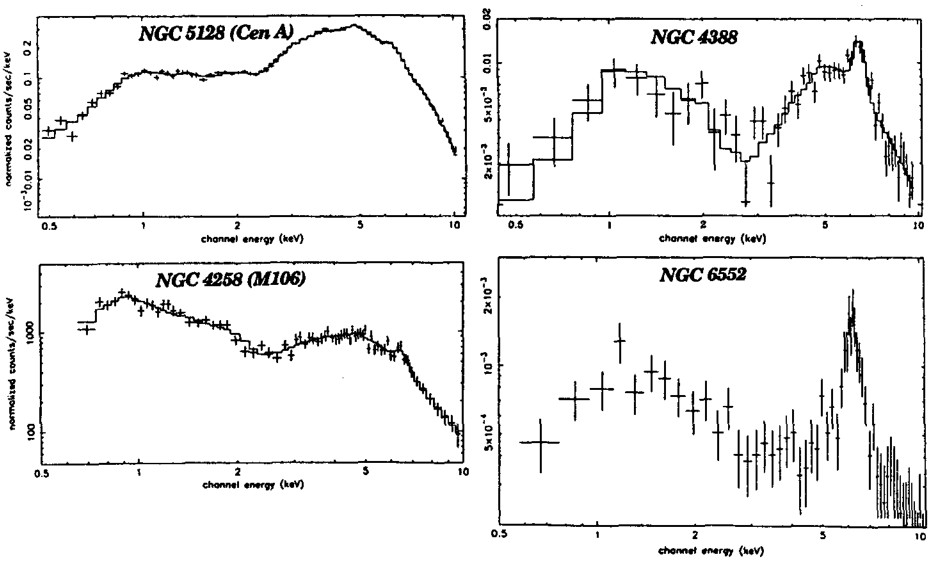

Fig. 8. Spectra of Syfert 2 galaxies showing heavy absorption.

Figure 8 shows such examples obtained with *ASCA* in the order of increasing equivalent width of the iron line. Notice a large equivalent width of the 6.4 keV emission line of NGC6652. These spectra show a hard component with a strong low-energy cut off and a separate soft component. The origin of the soft component is not too clear yet, but for Cen A and

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M106 it comes for a large part from an extended region.

On the other hand, some others apparently do not show heavy absorption, but show intense iron K-lines (Fig. 9). NGC1068 is a good example. These are all infrared-luminous galaxies. These cases can be understood that we observe only those X-rays scattered outside the totally hidden nucleus into the line of sight. A strong fluorescent iron K-line is expected in such a case, which is therefore a good indicator for a hidden nucleus. Soft X-rays from an extended region such as seen in Cen A and M106 may also contribute in the low-energy part of the spectrum.

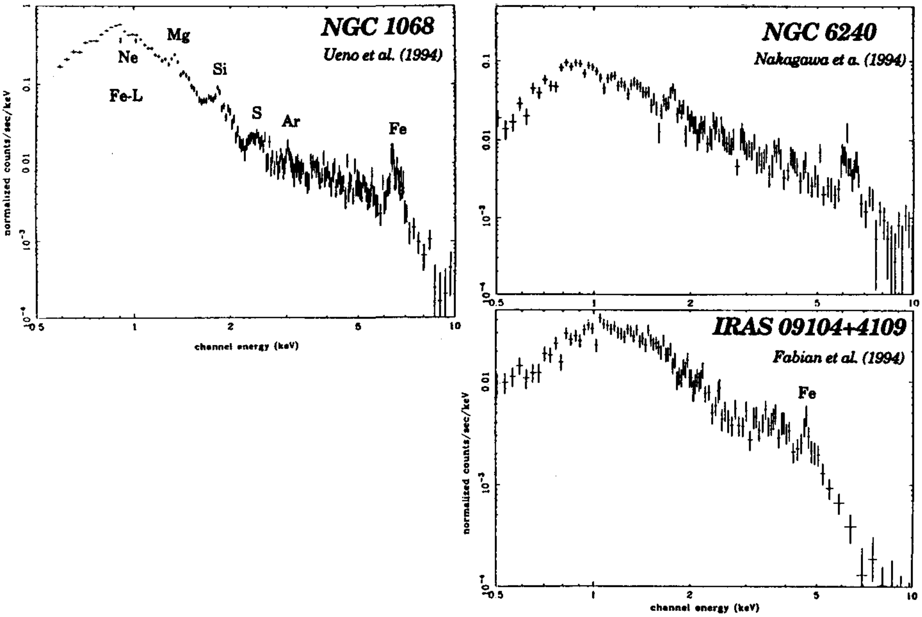

Fig. 9. Spectra of Seyfert 2 galaxies apparently with little absorption.

In those cases where we see scattered X-rays only, the luminosity could be largely underestimated. The recent *ASCA* result on an IRAS galaxy, IRAS 09104+4109 (Fabian et al.), which also exhibits a strong iron K-line suggests that, after correction for obscuration, the intrinsic bolometric luminosity of the hidden nucleus could be well above 10^{47} erg/s which makes it a luminous quasar. There appear to exist many more Seyfert 2 type galaxies which were not previously identified as shuch. Many of the infrared-luminous galaxies may be of this kind.

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7 Cosmic X-ray background

Finally, about the cosmic X-ray background. The presence of a bright X-ray background was known from the beginning of X-ray astronomy. After 30 years, our understanding of the origin of the cosmic X-ray background may have come to the final stage. The *ROSAT* deep survey has resolved at least 75% of the X-ray background into individual galaxies, most of them being AGNs over a wide redshift range. *AXAF* will further resolve it, possibly to practically 100%.

However, there still remains a problem called the "spectral paradox". The spectra of most AGNs so far measured show a single power law with a similar slope (energy index) around an average of ~ -0.7 in the energy range 2 - 20 keV. Whereas, the slope of the cosmic X-ray background is approximately -0.4 below 10 keV and steepens to -1.4 at high energies, showing a break around 20 keV. It is obvious that AGNs with the known "canonical" -0.7 slope alone cannot make up the entire X-ray background. A major portion of the background must come from galaxies having a flatter spectrum with a high-energy break. Yet, those galaxies of which the spectra were measured are limited to bright samples. Hence, the spectral survey of fainter galaxies is very crucial.

We have seen that some AGNs with the obscured nuclei show complex but overall flatter spectra. If these types of AGNs were numerous among faint galaxies, they should be important constituents of the cosmic X-ray background. Systematic study is going on, and we hope that the spectral paradox be solved in the near future.

8 Concluding remark

I have shown some examples to illustrate recent advances in X-ray astronomy. X-ray observations have revealed enormous richness in high-energy phenomena occurring throughout the universe. Yet, because of technical difficulties, the spatial and spectroscopic resolutions in X-ray observations today are still behind those in the radio and optical bands. On the other hand, this means that there is still a lot of room left for X-ray astronomy to grow as technology develops in the future. In fact, we can anticipate another revolutionary advance in X-ray astronomy cross over to the new century with *AXAF*, *XMM* and *Astro-E*.

Finally, there is no need to emphasize that astronomy grows with interactions and cooperations between multi-wavelength bands. Certainly X-ray astronomy is part of it.