Chandra’s Discovery of Activity in the Quiescent Nuclear Black Hole of NGC 821

G. Fabbiano¹, A. Baldi¹, S. Pellegrini², A. Siemiginowska¹, M. Elvis¹, A. Zezas¹, J. McDowell¹

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; gfabbiano@cfa.harvard.edu; abaldi@cfa.harvard.edu, aneta@cfa.harvard.edu, elvis@cfa.harvard.edu, azezas@cfa.harvard.edu, jcm@cfa.harvard.edu

²Dipartimento di Astronomia, Universita' di Bologna, via Ranzani 1, 40127 Bologna (Italy); silvia.pellegrini@unibo.it

May 18, 2004

ABSTRACT

We report the results of the Chandra ACIS-S observations of the elliptical galaxy NGC 821, which harbors a supermassive nuclear black hole (of $3.5 \times 10^7 M_\odot$), but does not show sign of AGN activity. A small, $8.5''$ long ($\sim 1$ kpc at the galaxy’s distance of 23 Mpc), S-shaped, jet-like feature centered on the nucleus is detected in the 38 ksec ACIS-S integrated exposure of this region. The luminosity of this feature is $L_X \sim 2.6 \times 10^{39}$ erg s$^{-1}$ (0.3-10 keV), and its spectrum is hard (described by a power-law of $\Gamma = 1.8^{+0.7}_{-0.6}$; or by thermal emission with $kT > 2$ keV). We discuss two possibilities for the origin of this feature: (1) a low-luminosity X-ray jet, or (2) a hot shocked gas. In either case, it is a clear indication of nuclear activity, detectable only in the X-ray band. Steady spherical accretion of the mass losses from the central stellar cusp within the accretion radius, when coupled to a high radiative efficiency, already provides a power source exceeding the observed radiative losses from the nuclear region.

Subject headings: galaxies: NGC 821 - galaxies: nuclei - X-ray: galaxies

1. Introduction

Luminous quasars, radio galaxies, and Seyfert galaxies have long been associated with accretion onto a massive black hole (see review Rees 1984), and the lack of nuclear emission
in most galaxies was alternatively debated as evidence for the lack of such a nuclear black hole, or for the lack of fuel reaching the hole (Phinney 1983).

We now know that virtually all galaxies host supermassive black holes (SMBH) in their nuclei. High resolution observations of the nuclei of elliptical galaxies and bulges have established the presence of these SMBHs (Richstone et al 1998; Magorrian et al 1998; van der Marel 1999), whose mass is loosely correlated with the galaxy/bulge luminosity (Magorrian et al 1998) and tightly correlated with the central velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al 2000) and the central light concentration (Graham et al 2001). These results remove the black hole variable from the equation, and make the absence of luminous AGN in these galaxies more puzzling. Although a few faint AGNs have been detected in X-rays (e.g. in the $L_X/L_E \sim 10^{-6-7}$ range, where $L_E$ is the Eddington luminosity of the SMBH; Fabbiano & Judah 1997; Pellegrini et al. 2003a; Ho et al. 2001; Fabbiano et al. 2003), we still do not have a clear picture of what impedes the formation of a luminous AGN, and of how this is related to the existence and physics of a circum-nuclear accretion disk (e.g., Martini et al. 2001). Given that elliptical galaxies tend to host large quantities of centrally concentrated hot interstellar medium (ISM; see Fabbiano 1989 for an early review), lack of fuel does not seem to be an option.

For example, the circum-nuclear regions studied so far with the Chandra ACIS show the presence of hot gas close to the accretion radius; this implies, when applying the spherical Bondi accretion theory, accretion luminosities values comparable to those of luminous AGNs, if the gas close to the SMBH joins an accretion disc with a standard radiative efficiency of $\sim 0.1$ (e.g., Loewenstein et al. 2001; Fabbiano et al. 2003). Since these luminosities are not observed, the options left are that the radiative efficiency is orders of magnitude lower, as in an advection dominated accretion flow (ADAF) and its variants (e.g., Narayan 2002), or that accretion is unsteady (Binney & Tabor 1995, Ciotti & Ostriker 2001). In addition, nuclear jets can carry away a large fraction of the estimated accretion power, a possibility that has been found very reasonable for M87 (Di Matteo et al. 2003), IC4296 (Pellegrini et al. 2003b) and IC1459 (Fabbiano et al. 2003). NGC 821 represents another promising case to test the hypotheses above.

NGC 821 is an E6 galaxy with possible disky isophotes and centrally peaked (power-law) surface brightness (Ravindranath et al 2001). At a distance of 23 Mpc (e.g., de Zeeuw et al. 2002), the ACIS resolution at the aim point corresponds to 55 pc. Prior to our Chandra observation, NGC 821 had been observed, but not detected, in X-rays with ROSAT ($< 5 \times 10^{40}$erg s$^{-1}$; Beuing et al. 1999). This limit is $\sim 10^5$ times below the Eddington luminosity of the nucleus, based on the SMBH mass of $2.8-5.8 \times 10^7 M_\odot$, which was measured from HST (STIS) spectra of the nuclear region coupled to dynamical modeling (Gebhardt
et al. 2003). NGC 821 was observed with Chandra as part of a mini-sample of extremely faint SMBHs extracted from the list of Ho (2002), which will be the subject of a follow-up paper. As reported in Ho (2002) and Ho et al. (2003), NGC 821 has not been detected in radio continuum nor in optical emission lines (Hα and Hβ), and is a good example of quiescent SMBH. Here we report the results of the Chandra ACIS observation of NGC 821, that has led to the discovery of an S-shaped feature, suggestive of either a weak two-sided X-ray nuclear jet, or of hot shocked gas.

2. Observations and Data Analysis

NGC 821 was observed with Chandra (Weisskopf et al 2000) ACIS-S (PI: Fabbiano) on November 26, 2002 (ObsID: 4408) and on December 1, 2002 (ObsID: 4006) for a total exposure time of 38 ks. Table 1 is a summary of the relevant properties of NGC 821 and of the observing log.

No significant background flares were observed in these data, so no further screening was necessary. A time-dependent gain correction (URL: http://cxc.harvard.edu/contrib/alexey/tgain/tgain.html) was applied to the Standard Data Processing Level 2 event files, before further analysis. The data were then analyzed using the CIAO v3.0.1 software (CALDB 2.23) and XSPEC v11.2.0 for the spectral fits.

2.1. X-ray image

The two observations were merged, taking into account the relative aspect solution of the two data sets, with the CIAO task merge_all. From the resulting dataset, images were extracted in three spectral bands (Red = 0.5 - 1 keV; Green = 1 - 2 keV; Blue = 2 - 4 keV), covering the spectral range in which most source counts are detected. The images were then

| Table 1. NGC 821: Properties and Chandra ACIS-S Observation Log |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| M0_B10 (mag) | D (Mpc) | Diam.(") | N_H (cm^-2) | L_X (erg s^-1) | L_Hα (erg s^-1) | M_• (10^7 M⊙) | 0'5 (pc) | ObsID | Date | T_exp. (ks) |
| -20.71 | 23 | 2.6 | 6.2×10^{20} | <5×10^{40} | 2.8-5.8 | 55 | 4408 | Nov. 26, 2002 | 24.6 |
| ... | ... | ... | <1.3×10^{38} | ... | ... | ... | ... | 4006 | Dec. 1, 2002 | 13.3 |

a Unless otherwise noted, the galaxy properties are as listed in NED (NASA / IPAC Extragalactic Database); b Beuing et al 1999; c Gebhardt et al. 2003, rescaled for the distance adopted here; d Prugniel & Simien 1996; e Ho et al. 2003
smoothed using \textit{csmooth} with scales ranging from 1 to 20 pixels (0.5" - 10"). Fig. 1 shows the resulting ‘true-color’ X-ray image of a 3' field centered on NGC 821. Given the small region considered, no exposure correction was needed. The ellipse indicates the $D_{25}$ isophote from RC3. Most of the X-ray emission is concentrated in the central regions of the galaxy, and it includes a diffuse component, a few point-like sources, and a brighter central/nuclear region.

A higher resolution ‘true-color’ image of the central region of NGC 821 is shown in fig. 2a, where the data are displayed at the original observed resolution, without smoothing. This figure shows clearly a north-south elongated, hard central feature. Within the \textit{Chandra} aspect uncertainties (< 0.5''), this feature is centered on the nucleus of NGC 821, at RA=02h08m21.14s, Dec=+10°59′41.7″ (J2000, with uncertainty of 1.25″; from the 2MASS survey, as reported in NED). While a point-like source may be superposed on the southern tip of this elongated feature, the general form is suggestive of a two-sided bent jet, or S-shaped filament centered on the nucleus. This feature is approximately 8.5″ long, corresponding to \sim 1 kpc at the distance of NGC 821.

2.2. Point source detection and spatial analysis of the nuclear feature

We ran the CIAO \textit{wavdetect} tool on the full-band ACIS image, with scales between 2 and 4 pixels (1-2''), and detected 11 sources (above 3 $\sigma$) in the area shown in fig. 1. We assume a power-law spectrum with $\Gamma = 1.8$ and Galactic $N_H = 6.4 \times 10^{20}$ cm$^{-2}$ (Stark et al 1992), consistent with the emission of low-mass X-ray binaries (LMXBs) detected in early-type galaxies (see Kim & Fabbiano 2003). With this spectrum, the detected sources have 0.3-10 keV ‘emitted’ fluxes in the $1.4 \times 10^{-15} - 1.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ range, corresponding to luminosities of $1.2 \times 10^{38} - 1.2 \times 10^{39}$ erg s$^{-1}$, if they indeed belong to NGC 821. The faintest sources we can detect in our exposure of NGC 821 are at the upper end of the luminosity distribution of the populations of LMXBs detected in other elliptical galaxies with \textit{Chandra} (see e.g., Kim & Fabbiano 2004). Based on these results, we expect that most LMXBs in NGC 821 will have $L_X \leq 1 \times 10^{38}$erg s$^{-1}$ and therefore will be undetectable. These LMXBs, however, will contribute to the unresolved ‘diffuse’ galaxian emission.

In the central region shown in fig. 2a, there are four sources: the isolated point-like source at the north-east of the central complex (source NE, with 0.3-10 keV $L_X = 4.7 \times 10^{38}$ erg s$^{-1}$), and three sources in the central elongated emission region; these are identified by ellipses in fig. 2b, and named S1, S2 and S3, going from north to south. Further analysis (see below) demonstrates that these three central emission regions are not point-like and therefore cannot be explained with the serendipitous positioning of three luminous galaxian LMXBs in NGC 821. No discernible features can be seen in the optical image of NGC 821 at
the positions of these three sources. Using the Deep Survey source counts in the 0.5-2 keV band (Rosati et al 2002), the number of expected sources at fluxes of $\geq 1.4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ is $\leq 8 \times 10^{-3}$, so that chance detection of background sources is very unlikely. We cannot exclude a peculiar clustering of very luminous galaxian X-ray binaries, and future deeper data will be needed to explore this point further.

To establish the spatial properties of sources S1, S2 and S3, we have compared the spatial distribution of counts from each of them with that of the on-axis image of the quasar GB 1508+5714 (Siemiginowska et al 2003a). GB 1508+5714 can be used as a good representation of the Chandra ACIS-S PSF for our analysis, since the sources we are interested in are also at the aim point and similarly hard. With a count rate of $\sim 0.05$ count s$^{-1}$, the image of GB 1508+5714 (ObsID 2241) is not affected by pile-up, and contains 5,300 counts within 2” of the centroid of the count distribution. From this image, we determine the ratio of counts within the 1”-2” annulus to those in the central 1” radius circle to be $\text{Ratio(PSF)} = 0.043 \pm 0.001$ (1$\sigma$). The isolated NE source in this central field yields $\text{Ratio(NE)} = 0.057 \pm 0.054$ (from a total of 36 source counts), entirely consistent with that of our reference quasar, confirming that GB 1508+5714 gives a good representation of the PSF. Instead, the analogous ratios for the background-subtracted counts from S1, S2 and S3 demonstrate that the emission is extended in all cases. Using the wavdetect centroids, we obtain $\text{Ratio(S1)} = 0.81 \pm 0.26$, $\text{Ratio(S2)} = 0.94 \pm 0.27$, and $\text{Ratio(S3)} = 0.29 \pm 0.10$. The total number of source counts in the three cases are 56, 67, and 71, respectively, larger than for source NE. This comparison demonstrates that the spatial distributions of the source counts from S1 and S2 are definitely not consistent with the PSF. Although the spatial count distribution of S3 is more peaked and could contain a point-like component, diffuse emission is also present. This analysis reinforces our suggestion that the central emission feature is intrinsically elongated.

Given that the central emission (S2) is not consistent with a point-source, we can only estimate a 3$\sigma$ upper limit on the luminosity of a nuclear point-like AGN. We used a 1” × 1” (2 × 2 pixels) sliding cell over the entire area covered by the S-shaped feature, and assumed as the background level the maximum value detected in the sliding cell. This conservative approach yields a 0.3-10 keV $L_X < 4.2 \times 10^{38}$ erg s$^{-1}$ for a power-law spectrum with $\Gamma = 1.8$ and line of sight Galactic $N_H$. This limit indicates that a central point-like AGN would have a luminosity not exceeding that of normal LMXBs.
2.3. Spectral analysis

We extracted spectral counts both from the S-shaped feature (regions in fig. 2b) and the surrounding diffuse emission. The latter was taken from a 20” circular region centered on the nucleus, excluding the S-shaped feature and the NE source. The field background was extracted from a source-free 50” radius circular area 1.8’ from the nucleus of NGC 821. Spectral counts were extracted separately for the two observations using the CIAO script `acisspec`, which extracts a spectrum for both the source and the background region and creates weighted response matrices and ancillary response files (ARF). The ARFs were corrected for the time-dependent degradation in the ACIS quantum efficiency, using the CIAO script `apply_acisabs`. The source spectra from the two observations were then coadded (using the FTOOLS `mathpha`) to optimize the signal-to-noise ratio of the data. We used the FTOOLS `addarf` and `addrmf` to combine the responses with their appropriate weights.

Hardness ratios (HR1=M-S/M+S; HR2=H-M/H+M; where S=0.5-1 keV, M=1-2 keV, and H=2-4 keV) are plotted (with 1 σ statistical errors) in fig. 3, and compared with power-law and Raymond-Smith emission models. The hardness ratios of the S1, S2, S3 regions are all consistent with hard emission, either a power-law spectrum with Γ between ~1 and ~2.2, or thermal emission with $kT \sim 2-20$ keV. The diffuse X-ray emission of an elliptical galaxy is the combination of the soft emission of the hot ISM and of the hard emission of the population of LMXBs below our detection threshold (see e.g, Kim & Fabbiano 2003). In NGC 821 the hardness ratios of the diffuse emission are hard, suggesting a dominant LMXB component and little hot ISM.

With XSPEC, we fitted the data in the 0.3-10 keV energy range, rebinned to have at least 15 counts in each energy bin. For the S-shaped feature we adopted an absorbed power-law model (XSPEC model: `wabs(wabs(pow)))`, with $N_H$ consisting of both a Galactic and an intrinsic component. The results of the fits are listed in Table 2, with 90% errors on one significant parameter. The S-shaped emission is well fitted with a power-law spectrum with $\Gamma \sim 1.8$, typical of AGN spectra, although the uncertainties are large. As discussed in § 2.2, there could be a possibly unrelated point-like source at the southern tip of the S-shaped feature. Given the very few counts detected in our observations, we were unable to perform a meaningful spectral analysis, eliminating this source. However, the X-ray hardness ratios of fig. 3 show that the X-ray colors for the three regions S1, S2, S3 are remarkably similar, and consistent with the power-law model derived from the minimum-$\chi^2$ fit.

For the diffuse emission, following e.g. Kim & Fabbiano (2003), an optically thin thermal component was added to the power-law model (XSPEC model: `wabs(wabs(apec+pow)))`. The metal abundance of the thermal component was fixed to 0.3 times the solar value (keeping the elemental solar ratios of Anders & Grevesse 1989). The spectrum of the diffuse galaxian
emission (see Table 2) is consistent with a hot gas with a temperature $kT \sim 0.5$ keV, or cooler, typical of X-ray-faint early-type galaxy halos (e.g. Pellegrini & Fabbiano 1994, Irwin & Sarazin 1998). The power-law component, although ill-defined, is needed to obtain an acceptable fit for the diffuse emission, as clearly suggested by fig. 3; this is in agreement with the presence of an unresolved LMXB population. The $\chi^2$ for a simple thermal model ($APEC$; Smith et al 2001) is 25.8 with 12 degrees of freedom. Comparing this with the two-component $\chi^2$ by means of an F-test, we obtain a chance probability of $10^{-3}$. Fitting the diffuse emission with a single power-law model, also results in a worse $\chi^2$, but in this case the F-test probability is only 12%. While the two-component model is plausible for the diffuse emission, the rather low signal-to-noise ratio of our data does not allow a stronger discrimination among models. In the following discussion we will use the results of the two-component model fit; however, future deeper observation of NGC 821 are essential to firmly constrain the characteristics of the hot ISM in this galaxy.

Table 2 also lists the best-fit unabsorbed luminosities for the S-shaped feature, the total diffuse emission and the thermal component of the diffuse emission. The latter is only 10% of the total diffuse emission, indicating that NGC 821 is singularly devoided of hot ISM. Strictly speaking, we have a (90%) upper limit of $3.5 \times 10^{38}$ erg s$^{-1}$ on the luminosity of the gaseous component. The uncertainties on these luminosities reflect the uncertainties on the spectral parameters. From the emission measure of the soft thermal component we estimate an ‘indicative’ electron density $n = 4.1^{+10.9}_{-1.5} \times 10^{-3}$ cm$^{-3}$. While future deeper data are needed for a definite measure, the above estimate is useful for gaining first-cut insights on the nature of the S-shape feature, and in this spirit we will use it in the following discussion.

Table 2. Results of Spectral Fits

|                  | Net Counts (0.3-10 keV) | $\chi^2$/dof | $N_H$ ($\times 10^{21}$ cm$^{-2}$) | kT (keV) | $\Gamma$ | $L_X$ (0.3 – 10 keV) (erg s$^{-1}$) |
|------------------|-------------------------|--------------|----------------------------------|----------|---------|----------------------------------|
| S-shaped         | 141                     | 6.7/5        | $1.41^{+1.84}_{-1.41}$           | ...      | $1.82^{+0.71}_{-0.56}$          | $2.6 \pm 0.5 \times 10^{39}$ |
| ...              | ...                     | 6.5/5        | $0.75^{+2.34}_{-0.75}$           | 5.14$^{+50.00}_{-2.99}$ | ... | $1.9^{+1.4}_{-0.4} \times 10^{39}$ |
| Diffuse          | 174                     | 6.5/10       | $< 9.00$                         | 0.46$^{+0.33}_{-0.25}$ | 1.27$^{+1.13}_{-0.68}$       | $3.5 \pm 0.6 \times 10^{39}$ |
| Thermal          | ...                     | ...          | ...                              | ...      | ...                              | $3.4 \pm 0.1 \times 10^{38}$ |
3. Discussion

NGC 821 was observed with Chandra because the existing ROSAT upper limit on the X-ray luminosity of its nuclear SMBH implied extremely sub-Eddington nuclear emission. Our observations fail to detect a point-like source at the nucleus, down to a 3σ limit of $L_X(0.3-10 \text{ keV}) < 4.2 \times 10^{38} \text{ erg s}^{-1}$, $\sim 100$ times fainter than the ROSAT limit (see Table 1). The nucleus is not detected in the FIR or in $\text{H}_2$ (Georgakaki et al. 2001) arguing against a strongly obscured AGN (and against a nuclear starburst). There is also no sign of strong intrinsic absorbing column in the X-rays (see Table 2). The general AGN ‘quiescent state’ is also supported by the lack of radio continuum and optical line emission (Ho 2002; Ho et al. 2003). We detect instead an elongated, possibly bent, emission feature, strongly suggestive of a two-sided X-ray jet or S-shaped filament. This feature, extending over $\sim 1 \text{ kpc}$, has a hard spectrum consistent with a power-law with best-fit $\Gamma \sim 1.8^{+0.7}_{-0.6} (\alpha=0.8)$ or, if thermal, $kT > 2 \text{ keV}$. The X-ray luminosity of this feature is $\sim 1.9 - 2.6 \times 10^{39} \text{ ergs s}^{-1}$, corresponding to $\sim 5 \times 10^{-7}$ of the Eddington luminosity of the SMBH.

The nature of this intriguing elongated feature is investigated below, considering the possibilities of a two-sided jet (§ 3.1) and of thermal emission from gas heated by some form of energy deposition resulting from nuclear activity (§ 3.2 and 3.3).

3.1. Is a jet directly emitting the hard X-rays?

We discuss here the possibility that the S-shaped, hard emission centered on the nucleus of NGC 821 is a two-sided nuclear jet, as in radio galaxies. The spectral power-law slope of this emission has large uncertainties (Table 2), but is consistent with the X-ray spectra of other jets (Siemiginowska et al. 2003b; Sambruna et al 2004). However, unlike other extragalactic X-ray jets seen in luminous AGNs, where $L_X(\text{jet})/L_X(\text{AGN}) \sim 1-15\%$ (e.g., Schwartz et al. 2003), this ‘jet’ has no associated core X-ray source, implying $L_X(\text{jet})/L_X(\text{AGN}) > 6$. This lack of core emission also differs from other X-ray weak AGNs, where only a point X-ray source has been seen, typically in nuclei with radio detections, and these are usually modelled as Comptonized jets (Baganoff et al. 2001, Markoff et al. 2001, Fabbiano et al 2003). An exception is M 87, with its core-jet structure (Di Matteo, Carilli & Fabian 2001). The NGC 821 ‘jet’ could be similar to the somewhat steeper spectrum ($\Gamma \sim 2.3$) M87 jet (Wilson & Yang 2002), where the nuclear point-like AGN is fainter compared with the jet ($L_X(\text{jet})/L_X(\text{AGN}) \sim 2$). The 0.5 kpc (one-sided) scale of the NGC 821 ‘jet’ is also similar to the $\sim 1.5$ kpc of the M 87 jet, while most radio/X-ray jets extend over much larger distances, up to 300 kpc (Siemiginowska et al. 2002, 2003b). The NGC 821 ‘jet’ is two-sided, putting a limit on relativistic beaming and suggesting only a relatively slow
expansion ($v < 0.3c$; see e.g. Leahy 1991). The typical expansion velocity of the M87 jet is 0.5c, though small features can reach 4-6c (Biretta et al. 1995, 1999).

If a jet is present, we can make some simple estimates of the activity timescale and of the energetics involved. First, based on the above limit on the expansion velocity ($v < 0.3c$), we can relate the size of the jet to the activity timescale, finding that the jet may have been propagating for a few thousand years, assuming free unimpeded propagation. However, it is more likely that the jet is disrupted by interaction with the surrounding hot ISM ($n = 4.1^{+10.9}_{-1.5} \times 10^{-3} cm^{-3}$) as, for example, may be occurring in NGC 1316, which has a similar ISM density ($0.01 cm^{-3}$ in the jet disruption region; Kim, Fabbiano & Mackie 1998). Theoretical simulations (De Young 1993) of jet propagation into a homogeneous ISM indicate that hot ISM with densities of 0.01 particles cm$^{-3}$, similar to those of NGC 821, can significantly slow down a jet $10^5$ times more powerful than the one we may have in NGC 821.

Considering that the jet is likely to interact with the surrounding hot ISM, its size may be indicative of equilibrium between the ram pressure of the expanding jet and the thermal pressure of the hot ISM. We estimate the thermal pressure of the ISM from the diffuse X-ray emission to be $\sim 1.5 \times 10^{-11}$ dyn cm$^{-2}$ ($P_{th} = 2n_e kT$). Equating this pressure to the ram pressure $P_{ram} = \rho_{ISM} v^2$, where $\rho_{ISM}$ is the mass density of the ISM, we derive a jet expansion velocity $v$ of 0.043c, consistent with the upper limit mentioned earlier, and corresponding to a jet expansion (or activity) timescale of $3.8 \times 10^4$ years. The jet kinetic energy can be estimated from $E_{kin} = 0.5P_{ram}V$, where $V$ is the volume occupied by the jet. To calculate $V$, we assumed a jet thickness of 10 pc and a length of 1 kpc, obtaining $V = 2.7 \times 10^{60}$ cm$^3$. The kinetic energy input to this volume is then $4.1 \times 10^{49}$ erg, and by dividing this $E_{kin}$ by the jet expansion time we derive a kinetic luminosity of $1.7 \times 10^{37}$ erg s$^{-1}$. This is $\sim 100$ times smaller than the X-ray luminosity. However, this may be a lower limit if the jet is “overpressured”, as in M87 where the radio cavities in the cluster gas suggest overpressurization by a factor $\sim 3$ with respect to the cluster gas (Reynolds 1997; Reynolds et al 1996). However, M87 has a jet kinetic luminosity of $\sim 10^{43}$ erg s$^{-1}$, and a radiative power of $\sim 10^{42}$ erg s$^{-1}$, far more powerful jet than in NGC 821.

What would be the emission mechanism responsible for the S-shaped emission of NGC 821, in the jet hypothesis? Synchrotron emission is plausible: $\alpha_{radio-X} \leq 0.7$ (estimated from the radio flux limit of 0.5 mJy at 5 GHz and the X-ray flux at 1 keV); this $\alpha_{radio-X}$ is consistent with the X-ray slope, and is typical of the synchrotron slope observed in radio lobes (Peterson 1997). The usual problem of short synchrotron lifetime for X-ray producing electrons (Feigelson et al. 1981), imply local particle re-acceleration 0.5 kpc from the nucleus. A radio detection not far below the current limit is expected if synchrotron radiation produces the S-shaped emission at the center of NGC 821. Also in this respect, the NGC 821 emission
could be consistent with the M 87 jet: Wilson & Yang find $\alpha_{\text{radio}-\text{X}} \sim 0.9$ for the knots of the M87 jet, and they prefer a synchrotron origin for the X-ray emission of these knots.

However $\alpha_{\text{radio}-\text{X}} \leq 0.7$ is also consistent with the values of $\alpha_{\text{radio}-\text{X}}=0.7-0.8$ reported for knots in powerful jets by Sambruna et al. (2004) who favor an Inverse Compton origin for the X-ray flux for most of the jet knots, based on the X-ray fluxes lying above an extrapolation of the radio-optical slope ($\alpha_{\text{RO}} > \alpha_{\text{OX}}$). So the value of $\alpha_{\text{radio}-\text{X}} \leq 0.7$ may be merely a coincidence, and is in any case only a limit, so it is worthwhile to consider an Inverse Compton origin. The seed photons for Comptonization could be either from the synchrotron photons within the jet (the ‘self-Compton’ case) or could be the external to the jet photon field. In the self-Compton process the ratio of the synchrotron to Inverse Compton luminosities is given by the ratio of energy densities of the magnetic to the synchrotron radiation field. In equipartition both luminosities are of the same order, and since the observed X-ray luminosity is a factor of at least $10^3$ higher than the radio upper limit, the self-Compton case is excluded.

External Comptonization is also ruled out: Felten & Morrison (1966, eq.47) showed that $I_S/I_C = U_B/U_{ph}(\nu_C/\nu_S)^{(3-m)/2}$. Here $I_S$ and $I_C$ are intensities of synchrotron and inverse Compton emission, $U_B$ is the energy density of magnetic field, $U_{ph}$ the energy density of the external photon field, $\nu_C/\nu_S$ is the ratio between the frequency of the Compton scattered photon and the frequency of the synchrotron photon, $m$ is the power law index of the electron distribution, which is linked to the spectral index, $\alpha_s$ of the synchrotron emission so $m = 1 - 2\alpha_s$. We measure $I_C$ as the X-ray luminosity, and $U_{ph}$ from the starlight from the central cusp of NGC 821 (Gebhardt et al. 2003, rescaling their V-band luminosity density for the distance in Table 1). The maximum synchrotron luminosity, $I_S$ comes from the 0.5 mJy flux limit at 5 GHz, integrating over the $10^7 - 10^9$ GHz range with a slope of 0.7, and it is $< 4.5 \times 10^{36} \text{erg s}^{-1}$. $U_B$ can be derived from the radio upper limit assuming equipartition of the magnetic field and the electrons. Because the jet expansion is not relativistic we can assume the bulk jet Lorentz factor $\Gamma \sim 1$, simplifying comparison of the radiation fields. Assuming equipartition (Burbidge 1959) between the $U_B$ and the electron energy density, gives the minimum magnetic field (Krolik, 1999, eq. 9.21), which can be expressed as: $B_{\text{min}} = 4819.84(L_0/V)^{2/7}\nu_0^{-1/7}(\nu_0/\nu_l)^{(1-2\alpha_s)/7} \text{G}$, where in our case $\nu_0 = 5$ GHz, $\nu_l$ is the lowest frequency of the synchrotron emission, $L_0$ is the monochromatic luminosity at 5 GHz, and $V$ is the emission volume. We obtain: $B_{\text{min}} = 2.5 \times 10^{-5} \text{G}$, and $U_B = 2.5 \times 10^{-11} \text{erg cm}^{-3}$.

Considering the radial dependence of the optical photon field, we obtain a maximum predicted Inverse Compton emission due to scattering of the starlight ranging from $3.7 \times 10^{36} \text{erg s}^{-1}$ at 1 pc galactocentric radius, to $7.9 \times 10^{35} \text{erg s}^{-1}$ at 500 pc (the maximum jet extension). We conclude that Inverse Compton radiation would be a small contribution to the X-ray emission, suggesting that synchrotron may be the dominant emission mechanism.
if the S-shape feature is indeed a jet.

### 3.2. Is hot gas responsible for the hard emission?

We examine here the possibility that the origin of the hard S-shaped emission is thermal. We consider two scenarios suggested by analogies with other galaxies: thermal emission from the jet-ISM interaction, as in NGC 1052 (Kadler et al 2004), and shocks in the ISM, resulting from an outburst of nuclear activity, as suggested in the case of NGC 4636 (Jones et al 2002).

An elongated feature in the central galaxy region, of temperature $kT \sim 0.5$ keV, was found with *Chandra* in NGC 1052, the prototype elliptical galaxy LINER (also at a distance of 22.6 Mpc, Knapp et al. 1978). This feature has 10 times the flux of the S-shaped emission in NGC 821 ($\sim 3.5 \times 10^{-13}$ erg cm$^{-2}$s$^{-1}$), and about double the linear size (Kadler et al. 2004). In NGC 1052 the extended emission has radio and optical counterparts, and may be more fan shaped than linear, though the photon statistics are limited in this short (2.3 ksec) ACIS observation. Kadler et al. suggest shock heating of gas, converting some of the kinetic energy of the observed radio jet into X-ray emission. In the case of NGC 821, if a jet is present, it could similarly deposit energy in the surrounding ISM, causing it to produce the hard thermal emission. However, if its kinetic power is of the order of that estimated in Sect. 3.1 ($\sim 10^{37}$ erg s$^{-1}$), this mechanism cannot explain the luminosity of the hard thermal emission measured with ACIS ($L_X \sim 1.9 \times 10^{39}$ erg s$^{-1}$, Table 2). Unless a jet is present with orders of magnitude larger kinetic power, other sources of energy deposition are needed.

An alternative analogy is offered by the hot ‘arms’ of NGC 4636 (Jones et al 2002), a giant elliptical in Virgo with no reported nuclear activity or jets. These arms, having a larger spatial scale (8 kpc) and a lower temperature ($\sim 0.5 - 0.7$ keV) than the S-shaped feature of NGC 821, are two symmetric features crossing the galaxy center, discovered in the *Chandra* ACIS data of NGC 4636. The NGC 4636 arms are accompanied by a temperature increase with respect to the surrounding hot ISM, which led to the suggestion by Jones et al. of shock heating of the ISM caused by a nuclear outburst. We will discuss this process at the end of Sect. 3.3 below, in the unsteady accretion hypothesis. As discussed in § 2.3, the S-shaped feature of NGC 821 could similarly be hotter than its surroundings. Assuming a temperature of $kT=3$ keV for this feature, close to the lower limit suggested by our spectral fit (Table 2), we obtain a density $n = 8.59^{+1.06}_{-1.07}$ cm$^{-3}$ (errors at 90%). Using the best-fit value (and a temperature of 3 keV), we obtain a thermal pressure exceeding by a factor of $\sim 14$ that quoted in §3.1 for the surrounding hot ISM, suggesting a non-equilibrium situation, if only thermal pressures are involved. However, given the uncertainties in both $T$ and $n$, the thermal pressures of both S-shaped feature and surrounding ISM could be similar. It is
clear that deeper Chandra observations are needed to better constrain the energetics of this feature.

3.3. Is accretion present?

Whether it is a jet or hot shocked gas, the S-shaped feature of NGC 821 requires a considerable energy input, an obvious source of which is accretion onto the nuclear SMBH. Taking at face value the indication of the two-component fit of the circum-nuclear diffuse emission, which is consistent with the presence of a $kT \sim 0.5$ keV thermal component, we can estimate the nuclear accretion rate, in the steady spherical accretion scenario of Bondi (1952). This estimate is rough, because the gravitational capture radius (which depends on the gas temperature and on the mass of the SMBH; see the textbook by Frank, King & Raine 2002) is $r_{\text{acc}} \sim 3 - 23$ pc in our case, smaller than the physical resolution of the image (55 pc, Table 1). In this estimate of $r_{\text{acc}}$ we have allowed for the uncertainties in both the SMBH mass and $kT$. Based on the circum-nuclear gas temperature and density, that we estimate from the emission measure of the diffuse thermal component to be $n = 4.1^{+10.9}_{-1.5} \times 10^{-3}\text{cm}^{-3}$, the Bondi mass accretion rate (also following Frank, King & Raine 2002) is $\dot{M}_{\text{acc}} = 1.1 \times 10^{-7} - 2.0 \times 10^{-5} \text{M}_\odot \text{yr}^{-1}$, including again all the uncertainties in the SMBH mass, $kT$ and $n$. The corresponding luminosity is $L_{\text{acc}} = 6.2 \times 10^{38} - 1.1 \times 10^{41} \text{ergs s}^{-1}$, with the customary assumption of 10% accretion efficiency. The luminosity of the S-shaped feature is within this range, therefore in principle it could be explained by Bondi accretion of the hot ISM. This conclusion, however, is most certainly not correct, because comparison with independent optical data, discussed below, shows that our uncertain X-ray data may have led to underestimating the circum-nuclear gas density and therefore $\dot{M}_{\text{acc}}$.

Since the hot ISM is the thermalized integrated result of the stellar mass losses, as a minimum one expects the total stellar mass loss rate $\dot{M}_*$ within $r_{\text{acc}}$ to be accreted (there may also be gas inflowing from outside $r_{\text{acc}}$). $\dot{M}_*$ can easily be obtained from the luminosity density profile recovered from HST data for the central galaxy region (Gebhardt et al. 2003). Using a conversion factor from luminosity to mass loss rate for an old stellar population at the present epoch (e.g., Ciotti et al. 1991), this leads to $\dot{M}_* = 9.8 \times 10^{-6}$ and $2.6 \times 10^{-4} \text{M}_\odot \text{yr}^{-1}$, for the two extreme values of $r_{\text{acc}}$. These $\dot{M}_*$ values are respectively a factor of $\sim 90$ and $\sim 13$ larger than the $\dot{M}_{\text{acc}}$ values derived above for the same $r_{\text{acc}}$. Given that this estimate of $\dot{M}_*$ is quite robust, we must conclude that either the derivation of $\dot{M}_{\text{acc}}$ above is inaccurate, or the gas is not steadily inflowing within $r_{\text{acc}}$. The former possibility cannot be excluded with the present data, since in our calculation of $\dot{M}_{\text{acc}}$ we used a density $n$ value that is an average measured over a region extending much farther out than $r_{\text{acc}}$; $n(r_{\text{acc}})$ is likely to be
significantly higher than this average (e.g., a factor of $\sim 30$ times higher, for a $n \propto r^{-0.9}$ profile).

Assuming that it is just the stellar mass loss rate within $r_{\text{acc}}$ that is steadily accreted, accretion luminosities $> 20$ times larger than the observed $L_X$ of the hard emission are recovered (from $L_{\text{acc}} = 0.1 \dot{M}_\odot c^2$). Then, the ”solutions” proposed for the other X-ray faint nearby nuclei must be revisited for NGC 821. These are (a) accretion occurs but with low radiative efficiency (e.g., Narayan 2002); (b) accretion sustains a jet (this can be coupled again to a low radiative efficiency), whose total power is of the order of $L_{\text{acc}}$, as in the modeling for IC 1459 (Fabbiano et al. 2003) and M87 (Di Matteo et al. 2003); (c) accretion is unsteady and therefore the hot ISM in the nuclear region needs not be inflowing (Siemiginowska et al 1996; Janiuk et al 2004). In this case the feedback from the central SMBH can be either radiative (Ciotti & Ostriker 2001) or mechanical (Binney & Tabor 1995, Omma et al. 2004) and make accretion undergo activity cycles: while active, the central engine heats the surrounding ISM, so that radiative cooling and accretion are offset; then the central engine turns off, until the ISM starts cooling again and accretion resumes. NGC 821 may be in a stage of such a cycle when a nuclear outburst has recently occurred. Note that the accretion luminosity that is radiatively absorbed by the ISM during an outburst (Ciotti & Ostriker 2001) largely exceeds the hard thermal emission observed at the center of NGC 821.

The presence of the central S-shaped feature that is hotter than the surrounding gas is uncontroversial evidence that central heating is at work, and therefore some type of feedback from the SMBH is occurring. The unsteady scenario seems promising to fit adequately the case of NGC821, also because this galaxy is clearly hot gas poor, as if recently swept by an outburst-driven wind. From our ACIS-S data we estimate an upper limit of $\sim 4 \times 10^6 M_\odot$ on the amount of hot ISM, many orders of magnitude smaller than for hot gas rich ellipticals (see Fabbiano 1989).

4. Conclusions

We have shown that NGC 821, which is used as template of a quiescent and normal ‘old elliptical’ (see, e.g. Ho et al 2003) shows clear signs of energy deposition by the nucleus: an elongated, bent, kiloparsec-size S-shaped feature, centered (within the $\sim 1.5''$ errors) on the nucleus. This feature has a $(0.3-10 \text{ keV}) L_X \sim 1.9 - 2.6 \times 10^{39} \text{ergs s}^{-1}$, and a hard spectrum consistent with a power-law with $\Gamma \sim 1.8$, or thermal emission with $kT > 2$ keV. It may be embedded in a faint hot ISM with $kT \sim 0.5$ keV.

This feature could represent the faintest yet reported extragalactic jet. We can exclude
Inverse Compton (either of radio photons or of the central stellar photon field) as an explanation of the X-ray emission. If this feature is indeed a non-thermal jet, this leaves synchrotron as a possible explanation. The $\alpha_{radio-X} \leq 0.7$ would be consistent with this hypothesis. In the jet scenario, we constrain the activity timescale to be $\sim 4 \times 10^4$ years. We also estimate that in this jet most of the power may be in X-ray radiation, rather than kinetic energy.

Alternatively, the emission could be thermal. It is unlikely that the detected luminosity could result from interaction of a jet with the surrounding ISM in this galaxy (as may occur e.g., in NGC 1052, Kadler et al 2004) because the radio upper limits imply a total jet kinetic power orders of magnitude below the detected X-ray luminosity. A more likely scenario is that of S-shaped shocks of the hot ISM, driven by an outburst of nuclear activity, as suggested in the case of NGC 4636 (Jones et al 2002). The characteristics of this feature (luminosity and hard spectrum) suggest that it is driven by nuclear activity. Accretion from stellar mass loss rate in the circum-nuclear region would produce a luminosity well in excess of the detected one, suggesting either low radiative efficiency (e.g., Narayan 2002) or unsteady accretion (e.g., Binney & Tabor 1995; Siemiginowska et al 1996; Ciotti & Ostriker 2001). The second scenario is supported by the very small amount of hot ISM that may be present in NGC 821. It remains unexplored by the current modeling of outbursts through hydrodynamical simulations whether and how an S-shaped structure can be created.

It is only in the X-ray band, thanks to the Chandra spatial resolution, that signs of nuclear activity are found in NGC 821. Either jet or shock explanation of the S-shaped nuclear feature detected with Chandra suggest a fairly recent nuclear outburst, now spent. However, the present data are not deep enough to either allow a detailed study of the morphology and spectral parameters of this feature, or a model-independent detection of the circum-nuclear hot ISM. A significantly deeper Chandra exposure will be needed to answer the many questions raised by the present data. Deeper VLA data are also needed to set a tighter constraint to the jet scenario.

We thank the Chandra X-ray Center DS and SDS teams for their efforts in reducing the data and developing the software used for the data reduction (SDP) and analysis (CIAO). We have used the NASA funded services NED and ADS, and browsed the Hubble archive. This work was supported by NASA contract NAS 8–39073 (CXC) and NASA grant GO3-4133X.

REFERENCES

Anders, F. & Grevesse, N. 1989, Geochimica et Cosmochimica Acta, 53, 197
Arnaud, K.A., 1996, Astronomical Data Analysis Software and Systems V, eds. Jacoby G. and Barnes J., ASP Conf. Series vol. 101

Baganoff et al. 2001, Nature, 413, 45

Beuing, J., Dbereiner, S., Bhringer, H. & Bender, R. 1999, MNRAS, 302, 209

Binney, J. & Tabor, G. 1995, MNRAS, 276, 663

Biretta, J.A., Zhou, F. & Owen, F.N., 1995, ApJ, 447, 582

Biretta, J.A., Sparks, W.B. & Macchetto, F., 1999, ApJ, 520, 621

Burbidge, G. R. 1959, ApJ, 129, 849

Ciotti, L. & Ostriker, J. P. 2001, ApJ, 551, 131

Ciotti, L., Pellegrini, S., Renzini, A. & D’Ercole, A. 1991, ApJ, 376, 380

De Young D., 1993, ApJ 402, 95.

de Zeeuw, P. T. et al. 2002 MNRAS, 329, 513

Di Matteo, T., Allen, S. W., Fabian, A. C., Wilson, A. S. & Young, A. J. 2003 ApJ, 582, 133

Di Matteo, T., Carilli, C. L., Fabian, A. C. 2001, ApJ, 547, 731

Fabbiano, G. 1989, ARAA, 27, 87

Fabbiano, G. & Juda, J. 1997, ApJ, 476, 666

Fabbiano, G., Elvis, M., Markoff, S., Siemiginowska, A., Pellegrini, S., Zezas, A., Nicastro, F., Trinchieri, G.& McDowell, J. 2003, ApJ, 588, 175

Feigelson E.D., Schreier E.J., Delvaille J.P., Giacconi R., Grindlay J.E., & Lightman A.P., 1981, ApJ, 251, 31.

Felten, J. E. & Morrison, P. 1966 ApJ, 146, 686

Ferrarese, L. & Merritt, D. 2000, ApJ 539, L9

Frank, J., King, A. & Raine, D. J. 2002 Accretion Power in Astrophysics: Third Edition, [Cambridge: Cambridge University Press]
Georgakakis, A., Hopkins, A. M., Caulton, A., Wiklind, T., Terlevich, A. I. & Forbes, D. A. 2001, MNRAS, 326, 1431

Gebhardt, K. et al. 2000, ApJ Letters, 539, L13

Gebhardt, K. et al. 2003, ApJ, 583, 92

Graham, A. W., Erwin, P., Caon, N., Trujillo, I. 2001, ApJ, 563, L11

Irwin J.A., & Sarazin C.L. 1998, ApJ, 499, 650

Janiuk, A., Czerny, B., Siemiginowska, A. & Szczerba, R. 2004, ApJ, 602, 595

Jones, C., Forman, W., Vikhlinin, A., Markevitch, M., David, L., Warmflash, A., Murray, S. & Nulsen, P. E. J. 2002, ApJ Letters, 567, L115

Ho, L. C. 2002, ApJ, 564, 120

Ho, L. C., Feigelson, E. D., Townsley, L. K., Sambruna, R. M., Garmire, Go. P., Brandt, W. N., Filippenko, A. V., Griffiths, R. E., Ptak, A. F., Sargent, W. L. W. 2001, ApJ 549, L51

Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 2003, ApJ, 583, 159

Kim, D.-W. & Fabbiano, G. 2003 ApJ, 586, 826

Kim, D.-W. & Fabbiano, G. 2004, ApJ, in press (astro-ph/0312104)

Knapp, G. R., Faber, S. M. & Gallagher, J. S. 1978, AJ, 83, 139

Krolik J.H., 1999, *Active Galactic Nuclei* [Princeton:Princeton University Press].

Leahy, J. P. 1991 in Beams and Jets in astrophysics, Edited by P.A. Hughes. Cambridge Astrophysics Series, No. 19, [Cambridge: Cambridge University Press], p. 100

Loewenstein, M., Mushotzky, R. F., Angelini, L., Arnaud, K. A. & Quataert, E. 2001, ApJ Letters, 555, L21

Magorrian, J., Tremaine, S., Richstone, D., Bender, R., Bower, G., Dressler, A., Faber, S. M., Gebhardt, K., Green, R. & Grillmair, C. 1998, AJ, 115, 2285
Markoff, S., Falcke, H., Yuan, F. & Biermann, P. L. 2001, A&A, 379, L13
Martini, P., Pogge, R. W., Ravindranath, S. & An, J. H. 2001, ApJ 562, 139
Narayan 2002, astro-ph/0201260
Omma, H., Binney, J., Bryan, G. & Slyz, A. 2004, MNRAS, 348, 1105
Pellegrini S., & Fabbiano G. 1994, ApJ, 429, 105
Pellegrini, S., Baldi, A., Fabbiano, G. & Kim, D.-W. 2003a, ApJ, 597, 175
Pellegrini, S., Venturi, T., Comastri, A., Fabbiano, G., Fiore, F., Vignali, C., Morganti, R. & Trinchieri, G. 2003b, ApJ, 585, 677
Peterson B.M., 1997, An Introduction to Active Galactic Nuclei [Cambridge: Cambridge University Press].
Phinney 1983, PhD thesis, University of Cambridge, UK
Prugniel, P & Simien, F. 1996 A&A, 309, 749
Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V. & Sargent, W. L. W. 2001, AJ, 122, 653
Rees, M. J. 1984 ARA&A, 22, 471
Reynolds, C. S. 1997, PhD thesis, University of Cambridge, UK
Reynolds, C. S., Fabian, A. C., Celotti, A., & Rees, M. J. 1996, MNRAS, 283, 873
Richstone, D. et al 1998, Nature, 395, 14
Rosati, P. et al 2002, ApJ, 566, 667
Schwartz D.A., Marshall H.L., Miller B.P., Worrall D.M., Birkinshaw M., Lovell J.E.J., Jauncey D.L., Perlman E.S., Murphy D.W., & Preston, R. A., 2003, New AR, 47, 462
Siemiginowska, A., Bechtold, J., Aldcroft, T. L., Elvis, M., Harris, D. E., Dobrzycki, A. 2002, ApJ, 570, 543
Siemiginowska, A., Czerny, B. & Kostyunin, V. 1996, ApJ, 458, 491
Siemiginowska, A., Smith, R. K., Aldcroft, T. L., Schwartz, D. A., Paerels, F., & Petric, A. O. 2003a, ApJ, 598, L15
Siemiginowska, A., Stanghellini, Carlo; Brunetti, Gianfranco; Fiore F., Aldcroft T.L., Bechtold J., Elvis M., Murray S.S., Antonelli L.A., & Colafrancesco S., 2003b, ApJ, 595, 643.

Sambruna R.M., Gambill J.K., Maraschi L., Tavecchio F., Cerutti R., Cheung C.C., Urry C.M. & Chartas G., 2004, ApJ in press. astro-ph/0401475.

Smith, R. K., Brickhouse, N. S., Liedahl, D. A., Raymond, J. C. 2001, ApJ, 556, L91

Stark, A. A., Gammie, C. F., Wilson, R. W., Bally, J., Linke, R. A., Heiles, C. & Hurwitz, M. 1992, ApJS, 79, 77

van der Marel, R. P. 1999, AJ, 117, 744

Weisskopf, M., Tananbaum, H., Van Speybroeck, L. & O’Dell, S., 2000, Proc. SPIE 4012, p. 2 (astro-ph 0004127)

Wilson A.S., & Yang Y., 2002, ApJ, 568, 133

Fig. 1.— True color adaptively smoothed image of NGC 821. The ellipse marks the 25th mag isophote.
Fig. 2.— a) True color image of the central region of NGC 821, unsmoothed. The cross and surrounding circle represent the 2MASS nuclear position and uncertainty, from NED. b) A larger field image showing both the *wavdetect* source regions (yellow) and the spectral extraction regions for the ‘jet’ and the diffuse emission (light blue).
Fig. 3.— X-ray colour-colour diagram of ‘jet’ and diffuse emission regions. Typical hardness ratios for a power-law model ($\Gamma = 1 - 2.5$) are plotted in blue. Typical hardness ratios for a thermal model ($kT = 0.25 - 20$ keV) are plotted in red. Galactic line-of-sight absorption ($N_H = 6.4 \times 10^{20}$ cm$^{-2}$, Stark et al 1992) is assumed in both models.
This figure "fig1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0405358v1
This figure "fig2a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0405358v1
This figure "fig2b.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0405358v1