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X-ray Source Populations in Galaxies

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Abstract This paper gives a short review of recent studies of the X-ray source populations of nearby galaxies. A more complete review of this subject can be found in Fabbiano & White (2003), from where this talk was partially extracted.

Key words: X-rays: sources; galaxies: X-rays

1 INTRODUCTION

While the presence of X-ray source populations in galaxies can be postulated from their existence in the Milky Way, imaging X-ray astronomy was needed to provide convincing proof of their existence (see e.g. Fabbiano 1989). The combination of sub-arcsecond resolution and moderate spectral resolution in the 0.1–10 keV range achievable with *Chandra* (Van Speybroeck *et al.* 1997; Weisskopf *et al.* 2000), complemented by the *XMM-Newton* (Jansen *et al.* 2001) data for the nearest galaxies (angular resolution of *XMM-Newton* is $\sim 15''$), are now making possible to study X-ray source populations in a large number of galaxies.

Although the most detailed data for a given source are always going to be derived from observations of Galactic X-ray sources, the study of X-ray source populations in external galaxies has unique advantages. These observations provide cleaner samples of sources with well defined distances (and thus luminosities), that can be associated to galaxian stellar populations without the uncertainties deriving from our particular position in the Milky Way. Moreover, having access to a large number of galaxies with different star-formation histories, we can observe and study extreme objects that may be missing in the X-ray population of the Milky Way, such as ultra-luminous X-ray sources (ULXs; e.g., Fabbiano 1989; Makishima *et al.* 2000).

2 X-RAY BINARY (XRB) POPULATIONS IN SPIRAL GALAXIES

Because of their proximity, nearby spiral galaxies is where the early work on extra-galactic X-ray source populations begun (see Fabbiano 1995). For the same reason, these are the galaxies where the deepest samples of sources have been acquired with *Chandra* and *XMM-Newton*. This field is evolving rapidly, with an increasing number of galaxies being surveyed and with the sensitivity limit being pushed to fainter fluxes, with ever deeper *Chandra* observations. The sub-arcsecond resolution of the *Chandra* mirrors (Van Speybroeck *et al.* 1997) allows both

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the separation of discrete sources from surrounding diffuse emission and the detection of much fainter sources than previously possible.

With these observations, it is now possible to derive X-ray luminosity functions (XLF) of sources in a given galaxy and also in different regions of the same galaxy. X-ray colors have been derived for some of these X-ray source populations. These colors have been compared with simple representative emission models and have been used to attempt a classification of the X-ray sources (e.g., Zezas *et al.* 2002a; Prestwich *et al.* 2003). The lack of standard photometry, however, makes comparison between different results laborious. In a few cases repeated observations of the same galaxy reveal widespread variability of the X-ray sources, consistent with the largest fraction of luminous sources being compact accreting binary systems (e.g., Kong *et al.* 2002; Williams *et al.* 2003; Fabbiano *et al.* 2003).

The XLFs of sources in a given system reflect the formation, evolution, and physical properties of the X-ray source population. These differences are evident for example in different regions of M31 (e.g., Kong *et al.* 2002) and M81 (Tennant *et al.* 2001; Swartz *et al.* 2003). The first report of XLF studies in M81 (Tennant *et al.* 2001) showed dramatic differences in the XLFs of bulge and disk sources. While the XLF of the bulge is reminiscent of the bulge of M31 (e.g., Kong *et al.* 2002), with a relatively steep power-law flattening at $L_X(0.2-8.0\,\mathrm{keV}) < 4\times10^{37}$ erg s^{-1}, the XLF of the disk follows a uninterrupted shallow power law (cumulative slope -0.50). Swartz *et al.* (2003) suggest that the break in the bulge XLF may be due to an aging $\sim$ 400 Myr old population of LMXBs. They also find that the disk population has different XLFs, depending on the source distance from the spiral arms: in particular, the very luminous ($> 10^{38}$ erg s^{-1}) sources responsible for the flat power law XLF are all concentrated on the arms; a break at high luminosities appears when spiral arm sources are excluded. Swartz *et al.* (2003) suggest that these most luminous sources are likely to be very young XRBs resulting from the star formation stimulated by the spiral density waves.

Comparison of the XLFs of nearby galaxies (and components thereof) with the XLFs of more distant systems provides a general coherent picture, pointing to steeper XLFs in older stellar populations (relative lack of very luminous sources). The XLFs of E and S0 galaxies have cumulative slopes in the range –1.0 to –2.0, generally consistent with those of the bulges of M31 and M81. These slopes are significantly steeper than those of sources associated with younger stellar fields in M31 and M81. A recent study of 32 nearby galaxies extracted from the *Chandra* archive (Colbert *et al.* 2003) confirms this basic difference between XLFs of old and younger stellar populations, finding cumulative slopes of ~ 1.4 and $\sim 0.6-0.8$ for elliptical and spiral galaxies respectively.

Actively starforming galaxies are consistent with this picture, having flatter XLFs (an abundance of very luminous sources). The best example is given by the merger system NGC 4038/39 (The Antennae), where nine ultra-luminous X-ray sources (ULXs; $L_X > 10^{39}$ erg s^{-1}, for a distance of 19 Mpc) were discovered with *Chandra* (Fabbiano, Zezas & Murray 2001). The cumulative XLF slope is –0.45 in The Antennae (Zezas & Fabbiano 2002; Fig. 1).

Grimm, Gilfanov & Sunyaev (2003) suggest that the XLFs of star forming galaxies scale with the star formation rate (SFR), thus advocating that high mass X-ray binaries may be used as a star formation indicator in galaxies. They find that at high SFRs the total X-ray luminosity of a galaxy is linearly correlated to the SFR, and suggest a 'universal' XLF of starforming galaxies described by a power law with cumulative slope of ~ -0.6 and a cut-off at $L_X \sim$ few $\times10^{40}$ erg s^{-1}. This result of course depends on how well is the SFR of a given galaxy known. This is a subject of considerable interest at this point, since various indicators are differently affected by extinction. The conclusion of a universal slope of the XLF of starforming galaxies may be at odds with the reported correlation between the XLF slope and the 60μm luminosity from a minisurvey of spiral and starburst galaxies observed with *Chandra* (Kilgard *et al.* 2002).

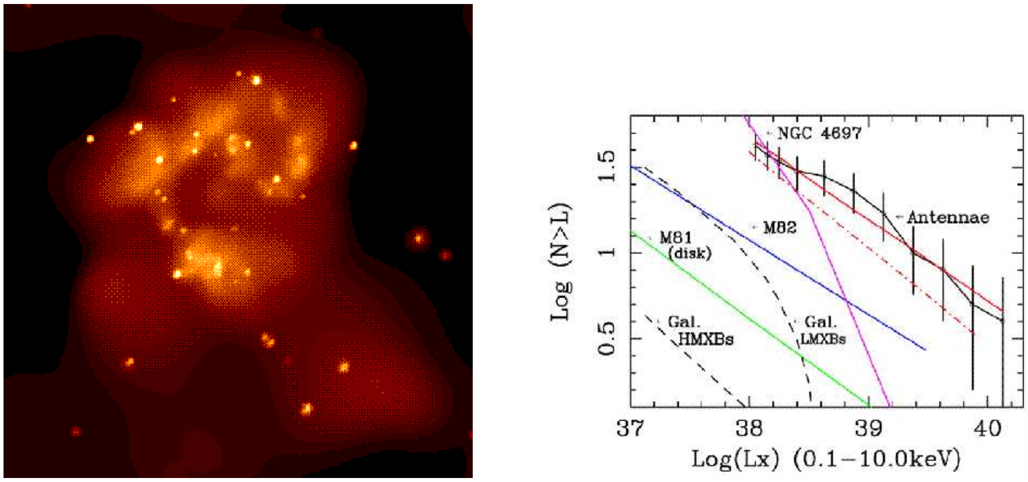

Fig. 1 Left: *Chandra* ACIS image of The Antennae (Fabbiano *et al.* 2001); Right: the XLF of The Antennae (points with error bars) compared with other galaxies, as labelled. Note the steep XLFs of the Galactic HMLXBs (bulge) and of the early-type galaxy NGC 4697 (Zezas & Fabbiano 2002).

Also, theoretical models (Kalogera & Belczynski 2003; Belczynski et al. 2003) suggest that XLF slopes depend on the age of the starburst, so it is possible that the 'universal' XLF slope is not truly universal, but reflects a selection bias, in that the sample used by Grimm, Gilfanov & Sunyaev (2003) may be dominated by starburtsts of similar ages.

3 XRB POPULATIONS OF E AND S0 GALAXIES

XRBs could not be directly detected in E and S0 galaxies with pre-*Chandra* telescopes, because of the distance of these galaxies and the limited angular resolution of the telescopes. The presence of XRBs in E and S0 galaxies was predicted by Trinchieri & Fabbiano (1985), based on an analogy with the bulge of M31, for which such a population could be detected (Van Speybroeck *et al.* 1979; see also Fabbiano, Trinchieri & Van Speybroeck 1987).

The *Chandra* images (Fig. 2) leave no doubt about the presence of rich populations of point-like sources in E and S0 galaxies. Published results, of which the first one is the paper on NGC 4697 by Sarazin, Irwin & Bregman (2000), include point-source detections in a number of galaxies.

The XLFs of the early-type galaxies observed with *Chandra* are generally steeper than those of star-forming galaxies, i.e. with a relative lack of luminous XRBs. These XLFs are generally well fitted with power-laws or broken power laws with (cumulative) slopes ranging from −1.0 to −1.8, and breaks have been reported both at 2-3$\times10^{38}$ erg s^{-1}, the Eddington luminosity of an accreting neutron star (Sarazin, Irwin & Bregman 2000; Blanton, Sarazin & Irwin 2001; Finoguenov & Jones 2002; Kundu, Maccarone & Zepf 2002), and at higher luminosities (10^{39} erg s^{-1}) (Jeltema *et al.* 2003, in NGC 720). While the former break may be related to a transition between neutron star and black hole binaries (Sarazin, Irwin & Bregman 2000), the latter, high luminosity break, could be produced by a decaying (aging) starburst component from binaries formed in past merging and star bursting episodes (Wu 2001; This possibility was suggested in the case of NGC 720, Jeltema *et al.* 2003). The XLFs of NGC 5128

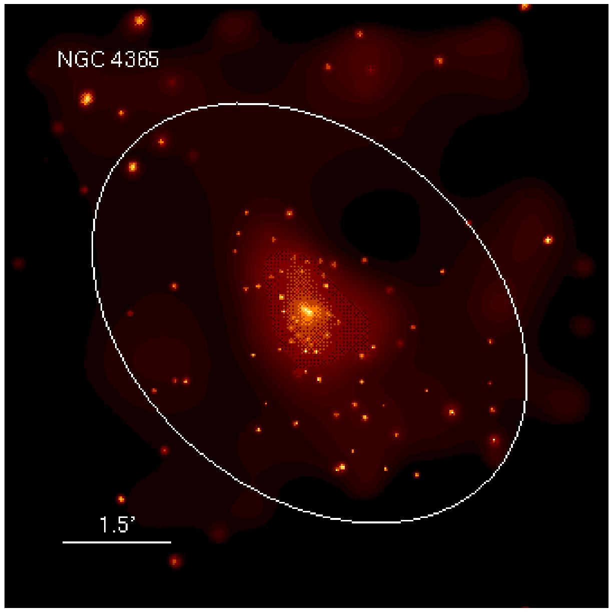

Fig. 2 *Chandra* ACIS image of the Virgo elliptical NGC 4365, using archival data. The white ellipse is the D_{25} isophote, from de Vaucouleurs *et al.* (1991).

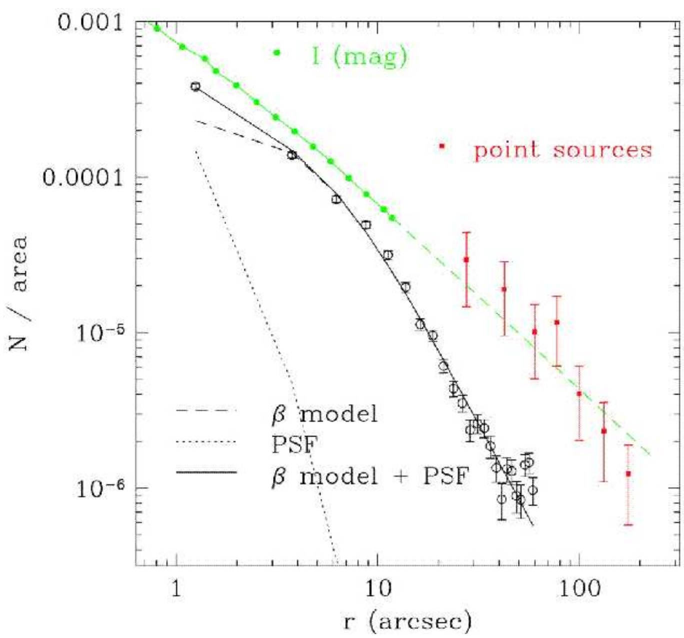

Fig. 3 Radial distributions of the emission components of NGC 1316. The gaseous component (hot ISM) is represented by the inner distribution of points. The cumulative XRB contribution is given by the outer set of points; the dashed line through these points is the extrapolation of the stellar (I) surface brightness (Kim & Fabbiano 2003).

(Kraft *et al.* 2001), obtained at different times and reflecting source variability, are well fitted with single power-laws in the luminosity range of $10^{37} - 10^{39}$ erg s^{-1}.

The effects of detection incompleteness have been recently explored extensively by Kim & Fabbiano (2003) in their derivation of the XLF of NGC 1316. Low-luminosity sources may be missed because of higher background/diffuse emission levels in the inner parts of galaxies, and also because of the widening of the *Chandra* beam at larger radii. Correcting for these effects with an extensive set of simulations, Kim & Fabbiano (2003) found that an apparent 2–3$\times 10^{38}$ erg s^{-1} break in the XLF of NGC 1316 disappeared when incompleteness was taken into account, and the XLF of this galaxy could be represented by an unbroken power-law down to luminosities of $\sim 3 \times 10^{37}$ erg s^{-1} (Fig. 4). This result shows that caution must be exercised in the derivation of XLFs, and that perhaps some of the previous reports should be reconsidered. If the XLFs extend unbroken to lower luminosities, the amount of X-ray emission from undetected XRBs in early-type galaxies can be sizeable, as it is the case in NGC 1316. This result is important not only for our understanding of the XRB populations, but also for the derivations of the parameters of the hot interstellar medium in these system (see Kim & Fabbiano 2003). Ignoring the contribution to the emission of hidden XRBs results in biases and erroneous results and may give the wrong picture of the overall galaxy dynamics and evolution. Moreover, the dominance at large radii of XRB emission over the hot ISM (see Fig. 3) in some (X-ray faint) ellipticals, does also affect adversely mass measurements of these galaxies from low-resolution X-ray data (Kim & Fabbiano 2003).

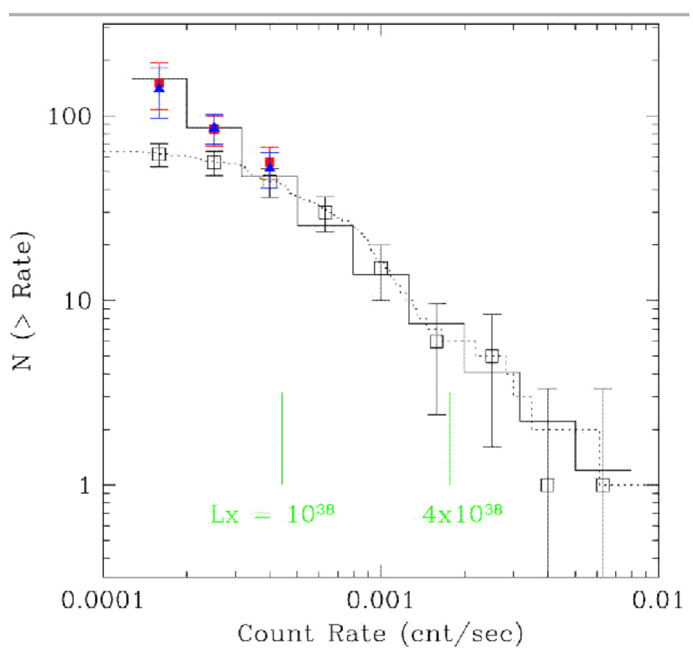

Fig. 4 Observed (empty squares) and corrected (filled points) XLFs of NGC 1316 (Kim & Fabbiano (2003).

4 ULTRA LUMINOUS X-RAY SOURCES - ULXS

ULXs (see Fabbiano 1989; Roberts & Warwick 2000; Colbert & Mushotzky 1999; Colbert & Ptak 2003) are extremely luminous X-ray sources, emitting well in excess of the Eddington luminosity of a spherically accreting and emitting neutron star ($\sim 2 \times 10^{38}$ erg s^{-1}). Usually, sources emitting at $\sim 10^{39}$ erg s^{-1} or above are included in this category. If these sources are emitting isotropically at the Eddington limit, masses in excess of those expected from stellar black holes are implied, up to in some cases, $\geq 100 M_{\odot}$ (e.g. Fabbiano 1989, 1995; Makishima *et al.* 2000). Colbert & Mushotzky (1999) dubbed this type of black holes 'intermediate mass black holes' (IMBH), to distinguish them from the stellar mass black holes found in Galactic black hole binaries, and also from the supermassive $10^7 - 10^9 M_{\odot}$ found at the nuclei of galaxies that are responsible for AGNs. With *Chandra* and *XMM-Newton* an increasing number of ULXs are being discovered and studied in galaxies (see Fabbiano & White 2003 for a review).

Although young supernova remnants may be responsible for ULX emission in some cases (e.g Fabian & Terlevich 1996), there is now sufficient evidence from spectral and variability data, to establish that the majority ULXs are indeed compact systems, most likely accreting binaries (e. g., Makishima *et al.* 2000; Kubota *et al.* 2001; La Parola *et al.* 2001). Fig. 5 shows the spectral variability of the ULXs discovered with *Chandra* in the Antennae galaxies (Fabbiano et al. 2003a). Both Cyg X-1 like high/soft-low/hard as well as high/hard-low/soft variability was detected in these ULXs. The latter type of variability can also be found in a few Galactic XRBs (1E 1740.7–2942, GRS 1758–258, GX 339–4, Smith *et al.* 2002; see also the *XMM-Newton* results on GRS 1758-258, Miller *et al.* 2002). This spectral variability may be indicative of the competition between the relative dominance of the accretion disk versus the innermost hot accretion flow.

The discovery of low-temperature components in the *XMM-Newton* spectra of ULXs, such as in the NGC 1313 ULXs, is consistent with emission from an IMBH accretion disk (Miller *et al.* 2003a). The very luminous ULX in M82 has also been proposed as a promising IMBH candidate (e.g., Strohmayer & Mushotzky 2003). However, the presence of IMBHs in all the ULXs is not universally accepted. Two other models have been advanced, which do not require IMBH masses. The large number of ULXs found in The Antennae (Fabbiano, Zezas & Murray 2001) led to the suggestion that they may represent a normal stage of XRB evolution (King *et al.* 2001). In the King *et al.* (2001) model, the apparent (spherical) accretion luminosity is boosted because of geometrical collimation of the emitting area in thick accretion disks, resulting from the large thermal-timescale mass transfer characterizing the later stages of a massive XRB. Exploiting the similarity with Galactic microquasars, the jet emission model of Körding *et al.* (2002) produces enhanced luminosity via relativistic beaming.

In the Antennae, comparison with *HST* data shows that the ULXs are offset from star-forming stellar clusters. While coincidence with a stellar cluster may be due to happenstance because of the crowded fields, the absence of an optical counterpart is a solid result and suggests that the ULXs may have received kicks at their formation (Zezas & Fabbiano 2002), which may be unlikely in the case of a massive IMBH forming in a dense stallar cluster (e.g. Miller & Hamilton 2002). An alternate IMBH scenario, discussed by Zezas & Fabbiano, is that of primordial IMBHs drifting through stellar clusters after capturing a companion (Madau & Rees 2001).

Recent results on supersoft variable ULXs suggest that the emitting region may not be associated with the inner regions of IMBH accretion disks in these sources, but may be due to Eddington-driven outflows from a stellar mass black hole (Mukai *et al.* 2003). *Chandra* time monitoring observations of The Antennae have led to the discovery of one of these variable supersoft sources (kT = 90 – 100 eV for a blackbody spectrum), reaching ULX luminosities of

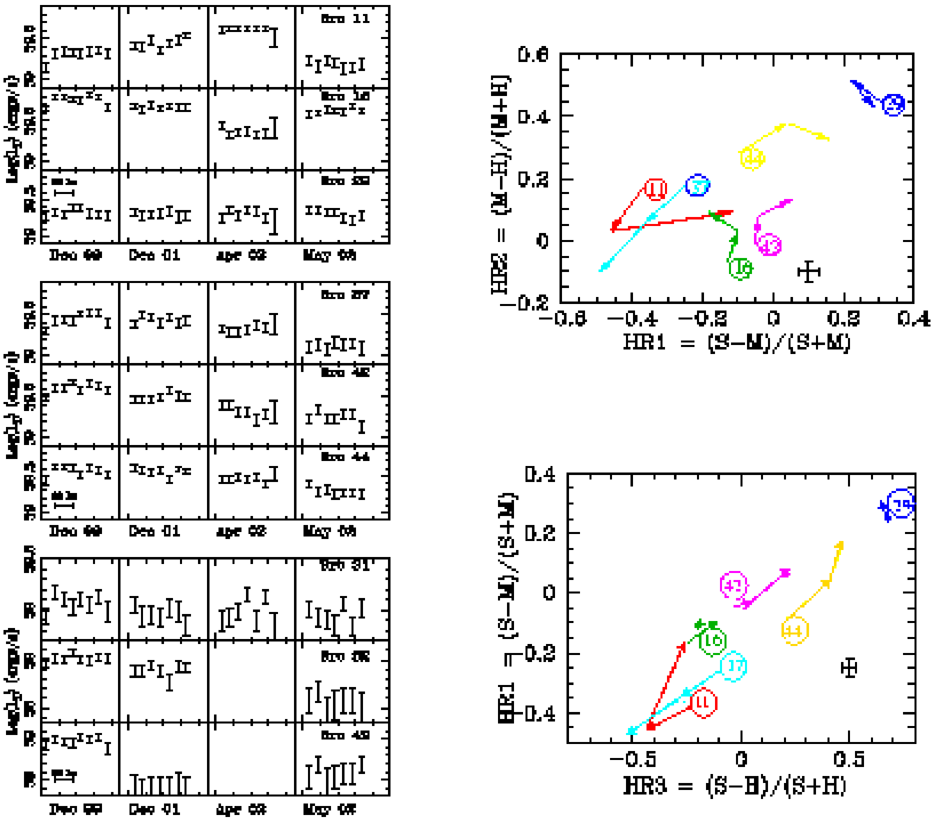

Fig. 5 Left: *Chandra* light curves of the ULXs of The Antennae. Right: color-color diagrams of the most luminous sources (Fabbiano *et al.* 2003a).

$2.4{\times}10^{40}$ erg s^{-1} (Fabbiano *et al.* 2003b). The assumption of unbeamed emission would suggest a black hole of $\geq 100 M_{\odot}$. However the radiating area would have to vary by a factor ~ 1000 in this case, inconsistent with gravitational energy release from within a few Schwarzschild radii of a black hole. As discussed in (Fabbiano *et al.* 2003b), a surprising possible solution is a white dwarf with $M \sim 1 M_{\odot}$, at the Eddington limit, with a variable beaming factor (up to a beaming factor $b \sim 10^{-2}$). A second possible solution involves outflows from a stellar–mass black hole, accreting near the Eddington limit (as in Mukai *et al.* 2002) but with mildly anisotropic radiation patterns ($b \sim 0.1$, as in King *et al.* 2001). Similar sources are reported in M81 (Swartz *et al.* 2002), NGC 300 (Kong & Di Stefano 2003), and other nearby spiral galaxies (Di Stefano & Kong 2003; Kong 2003).

5 CONCLUSIONS

X-ray studies of galaxies are now yielding copious information on the properties of their XRB populations. The classification and study of these different populations is providing a unique tool for understanding the origin and evolution of XRBs, and for relating these sources to the evolution of the stellar populations of the parent galaxies, both in the nearby and the far-away universe.

This work would not have happened without the vision of Riccardo Giacconi, who pushed forward the high resolution X-ray telescope concept, and the work of Leon Van Speybroeck, who designed the *Chandra* optics. This work benefitted by the Aspen Summer Workshop on Compact X-ray Sources (Summer 2002). I aknowledge partial support from the *Chandra* X-ray Center under NASA contract NAS 8-39073.

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