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X-ray and infrared properties of normal galaxies

WHY GALAXIES FROM SPACE OBSERVATORIES?

Galaxies are key components of the Universe and have been studied in astrophysics for several different and important reasons. Galaxies trace the distribution of matter and can be used as standard candles to derive information on the expansion and large-scale structure of the Universe. From these results constraints can be set on both cosmology and cosmogony scenarios. Galaxies evolve: they form, their stellar population evolves, they interact and merge. Understanding the forces governing galaxy formation and evolution is paramount for our understanding of the properties of galaxies and their components. Galaxies are where primordial matter gives birth to stars, and where stars evolve and form elements, enriching the interstellar medium (ISM) from whence the next stellar generations will be born. Therefore our understanding of stellar evolution and chemical evolution is intimately connected with our understanding of galaxies and their evolution.

Most of the work on galaxies – be it related to cosmology, galaxy formation and evolution, or present-day galaxy properties – has been supported by ground-based, mostly optical observations. While a lot has been learned this way, the optical window is only a small part of the entire emission spectrum of galaxies, and the information it provides is mostly limited to the normal stellar component, whose emission peaks in the optical wavelengths. Moreover, optical light is significantly absorbed by ambient dust, especially in the blue, where the emission of the massive younger stellar population peaks. The importance of widening the observing window on galaxies is made clear by ground-based radio and near- to mid-IR observations, which have provided a way of penetrating deeper into dusty star-forming regions; have allowed the study of the cold ISM and thus the discovery of extended, dark, massive halos in spiral galaxies; and have revealed the properties of both galaxian magnetic fields and highly energetic particles.

With space observatories, the observing window on galaxies has been opened even further, and a whole new set of phenomena has come into view. The waveband coverage has been extended to the UV (International Ultraviolet Explorer, IUE; Hubble Space Telescope, HST; Extreme UltraViolet Explorer, EUVE), mid- and far-IR (Infrared Astronomical Satellite, IRAS; Infrared Space Observatory, ISO), and X-rays (Einstein; Roentgen Satellite, Rosat; Advanced Satellite for Cosmology and Astrophysics, ASCA; BeppoSAX; Chandra; XMM-Newton). Each of these wavebands has given astronomers the means to explore new aspects of galaxies, including states of extreme star formation and nuclear activity, as well as the different phases of the ISM (cold, warm, hot, gaseous, dusty) and the latest stages of stellar evolution. In this chapter we concentrate on the impact of X-ray and IR space observatories. This is not a complete review of all the work that has been done in these areas, but is meant to give a general feel for these fields as they are today.

A BRIEF HISTORY OF X-RAY OBSERVATIONS OF GALAXIES

The first X-ray satellite, Uhuru, was launched from Kenya in December 1970. It was sensitive to photons in the

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2–10 keV energy range. Uhuru is not an acronym; it means "freedom" in Swahili, and was so named because the day of the launch was the National Holiday of Kenya. Uhuru had been conceived and built by a team of physicists-turned-astronomers, led by Riccardo Giacconi at AS&E in Cambridge, MA. Uhuru led to the discovery of intense X-ray emission from compact stellar remnants (neutron stars, black holes, white dwarfs) in binary systems in the Milky Way, as well as from active galactic nuclei (AGNs; see Chapter 23), and hot plasmas in clusters of galaxies. X-ray emission from sources in the Magellanic Clouds and from M31 was detected with Uhuru, but other normal galaxies escaped detection because their fluxes were below the Uhuru source detection threshold (see Giacconi and Gursky (1974) for a review of Uhuru results).

To be able to detect and study in X-rays a significant number of normal galaxies, we had to wait for the first true X-ray telescope, the Einstein Observatory, also developed by a team led by Giacconi, including groups at the Smithsonian Astrophysical Observatory, Massachusetts Institute of Technology, Goddard Space Flight Center, and Columbia University. Einstein was launched by NASA in 1978 (Giacconi *et al.* 1979). With the Einstein grazing-incidence mirrors, X-rays from celestial objects could be focused onto position-sensitive focal plane detectors. Focusing optics resulted in two very significant advantages: the relatively small beam (~5″ to ~45″, depending on the Einstein focal plane instrument) meant that the background noise in the detection area was much smaller than in any of the previous non-imaging X-ray satellites, resulting in the detection of thousand-fold fainter sources (Figures 1 and 2); and the imaging capability for the first time let us see clearly the morphology of the X-ray sources (Figure 3). These capabilities were crucial for opening up the X-ray window on galaxies. Normal galaxies feature in two papers in the first ever set of Einstein publications. The survey of M31, the Andromeda Galaxy, the large spiral galaxy closest to us, revealed a population of bright point-like sources and gave us for the first time a picture of what our own Milky Way might look like in X-rays to an external observer (Van Speybroeck *et al.* 1979). The peculiar asymmetric extended emission of M86 in the Virgo Cluster suggested the presence of a hot gasous halo interacting with the hot cluster gaseous medium, which had been discovered with Uhuru (Formal *et al.* 1979). The foundations of what we now know about the X-ray emission of galaxies were established with Einstein observations (Fabbiano 1989).

Subsequent X-ray satellites, the Germany–USA Rosat, the Japan–USA ASCA, and the Italy–Netherlands BeppoSAX, have further expanded our knowledge of the X-ray properties of galaxies and widened the observable X-ray window in several ways. Rosat was more sensitive at lower energies than Einstein and had slightly better angular resolution.

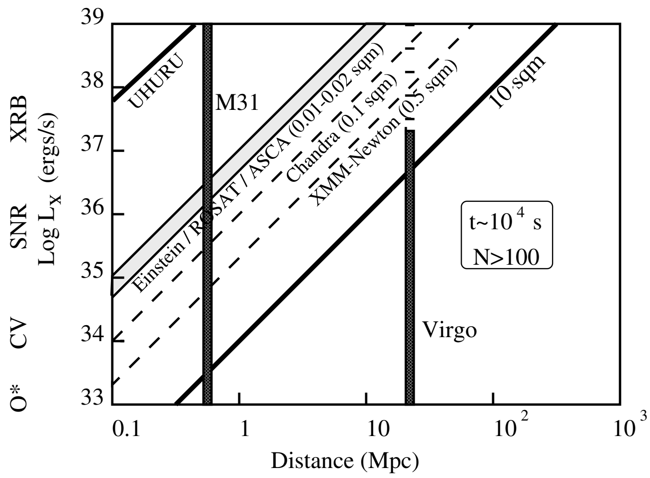

Figure 1 The sensitivity of different X-ray satellites to the detection of 100 counts in 10,000 s observations from typical galactic sources at different distances. For imaging telescopes the collecting area is indicated. Note, however, that unless the telescope has good enough angular resolution (Figure 3) the sources are likely to be confused, and therefore their individual contributions cannot be detected. The *y*-axis gives X-ray luminosities as well as typical X-ray emitters in given luminosity ranges, from luminous O stars to cataclysmic variables (CV), supernova remnants (SNRs) and X-ray binaries (XRBs). The *x*-axis is a distance scale. Two benchmark distances, to M31 and the Virgo Cluster of galaxies, are marked by vertical stripes.

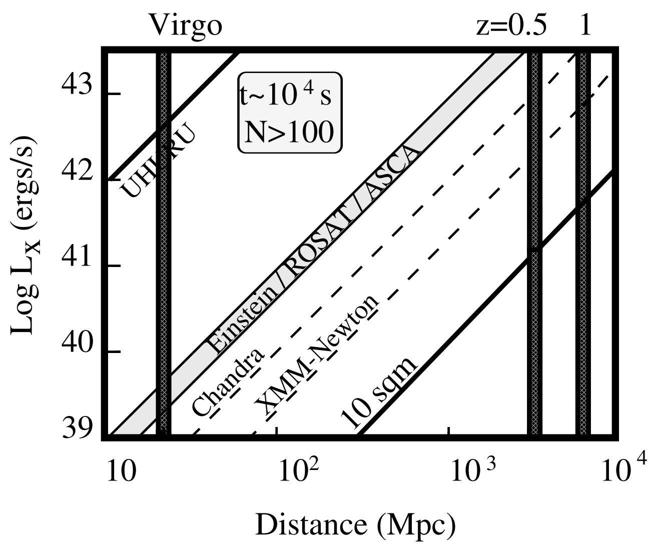

Figure 2 The sensitivity of different X-ray satellites to the detection of global emission from galaxies. Galaxy luminosities are mostly in the 10^{39}–10^{41} erg s^{-1} range, but some E and S0 galaxies can be as luminous as 10^{42}–10^{43} erg s^{-1} (Fabbiano 1989). Note that a significant advance in collecting area (to 10 m^2) will be needed to begin studying normal galaxies at cosmologically relevant distances.

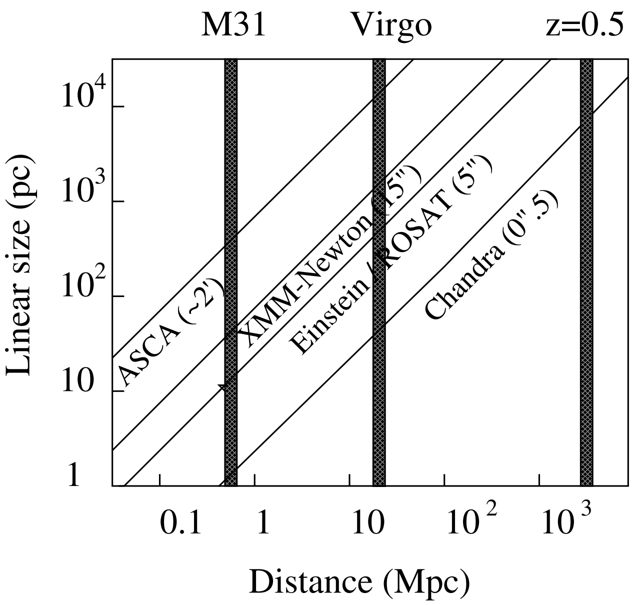

Figure 3 Linear sizes (in parsecs) equivalent to the angular resolution of X-ray telescopes as a function of the galaxy distance. While Chandra's sub-arcsecond resolution is needed to resolve dense stellar regions in M31 (e.g., near the nucleus), Einstein, Rosat, and XMM-Newton can resolve and study most bright X-ray sources. At the distance of the Virgo Cluster, Chandra achieves a linear resolution comparable to that of Einstein and Rosat for M31. The individual source detection sensitivity of previous missions (Einstein and Rosat), as well as that of XMM-Newton, is significantly impaired by confusion within the parent galaxy at the Virgo distance. The angular resolution of ASCA is significantly inferior to that of the other imaging X-ray missions. Note that 10^4 pc – ASCA's linear resolution at Virgo – is a typical galaxy size.

These characteristics have led to a better understanding of the spatial morphology of the X-ray emission of galaxies, and to the detection and study of the soft X-ray-emitting ISM of spiral galaxies. ASCA, was the first X-ray observatory equipped with CCD detectors. These detectors have spectral resolution 5 to 10 times superior than previous instruments, and are able to reveal X-ray emission lines from hot plasmas. Thus for the first time a study of the metal composition of the hot ISM of galaxies could be seriously attempted. ASCA (and BeppoSAX) also extends the observing windows to energies of 10 keV, significantly higher than the 2–4 keV upper reaches of Einstein and Rosat. This allowed the study of different spectral components of the X-ray emission, peaking in different energy ranges. For example, a softer component from a hot ISM and a harder component possibly from a population of X-ray binaries can be detected in the ASCA spectra of elliptical galaxies (Matsushita *et al.* 1994). However, ASCA's angular resolution (Figure 3) is ~2′, significantly inferior to those of Einstein and Rosat, and as a result detailed studies of individual galaxies cannot be pursued in most cases.

We are now at a very exciting time for X-ray astronomy. In July 1999, NASA successfully launched Chandra, the third Great Observatory, following the Hubble Space Telescope and the Compton Gamma Ray Observatory. The European Space Agency (ESA) successfully followed suit with XMM-Newton in December of the same year. Chandra and XMM-Newton represent a complementary quantum leap in sensitivity, imaging capabilities, and spectral resolution compared with the previous generation of X-ray observatories, and both are going to deepen and perhaps revolutionize the way we look at galaxies in X-rays.

X-RAY PROPERTIES OF GALAXIES

Extrapolating from the results of Uhuru and subsequent non-imaging X-ray missions (the UK Ariel 5; the US–Netherlands Astronomical Netherlands Satellite, ANS; and the US SAS 3 and HEAO 1), one could conclude that not much excitement lay ahead in the X-ray observations of galaxies. This was indeed the feeling of a good number of scientists in the Einstein team during the initial discussions of time allocation to different observing programs. It was thought that normal galaxies would emit because of their population of galactic sources, as happens in the Milky Way, and that the X-ray emission would be totally dominated by the nuclear source in the case of AGNs. While this is true, it is only a small part of the story. Twenty years ago, when X-ray astronomers first pointed Einstein at normal galaxies, they were engaged in a very successful fishing expedition. The Einstein survey of normal galaxies led to the discovery of hot ISM in E and S0 galaxies and of hot gaseous outflows from starburst nuclei, and demonstrated how X-ray emission is not an isolated phenomenon to be studied by X-ray astronomers, but is instead closely connected to the global emission properties of galaxies (see reviews by Fabbiano (1989, 1996a) and the Einstein catalog and atlas of galaxies (Fabbiano *et al.* 1992)).

Galaxies are key objects in the study of cosmology, the life cycle of matter, and stellar evolution. X-ray observations have given us a new key band for understanding these building blocks of the Universe, with implications ranging from the the study of extreme physical situations, such as can be found in the proximity of black holes, or near the surface of neutron stars; to the interaction of galaxies and their environment; to the measure of parameters of fundamental cosmological importance. In this chapter we discuss the unique contributions to our understanding of the Universe that are provided by X-ray observations of galaxies.

X-ray binaries and supernova remnants

A review of the Einstein and first Rosat results on discrete X-ray sources in external galaxies can be found in Fabbiano (1995a). Although the sample of detected sources has increased since, the basic conclusions are still valid. X-ray observations of the Milky Way and the Magellanic Clouds demonstrate that the majority of bright, individual X-ray sources are binary systems containing one of the compact remnants of stellar evolution: white dwarfes, neutron stars, or black holes. The X-ray emission is the result of gravitational accretion of the atmosphere of the companion star onto this compact object. Thus, the discrete X-ray source population of galaxies gives us a direct view of the end stages of stellar evolution, and of the higher-mass component of the stellar population. While the study of individual sources is best restricted to the Milky Way, because of the much higher fluxes, external galaxies present unique advantages in the study of the population properties of X-ray sources. All sources within a given galaxy are at the same distance from us, so the study of luminosity distributions is much less prone to error than with X-ray sources in our Galaxy, where the distance uncertainties are large. If fairly face-on galaxies are targeted, the effect of differences in interstellar extinction will also be much smaller than in the Milky Way sample, where directional effects due to the position of the Solar System in the galactic plane affect the measurements.

For the same reasons, systematic studies of properties of supernova remnants (SNRs), that can be used to explore their evolution, are best done with external galaxies. Most SNRs are spectacular, extended, expanding shells of hot plasmas and energetic particles, created by the shock waves of the supernova explosion and the interaction of the stellar debris with the surrounding ISM. An example of a study of a well-defined sample of SNRs, for which the distance is known (or all at the same distance within a galaxy), is the diameter–luminosity relation, which can probe both the age of the remnant and the host ISM (e.g., Long and Helfand 1979).

Because high-quality imaging is needed for these studies, Einstein and Rosat have been the two observatories that have contributed most to this field. Observations of nearby spiral galaxies have revealed variable sources with characteristics similar to those of Milky Way sources. The luminosity distributions appear to vary in different galaxies. A notable but not unique case is that of M81, where the X-ray sources appear brighter than in M31 and the Milky Way (Fabbiano 1995a).

While these studies open exciting new avenues, much more sensitivity and resolving power than has been available so far are required to extend them beyond exploratory exercises. Chandra is already making a difference, as can be seen from the images released to the public, but very long exposures will be needed in most cases. A large-area telescope (~$10\,\mathrm{m}^2$) with Chandra-like resolution will be needed to sample at significant depths the luminosity function of discrete X-ray sources in galaxies at the distance of the Virgo Cluster and beyond (Figures 1 and 3): The potential of these X-ray population studies is great, with implications for the study of the most massive portion of the stellar mass distribution, that can be detected through remnants in luminous X-ray binaries, and for a systematic study of the interplay of SNRs with the ISM in different galaxies.

Super-Eddington sources: Black hole hunting grounds

A surprising and interesting result of imaging observations of nearby galaxies has been the large number of sources detected with luminosities well above the Eddington luminosity for solar-mass ($1M_\odot$) accreting objects (~$10^{38}\,\mathrm{erg\,s^{-1}}$). The Eddington luminosity is the luminosity at which the gravitational pressure of the accreting material is balanced by the radiation pressure, and it represents a natural limit on the power that can be radiated by an accreting object. Given their luminosities, which exceed those of Milky Way sources and sources in M31, these very luminous sources cannot be steadily accreting neutron star binaries. They can be divided into a few categories: nuclear sources; X-ray counterparts of young SNRs; and other unidentified objects. With the exception of the SNR counterparts, and of sources that future higher-resolution observations may reveal as extended complex emission regions, these sources may host intermediate-mass to massive black holes (Fabbiano 1995a, 1998, Makishima *et al*. 2000).

X-ray emission from massive nuclear black holes in nearby galaxies gives us a probe into the accretion mechanisms and has implications for the evolution of AGNs (see Chapter 23). Relatively low-activity AGN and LINER (low-ionization nuclear emission line region) nuclei have been detected as luminous X-ray sources (in the range ~$10^{39}-10^{41}\,\mathrm{erg\,s^{-1}}$) (Fabbiano 1996b). Although these luminosities would be in the super-Eddington regime for a normal X-ray binary, for nuclear sources due to accretion onto massive nuclear back holes, the accretion must be very inefficient. This is certainly the case for the nuclear source in M104, the Sombrero Galaxy (Fabbiano and Juda 1997), where the dynamics of the nuclear area point to a $10^8 M_\odot$ black hole (Kormendy and Richstone 1995). Given this nuclear mass, the X-ray luminosity of the nucleus of the Sombrero Galaxy is ~4×10^{-7} that of the Eddington luminosity.

In M33, a bright and variable nuclear source is also present (e.g., Peres *et al*. 1989), but its nature is more mysterious. It is possible that it may be a super-Eddington accretion binary (Takano *et al*. 1994).

Some at least of the non-nuclear super-Eddington sources may be accretion binaries. Their luminosities

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