ARE THERE ADAFS IN NEARBY GIANT ELLIPTICAL GALAXIES?

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ABSTRACT

Recently it has been suggested that the hard x-ray power-law tails exhibited in the ASCA spectra of several nearby giant elliptical galaxies are caused by low-radiative efficiency accretion flows (ADAFs) onto a massive black hole in the centers of the galaxies. The estimated fluxes from these central ADAFs as derived from the ASCA x-ray spectral analyses indicate that they may be visible as x-ray point sources. We analyze archival ROSAT HRI images of three such galaxies, NGCs 1399, 4636, and 4696, to determine whether point x-ray sources consistent with ASCA -derived fluxes are present in the centers of the galaxies. We find that the upper limit for the flux of a central point x-ray source in each of these galaxies as determined by the ROSAT HRI data is only marginally consistent with the predicted flux inferred from the ASCA spectra. We suggest that although a central point source, such as a ADAF associated with a massive black hole, cannot be completely ruled out, they can only account for a fraction of the flux of the observed hard x-ray power law components.

Subject headings: galaxies: elliptical, x-rays

1. INTRODUCTION

The presence of both massive ($10^9 M_\odot$) black holes in the centers nearby elliptical galaxies (Kormendy and Richstone 1995) and extensive atmospheres of $kT \sim \text{keV}$ gas (Trinchieri, Fabbiano, and Canizares 1986) suggest that these galaxies should also possess central point x-ray sources of luminosities of $L_x \sim 10^{45}$ erg sec$^{-1}$ associated with the accretion of gas onto the black hole. In reality these galaxies exhibit x-ray luminosities $< 10^{39}$ of this magnitude, including the contribution from the hot galactic atmosphere (Pellegrini 1999). This fact has motivated the development of scenarios where accretion onto the central black hole occurs via “advection-dominated accretion accretion accretion flows” (ADAFs) (e.g. Narayan and Yi 1995; Abramowicz et al. 1995; DiMatteo et al. 2000). By means of poor collisional coupling between very hot ions and radiatively efficient electrons, and the presumption of a coexisting wind or outflow (Blandford and Begelman 1999), such scenarios result in accretion onto the black hole at a small fraction of the Bondi (1952) rate, producing a correspondingly small x-ray luminosity. Furthermore, hard power-law components (photon index $\Gamma \sim 0.6 - 1.5$) detected in the ASCA x-ray spectra of six nearby giant elliptical galaxies with radio-quiet cores have been suggested to be produced by an ADAF atmosphere around their central black holes (Allen, DiMatteo, and Fabian 2000, hereafter ADF2000). These spectra are for the entire galaxies, and although contamination from from galactic x-ray binaries is possible, ADF2000 suggest that the power-laws exhibited in the spectra are significantly harder than that produced by x-ray binaries or from standard AGN. If these hard power-laws really are black hole-ADAF signatures, then based on the ADF2000 estimates for their photon indices and normalizations they could appear as relatively strong point sources in the ROSAT HRI: although the ADAF mechanism can suppress a very large x-ray brightness, in principle it can still be detected. Some of these galaxies offer circumstantial evidence of nuclear activity. The HRI analysis of M87 by Reynolds et al. (1996) and Harris et al. (1998) combined with the ADF2000 spectral analysis make a plausible case for the association of M87’s hard power-law tail with a massive black hole ADAF (see ADF2000). M87 also possesses a prominent x-ray and radio jet, thus energetic activity associated with a central source is clearly indicated. The cores of NGC 1399, 4636, and 4696 are much weaker in radio power than M87 (Slee et al. 1994).

We consider whether the preponderance of the observed hard x-ray emission in some of the galaxies discussed in ADF2000 should be attributed to a massive black hole-ADAF. DiMatteo et al. (1999; hereafter D99) determined upper limits for three of these galaxies, NGCs 4472, 4636, and 4649; these were comparable to the ASCA fluxes in the case of NGCs 4472 and 4649, but in the case of NGC 4636 the HRI upper limit was a factor of two lower than the ASCA measurement. In this article we present analysis of ROSAT HRI images of additional ADAF candidates from the list of the ADF2000 galaxies, NGCs 1399, 4696, as well as NGC 4636. We find that the upper limit for the flux of a central point x-ray source in each of these galaxies as determined by the ROSAT HRI data is either smaller than the predicted flux inferred from the ASCA spectra, or only marginally consistent. Our result for NGC 4636 is comparable to that determined by D99, i.e., lower than the
ASCAs inferred flux by a factor of $\sim 1.4$. Thus, if ADAF sources associated with central black holes exist in these galaxies, they can only account for only a fraction of the hard power-law x-ray emission observed in the galaxies’ ASCA spectra.

2. OBSERVATIONS

The observations were obtained from the HEASARC ROSAT data archive, and are summarized in Table 1. The observations were subjected to the “dewobbling” recipe described in the PROS User Guide (1998) in order to improve the spatial resolution of the HRI image. This procedure groups the HRI photons by phase bins of the telescope’s 402 sec wobble period, determines a separate image for each of these phase bins, and then reassembles the images to a common image centroid. We have checked whether this scheme recovers the ROSAT/HRI point source response function: in the case of NGCs 1399 and 4636, point sources within a few arcmin of the HRI field center appear to have a corrected FWHM of $\sim 6''$. Therefore we have used this FWHM for the convolution of the model galactic surface brightness, including a central point source (see §3).

In the case of NGC 4696, there is no point source of sufficient strength within the HRI image field to check the recovery of the HRI resolution, so we have assumed a $6''$ FWHM for model fitting. The effective observation times are calculated from the good time intervals covered by the list of wobble phases used to compose the dewobbled image.

3. SPATIAL ANALYSIS AND RESULTS

Using the dewobbled images, we extract azimuthally-averaged counts per HRI pixel in 24 2.5''wide annulæ centered on the galaxies. The x-ray centers are determined by the peak of x-ray contours of the surface brightness of the galaxy core. We note that in the cases of NGCs 1399 and 4636 the ROSAT x-ray position agrees within $\sim 2''$ of their optical centers (the putative central black hole position), while the x-ray peak for NGC 4696 is within $\sim 6''$ of both the HST position for the nucleus and the location of the nuclear radio source (Sparks, private communication; O’Dea et al. 1994). This may be consistent with the ROSAT pointing accuracy, however if the x-ray peak is not associated with the true galactic nucleus, the upper limit to the flux from an ADAF associated with a nuclear black hole is much smaller than the value we determine from our model that we describe below. From each annulus we subtract a background determined from a 5'' wide annulus at radius of $\sim 12''$. The pixel brightness in a given annulus is assigned to the mean radius of the annulus. Background point sources are removed where necessary. The data points are fit to a $\beta$-profile model for the extended galactic x-ray surface brightness, $S_X = S_{X0}(1 + r^2/r_c^2)^{3\beta-1/2}$, and a central central point source, both convolved with the dewobbled ROSAT HRI point source response function of $6''$ (Brown and Bregman 1999). This composite model is a simple representation of the essential question that we wish to answer: to what extent must a central point source be included with extended emission to describe the galactic surface brightness? Note that the $\beta$-profile model may be less than ideal to describe the extended emission - it cannot account for asymmetry and substructure (e.g., NGC 4696) - however, we are not attempting to find the best model to describe the global x-ray emission, but a measure as to the point-source like behavior of the center compared to a flat emission “core”. Given the core-like behavior of the emission at small radii, and the power-law like behavior at large radii, the $\beta$-profile model is a reasonable proposition as a gross description of the extended emission of the galaxies.

The $\beta$-profile + point source model best fit results, and the 99% confidence upper limits to the count rates from a central point source in each galaxy are listed in Table 1. These are determined by increasing the magnitude of fixed point source until the fit for the remaining $\beta$-profile parameters yields a $\Delta \chi^2 > 6.64$ above the best fit. The maximum point source strength determined in precisely the same manner for the undewobbled images is substantially lower for all three galaxies, by factors of $1.5-7$. Plots of the surface brightness for all three galaxies, along with the profiles of the best fit models and those with the upper limit of central point source brightness, are given in figures 1-3.

Figures 4-6 shows the 2-10 keV flux and photon index $\Gamma$ for the ASCA power-law components determined by ADF2000 (including 90% confidence limits on a single interesting parameter) compared to our upper limits for the flux determined from the HRI count rates for a central point source, as a function of $\Gamma$. These PIMMS estimates are shown for the column absorption densities given by the maximum value of either Stark et al. (1992) or the best-fit values derived from analysis of ROSAT PSPC spectra (Davis and White 1996; see Table 2).

4. DISCUSSION AND SUMMARY

We note that for all three galaxies the optimal values for the ASCA flux and photon index fall above our HRI upper flux limits, including effects of absorption, although the large uncertainties in photon index allow for marginal consistency between the ASCA values and the upper flux limits (e.g., NGC 1399). ADAF models for the hard x-ray emission component suggest a photon index of $\Gamma \sim 1.4$, and the ensemble average of ASCA results for the putative ADAF power law components is $\Gamma \sim 1.2$ (ADF2000). Our results indicate that for NGCs 1399 and 4696 photon indices $\Gamma > 1$ are ruled out unless the flux from a putative ADAF is a fraction ($\sim 0.40-0.70$) of the ASCA power-law component. In the case of NGC 4636, our result approximately agrees with an earlier analysis by D99, namely that at the optimal photon index the HRI upper limit for the flux is significantly lower (here a factor of $\sim 1.4$) than the measured ASCA flux, including the effects of measured absorption. Unlike the other two galaxies, photon indices $\Gamma < 1$ for the ASCA power-law component are ruled out. A “universal” photon index of $\Gamma \sim 1.2$ to describe the bulk of the hard x-ray emission from an ADAF source in all three of these galaxies is not consistent with the HRI upper flux limits. In the case of NGC 4636, the larger photon index may be consistent with the presence of a significant contribution in the power-law component from other sources, such as binary x-ray sources. ADF2000 noted that extrapolation of the $L_X/L_B$ relation of Fabbiano and Trinchieri (1985) measured for irregular and spiral galaxies of the power-law components of NGCs 1399 and 4636 was consistent with substantial contribution from x-ray bina-
The galaxy was best fit with a two-temperature plasma model, while the core was well described by a single temperature plasma of 1 keV. This outer region overlaps with the 6′ circular extraction region for the ASCA GIS used in the analysis of this galaxy by ADF2000.

ADF2000 also suggest that the flat photons measured for these sources by ASCA are central ADAFs with intrinsic photon indices of $\Gamma \sim 1.4$, flattened by anomalously high absorption along the cores of these galaxies of $N_H \gtrsim 10^{21}$ cm$^{-2}$. However, such an excess is not indicated from ROSAT PSPC observations of Davis and White (1996), nor is excess absorption observed by the ROSAT PSPC in giant elliptical galaxies containing cooling inflows located at low galactic column, such as NGC 1399 (Jones et al. 1997; David et al. 1994). Buote (2000) has suggested a resolution of the disagreement between the ASCA and ROSAT column estimates by oxygen absorption at 0.4 – 0.8 keV caused by a warm component of gas in the core of NGC 1399, associated with mass dropout in the cooling inflow. As all three of the galaxies we consider here have cooling inflows, we leave it as a possibility that this effect has supressed the brightness of their central ADAFs as observed by the ROSAT/HRI.

We present the HRI spatial analysis of the central regions of three nearby giant elliptical galaxies in which hard power-law components have been detected in the ASCA x-ray spectrum. We find the overlap of error regions for the ASCA power-law flux and photon indices with our HRI-determined 99% confidence upper flux limits for a central point source is either marginal or small for all three galaxies. Thus associating the entirety of this hard x-ray component with a central x-ray source (like an massive black hole ADAF) is unlikely, unless anomalously high absorption, possibly related to the cooling inflows in the cores of each of these galaxies, absorbs a substantial amount of the ADAF x-ray flux in the ROSAT passband. Otherwise, if we require that the range of possible values of $\Gamma$ as determined by ADF2000 is consistent with our upper limits for the galaxies’ flux, then the flux attributed to the central source can only be a fraction of the measured ASCA flux for the observed power-law component.

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| Target NGC | ROSAT Seq. ID | Exposure (ksec) |
|------------|---------------|-----------------|
| 1399       | rh600831a01   | 76699           |
| 4636       | rh600218a01+a02 | 11813         |
| 4696       | rh700320a01   | 13822           |

Table 1

The log of ROSAT analyzed observations for each galaxy

Table 2

The beta-profile + central point source best fit results, and the 99% confidence level upper limits for ROSAT HRI count rates. Also included are the galaxies’ absorption column densities, taken to be the larger of the measured values of Stark et al. (1992) and the best fit values for ROSAT PSPC spectra analyzed by Davis and White (1996).
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Fig. 1.— Plot of the radial surface brightness for NGC 1399, along with the profiles of the best fit of a $\beta$-profile + central point source model (dotted line; best-fit values of parameters given in legend), and that with the upper limit of central point source brightness (dashed line).
Fig. 2.— Plot of the radial surface brightness for NGC 4636; lines and legend identical to figure 1.

NGC 4636

ROSAT/HRI (6" FWHM)

counts/pixel

\[ r_c = 6.0 \text{ arcsec} \]

\[ \beta = 0.38 \]

\[ S_g = 1.3 \text{ cnt arcsec}^{-2} \]

\[ S_p = 0.9 \text{ cnt arcsec}^{-2} \]
Fig. 3.— Plot of the radial surface brightness for NGC 4696; lines and legend identical to figure 1.

\[ r_c = 6.1 \text{ arcsec} \]
\[ \beta = 0.36 \]
\[ S_g = 2.8 \text{ cnt arcsec}^{-2} \]
\[ S_p = 0.0 \text{ cnt arcsec}^{-2} \]
Fig. 4.— The curve indicates the upper limit to the 2-10 keV flux for a central point source in NGC 1399, assuming a power-law spectrum, derived from the HRI count rate upper limit (99% confidence limit), and includes the value of absorption column taken from Table 2. The abcissa is the power-law photon index $\Gamma$. The data point plotted is the best fit value for flux and $\Gamma$ determined from the ASCA spectrum analyzed by ADF2000, with 90% confidence error bars.
Fig. 5.— Plot identical to Fig. 4 for NGC 4636; with absorption taken from Table 2.
Fig. 6.— Plot identical to Fig. 4 for NGC 4696.