Observations of Galaxies with Future X-ray Observatories

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Abstract. Normal galaxies are faint and complex X-ray sources that provide very powerful probes for fundamental astrophysical questions. Examples include: the study of populations of X-ray emitting sources; the study of the entire spectrum of black-hole phenomena; and galaxy formation and evolution in interaction with the surrounding environment. While exciting, all these fields require Chandra sub-arcsecond resolution, and at least comparable spectral capabilities. They also require much large collecting areas. I argue that this is the direction we must plan for future X-ray observatories.

1. Introduction: the X-ray emission of galaxies

Normal galaxies (i.e. those not dominated by an AGN) are relatively faint X-ray sources, in most cases fainter than the detection threshold attainable with non-imaging X-ray observatories. It is therefore not surprising that the study of their X-ray properties became possible only in the late 1970s-early 1980s, after the launch of the \textit{Einstein Observatory}, the first imaging X-ray telescope (Giacconi et al 1979).

Strange as it seems now, at the time there was a fairly widespread misconception that galaxies would be ‘boring’ targets of X-ray observations, giving us information only on the collective emission of Milky-Way-like populations of accreting binaries and SNRs. Fortunately, the data soon proved this wrong.

We now know that X-ray sources in all types of galaxies include not only XRB and SNR (and these are very interesting on their own right as probes into extreme forms of matter), but also a diffuse hot gaseous interstellar medium, either gravitationally bound as in X-ray luminous E galaxies, or in partial outflow or winds, as for example in the starburst galaxy M82. Moreover, observations of galaxies are essential for studying the whole gamut of nuclear emission, extending from QSOs to low-luminosity nuclei. This includes starburst nuclear regions, LINERS and low-luminosity AGN (see reviews, Fabbiano 1989, 1996). With X-ray observations we can probe the physics of these components and their astrophysical implications for galaxy formation and evolution as well as cosmology.

All this knowledge was the result of the \textit{Einstein} observations, followed by the higher angular resolution (but softer energy band) ROSAT, and by the wide-energy-band (but larger-beam) satellites ASCA and BeppoSAX.
Now, with Chandra and XMM-Newton, this field is being pushed to new heights. In what follows, I will summarize the principal scientific themes for which X-ray studies of galaxies are relevant, and I will then point out the implied requirements for future X-ray observatories. Previous papers discussing this type of requirements, which are still valid, are Fabbiano (1990) and Elvis & Fabbiano (1997).

2. Science Themes

Galaxies can be considered test particles tracing the large-scale distribution of matter in the Universe, but they are also complex ‘living’ organisms. They form, they age, they interact and merge, they rejuvenate, they interact with and modify their environment. X-ray observations can provide precious and unique insight into this life-cycle, and into the life-cycle of the galaxian components.

2.1. Populations of X-ray sources: formation and evolution

It is well known that strong X-ray emission may arise from stars in the final stages of their evolution, either from Supernova Remnants (SNR) or from binary systems (XRB) including a white dwarf, a neutron star, or a black hole. Galactic XRBs and SNRs were among the first types of X-ray source discovered in X-rays and have been studied intensely since the Uhuru days (see Giacconi & Gursky 1974). The study of Galactic X-ray sources has provided a wealth of information on these systems and a good understanding of the nature of individual objects, but questions about their population properties, relations to their galaxian environment and stellar populations, and evolution can be answered only by observing a wide range of external galaxies.

While this type of work had been attempted with Einstein and ROSAT for M31 and a few other nearby galaxies (see Fabbiano 1995), it is only with Chandra that this field is starting to blossom. The reason is simple: angular resolution. Chandra’s sub-arcsecond resolution corresponds to physical sizes of \( \sim 70 \) pc at a distance of \( \sim 30 \) Mpc (and \( \sim 35 \) pc at the Virgo Cluster). Given the relative sparse distribution of luminous X-ray sources, in most cases this resolution allows the detection of individual bright X-ray sources at least out to these distances. Moreover, because of the very small Chandra beam, only a few photons are needed for a significant detection. As a result, X-ray luminosity functions (XLF) of galaxian sources have recently been derived with unprecedented sensitivity from Chandra observations. Early results include the XLF of NGC 4697 (Sarazin, Irwin & Bregman 2000) an X-ray-faint elliptical galaxy at a distance of 16 Mpc, where for the first time the XRB population was directly detected. In this XLF, a break near \( 3 \times 10^{38} \) ergs/s was reported and interpreted as the signature of a population of black-hole binaries. In M81, at a distance of 3.5 Mpc, the XLF can be followed down to luminosities of \( \sim 3 \times 10^{37} \) ergs/s, and different distributions are found for bulge and disk sources (Tennant et al 2001). The XLFs of the starburst galaxy M82 and of the merging galaxies NGC 4038/9 (Zezas et al 2001) show significant extensions to very high luminosities, well above those seen in Milky Way sources, suggesting the presence of a short-lived population of very luminous XRBs, possibly associated with black holes of masses surpassing those of Galactic black-hole binaries.
These results are exciting, because they provide a very powerful new tool for studying the population of X-ray sources and from this inferring constraints either on their formation history as it relates to intense star formation episodes in the mother galaxy (e.g. Wu 2001), or on the nature of some of these sources.

However, we must remember that Chandra is a small telescope, so that prohibitive observing times will be needed to obtain XLFs from a large enough sample of galaxies, extending down to luminosities well in the range of normal XRBs. Moreover, while 10 photons make a very significant source, they cannot give us any useful information on the spectral signature of the emission. The latter is needed to identify different types of X-ray sources, and in particular to separate SNRs from XRBs. XMM, with its larger collecting area, will allow a systematic spectral study of the populations of X-ray sources in the very nearby universe, but source confusion (comparable or worse than that of the ROSAT HRI) will be the limiting factor for distances larger than a few megaparsecs.

If we want to continue populations studies in the future, and extend them to a large number of galaxies and to the spectral dimension, we need to consider an X-ray telescope that retains Chandra’s imaging and spectral capabilities, while providing a significantly larger collecting area.

2.2. Small to Humongous Black Holes

Studying Black Holes and the range of phenomena associated with the interaction of matter with Black Holes is certainly an exciting field, and a field to which X-ray observations can give unique contributions. It is generally believed that luminous AGN are the result of accretion onto massive ($\sim 10^7-8 M_\odot$) nuclear black holes, and dynamical evidence now points to the widespread association of such black holes with galaxian bulges (Magorrian et al 1998). At the other end of the spectrum of black hole masses, black holes of a few solar masses have been identified as the compact source in some Galactic XRBs (see Tanaka & Lewin 1995). These two categories of black holes may have different origins (albeit always involving gravitational collapse): the massive nuclear black holes may either be primordial, or be the result of accretion onto a nuclear seed black hole during the lifetime of the host galaxy; the few-solar-mass black holes in XRBs are the likely product of the evolution and final collapse of a star too massive to end up as a neutron star.

But is this the entire spectrum of black hole masses? Are there any intermediate mass black holes (in the $\sim 100 M_\odot$ range)? This type of object had been hypothesized as the accretor in exceptionally luminous sources first discovered in external galaxies with Einstein, and named ‘Super-Eddington sources’, because their X-ray luminosity was well in excess of that of accretion onto a solar-mass neutron star (see Fabbiano 1995). ASCA monitoring revealed spectral and spectral/temporal characteristics reminiscent of black hole Galactic XRBs (e.g. Makishima et al 2000; Kubota et al 2001) in a few of these sources, but for most of them, even with Einstein’s and ROSAT’s 5” resolution, it could not be excluded that the emission arose from extended regions or clumps of more normal sources.

With Chandra, the census of ‘Super-Eddington sources’ is increasing dramatically. These sources have been separated out and detected in large numbers in previously confused bright emission regions associated with intense star for-
formation activity (e.g. in M82, Matsumoto et al 2001, Kaaret et al 2001; the Antennae galaxies, Fabbiano, Zezas & Murray 2001; NGC 253, Weaver, Strickland & Heckman 2001), and what previously appeared as an interesting but relatively rare occurrence is now a widespread phenomenon. Moreover, the luminosities of some of these sources would imply black holes in the $\geq 100 M_\odot$ range if spherical accretion applies. Are these sources really this massive? And if so, how did they form? A single stellar progenitor may require an unrealistically high mass. Could these objects result from direct collapse of massive molecular clouds, or from accretion onto seed black holes in compact star clusters? Or perhaps these sources are not that massive after all and beaming in a fraction of ‘normal’ XRBs could explain their very high luminosities (King et al 2001). Clearly this is an exciting field, that requires follow-up and in-depth study, both from the point of view of deriving ‘deep’ XLFs of galaxies to model different X-ray source populations, and for constraining spectral and time variability signatures.

Other examples, also related to the physics of accretion on black holes, which are now opening up with Chandra, include: (1) the search for the X-ray-faint counterparts of quiescent nuclear massive black holes (e.g. Di Matteo, Carilli & Fabian 2001); (2) the study of circumnuclear regions, and of the interplay between starburst and AGN phenomena (Ogle et al 2000).

These are all examples of requirements for a large area telescope, that otherwise preserves Chandra’s angular resolution. High angular resolution and sensitivity are needed to detect faint sources in crowded regions; collecting power is needed so that spectral and timing data can be obtained and used for constraining emission models.

2.3. Galaxy Formation and Evolution

X-ray observations give us a unique way to explore phenomena occurring during galaxy formation, that are important for the evolution of both galaxies and their surrounding medium.

Besides the populations of luminous X-ray sources discussed in the previous sections, star formation activity in nearby galaxies produces a hot ISM, that in most extreme cases escapes from the parent galaxy with galactic-scale superwinds (e.g. Fabbiano 1988; Lehnert & Heckman 1996). It is not difficult to imagine that if these winds occur in relatively minor local examples of this phenomenon, they must have been much more powerful and widespread at the epoch of the collapse of the primordial pre-galaxian cloud and the ensuing violent formation of early generations of stars. Vestigial evidence of these winds exists in the presence of metals in the intracluster medium, that was revealed by X-ray spectroscopy (e.g. Fukazawa et al 2000). Superwinds are also now being detected with the Keck telescope in the optical spectra of high redshift galaxies (Shapley et al 2000). In addition to star formation, nuclear activity may also trigger superwinds in elliptical galaxies (Ciotti & Ostriker 2001), and galaxy interaction and merging may also be a factor (D’Ercole, Recchi & Ciotti 2000).

Thanks to the results of X-ray observations, the old concept of ‘closed-box’ models for galaxy evolution, where the evolution could be traced only in terms of stellar evolution in a defined volume of space, is not longer viable. More complex ‘feedback’ models and hydrodynamical simulations connecting galaxy and cluster (ambient) evolution are being developed (Cavaliere, Giacconi
& Menci 2000). Since the hot superwinds are the main vector by which energy - and metals - are transferred from galaxies to the surrounding medium, direct X-ray observations provide unique constraints to these models. In particular, detailed spatial/spectral X-ray observations of relatively nearby galaxies can be used as a way to calibrate these simulations. By themselves and in comparison with similarly resolved multiwavelength data, X-ray observations are needed for understanding the detailed and complex astrophysical phenomena affecting all the phases of the ISM, and its interaction with stellar evolution and magnetic fields (e.g. McKee & Ostriker 1977; Cox & Anderson 1982).

A detailed study requires spatial and energy resolution, and collecting power, such that individual features (clouds, superbubbles) of the hot ISM can be mapped both spatially and spectrally. Given that Chandra images of nearby systems reveal typical scales of hundreds of pc for some of these features (Fabiano, Zezas & Murray 2001), a lesser angular resolution would not allow this type of comparisons. As already remarked, however, the number of photons required for a spatial/spectral mapping is above what a reasonably long Chandra observation can provide in most cases, requiring a significantly larger collecting area.

3. The Future: building upon Chandra

In science we should always strive to go forward and to explore new aspects of the observable universe. Because of their sub-arcsecond angular resolution, joined with spectral resolution, Chandra observations are resulting in an impressive leap forward in our understanding of the X-ray properties of galaxies and their components. Moreover, this angular resolution makes possible a direct comparison with optical-UV Hubble data and high resolution radio data, opening up a truly panchromatic understanding of the processes and of the nature of the X-ray sources. Future comparison with SIRTF results will expand this to the IR as well. With Chandra there is definitely the feeling that X-ray astronomy has fully come of age as a way to explore the astrophysical properties of the universe, rather than being an exploratory discipline for a small congress of devotees.

How can we improve on this? We must preserve sub-arcsecond angular resolution, while retaining or improving the spectral resolution and substantially improving the telescope collecting area.

This work was partially supported under NASA contract NAS8-39073 (CXC).

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