Galaxies Surveys with Future X-ray Observatories

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How do we Build Future X-ray Observatories to Study Galaxies?

G. Fabbiano

1Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138, USA

Abstract.
Galaxies are key objects for the study of cosmology, the life cycle of matter, and stellar evolution. X-ray observations have given us a new key window into these building blocks of the Universe, that allows us to investigate their hot gaseous component. While significant advances in our knowledge are expected from Chandra and XMM, there is a number of fundamental questions that require a next generation of X-ray telescopes. These telescopes need to be 10-30 square meter class telescopes, with Chandra-like resolution, and with a suite of instruments allowing spectral imaging at moderate to high resolution.

1 Why Galaxies in X-rays?

Galaxies are key objects for the study of cosmology, the life cycle of matter, and stellar evolution. Insights into the nature and evolution of the Universe have been gained by using galaxies to trace the distribution of matter in large scale structures; mass measurements, whenever feasible, have revealed the presence of Dark Matter; galaxies evolution and intercourse with their environment are responsible for the chemistry of the Universe and ultimately for life. X-ray observations have given us a new key band for understanding these building blocks of the Universe, with implications ranging from 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.

The discrete X-ray source population of galaxies gives us a direct view of the end-stages of stellar evolution. Hot gaseous halos are uniquely visible in X-rays. Their discovery in E and S0 galaxies has given us a new, potentially very powerful, tool for the measurement of Dark Matter in galaxies, as well as for local estimates of $\Omega$. Galaxy ecology - the study of the cycling of enriched materials from galaxies into their environment - is inherently an X-ray subject. Escape velocities from galaxies, when thermalized, are kilovolt X-ray temperatures. The X-ray band is where we can directly witness this phenomenon (e.g in M82; NGC 253; see and refs. therein)(fig 1).
The study of galaxies and their components in the local universe allows us to establish the astrophysics of these phenomena. This knowledge can then be used to understand the properties of galaxies at the epoch of formation and their subsequent evolution, both in the field and in clusters.

2 Requirements for an X-ray Telescope

Fig. 2 summarizes the requirements for an X-ray telescope that will significantly advance our knowledge of galaxies. The purpose of this telescope is two-fold:

1) **Very detailed studies** of the X-ray components of nearby galaxies, to gain the needed deeper astrophysical understanding of their properties. Nearby galaxies offer an unique opportunity for studying complete uniform samples of galaxian X-ray sources (e.g. binaries, SNRs, black hole candidates), all at the same distance, and in a variety of environments. This type of information cannot be obtained for Galactic X-ray sources, given our position in the Galaxy. These population studies will be invaluable for constraining X-ray properties and evolution of different types of sources.

2) **Study of deep X-ray fields**, where galaxies are likely to be a very large component of the source population. Looking back in time, and comparing these
Requirements on an X-ray Observatory

| Collecting Area > 10 sqm |
|--------------------------|
| Galaxies are rather faint. We need the photons! |

| Angular Resolution < 1\(^\circ\) |
|----------------------------------|
| No turning back after Chandra! |

| Large f.o.v. ~ 15\(^\circ\) |
|-----------------------------|
| For efficient observations of nearby galaxies and efficient deep surveys |

| Spectroscopy |
|--------------|
| res. 10-20 multicolor photometry (CCD) |
| res. ~ 1000 spectroscopy |

| Large Bandwidth |
|-----------------|
| needed to study the entire range of X-ray components from hot ISM to active nuclei |

Figure 2: Science driven requirements for a future X-ray telescope

results with the detailed knowledge of the X-ray properties of more nearby objects, we will be able to study galaxy evolution in the X-ray band. We will be able to look at galaxies when substantial outflows were likely to occur and therefore witness the chemical enrichment of the Universe at its most critical time.

I discuss below in more detail three key elements of fig. 2: collecting area, angular resolution, and spectral capabilities.

**Collecting Area** - A collecting area in the 10-30 sq.meters range is needed for both in-depth studies of individual galaxies in the nearby Universe (fig. 3), and for looking back in time (fig. 4).

**Angular Resolution** - Arcsecond or better angular resolution is a must, to avoid confusion in both the study of nearby galaxies, and in the study of deep fields. Chandra images demonstrate the richness of detail one obtains with subarcsec resolution. With Chandra-like angular resolution galaxies can be picked out easily from unresolved stellar-like objects in deep exposures. Fig. 5 shows the deep X-ray count that can be reached with a 25sqm telescope in 100ks. In the deepest decade galaxies will be a major contributor and may even dominate the counts, if there is luminosity evolution in the X-rays, comparable to that observed in the FIR.
Figure 3: Detection limits of sources in galaxies

Figure 4: Detection limits of galaxies as a function of distance
Based on the HDF results (8), high z galaxies may be visible. However, arcsec resolution is needed to avoid confusion at these faint fluxes (4); as demonstrated by recent simulations by G. Hasinger.

Such deep exposures would allow the study of the evolution of galaxies in X-rays, and of the evolution of their stellar binary population as well as of their hot gaseous component. Based on the Madau cosmic SFR, White & Ghosh (12) show that a comparison of the z-dependence of the X-ray and optical luminosity functions is related to the evolution of the X-ray Binary population in galaxies. Moreover, if hot outflows are prominent at early epochs we will have a first hand account of the metal enrichment of the Universe.

**Spectral Capabilities** - Fig 6 illustrates the scope of the spectral work one would like to perform. With X-ray spectroscopy we can determine the physical status of hot plasmas as well as their chemical composition. We can also measure cooler ISM by studying the absorption spectra of background quasars. Spectroscopy goals related to galaxy studies are described in figs. 7 and 8.
Spectroscopy

\[ \lambda/\Delta \lambda \sim 10-20 \]

- CCD multi-band photometry of galaxies and individual sources/components
- spectral components
- emission mechanisms
- elemental abundances (first cut)
- absorption edges
  - cold absorbers < 10^5 K

\[ \lambda/\Delta \lambda = \text{or} > 1000 \]

- high resolution spectroscopy
- slit and gratings
  - non-dispersive
- abundances
- plasma diagnostics
- kynematics
  - e.g. outflows ~300 km/s
- absorption lines
  - warm absorbers ~10^6 K

Spectroscopy needs Angular Resolution
- source complexity
- imaging of dispersed high res. spectra

Figure 6: Spectral Capabilities

Spectroscopy Goals

(10sqm; 10ks observations)

**Local Group to 10 Mpc**

- R=1000 (or greater) spectra of individual bright sources
  (>10^37 ergs/s at 10 Mpc; > 10^35 ergs/s in M31)
- R=10 spectra and colors of fainter sources
  (1" HPD needed to resolve sources)

Study uniform samples of X-ray sources in different environments

- key factors in source evolution
- SS433 double-jet sources out to M51
- binary Doppler shifts (and so masses) in M31
- SNR turbulent velocities in LMC
- spatial/spectral properties of the hot ISM

Figure 7: Spectroscopy Goals in the near Universe
Spectroscopy Goals
(10sqm; 10ks observations)

Out to Coma (100 Mpc)
R=1000 spectra of all galaxies brighter than 10^40 ergs/s
(bright S, large fraction of E and S0)
T, density structure, chemical composition, motions of hot ISM of E, S0
measure masses
Supernova expansion velocities and abundances

Out to 500 Mpc
R=10 spectra of all galaxies brighter than 10^40 ergs/s
z<1 bright E galaxies (>10^42 ergs/s; no evolution)

Figure 8: Spectroscopy Goals at larger distances

How do these requirements compare to the characteristics of planned future X-ray observatories (Constellation X under study by the NASA community, and XEUS under study in Europe) is shown in Figs 9 and 10. While spectra and bandwidth characteristics of these missions under study accomplish our goals in both cases, the other requirements fall below those we need. XEUS has the required large collecting area, while Con-X area is significantly smaller. In both cases angular resolution is significantly sub-Chandra. Based on what Chandra has shown and on the characteristics of the objects we want to study - galaxies are complex objects - a Chandra-like resolution is a must. The field of view is also small in both cases, especially in the case of Con-X.

As we have done in the past, we advocate that the X-ray community consider a large area, Chandra-like resolution mission to push X-ray astronomy from an exploratory discipline to a discipline at a par with the other wavelength astronomies. Both the scientific potential of the studies that can be performed with such a telescope, and more directly the exciting discoveries resulting from Chandra’s high resolution images, support this project.

References
## Future Prospects: Constellation X (NASA)

| Coll. Area   | Ang.Res. | F.o.V. | Spectra | Bandwidth |
|--------------|----------|--------|---------|-----------|
| We need      | >10 sqm  | Chandra <1" | ~15'   | res. 12-20 ~1000 | 0.1 - 10 keV |
| Con. X       | 1.5 sqm  | 15"-5"  | ~2'     | OK        | OK         |

The Con X team has achieved 15" res. and is now moving towards 5"

**Can better resolutions be achieved?**

Recent developments of large f.o.v. multi-pixel calorimeters very exciting for the study of extended complex objects (Blas Cabrera’s group at Stanford).

**Can the collecting area be increased by adding more spacecraft?**

Figure 9: Comparison of our goals with the Constellation X plans

## Future Prospects: XEUS (ESA)

| Coll. Area | Ang.Res. | F.o.V. | Spectra | Bandwidth |
|------------|----------|--------|---------|-----------|
| We need    | >10 sqm  | Chandra <1" | ~15'   | res. 12-20 ~1000 | 0.1 - 10 keV |
| XEUS       | 25 sqm   | 5"-2"  | ~5'     | OK        | OK         |

Optics based on XMM model. Team confident about 5", 2" goal.

**Can the F.o.V be larger?**

Figure 10: Comparison of our goals with the XEUS plans
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