JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
36: 213 ∼ 222, 2003

CHANDRA X-RAY OBSERVATIONS OF EARLY TYPE GALAXIES

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(Received June 4, 2003; Accepted August 17, 2003)

ABSTRACT

We review recent observational results on early type galaxies obtained with high spatial resolution Chandra data. With its unprecedented high spatial resolution, Chandra reveals many intriguing features in early type galaxies which were not identified with the previous X-ray missions. In particular, various fine structures of the hot ISM in early type galaxies are detected, for example, X-ray cavities which are spatially coincident with radio jets/lobes, indicating the interaction between the hot ISM and radio jets. Also point sources (mostly LMXBs) are individually resolved down to Lx = a few x 10^{37} erg sec^{-1} and it is for the first time possible to unequivocally investigate their properties and the X-ray luminosity function. After correcting for incompleteness, the XLF of LMXBs is well reproduced by a single power law with a slope of -1.0 – -1.5, which is in contrast to the previous report on the existence of the XLF break at $L_{X,Eddington}$ = 2 x 10^{38} erg sec^{-1} (i.e., Eddington luminosity of a neutron star binary). Carefully considering both detected and undetected, hidden populations of point sources we further discuss the XLF of LMXBs and the metal abundance of the hot ISM and their impact on the properties of early type galaxies.

Key words : X-rays: galaxies – galaxies: ellipticals and lenticular, cD – galaxies: ISM

I. INTRODUCTION

High quality X-ray data obtained with the unprecedented sub-arcsec resolution (van Speybroeck 1997) of the Chandra X-ray Observatory (Weisskopf et al. 2000) are uncovering mysteries of the Universe. With XMM-Newton in orbit, another European X-ray satellite, it is now the most exciting time in X-ray Astronomy and Astrophysics. The significantly improved spatial resolution is particularly critical in studying extended sources, such as the hot ISM in early type galaxies. It is well known that the hot ISM is maintained in 0.5 – 1 keV in both elliptical and spiral galaxies, the former often containing a large amount of the hot ISM (eg., Fabbiano, Kim, & Trinchieri 1992). In addition to the hot ISM, there are various X-ray emitting sources in early type galaxies, such as AGNs (active galactic nuclei) and LMXBs (low mass X-ray binaries). However, they have not been well identified by the previous X-ray missions, mainly due to the poor spatial resolution. With the superb Chandra resolution, for the first time, we are able to directly detect various X-ray sources and investigate individual components without ambiguity.

As an example of high quality Chandra images of early type galaxies, Figure 1 shows the X-ray emitting hot ISM of NGC 4636 (see also Jones et al. 2002). NGC 4636 is one of the X-ray bright elliptical galaxies in the Virgo cluster with M_{gas} = 2 x 10^{10} $M_{\odot}$ (Fabbiano et al. 1992). As opposed to featureless, smooth X-ray images obtained in the pre-Chandra X-ray missions (eg., Trinchieri et al. 1994), the Chandra image is revealing in detail fine sub-structures of the hot ISM. In NGC 4636, there exists a spiral arm-like feature, extending to both sides (upper-left and lower-right) of the center of NGC 4636. They are about 8 kpc long. The sharp leading edges are interpreted as shock fronts associated with the recent nuclear activity (Jones et al. 2002). This subtle, fine structure clearly illustrates why the spatial resolution is so important.

With the Chandra data, we now have uncontroversial proof of the existence of populations of X-ray binaries in all E and S0 galaxies and of their large contribution particularly to the emission of X-ray-faint galaxies (see Sarazin et al. 2001; Angellini et al. 2001; Kim and Fabbiano 2003a). In Figure 2, the Chandra X-ray image of NGC 1399 is shown. NGC 1399, a dominant elliptical galaxy in the Fornax cluster, is also one of the X-ray bright elliptical galaxies with M_{gas} = 4 x 10^{10} $M_{\odot}$ (Fabbiano et al. 1992). Again the Chandra image reveals that the diffuse X-ray emission is far from being smooth. It also shows AGN in the center, although weak, compared to typical AGNs. The most striking result is that 140 point sources are identified inside the galaxy (Angellini et al. 2001). In addition to being identified as a point source, their spectral properties (kT ∼ 5-10 keV) and radial distribution (following the radial distribution of the optical, stellar light) clearly support that they are mainly LMXBs with an accreting neutron star. So far, the existence of LMXBs was suggested only by indirect means, for example, by analyzing mixed spectra extracted within a large beam or by extrapolating sources found in nearby galaxies.

Proceedings of the APCTP Workshop on *Formation and Interaction of Galaxies*

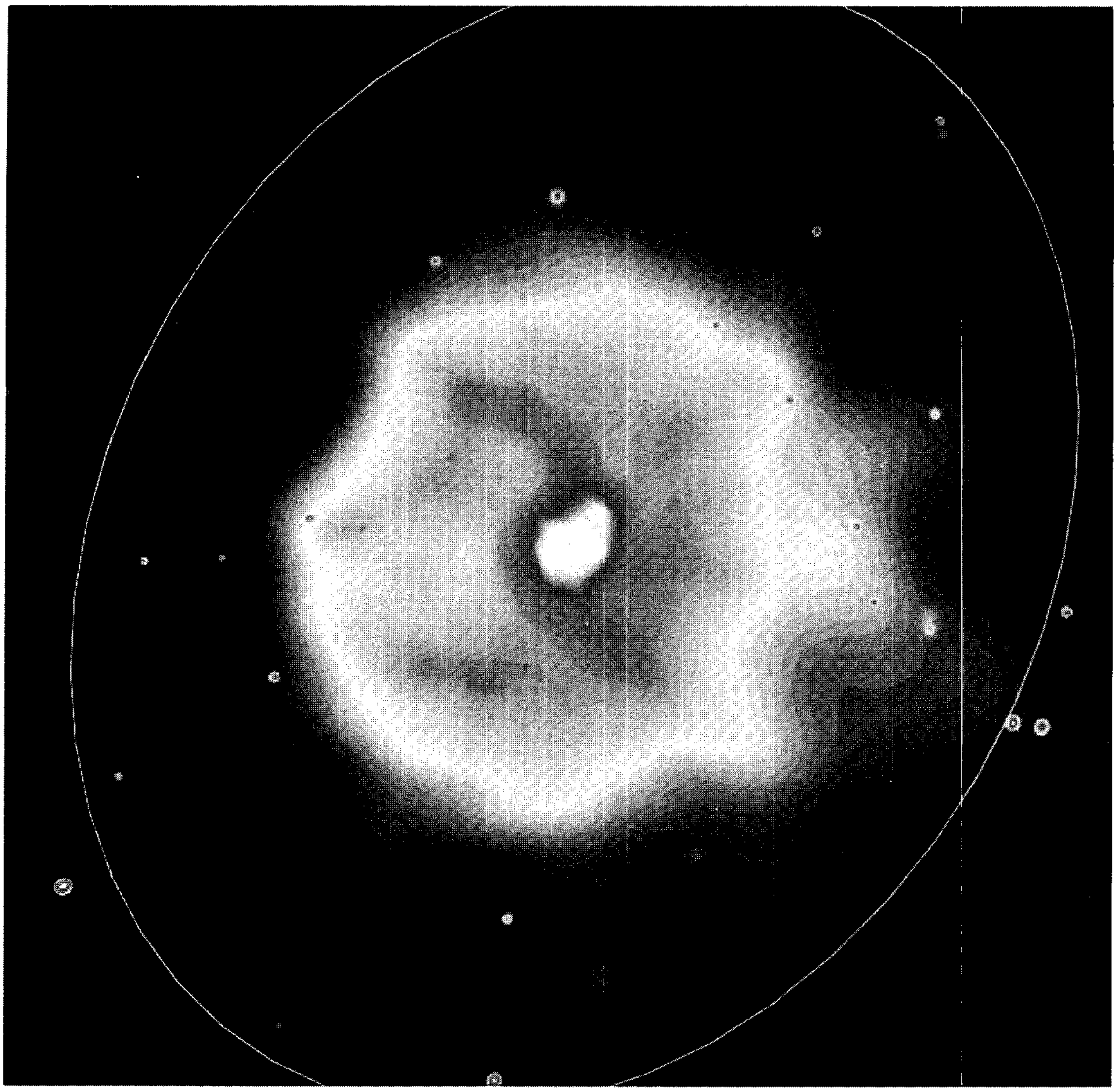

Fig. 1.— Chandra X-ray image of NGC 4636, an elliptical galaxy in the Virgo cluster. The image is adaptively smoothed with csmooth available in CIAO. A spiral arm-like feature is seen inside the ~0.8 keV degree hot gas. The large ellipse indicates the optical figure of NGC 4636 (D_{25}).

With Chandra, we are now able to investigate individual point sources in detail.

In section II, we present in detail results of a case study with NGC 1316 to illustrate fine sub-structures of the hot ISM and the importance of completeness in determining the XLF of LMXBs. In section III, we apply the same technique to a large sample of early type galaxies to determine average properties of LXMBs. Taking a full account of a hidden population of LMXBs, we discuss the metal abundance of the hot ISM by utilizing both Chandra and XMM data in section IV and the binding mass of early type galaxies in section V. We finally summarize our results in section VI.

II. CASE STUDY: NGC 1316

NGC 1316, also called Fornax A for its radio source, is one of the peculiar elliptical galaxies with numerous tidal tails that suggest a recent merger history, several low-mass, gas-rich mergers occurring over the last 2-3 Gyr (Schweizer 1980; Kim, Fabbiano and Mackie 1998). With the previous ROSAT HRI observations, Kim et al. (1998) suggested, with a marginal statistical significance, a possible interaction between the hot ISM and radio jets, which was the first evidence reported in elliptical galaxies. Now, the Chandra observations confirm that the hot ISM contains X-ray valleys (or cavities),

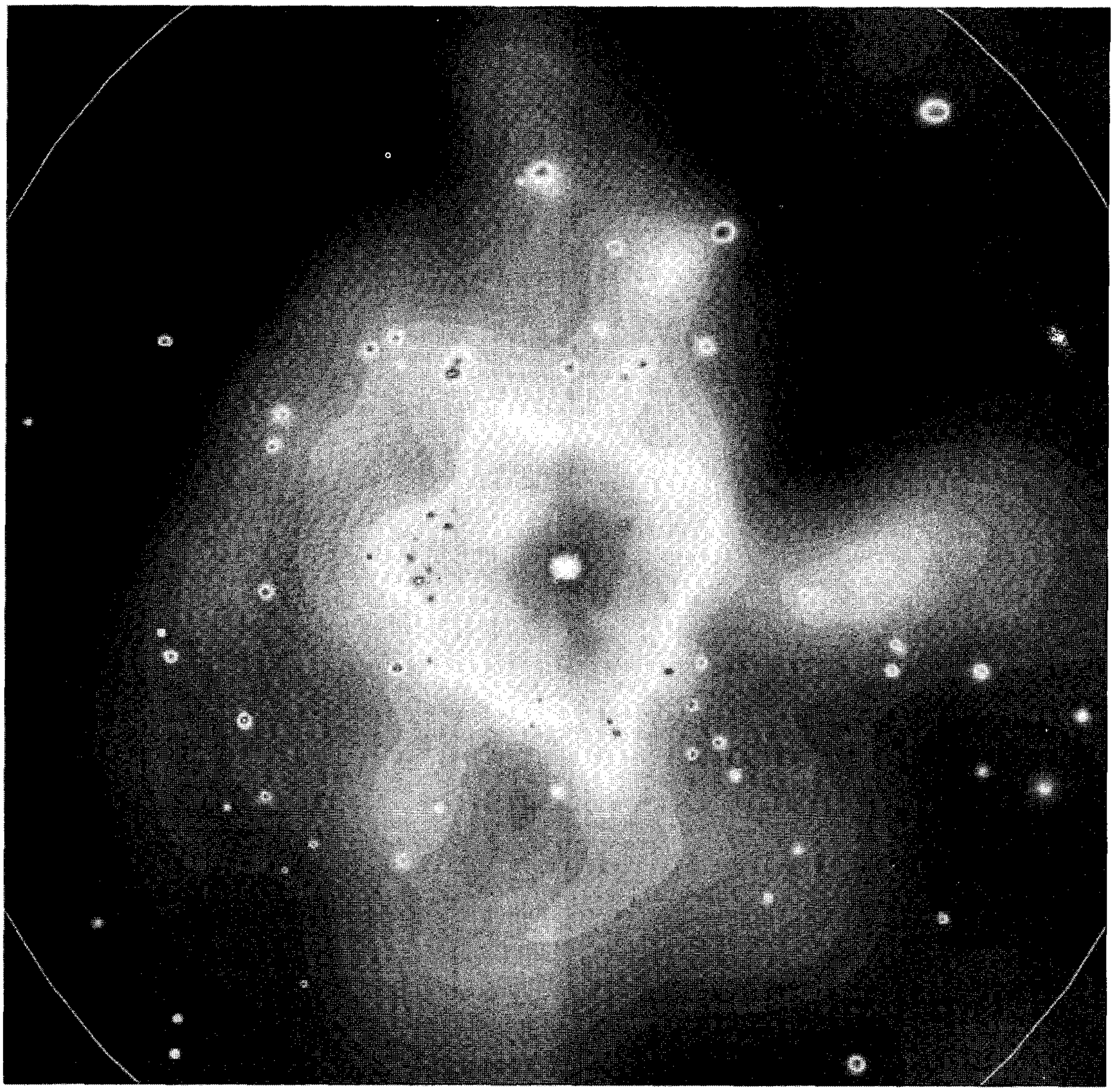

Fig. 2.— Chandra X-ray image of NGC 1399, an elliptical galaxy in the Fornax cluster. The green ellipse, partially seen at the corners, indicates the optical figure of NGC 1399 (with a size of 7 arcmin). Within the optical galaxy, more than 100 point sources, mostly low-mass X-ray binaries (LMXB), are individually identified.

devoid of hot gas, where the radio jets in projection propagate. Figure 3 shows the direction of radio jets (from the 1.5GHz VLA map of Figure 2b in Geldzahler and Fomalont 1984) superposed on the X-ray image. The radio jets propagate along PA $\sim$ 120° and 320° and slightly bend at their ends toward PA $\sim$ 90° and 270°, respectively (Geldzahler and Fomalont 1984). It is clearly seen that the radio jets in projection (1) run perpendicular to the direction of the NE-SW elongation of the central X-ray distribution, which is also the direction of the optical figure, and (2) propagate through the valleys of the X-ray emission, confirming the results of the ROSAT HRI observations (Kim et al. 1998). This alignment suggests that the X-ray valleys are cavities in the hot ISM caused by exclusion of hot gas from the volumes occupied by the radio jets. Similar relations between the radio jets/lobes and X-ray features have been reported in the Chandra observations of several early type galaxies and clusters, e.g., NGC 4374 (Finoguenov and Jones 2001), Hydra A (McNamara et al. 2000), Perseus cluster, (Fabian et al. 2000) and Abell 4095 (Heinz et al., 2002).

Although NGC 1316 has luminous radio lobes (the third brightest object in the sky), the radio emission from the active galactic nucleus (AGN) is relatively faint. Fornax A contains a relatively weak radio core

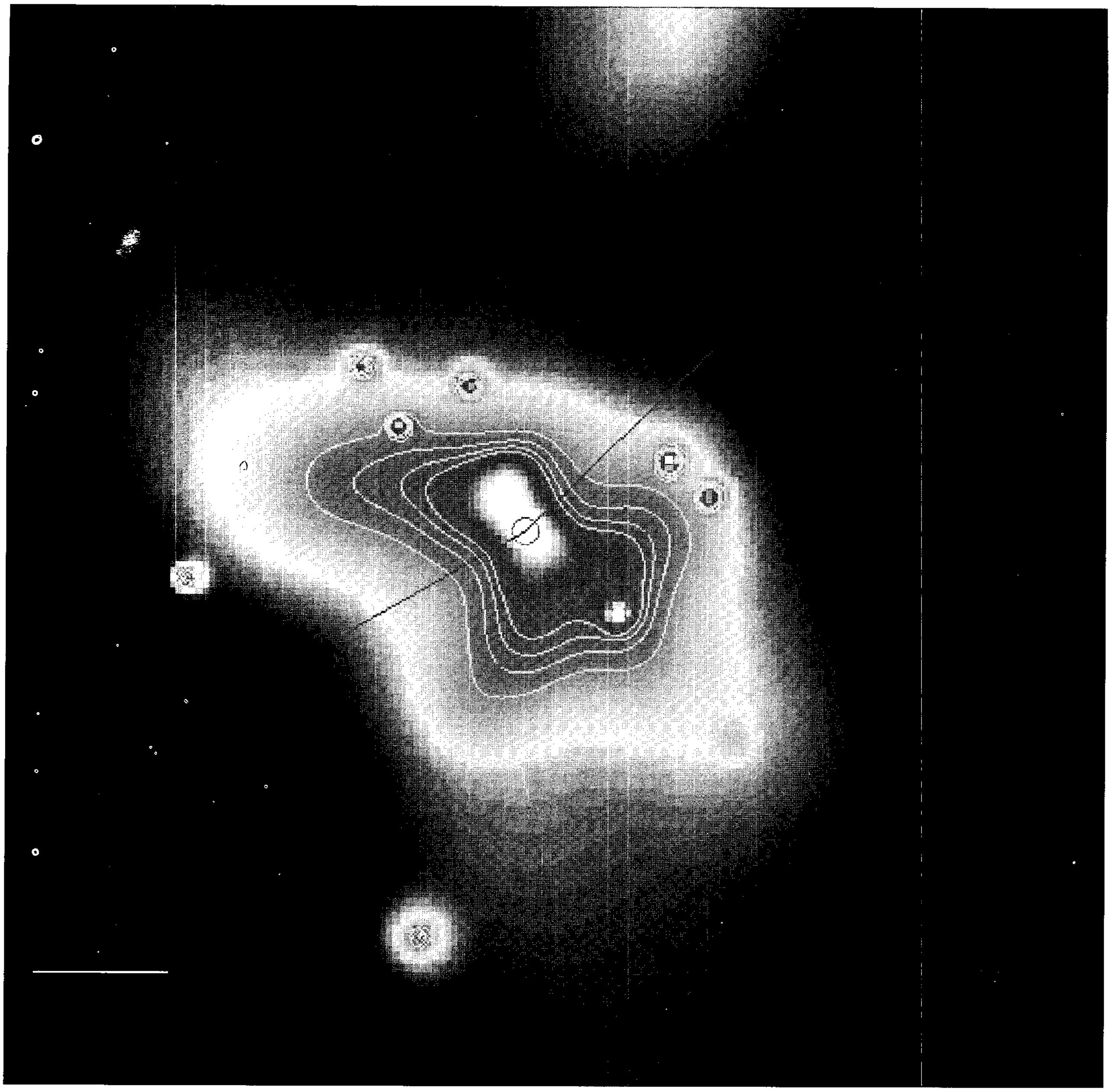

Fig. 3.— Chandra X-ray image of the central part of NGC 1316, another elliptical galaxy in the Fornax cluster. The horizontal bar at the lower left corner indicates 10 arcsec. The red lines, extending toward left (and slightly lower) and upper-right from the nucleus, indicate the direction and extent of radio jets, which in projection coincide with the X-ray valleys.

with a total power of $\sim 10^{38}$ erg sec^{-1} (Geldzahler and Fomalont 1984). We note that the current nuclear radio power is too weak to sweep the hot ISM out of the X-ray cavities as it would take longer than $\sim$10 Gyr for the minimum energy required by pV $\sim 10^{56}$ erg, where the pressure was taken from Kim et al. (1998). This indicates that the nuclear activity was much stronger in the past, as suggested by Ekers et al. (1983). Mergers, which took place a few Gyr ago, might have ignited the AGN activity, which in turn swept out the hot gas and also powered the huge radio lobes.

The spectrum of the nuclear source (with Lx = 5 x 10^{39} erg sec^{-1}) is well fitted with a power-law with photon index Γ_{ph} ~1.7, typical for bright AGNs. Based on the relationship between M_{BH} and the stellar velocity dispersion σ (Tremaine et al. 2002), the estimated mass of the nuclear black hole of NGC 1316 is about M_{BH} = 1-2 x 10^8 $M_\odot$ for σ = 221 km sec^{-1} (Kuntschner 2000). The X-ray luminosity of the nuclear source then corresponds only to 10^{-6} x $L_{Eddington}$. The nature of the sub-Eddington AGN is extensively discussed in recent literatures and we refer for further discussions of this type of sources to e.g., Ho et al. (2001), Pellegrini et al. (2002), Fabbiano et al. (2003).

In contrast to NGC 4636 (Figure 1) and NGC 1399 (Figure 2), NGC 1316 is an X-ray faint elliptical galaxy with M_{gas} = 10^9 $M_\odot$, about 3% of that in NGC 1399 (Kim et al. 1998). The main X-ray source from the X-ray faint elliptical galaxies is LMXBs, instead of the hot ISM component which is the dominant source in typical X-ray bright galaxies. NGC 1316 is, therefore, a good target to investigate the LMXB population. The cumulative XLF is shown in Figure 4, where both binned (open squares) and unbinned (dotted line) distributions are plotted. A single power-law model was used to reproduce the data with Lx > 1.2 x 10^{38} erg sec^{-1} where completeness starts to drop. The best-fit power-law slope is -1.3 ± 0.05. These values are consistent with those found in other early type galaxies (e.g. Sarazin et al. 2000), but much steeper than those in spirals and star burst galaxies (Prestwich et al. 2001; Zezas and Fabbiano 2002), indicating different stellar evolution histories. The XLF becomes flatter with decreasing source luminosity. We have investigated this effect further to ascertain if it may be due to a physical break in the distribution of source luminosities (e.g. as suggested by Sarazin et al. 2000; Blanton et al. 2001 in other early-type galaxies), or it may result from biases affecting the detection threshold of the data. We have run extensive simulations to quantitatively assess incompleteness. Figure 5 illustrates incompleteness and its impact on the XLF determination (for details, see Kim and Fabbiano 2003a). The corrected XLFs using two independent techniques are plotted in Figure 4 (red squares and blue triangles). The corrections are consistent with each other and clearly demonstrate that the single power law (the solid line histogram), that was determined from the uncorrected XLF at Lx > 1.2 x 10^{38} erg sec^{-1}, does fit well the corrected data. In conclusion, the apparent flattening of the XLF of NGC 1316 is fully accountable by incompleteness and we find no evidence of breaks, down to source luminosities of ~3 x 10^{37} erg sec^{-1}.

As the XLF is steep (α < -1), there will be a significant number of faint, undetected LMXBs, mixed with the diffuse X-ray emission and the contribution of the hidden population of LMXBs to the observed X-ray emission critically depends on the low-luminosity XLF. As seen in the bulge of M31, it is possible to have a break at Lx ~ 10^{37} erg sec^{-1} (Kong et al. 2002). If the XLF continues as an uninterrupted power-law down to 10^{37} erg sec^{-1}, the total X-ray luminosity of the hidden population of LMXBs of NGC 1316 would be comparable to that of the detected sources. If the XLF has a break at the lowest observed Lx (i.e., ~ 3 x 10^{37} erg sec^{-1}), the luminosity ratio of hidden to detected sources is about 0.4. We note that the amount of hard component required in the spectral fitting of the diffuse X-ray emission is fully within this acceptable range. The hidden population of LMXBs is also important to measure the spectral parameters of the hot ISM such as temperature and metal contents both of which are critical to understand the structure and evolution of the hot ISM and the galaxy (see section IV.)

III. XLF OF LXMBs: IS THERE A *UNIVERSAL* XLF BREAK?

It was previously suggested that the XLF of LMXBs in early type galaxies exhibits a break at the Eddington luminosity of neutron stars ($L_{X,Eddington} = 2\times10^{38}$

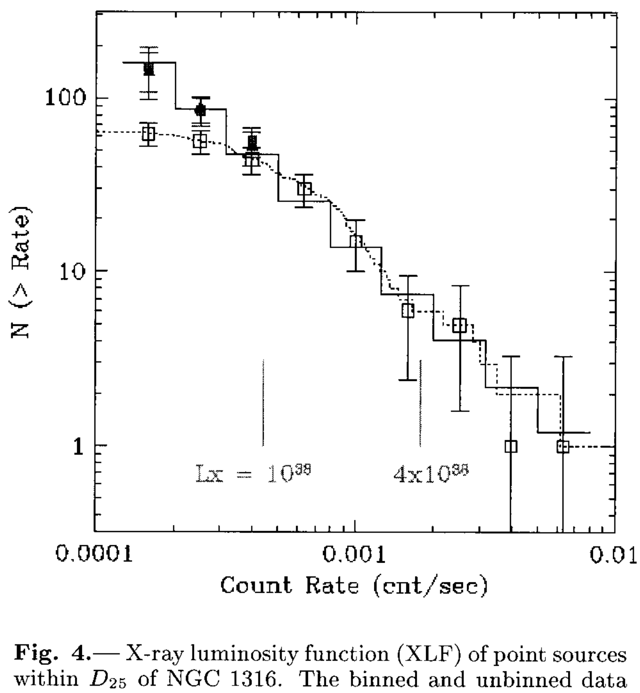

Fig. 4.— X-ray luminosity function (XLF) of point sources within D_{25} of NGC 1316. The binned and unbinned data are denoted by open squares and a dotted line, respectively. The solid histogram indicates the model prediction with a single power law, fitted at Lx > 1.2 x 10^{38} erg sec^{-1}. Three red squares and blue triangles at the lowest Lx bins represent the XLF corrected using two different approaches for estimating incompleteness in source detection.

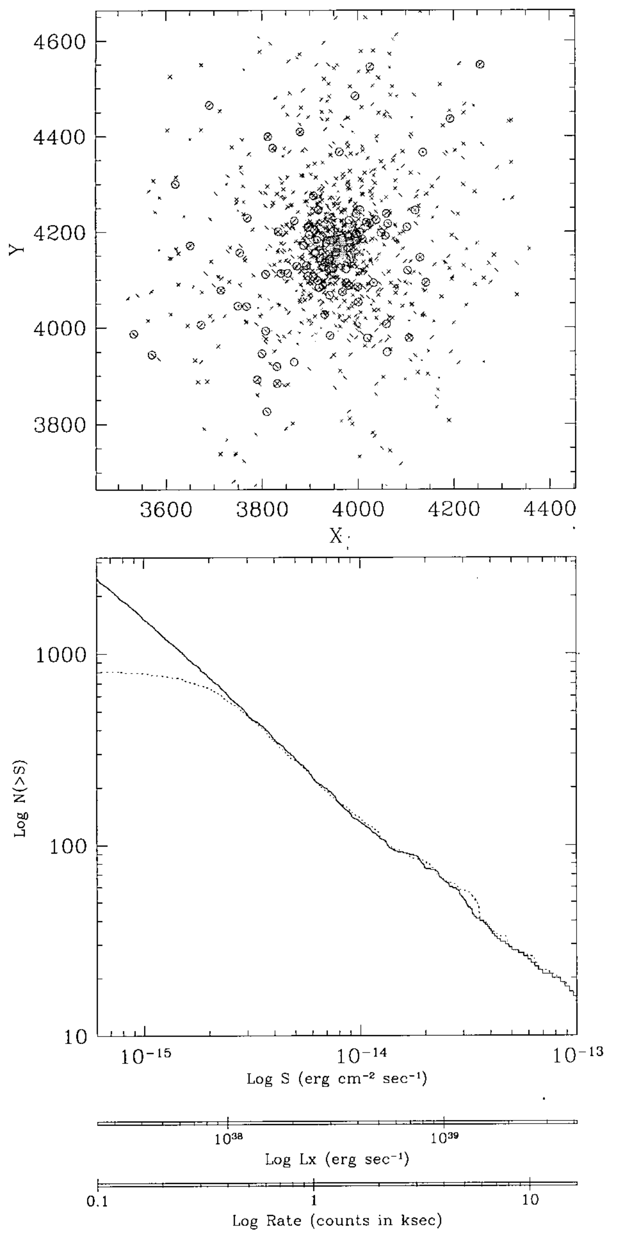

Fig. 5.— (a) Spatial distribution of simulated sources (marked by x) for the ACIS observation of NGC 1316. A circle on x indicates a detection, while x with a circle indicates a non-detection. Only 1000 random sources are plotted, for visibility. (b) Comparison of input (solid line) and measured (dotted line) XLFs (made with 20,000 simulated sources). The ratio of detected to input numbers of sources is applied directly to correct XLF. The incompleteness becomes significant at Lx $\lesssim 10^{38}$ erg sec^{-1}.

erg sec^{-1}), possibly indicating different populations of LMXBs consisting of neutron stars and black holes (e.g., Sarazin et al. 2000; Blanton et al. 2001). It is intriguing because this result bears an important key to accretion physics (eg., Belczynski et al. 2003) and it could also be used as a distance estimator (Sarazin et al. 2000). However, we do not find any break in NGC 1316 (Kim and Fabbiano 2003a) down to a few x 10^{37} erg sec^{-1} when incompleteness corrections were applied by way of two independent methods of extensive Monte Carlo simulations. We have applied the same technique of completeness correction to other early type galaxies for which Chandra data are publicly available. In general, near the center of early type galaxies where the PSF is usually smallest as the galaxy center is mostly likely at the focus, the strong diffuse emission considerably reduces the detection probability. On the other hand, at the outskirts, the PSF becomes considerably larger, hence the detection probability becomes lower (see Figure 5).

Figure 6 illustrates XLFs before and after the incompleteness correction with 14 early type galaxies (Kim and Fabbiano 2003b). It is clear that there is no 'universal' break at $L_{X,Eddington}$, the boundary between neutron star and black hole binaries.

The accurate measurement of XLFs provides an important clue for our understanding of the star formation history via the formation and evolution of binary systems in early type galaxies In particular, it is expected that the Eddington-limited accretion leads to a 'bump' in XLF at $L_{X,Eddington}$ (eg., Belczynski et al. 2003), which might look similar to the XLF break. With the combined XLF, we limit the bump to be an order of 20% or less. The absence of the strong bump suggests that the Eddington limit is not playing an important role in accretion and this constraint should be taken into account to build theoretical models.

In addition to the importance of the XLF (and its implication on the star formation history) and the presence or absence of the XLF break (and its effect on accretion physics), the XLF slope at the fainter luminosity end potentially implies that a considerable number of point sources are undetectable even in the Chandra observations. Without proper consideration of the hidden population of LMXBs, many important results obtained with the X-ray data will be seriously in question. In particular, they include two important physical quantities which could be directly measured by the X-ray data: the metal abundance of the hot ISM and the binding mass. The next two sections are dedicated to these two issues.

IV. METAL ABUNDANCE IN THE HOT ISM

The abundance of heavy elements is one of the key quantities for our understanding of the evolutionary status of the hot ISM in terms of the supernova rate (Ia and II), IMF, mass ejection and onset of galactic

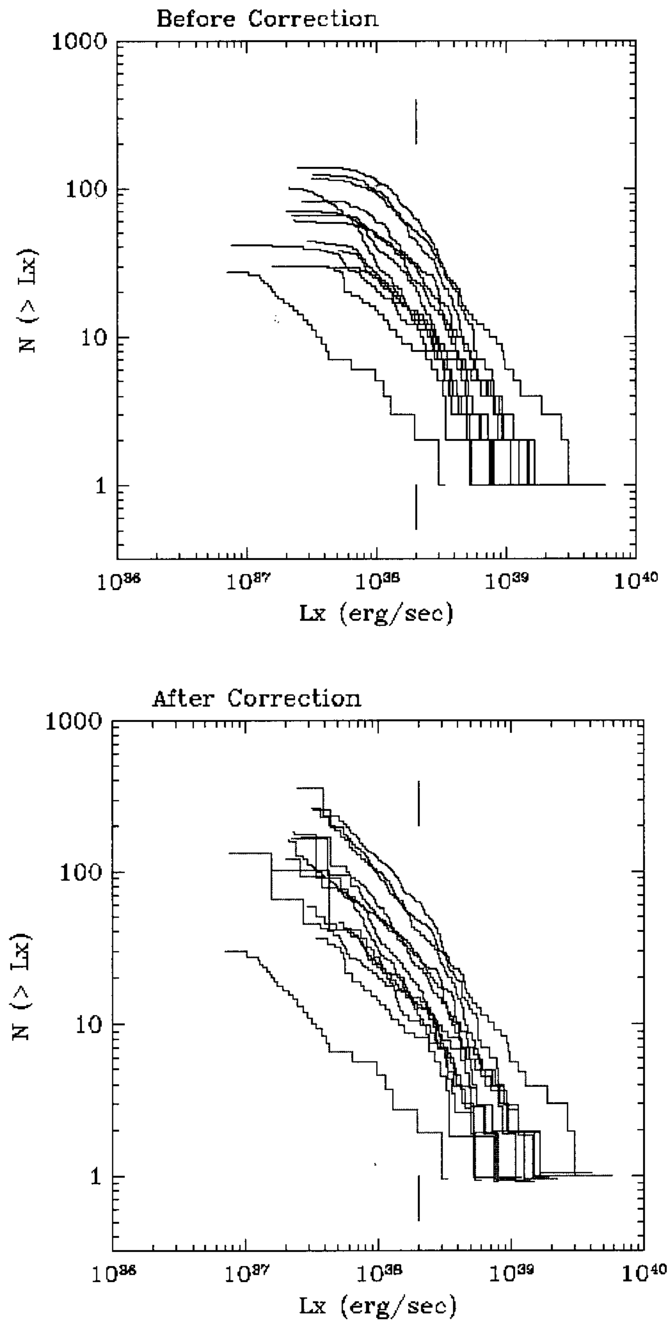

Fig. 6.— XLFs of LXMBs from 14 early type galaxies (a) before and (b) after correction. The location of $L_{X,Eddington} = 2 \times 10^{38}$ erg sec^{-1} is marked by vertical bars in both figures.

winds (eg., Renzini et al. 1993; Matteucci and Gibson 1995). Yet its measurement is difficult and controversial. While stellar evolution models (with both Type II and Ia SNe) predict the Fe abundance to be 2-5 times solar (eg., Arimoto et al. 1997), observational results tend to suggest lower, even sub-solar values (e.g., Awaki et al. 1994). This apparent discrepancy is at least in part due to our inability to find the correct spectral model. Different models may give acceptable spectral fits, and the accepted practice is to adopt the simplest possible model; however the answer may not be astrophysically meaningful, because of the complexity of the X-ray sources. Fits of the ROSAT and ASCA data with single temperature Raymond-Smith spectra (with/without an additional hard component for LMXBs) suggested a hot ISM almost totally devoid of metals in early type galaxies (eg., Awaki et al. 1994; Loewenstein et al. 1994; Davis and White 1996; Matsumoto et al. 1997; Iyomoto et al 1998), while more complex models allowed a metal content more in keeping with the stellar metallicities (e.g., Trinchieri et al. 1994; Kim et al., 1996; Buote and Fabian, 1998; Matsushita et al 2000). With the Chandra observations of NGC 1316, Kim and Fabbiano (2003a) could remove this ambiguity and convincingly exclude the possibility of extremely low metal abundances in the hot ISM by removing the regions of the data-cube occupied by detected point-like sources (AGN and LMXBs) from the spectral data and by establishing the temperature gradient of the hot ISM. Buote et al. (2003; astro-ph/0205362) have recently reported a similar result from the analysis of the XMM-Newton spectra of NGC 5044. However, neither of these observations could provide Fe abundances as high as a few times solar, as those suggested by stellar evolution models (e.g., Arimoto et al. 1997)

The best results can be obtained by combining the capabilities of Chandra and XMM-Newton - Chandra can identify LMXBs deep into the luminosity function, while XMM-Newton provides high S/N spectra. This is demonstrated by our recent analysis of NGC 507, a group-dominant X-ray bright elliptical galaxy. Previous measurements of the metal (mainly Fe) abundance in the hot ISM of NGC 507 span a wide range from 0.3 to 2 solar, depending on spectral models applied (Kim & Fabbiano 1995; Matsumoto et al. 1997; Buote 2000). With our recent Chandra and XMM-Newton analysis (Kim, Fabbiano and Brickhouse, 2003 in preparation; also in 2002 BAAS 34, 14.04), we find that (1) the temperature increases outward (confirming the results of Kim and Fabbiano 1995) from 0.7 to 1.3 keV and (2) the X-ray spectrum extracted from the central 80" region is well reproduced by a 3 component model, consisting of 0.7 keV soft thermal emission + 1.3 keV thermal emission + 5-10 keV hard LMXB component (it is also well reproduced by a cooling flow model with kT_{low}=0.7 + a hard LMXB component). Yet the determination of metal abundance is still not clear-cut. The best fit Fe abundance (Z_{Fe}) is either (case A) $\lesssim$ 1 solar, or (case

B) 2-3 solar, depending on the amount of absorption (important at lower energies, $\lesssim$ 0.7 keV) and the contribution to the diffuse X-ray emission from the hidden population of LMXBs (important at higher energies, $\gtrsim$ 2 keV). See Figure 6 for case A and B. Note that the fitting results are remarkably similar. The degeneracy occurs because the amount of absorption and (hidden) LMXBs could reduce/enhance model predictions at the low and high energies, ie., effectively altering the required strength of the Fe peak at ~1 keV. In case B, the required absorption is consistent with the galactic N_H and the LMXB component is similar to that of NGC 1316 (after scaling for L_B) with a hidden population of LMXBs down to 10^{37} erg sec^{-1} (where XLF starts to flatten in the deep Chandra observations of the bulge of M31; Kong et al. 2002). Therefore, case B may be favored over case A where N_H would be double and the LMXB contribution would be 1/4. If confirmed, this would be *the first observational evidence that the Fe abundance is a few times solar*, as predicted by the stellar evolution model (eg., Arimoto et al. 1997).

However, the interpretation of NGC 507 spectra suffers from two uncertainties in: (1) the exact amount of absorption and (2) the contribution from (hidden) LMXBs.

The galactic line of sight N_H is 5.3 × 10^{20} cm^{-2}. Neither IRAS FIR (Knapp et al. 1989) nor HI observations (Knapp et al. 1985) of NGC 507 indicate significant internal absorption from NGC 507 and appears to support case B. However, Arabadjis & Bregman (1999) suggested that while for $N_{H,21cm} < 5 \times 10^{20}$ cm^{-2} there is a tight relationship between $N_{H,21cm}$ and the X-ray absorption column $N_{H,X}$, for $N_{H,X} \gtrsim 5 \times 10^{20}$ cm^{-2} the X-ray absorption column $N_{H,X}$ could be double $N_{H,21cm}$ due to galactic molecular gas. The suggested extra absorption is similar to what is required in case A. We therefore need an independent way of measuring the exact amount of absorption.

The Chandra observations of NGC 507 have detected only a small number (3 in the 16 ks ACIS-S observation and 5 in the 40ks ACIS-I observation) of non-nuclear point sources within D25, mainly because NGC 507 is too far away (D=65.8 Mpc; only sources like ULXs would have been detected, see Kim, Fabbiano and Brickhouse 2003). To determine the amount of the LMXB component, we relied on the relationship between the X-ray luminosity of LMXBs and the optical luminosity of the galaxy. However, $L_X(LMXB)$ for a given optical luminosity may vary from one galaxy to another by as much as a factor of 4 (e.g., White et al. 2002), which makes case A and case B of NGC 507 indistinguishable. The best approach is, therefore, to identify as many LMXBs as possible and remove them from the diffuse X-ray emission. We are currently working with a large data set to better constrain these two uncertainties.

Based on the sub-solar metal abundances estimated with ASCA spectra, it was suggested that SN II domi-

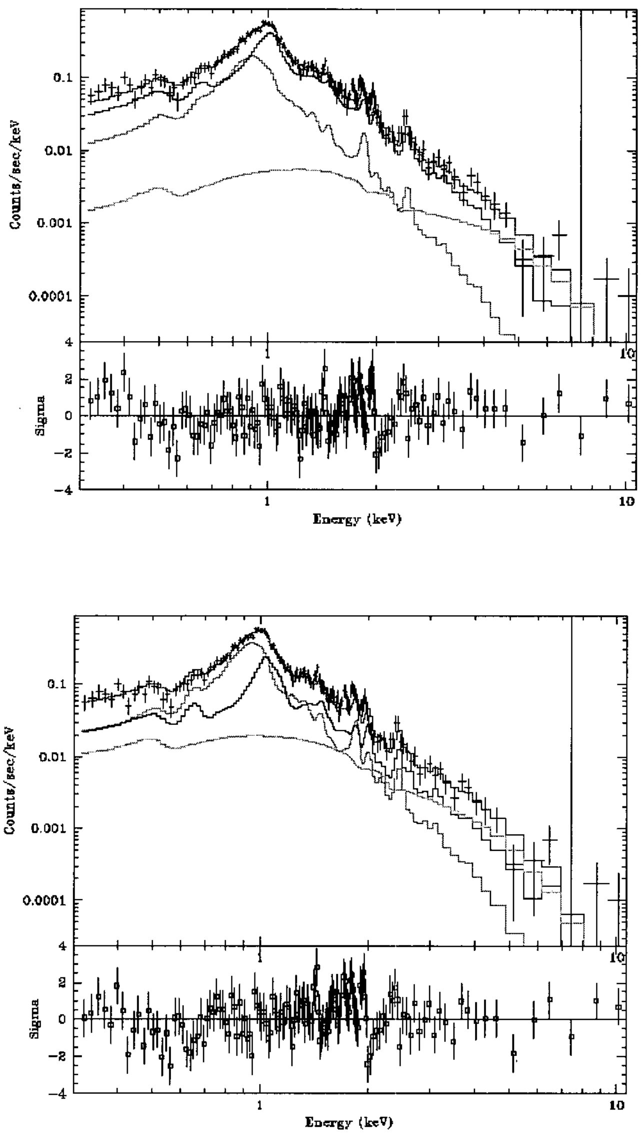

Fig. 7.— An example of spectral degeneracy. NGC 507 XMM spectra are well reproduced with 3-component models with widely different Z_{Fe}. (a) Z_{Fe} = 0.6-0.8 solar with N_H = 2 x galactic and a hard component = 1/4 for its L_B. (b) Z_{Fe} = 2-3 solar with N_H = galactic and a hard component comparable for its L_B.

nate in young early-type galaxies and drive early galactic winds. This would imply a considerably flatter IMF and require a lower SN Ia activity (eg., Loewenstein et al. 1994; Mushotzky et al. 1994; Matsumoto et al. 1997), than had been assumed in these galaxies on the basis of stellar evolution models (eg., Renzini et al. 1993; Arimoto et al. 1997). However, these conclusions are questionable, until the metal abundance is unambiguously determined. In particular the relative abundance of Fe and α-elements is key to discriminate the importance of SN type II and type Ia (eg., Renzini et al. 1993; Loewenstein et al. 1994) and hence provides a important clue for the evolution of the hot ISM and the whole galaxy. It appears that the relative abundance of Fe to Si (or S) is more or less constant, regardless of spectral models, in the case of NGC 507 (either case A or B above). Z_{Si}/Z_{Fe} is 1 - 1.4, depending on the solar value of Fe [note that the meteoric value is about 1.4 times smaller than the photospheric value of Anderson and Grevesse (1989)], indicating that 30-70% of the Fe mass is originated from SN Ia.

V. BINDING MASS OF EARLY TYPE GALAXIES

Another important yet controversial topic has been the ability of measuring the gravitational mass of E and S0 galaxies, based on the assumption of hot halos in hydrostatic equilibrium (see e.g. Fabbiano 1989; Trinchieri, Fabbiano & Canizares 1986). In particular, it was pointed out by the above authors that this method would not apply (or at least would be extremely uncertain) in the case of X-ray-faint galaxies. The mass measurement based on the equation of hydrostatic equilibrium (see e.g. discussion in Trinchieri et al 1986) hinges on 4 quantities (outer radius of the halo, temperature, density and temperature gradients at this radius). For example, in NGC 1316, Kim and Fabbiano (2003a) have found that the X-ray binaries dominate the emission at the outer radii, while the gas extends out to ~60" (5.4 kpc). For comparison, Forman et al (1985) have taken 19 kpc of the halo radius in the mass estimate, comparable to the radius of the region within which LMXBs are detected. The temperature of the halo was assumed to be 1 keV (as opposed to 0.5 keV in Kim and Fabbiano 2003a). Clearly, data with less angular and spectral resolution than Chandra's would not (1) allow to separate point sources from diffuse emission, giving a mistaken larger radius for the hot halo, and a more relaxed radial distribution; (2) also the temperature of the halo may appear larger than it really is, because of contamination with the harder LMXB emission, if these cannot be removed spatially or spectrally; (3) the halo may not be in a state of hydrostatic equilibrium, if for example is subject to winds at the outer radii, as it may be the case in NGC 1316 where the radio jets have been likely interacting with the hot ISM. This type of uncertainty is common to all pre-Chandra mass measurements of X-ray faint E and S0 galaxies: because of the problems exemplified in the case of NGC 1316, these measurements would tend to err in excess, even if the hot ISM were in hydrostatic equilibrium.

There are several other interesting subjects which we did not discuss here. They include: (1) the connection of LMXBs with globular clusters. Angellini et al. (2001) reported that 70% of LMXBs in NGC 1399 (Figure 2) are coincident with globular clusters within a region observed by the Hubble Space Telescope, implying that LMXBs are preferentially formed in globular clusters. If confirmed, this connection will significantly improve our understanding of the formation and evolution of binary stars. (2) Ultra luminous X-ray sources (ULX). Several brightest sources have their X-ray luminosity higher than that of stellar mass black hole binaries, ie., Lx > 10^{39} erg sec^{-1}. If they emit X-rays isotropically (ie., unbeamed), the black hole mass of these systems are 100 - 1000 $M_{\odot}$, intermediate between stellar mass black holes and super-massive black holes in the center of galaxies. Although their nature is not well understood, they are quite common as they are reported in a rapidly-growing number of galaxies (eg., Humphrey et al 2003). (3) Low luminosity AGNs. As discussed briefly in section II, AGN luminosities in typical giant elliptical galaxies are often extremely sub-$L_{Eddington}$. Although several possibilities of radiative inefficient accretion flows (or extreme obscuration) are being discussed (including e.g., ADAF, CDAF, and jet-dominated emission), the nature of the sub-Eddington AGN is still puzzling (see Fabbiano et al. 2003).

VI. SUMMARY

High spatial resolution data obtained by the Chandra X-ray Observatory provide new insights in our understanding of the hot ISM, LMXBs, and nucleus (AGN) in galaxies and the galaxy itself. In almost all galaxies observed so far, the hot ISM is neither smooth nor featureless. Many interesting, fine sub-structures are being revealed, including shock fronts possibly associated with nuclear activities in NGC 4636 (Figure 1) and X-ray valleys interacting with radio jets in NGC 1316 (Figure 3). A large number of LMXBs (often more than 100 in a single galaxy) are individually identified (Figure 2). The XLF of LMXBs is well reproduces with a single power law with ($\alpha \sim$ -1.3). The absence (or weakness) of the XLF bump at $L_{X,Eddington}$, which is expected in the Eddington-limited accretion suggests that the Eddington limit may not be critical. Because the XLF of LMXBs in early type galaxies is steep, there are still a significant number of undetected, faint LMXBs. With the hidden population of LMXBs, the metal abundance is about one solar or could be even as high as a few times solar, which is then consistent with stellar evolution models. The abundance ratio of Fe and α-elements suggests that about a half of the Fe mass is originated from SN Ia.

This work was supported by NASA grant GO1-

2082X and NAG5-9965.

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