RELATIVE SIZES OF X-RAY AND OPTICAL IMAGES OF ELLIPTICAL GALAXIES: CORRELATION WITH X-RAY LUMINOSITY

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Abstract

Optical parameters of elliptical galaxies are tightly correlated, but their x-ray parameters vary widely. The x-ray luminosity $L_x$ ranges over more than an order of magnitude for ellipticals having similar optical luminosity $L_B$. The source of this scatter has been elusive. We show here that the dispersion in $L_x$ for fixed optical luminosity $L_B$ correlates strongly with the dimensionless ratio of the sizes of the x-ray and optical images, $r_{ex}/r_e$. A distance-independent variant of this correlation is $L_x/L_B \propto (r_{ex}/r_e)^{0.60\pm 0.30}$. This correlation may be a natural result of mergings and tidal truncations that occurred during the early formation of ellipticals in groups of galaxies. The shapes of the x-ray images also vary: some are compact (e.g. NGC 4649, 7626, 5044), others diffuse (e.g. NGC 4636, 1399).

Subject headings: galaxies: elliptical and lenticular – galaxies: cooling flows – galaxies: evolution – galaxies: halos – x-rays: galaxies

1. INTRODUCTION

X-ray and optical luminosities of massive elliptical galaxies ($L_B \geq 1.6 \times 10^{44}$ erg s$^{-1}$) are correlated, $L_x \propto L_B^p$, with $p \approx 2.0 \pm 0.2$ (Eskridge, Fabbiano, & Kim 1995a). The exponent $p \approx 2$ can be explained as thermal x-ray emission from interstellar gas heated to the galactic virial temperature $T \sim 10^7$ K (e.g. Tsai & Mathews 1995). However, the scatter of $L_x$ about this correlation is enormous, considerably exceeding an order of magnitude (e.g. Eskridge, Fabbiano, & Kim 1995a). Many attempts have been made to understand the reason for this large scatter but no single explanation is generally accepted (D’Ercole et al. 1989; White & Sarazin 1991; Ciotti et al. 1991; Mackie & Fabbiano 1997).

In our recent studies of the gas-dynamical evolution of the hot interstellar gas in ellipticals, we have found that most or all bright ellipticals contain an additional component of very old and extended hot gas in addition to gas ejected from currently evolving galactic stars (Brighenti & Mathews 1997). This realization – and the known variation in the size of x-ray images (Loewenstein 1997) – led us to speculate that the variation in $L_x$ could result from the transfer of hot gas and dark matter between galaxies when they resided in small, elliptical-rich groups. Most of these groups observed today are dominated by a single large elliptical which has evidently grown in size and prominence at the expense of other group galaxies by some combination of mergers and tidal stripplings. These dynamical developments occur rapidly during the early phases of group formation (Merritt 1985). Some of these group-dominant ellipticals have now joined richer clusters and brought along their relative allotments of hot halo gas. With this evolutionary hypothesis in mind, we were led to consider the relative sizes of the x-ray and optical images as a possible explanation for the large range in $L_x$ for given $L_B$. In this letter we show that the relative sizes of the images does indeed correlate strongly with residuals measured from the $L_x \propto L_B^p$ relation.

2. RATIO OF EFFECTIVE RADIi AND $L_x$

Optical sizes of elliptical galaxies are characterized by the effective radius $r_e$ defined as the radius that includes half the projected light. Similarly we define an effective x-ray radius $r_{ex}$ that includes half the total x-ray luminosity $L_x$ in projection. Unfortunately, relatively few elliptical galaxies have been observed with sufficient spatial resolution to allow a determination of $r_{ex}$ and, for those galaxies having sufficient resolution, $r_{ex}$ is not explicitly provided. In a search through the recent literature we have identified eleven ellipticals having well resolved x-ray surface brightness distributions $\Sigma_x(r)$ and for which the local background radiation has been removed. We have determined the effective radius $r_{ex}$ from the defining integral condition

$$\int_0^{r_{ex}} \Sigma_x(r)2\pi rdr = \frac{1}{2} \int_0^{r_{in}} \Sigma_x(r)2\pi rdr$$

where $r_{in}$ is the outermost extent of the (background-subtracted) x-ray image. In computing the integrals
above we assume that $\Sigma_x$ is constant within the innermost observed radius. Our values of $r_{ex}$ are insensitive to this inner extrapolation.

In Table 1 we list the ellipticals for which $r_{ex}$ can be accurately determined and the appropriate reference for $\Sigma_x(r)$ in the final column. For several galaxies – NGC 720, 4649, and 5044 – $\Sigma_x(r)$ has been determined by more than one detector or method. In the following discussion we have determined $\Sigma_x(r)$ from the uppermost entry in Table 1, but our results are not sensitive to this choice. As can be seen from Table 1, the x-ray effective radius $r_{ex}$ is relatively insensitive to the slightly different band passes of the ROSAT and Einstein detectors.

For optical and x-ray luminosities and assumed distances in Table 1 we have chosen values listed by Eskridge et al. (1995a). We have made this choice for several reasons: the wide scatter in $L_x$ is clearly seen in these data, a uniform procedure has been used to determine $L_x$, and the substantial prior investment with these data by Eskridge et al. (1995a, 1995b) in seeking statistical correlations. As with the observed $L_x$ values, for group galaxies we regard the hot gas as an intrinsic property of the central galaxy, not of the group or poor cluster.

In Figure 1a we show the scatter of these eleven well-resolved galaxies around the mean correlation line $L_x \propto L_B^{2.0 \pm 0.2}$ determined with the E-M algorithm by Eskridge et al. (1995a) using all observed ellipticals in their sample (see their Figure 6a). Most of our galaxies lie above the mean correlation since well-resolved ellipticals tend to be intrinsically more luminous. We define residuals in Figure 1a as the vertical (logarithmic) distance of each galaxy from the mean correlation line. In Figure 1b we plot these residuals against the dimensionless ratio of the x-ray to optical sizes, $r_{ex}/r_e$. A general correlation is apparent in Figure 1b, indicating that the scatter in Figure 1a is in fact largely due to the variation of the relative sizes of the images. The dashed line in Figure 1b is a linear fit to the data assuming uniform errors. The obvious correlation in Figure 1b is also real: a Spearman rank-order test indicates a probability of only 0.02 that eleven randomly chosen points would produce a correlation of this strength. This probability would be even smaller if the deviant outlier NGC 5044 were removed or if we had used the ASCA data of Fukazawa et al. (1996) to determine $r_{ex}$. We prefer the ROSAT data of David et al. (1994) for NGC 5044 since ROSAT has somewhat superior spatial resolution.

A distance independent version of the luminosity-size correlation is shown in Figure 2 which can be fit with least squares with slope $L_x/L_B \propto (r_{ex}/r_e)^{0.60 \pm 0.30}$. Since $r_e$ and $L_B$ have a limited range in the sample, this correlation is driven primarily by $L_x$ and $r_{ex}$. There is no obvious reason why NGC 5044 does not participate in the correlation. Because the x-ray emissivity varies as the square of the plasma density, we expect quite generally $L_x \propto (n_x)^2 r_{ex}^3 \propto M_x^2 r_{ex}^3$ where $M_x$ is the mass of hot gas. Therefore, the correlation in Figure 2 implies a non-trivial relationship between $\langle n_x \rangle$ or $M_x$ and $r_{ex}$ that depends on some internal attribute of the galaxies or their history. Evidently, $r_{ex}/r_e$ is a “second parameter” in the variation of $L_x$ with $L_B$, i.e., $L_x \propto L_B^{2}(r_{ex}/r_e)^{0.60 \pm 0.30}$.

The outer x-ray isophotes of these galaxies are influenced by the assumed background level which depends on their local environment. To explore the sensitivity of the correlation in Figure 2 to the choice of background level, we arbitrarily truncated the images of the galaxies at $r = r_t$ and re-evaluated $r_{ex}$ and $L_x$ as functions of $r_{cut}$. Figure 3 shows how rapidly $r_{ex}$ and $L_x$ approach the values in Table 1 as $r_{cut} \to r_t$. There is clearly a range in the degree of compactness among the x-ray images. While most galaxies appear to be well resolved, values of $r_{ex}$ and $L_x$ for NGC 7619, 2563, 1399 and 4636 are still varying appreciably with projected radius at $r = r_t$. These galaxies also have the largest $r_{ex}/r_e$ in Table 1 and large $r_{ex}/r_e$ (Figure 2). Several explanations are possible for this variety of convergence rates: it may be a real effect demonstrating a lack of x-ray homology, it could arise from errors or inconsistencies in the adopted background levels or it could be an artifact of environmental influences on the hot gas including isophotal asymmetries. NGC 4636, noticeably low in both plots in Figure 3 and known to be interacting with environmental gas, has a markedly asymmetric x-ray image (Trinchieri et al. 1994). However, suppose that for some reason the assumed background was too large for these four galaxies and that $r_{ex}$ and $L_x$ actually continue to increase at $r > r_t$. At $r = r_t$, the slopes $d \log L_x/d \log r_{ex}$ for these four galaxies are 0.6, 0.8, 0.7, and 0.5 respectively. If the x-ray images for these galaxies extend beyond $r_t$ in a smooth way, their points in Figure 2 would move toward the upper right, approximately along the correlation. Therefore, errors in choosing the local x-ray background are unlikely to undermine the correlation in Figures 1b and
2 nor can they be large enough to change $L_x$ by almost two orders of magnitude, the full range represented in these figures. The other seven ellipticals are better resolved and less subject to background errors. We conclude that the radial variation of x-ray emission differs among these ellipticals: some are compact (e.g. NGC 4649, 7626, 5044), others diffuse (e.g. NGC 4636, 1399).

3. DISCUSSION

White and Sarazin (1991) examined many possible causes of the large dispersion in $L_x$. Although they did not identify an intrinsic property of ellipticals that correlated with residuals in the $L_x, L_B$ diagram, they did find that ellipticals with low $L_x/L_B$ have $\sim 50\%$ more neighbor galaxies than those with high $L_x/L_B$. Assuming that the high incidence of neighbor galaxies indicates a higher galactic space density, White and Sarazin proposed that the scatter in $L_x$ may be related to some environmental effect such as ram pressure stripping or galactic mergers. Mackie & Fabiano (1997) also find a weak correlation of $L_x/L_B$ with the apparent local density of galaxies. By comparison, the correlation we have found does involve a fundamental intrinsic property of the galaxies, $r_{ex}/r_e$. Moreover, if our motivating conjecture of dynamical halo mass transfer is correct, the observed disparity in $r_{ex}/r_e$ among ellipticals is likely to originate not in regions of very high density (i.e. rich clusters) where some of the bright ellipticals currently reside, but in group environments where the ellipticals were originally formed and where mergers and tidal interactions were more efficient. Low orbital velocities and hot gas densities in groups make ram stripping ($\propto pv^2$) less likely there but it could account for some lowering of $L_x$ in rich cluster environments (e.g. NGC 4406 in Virgo).

D’Ercole et al. (1989) and Ciotti et al. (1991) suggested that large variations in $L_x$ for given $L_B$ can occur if the interstellar gas in ellipticals is currently undergoing a dynamic readjustment from wind solutions (low $L_x$) to subsonic flows (high $L_x$). Initial galactic wind solutions occur in their models because of the large Type Ia supernova rates assumed at early times. The precise time that ellipticals undergo the transition from wind to subsonic flow, according to their proposal, depends on variations among other galactic parameters such as the mass and structure of the dark halos or the stellar mass to light ratio, resulting in the scatter in Figure 1a. However, Loewenstein & Matthews (1991) showed that the current iron abundance in the hot interstellar gas would be 3 - 4 times solar it the Type Ia supernova rate had been large enough to drive winds at earlier times. Since this is much larger than the mean iron abundance in ellipticals found by ASCA, $\lesssim 0.5$ solar (Loewenstein 1997), a nearly synchronized dynamical readjustment of interstellar gas in ellipticals is unlikely to be responsible for the wide scatter in Figure 1a.

Our discovery of the $(r_{ex}/r_e)$-residual correlation was motivated by the possibility that ellipticals exchange hot gas and dark matter during dynamical interactions in small groups, but it is not easy to demonstrate conclusively that this explanation is correct. The notion that halo material is disproportionately allocated to group ellipticals is consistent with observations of elliptical-rich groups in which the x-ray emitting gas is almost exclusively associated with the central group-dominant elliptical (Mulchaey et al. 1996; Mulchaey & Zabludoff 1997). Dynamical studies of evolving galaxy groups (Merritt 1985; Bode et al. 1994; Garcia-gomez et al. 1996; Athanassoula et al 1997; Dubinski 1997) describe how group-dominant ellipticals grow at the expense of other member galaxies either by wholesale mergers or from tidally truncated halo debris. Mergers were rapid initially since all group galaxies had massive halos, but later subsided as non-dominant galaxies began to interact primarily with the halo of the group-dominant galaxy; this explains the large number of groups still present today (Zabludoff & Mulchaey 1997). The relative amount of dark matter and hot halo gas acquired by group-dominant ellipticals is stochastically variable. The correlation in Figure 2 may be a natural outcome of this group evolution in which $L_x$ and $r_{ex}$ in bright dominant ellipticals are enhanced while $L_x$ and $r_{ex}$ are reduced in donor ellipticals. Since the dark halo and hot gas extend far beyond $r_e$, relatively little stellar matter is tidally exchanged; donor and receiver ellipticals may have similar $L_B$.

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REFERENCES


Fig. 1.— (a) Location in the $L_x$, $L_B$ plane of eleven ellipticals having well-resolved x-ray images. The line shows the mean correlation of all ellipticals observed with Einstein. (b) Ratio of x-ray and optical effective radii plotted against vertical residuals from the correlation line in Fig 1a. The dashed line is a linear fit to the data.

Fig. 2.— Distance-independent plot of $L_x/L_B$ against $r_{ex}/r_e$.

Fig. 3.— (a) Variation of the effective x-ray radius $r_{ex}$ as the abbreviated image radius $r_{cut}$ increases toward the outer radius of the x-ray image $r_t$; (b) Variation of $L_x$ with $r_{cut}/r_t$. The galaxy lists in both plots are in descending order of $r_{ex}$ or $L_x$ evaluated at $r_{cut}/r_t = 0.5$.

This 2-column preprint was prepared with the AAS LaTeX macros v4.0.
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<th>log $L_x$ a (erg s$^{-1}$)</th>
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aFrom Eskridge, Fabbiano, & Kim (1995a).
bEffective radii from Faber et al. (1989).
dBackground normalization “b”.
eBackground normalization “a”.

Table 1
OPTICAL AND X-RAY PROPERTIES OF ELLIPTICAL GALAXIES