

# Global X-ray emission and central properties of early type galaxies

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**Abstract.** *Hubble Space Telescope* observations have revealed that the central surface brightness profiles of early type galaxies can be divided into two types: “core” profiles and featureless power law profiles, without cores. On the basis of this and previous results, early type galaxies have been grouped into two families. One consists of coreless galaxies, which are also rapidly rotating, nearly isotropic spheroids, and with disk-like isophotes. The other is made of core galaxies, which are slowly rotating and boxy-distorted. Here I investigate the relationship between global X-ray emission and shape of the inner surface brightness profile, for a sample of 59 early type galaxies. I find a clear dichotomy also in the X-ray properties, in the sense that core galaxies span the whole observed range of  $L_X$  values (roughly two orders of magnitude in  $L_X$ ), while power law galaxies are confined to  $\log L_X (\text{erg s}^{-1}) < 41$ . Moreover, the relation between  $L_X$  and the shape of the central profile seems to be the strongest among the relations of  $L_X$  with the basic properties characterizing the two families of early type galaxies. As an example,  $L_X$  is more deeply connected with the shape of the central profile than with the isophotal shape distortion, or the importance of galactic rotation. So, a *global* property such as  $L_X$ , that measures the hot gas content on a galactic scale, turns out to be surprisingly well linked to a *nuclear* property.

Various possible reasons are explored for the origin of the different  $L_X$  behavior of core and power law galaxies. While a few explanations can be imagined for the large spread in the X-ray luminosities of core galaxies, an open problem is why power law ones never become very X-ray bright. It is likely that the presence of a central massive black hole, and possibly also the environment, play an important role in determining  $L_X$  (i.e., the hot gas content). Therefore the problem of interpreting the X-ray properties of early type galaxies turns out to be more complex than thought so far.

**Key words:** galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: ISM – galaxies: nuclei – X-rays: galaxies

## 1. Introduction

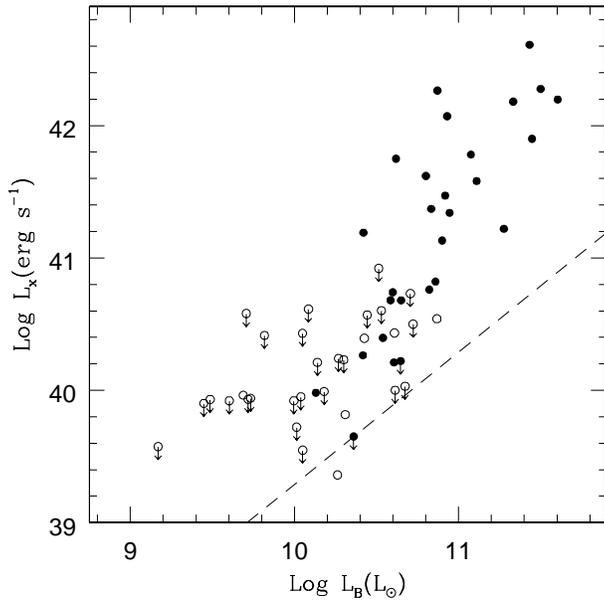
With *Hubble Space Telescope* the central surface brightness profiles of nearby galaxies can be studied with a resolution limit of  $\sim 0''.1$ , which corresponds to, e.g.,  $\lesssim 10$  parsecs in Virgo. So, a

large number of early type galaxies have been observed with unprecedented detail in their central regions (e.g., Jaffe et al. 1994, Ferrarese et al. 1994, Lauer et al. 1995, Forbes et al. 1995; Faber et al. 1997, hereafter F97). It turns out that the most luminous galaxies show outer power law profiles that break internally to shallow inner profiles  $I \propto R^{-\gamma}$ , with  $\gamma < 0.3$ . These galaxies are said to have cuspy cores<sup>1</sup>; their break radii typically range from 50 to 1000 pc. Faint galaxies show instead steep featureless power law profiles that lack cores down to the resolution limit. Their central surface brightness slope is typically  $\gamma > 0.5$ , with  $\gamma \approx 0.8$  on average. At intermediate luminosities core and power law galaxies coexist.

These central properties correlate with isophotal shape and amount of rotation: core galaxies tend to be boxy and slowly rotating, whereas power law galaxies tend to be disk-like and rapidly rotating (F97). At intermediate luminosities, where power law and core galaxies coexist, the presence of a core is a better predictor of boxiness or slow rotation than luminosity; the same can be said for the absence of a core and diskiness, or high rotation. So, it has been suggested that early type galaxies can be divided into two families: one includes those galaxies that are coreless, nearly isotropic spheroids, rotate rapidly, and have disk-like isophotes; the other ones that have cores, rotate slowly, are possibly moderately triaxial and boxy-distorted (Kormendy & Bender 1996).

In this paper I investigate whether power law and core early type galaxies (ellipticals and S0s) differ systematically also in their soft X-ray luminosities. I find that power law galaxies are confined below  $\log L_X (\text{erg s}^{-1}) = 41$ , while core ones can reach  $L_X$  values at least one order of magnitude higher. This holds even in the range of optical luminosities where the two families coexist. So, the central properties of early type galaxies are tightly related to, and possibly at the origin of, their global X-ray emission. A key factor could be the presence of a central massive black hole. In fact, it has been suggested that nuclear massive black holes are important for explaining the dichotomy of the inner light profiles, as they should have substantial influence on the dynamics and evolution of the surrounding gas and stars (e.g., Cipollina & Bertin 1994, van der Marel 1999, Merritt 1999, Nakano & Makino 1999). I also explore the alternative

<sup>1</sup> In the following I use the nomenclature “core profile” to refer to a profile with a cuspy core, and to “core galaxy” to refer to a galaxy with a cuspy core.



**Fig. 1.** The  $L_X$ – $L_B$  diagram for early type galaxies with inner surface brightness profile measured by *HST*. Power law galaxies are shown with open circles and core galaxies with full circles. Upper limits on X-ray luminosities are shown with a downward arrow. The data used are those in Table 1. The dashed line ( $L_X \propto L_B$ ) is an estimate of the stellar sources contribution to the X-ray emission (from Kim et al. 1992).

possibility that the other basic properties characterizing the two families (importance of rotation and isophotal shape distortion) affect the global  $L_X$ . This hypothesis is less plausible because the trend of  $L_X$  with these other properties is less sharp. Finally, I also examine the effects on  $L_X$  that may be produced by differences in the environment.

## 2. The sample

F97 present the fits of the surface brightness profiles for a large sample of early type galaxies observed with WFPC1; they modeled the data with a double power law with a break radius, derived the inner surface brightness slope (the  $\gamma$  parameter) and gave the classification into core or power law galaxy accordingly. This classification is given by the same authors for nine more early type galaxies in Magorrian et al. (1998). Crane et al. (1993), Ferrarese et al. (1994), Forbes et al. (1995) and Quillen et al. (1999) also present *HST* central profiles for a number of early type galaxies, and fit them with double power laws which govern the inner and the outer slopes. For all these galaxies, following F97, I have adopted the criterion of classifying them as power law galaxies when the central brightness profile does not show an inner break, and as core galaxies when it does. In the first case the inner slope always turned out to be larger than 0.3, and in the second case smaller than 0.3.

I have cross-correlated the sample of Es and S0s with inner profile measured by *HST* with existing catalogs of X-ray emission, namely the *Einstein* based catalog (Fabbiano et al. 1992), the *ROSAT* all-sky survey based catalog (Beuing et al. 1999), and the list of 61 early type galaxies observed with the *ROSAT*

PSPC by Irwin & Sarazin (1998). So, I have collected a sample of 59 galaxies with information on both the X-ray emission (detection or upper limit) and the central surface brightness properties<sup>2</sup>. 39 of these objects come from F97, 9 from Magorrian et al. (1998), 5 from Forbes et al. (1995), 3 from Quillen et al. (1999), 2 from Ferrarese et al. (1994), and 1 from Crane et al. (1993). The order of priority for taking the X-ray information has been as follows: first the Beuing et al. catalog, then the Irwin & Sarazin list, and finally the *Einstein* based catalog. In the final sample, the X-ray information comes from the *ROSAT* all-sky survey catalog for 43 objects, from the Irwin & Sarazin list for 5 objects, from the *Einstein* based catalog for 9 objects, and for 2 Coma galaxies (NGC4874 and NGC4889) from the *ROSAT* study of the Coma cluster by Dow & White (1995).

### 2.1. The X-ray luminosities

Two corrections need to be applied to the X-ray data of the literature. The first is a correction for the different passbands: *Einstein* based luminosities refer to the 0.2–4 keV energy band, while the *ROSAT* based data refer to 0.5–2 keV for the Irwin & Sarazin list, to 0.64–2.36 keV for the all-sky survey list, and to 0.4–2.4 keV for Dow & White (1995). I have transformed all X-ray luminosities to the (0.2–2) keV band values. This correction has been applied by taking into consideration the different spectral parameters used to derive the X-ray luminosities: thermal emission had been used with temperatures from 0.7 to 1 keV, Galactic neutral hydrogen absorption, and metallicities from 0.5 solar to solar. The amount of correction on  $\log L_X$  ranges from  $-0.030$  for the *Einstein* luminosities, to  $+0.072$  and  $+0.071$  for the luminosities in the Irwin & Sarazin and all-sky survey lists, and to  $+0.025$  for the two Coma galaxies.

The second correction is the rescaling of the luminosities to the same distance scale. To maximize the number of galaxies with the same source for the distance, I have adopted the distances given by Beuing et al. (1999). For eight galaxies not present in their catalog I have adopted the distances given by F97, after rescaling (they refer to  $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , while the distances of Beuing et al. refer to  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). Table 1 summarizes the observational information used in this paper.

## 3. The relation between $L_X$ and the central brightness profile

Fig. 1 plots the  $L_X - L_B$  relation for the galaxies in this sample, with different symbols for core and power law galaxies (full and open circles respectively). We note that:

<sup>2</sup> The whole sample of galaxies with information on both the X-ray emission and the central profile includes three more objects (M87, NGC3862, and NGC6166). These have been removed because their very high X-ray emission ( $L_X \gg 10^{42} \text{ erg s}^{-1}$ ) is known to be largely contaminated by the presence of a ‘classical’ AGN, while in the present study only normal early type galaxies are considered (see also Sect. 5.2). All these three galaxies have cores.

**Table 1.** Galaxy properties

Name	d <sup>a</sup> (Mpc)	$\log L_X^b$ ( $\text{erg s}^{-1}$ )	$\log L_B^c$ ( $L_\odot$ )	$100 \cdot a_4/a^d$	Profile <sup>e</sup>	$\gamma^f$
NGC524	40.0	40.82	10.86		$\cap$	0.00
NGC596	39.6	<40.50	10.72	1.30	$\backslash$	0.55
NGC720	35.2	41.37	10.83	0.35	$\cap$	0.06
NGC821	37.7	<40.73	10.66	2.50	$\backslash$	
NGC1172	47.1	<40.92	10.51		$\backslash$	1.01
NGC1052	29.3	40.68	10.59	0.00	$\cap$	0.18
NGC1316	26.4	41.22	11.28	1.00	$\cap$	0.00
NGC1399	26.8	42.26	10.87	0.10	$\cap$	0.07
NGC1400	31.3	40.39	10.43	0.00	$\backslash$	0.35
NGC1426	30.9	<40.24	10.27	0.00	$\backslash$	0.85
NGC1427	26.3	39.82	10.31	0.35	$\backslash$	0.76
NGC1439	30.9	<40.23	10.30	-0.10	$\backslash$	0.83
NGC1553	18.2	40.43	10.61		$\backslash$	0.74
NGC1600	98.6	41.90	11.45	-0.75	$\cap$	0.08
NGC2300	45.6	41.62	10.80	0.55	$\cap$	
NGC2778	37.2	<40.43	10.05	-0.15	$\backslash$	
NGC2832	136.2	42.61	11.43	-0.30	$\cap$	0.02
NGC3115	9.6	39.36	10.26		$\backslash$	0.78
NGC3377	13.3	<39.72	10.01	1.05	$\backslash$	0.29
NGC3379	13.2	<39.65	10.36	0.10	$\cap$	0.18
NGC3384	12.0	<39.55	10.05		$\backslash$	
NGC3599	20.4	<39.94	9.73		$\backslash$	0.79
NGC3608	32.5	40.40	10.54	-0.20	$\cap$	0.00
NGC4168	43.8	40.68	10.65	0.37	$\cap$	0.14
NGC4239	21.0	<39.93	9.49		$\backslash$	0.65
NGC4278	14.6	39.98	10.13	-1.00	$\cap$	
NGC4291	36.7	41.19	10.42	-0.40	$\cap$	
NGC4342	27.0	<40.58	9.71		$\backslash$	1.47
NGC4365	20.2	40.21	10.61	-0.95	$\cap$	0.15
NGC4374	20.7	40.76	10.82	-0.40	$\cap$	0.31
NGC4387	24.5	<40.41	9.82	-0.75	$\backslash$	0.72
NGC4406	20.8	42.07	10.93	-0.70	$\cap$	0.08
NGC4434	20.3	<39.92	9.60	0.44	$\backslash$	0.70
NGC4458	20.8	39.96	9.69	0.34	$\backslash$	0.49
NGC4464	20.3	<39.90	9.45		$\backslash$	0.88
NGC4467	24.5	<39.57	9.17		$\backslash$	0.98
NGC4472	20.3	41.78	11.08	-0.25	$\cap$	0.04
NGC4473	20.8	40.26	10.42	0.90	$\cap$	
NGC4478	24.5	<40.61	10.09	-0.75	$\backslash$	0.43
NGC4494	22.5	<40.03	10.67	0.30	$\backslash$	
NGC4551	20.8	<39.93	9.72	-0.65	$\backslash$	0.80
NGC4552	20.8	40.74	10.60	0.01	$\cap$	0.00
NGC4564	20.7	<39.95	10.04	1.00	$\backslash$	0.05
NGC4589	36.6	<40.22	10.65	0.55	$\cap$	
NGC4621	20.7	<40.00	10.61	1.50	$\backslash$	0.50
NGC4636	19.9	41.75	10.62	-0.10	$\cap$	0.13
NGC4649	20.7	41.34	10.95	-0.35	$\cap$	0.15
NGC4660	20.7	<39.92	10.00	2.70	$\backslash$	
NGC4697	22.5	40.54	10.87	1.30	$\backslash$	0.74
NGC4742	23.0	<40.21	10.14	0.41	$\backslash$	1.09
NGC4874	149.3	42.28	11.50	-0.30	$\cap$	0.13
NGC4889	149.3	42.20	11.60	0.01	$\cap$	0.05
NGC5198	51.3	<40.60	10.53		$\backslash$	0.88
NGC5982	59.3	41.47	10.92	-0.80	$\cap$	0.11
NGC7332	32.5	<40.57	10.44		$\backslash$	0.90
NGC7457	22.2	<39.99	10.18	0.00	$\backslash$	

**Table 1.** (continued)

Name	d <sup>a</sup> (Mpc)	$\log L_X^b$ ( $\text{erg s}^{-1}$ )	$\log L_B^c$ ( $L_\odot$ )	$100 \cdot a_4/a^d$	Profile <sup>e</sup>	$\gamma^f$
NGC7626	74.3	41.58	11.11	0.20	$\cap$	0.21
NGC7768	164.5	42.18	11.33	0.00	$\cap$	0.00
IC1459	33.1	41.13	10.90	-0.10	$\cap$	0.18

<sup>a</sup> Distance, with  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (see Sect. 2.1).

<sup>b</sup> X-ray luminosity (see Sect. 2.1).

<sup>c</sup> B-band luminosity calculated using the  $B_T^0$  values of de Vaucouleurs et al. (1991) and the distances in the second column.

<sup>d</sup> Isophotal shape parameter;  $a_4/a$  is the coefficient of the cosine distortion term expressed as a percentage of major axis length. Sources for  $a_4/a$  are F97, Bender et al. (1989), Goudfrooij et al. (1994), Peletier et al. (1990), Franx et al. (1989a), Møller et al. (1995).

<sup>e</sup> Profile class:  $\cap$ =core,  $\backslash$ =power law.

<sup>f</sup> Slope of the surface brightness profile in the central regions ( $I \propto R^{-\gamma}$ ). The references for the  $\gamma$  values are given at the beginning of Sect. 2.

1) The least optically luminous galaxies and the most optically luminous ones are respectively power law and core galaxies, as in the sample studied by F97.

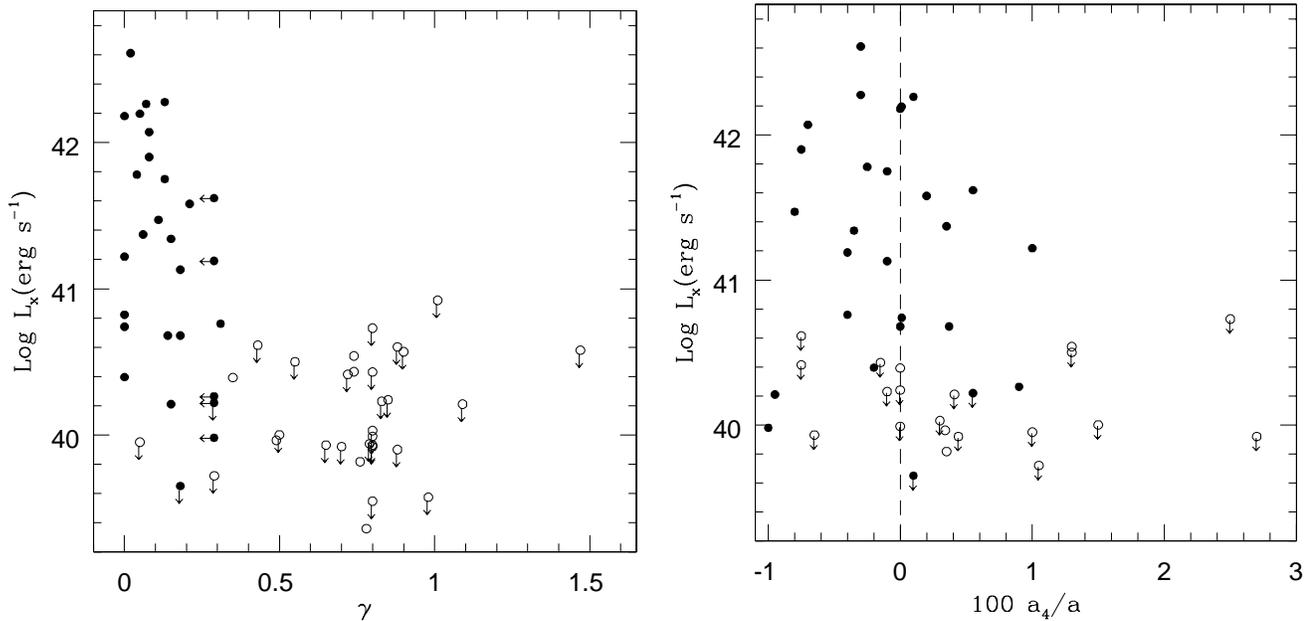
2) The least X-ray luminous galaxies and the most X-ray luminous ones are again respectively power law and core galaxies, consistent with the known  $L_X-L_B$  correlation. For the whole *Einstein* sample of 148 early type galaxies  $L_X \propto L_B^{1.8-2}$ , although with a large scatter of more than two orders of magnitude in  $L_X$  at any fixed  $L_B > 3 \times 10^{10} L_\odot$  (Eskridge et al. 1995). For a magnitude-limited sample of early type galaxies with X-ray emission measured by the *ROSAT* all-sky survey, Beuing et al. (1999) find  $L_X \propto L_B^{2.2 \pm 0.1}$  and a scatter at least as large as that found by Eskridge et al. (1995).

3) At intermediate  $L_B$ , where they coexist, core galaxies span the whole range of  $L_X$  values (roughly two orders of magnitude in  $L_X$ ), while power law ones are confined below  $\log L_X (\text{erg s}^{-1}) = 41$  (hereafter  $L_{X,UP}$ ).

It looks as if power law galaxies cannot be more X-ray luminous than  $L_{X,UP}$ , while core galaxies show  $L_X$  values extending from the lowest to the highest  $L_X$  observed. In Fig. 2 this result is shown from the point of view of the relation between  $L_X$  and the central surface brightness slope  $\gamma$  (defined in Sect. 2). A sharp transition in  $L_X$  as  $\gamma$  drops below 0.3 (as for core galaxies) is clearly seen: the X-ray brightest galaxies are exclusively core galaxies, and power law galaxies are never X-ray brighter than  $L_{X,UP}$ , independently of the  $\gamma$  value.

### 3.1. Statistical analysis

How strong is the result presented above, from a statistical point of view? Is the confinement of power law galaxies to  $L_X < L_{X,UP}$  a result of the  $L_X-L_B$  correlation, or is it statistically significant in general, for all of them? To establish this, I made some statistical tests for the galaxies in the range of  $L_B$  values where power law and core galaxies coexist. This range has been chosen close to that indicated by F97, who find that core



**Fig. 2.** The relation between  $L_X$  and the slope of the central surface brightness profile  $\gamma$  (left) or the  $a_4/a$  parameter (right) for the galaxies in Table 1. Power law galaxies are shown with open circles and core galaxies with full circles. Upper limits on X-ray luminosities are shown with a downward arrow. Those galaxies for which just the classification into core or power law is given are put respectively at  $\gamma = 0.3$ , with an arrow pointing leftwards, and at the average  $\gamma$  value for their family (i.e., 0.8, see Sect. 1). The vertical dashed line in the  $L_X$ - $a_4/a$  plot separates boxy and disky galaxies.

and power law profiles coexist for  $-22 < M_V < -20.5$  (with  $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ); by assuming a  $B-V=1$  and rescaling to  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , this range corresponds to  $10.36 < \log L_B (L_\odot) < 10.96$ . Considering also the distribution of power law galaxies in Fig. 1, as overlap range for the present sample I have adopted  $10.40 \leq \log L_B (L_\odot) \leq 10.90$ . In this range there are 15 core galaxies and 10 power law galaxies.

First I have checked if these two sets of galaxies are consistent with being drawn from the same distribution function of  $L_B$ . To check this I have used a variety of two-sample tests [discussed in Feigelson & Nelson (1985), and contained in the ASURV package] to verify the null hypothesis that the two sets are drawn from the same parent distribution. All these tests give a probability  $P \approx 0.4$ , from which one usually concludes that the two sets are consistent with coming from the same distribution<sup>3</sup>. I obtain an even higher probability when using the Kolmogorov-Smirnov test ( $P = 0.57$ ).

Next, I have repeated the two-sample tests for the  $L_X$  values, in order to check whether power law and core galaxies (again for  $10.40 \leq \log L_B (L_\odot) \leq 10.90$ , where they coexist) are consistent with being drawn also from the same  $L_X$  distribution. I have obtained that the null hypothesis cannot be supported. The probabilities given by all the tests are around 0.003. So, the two sets come from different  $L_X$  distributions at the  $\sim 3\sigma$  level.

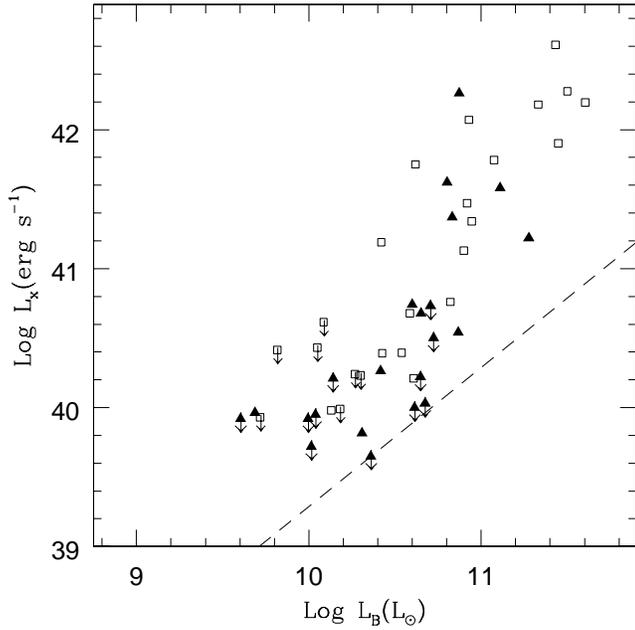
<sup>3</sup> A value of  $P = 0.4$  means that the observed difference in the  $L_B$  distributions can be obtained in  $\sim 40\%$  of the cases, using two samples of the same sizes as those used here, and drawn from the same parent population.

In conclusion, in the  $L_B$  range where they coexist, core and power law galaxies are similar from the point of view of their optical luminosity, while they clearly differ in their X-ray properties.

A linear regression analysis for data sets with censoring in one variable, with the expectation and maximization (EM) algorithm, and the Buckley-James algorithm (Isobe et al. 1986), gives a best fit slope for the  $L_X$ - $L_B$  relation of  $1.8 \pm 0.3$  for core galaxies. This slope is close to the best fit slope obtained from the analysis of larger samples (Eskridge et al. 1995, Beuing et al. 1999; see Sect. 3). An estimate of the best fit slope for power law galaxies is not realistic because of the low number of detections (6 only); however, in this case a regression analysis gives a best fit slope consistent with unity. So,  $L_X \propto L_B$  could be a good description of the  $L_X$ - $L_B$  relation for power law galaxies, while the observed deviation of the  $L_X$ - $L_B$  relation from a linear one could be produced by core galaxies.

#### 4. Relation of $L_X$ with other basic galaxy properties

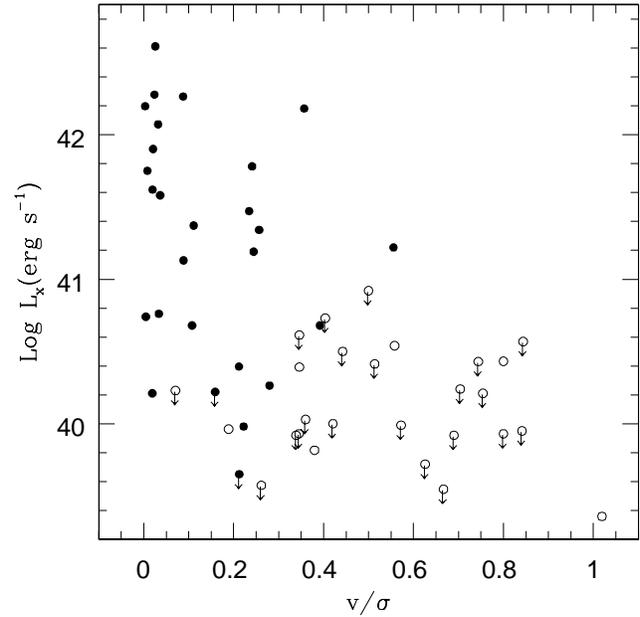
Not surprisingly, the behavior of the X-ray emission with respect to the shape of the central brightness profile is reminiscent of the trend of  $L_X$  with respect to the other basic properties characterizing early type galaxies, already mentioned in Sect. 1: one is the deviation of the isophotal shape from a pure elliptical shape, and is described by the  $a_4/a$  parameter introduced by Bender et al. (1989); the other is the degree of anisotropy in the velocity dispersion tensor, as measured by the anisotropy parameter  $(v/\sigma)^*$  ( $v$  is the maximum rotational velocity and  $\sigma$  is the stellar velocity dispersion in the central regions; e.g.,



**Fig. 3.** The  $L_X$ – $L_B$  diagram for the early type galaxies in Fig. 1, with isophotal shape measurement available in the literature. Disk galaxies (those with  $100 \cdot a_4/a > 0.01$ ) are shown with full triangles and boxy galaxies with boxes. The data are taken from Table 1, and the dashed line is as in Fig. 1.

Davies et al. 1983). Disk ( $a_4 > 0$ ) objects are generally low X-ray emitters and flattened by rotation; boxy ( $a_4 < 0$ ) and irregular objects show the whole range of  $L_X$  and various degrees of velocity anisotropy (Bender et al. 1989; see also Fig. 3). The relationship between X-ray emission and  $a_4/a$  has been reanalyzed by Eskridge et al. (1995) for the sample of *Einstein* galaxies: they confirm that the most X-ray luminous galaxies are boxy, and find that the trend of  $L_X$  with  $a_4/a$  is a wedge, with no highly disk objects at high X-ray emission. Pellegrini et al. (1997) find similar results for the relation between  $L_X$  and  $v/\sigma$  (a measure of the importance of rotation), or  $(v/\sigma)^*$ : at high  $v/\sigma$  or  $(v/\sigma)^*$  there are no galaxies with high  $L_X$  (see also Fig. 4).

What is surprising is that the  $L_X$ – $\gamma$  relation is *sharper* than that between  $L_X$  and isophotal distortion, or  $v/\sigma$  (these are more wedges than L-shapes, as described above). As an example, I consider here in detail the  $L_X$ – $\gamma$  and the  $L_X$ – $a_4/a$  relations (Fig. 2;  $a_4/a$  has been measured for 47 of the galaxies in Table 1). While the  $L_X$ – $\gamma$  relation shows clearly a dichotomy in the X-ray properties, the  $L_X$ – $a_4/a$  relation looks like a wedge, because not all disk galaxies are low X-ray emitters. There are in fact both power law and core galaxies (i.e., X-ray faint and X-ray bright objects) for  $0 \leq 100 \cdot a_4/a \leq 1$ . This fact is explained by an inspection of Fig. 3, that is another version of Fig. 1 where disk and boxy galaxies are plotted with different symbols: disk and boxy objects are more mixed in the  $L_X$ – $L_B$  relation than core and power law galaxies. So, Figs. 2 and 3 show that *all* power law galaxies have  $\log L_X < L_{X,UP}$ , while the same is not true for galaxies with disk isophotes.



**Fig. 4.** The relation of  $L_X$  with the ratio between the maximum rotational velocity  $v$  and the central velocity dispersion  $\sigma$  (Sect. 4). Power law galaxies are shown with open circles and core galaxies with full circles. The values of  $\sigma$  come from McElroy (1995);  $v$  has been measured for 54 galaxies in Table 1, by Davies et al. (1983), Franx et al. (1989b), Fried & Illingworth (1994), Bender et al. (1994), Fisher et al. (1995).

One concludes that a *global* property such as  $L_X$  is *tightly connected with a nuclear property*, such as the inner profile shape, and more so than with other characterizing galaxy properties as the isophotal shape. This occurs in spite of the fact that there are more objects in the  $L_X$ – $\gamma$  plot than in the  $L_X$ – $a_4/a$  one; an effect of “blurring”, because a larger sample is considered, is expected to affect the  $L_X$ – $\gamma$  plot more than the  $L_X$ – $a_4/a$  one.

It must be noted that the absence of a sharp transition in the  $L_X$ – $a_4/a$  relation might be produced, at least in part, by the uncertainties associated with the definition of  $a_4$ . In fact, the  $a_4$  values given in Table 1 refer to an average between 10 and 60 arcsec, i.e., between typically 0.2 and 1 optical effective radius, where the shape of the isophotes is known to vary within the same galaxy, sometimes also significantly (e.g., van den Bosch et al. 1994).

## 5. Discussion

The results obtained here indicate that the two families of early type galaxies recently singled out have also a distinct X-ray behavior in the (0.2–2) keV band. The trend between  $L_X$  and the shape of the central profile is similar to the trends between  $L_X$  and the isophotal shape distortion, or the degree of rotational support. However, it is much sharper than the other two, and it could be at the origin of the difference in the X-ray properties.

What are the possible causes of this segregation of power law galaxies to  $L_X < L_{X,UP}$ , and how do core ones evade it? Can the change in the shape of the density profile in the central

regions be responsible for such a disparate behavior of  $L_X$ ? Or are some other galaxy properties, to which the change in the shape of the surface brightness profile is linked, responsible for this difference? For example, besides isophotal shape and rotation, distinct evolutions, where an important role is played also by massive black holes, could be responsible for the settling of the two types of profiles (Sect. 1) and also have an effect on  $L_X$ .

In the following I speculate on a few conceivable causes of the different  $L_X$  behavior in the two families of early type galaxies. I will focus first on the direct effect of the inner profile shape on  $L_X$ ; then on that of a massive black hole (MBH); finally on those expected from possible differences in the environment. I assume that the scatter in  $L_X$  is related to a largely varying quantity of hot gas within galaxies, as demonstrated observationally by considering their spectral properties (e.g., Matsumoto et al. 1997).

### 5.1. Direct effects of the basic properties of power law and core galaxies on their hot gas flows

Ciotti et al. (1991) simulated the evolution of the hot gas behavior over the galaxy lifetime for spherical mass distributions having King profiles (i.e., with flat cores), including type Ia supernova heating. They showed that the large  $L_X$  range observed at fixed  $L_B$  can be produced by small differences in the gravitational potential energy of the gas, which cause the gas flows to be in the wind, outflow or inflow stages. Later Pellegrini & Ciotti (1998) produced a set of hydrodynamical simulations where the spatial luminosity distribution at small radii has a power law form ( $\propto r^{-2}$  as in the Jaffe law; this corresponds to the central luminosity density profile of power law galaxies, Gebhardt et al. 1996). The resulting gas flows are mostly partial winds: an inflow develops in the central region, while the external parts are still degassing. A large spread in  $L_X$  at fixed  $L_B$  is again produced by varying the model input parameters in their observed ranges, and corresponds to variations in the size of the inflow region. In particular, for  $10.4 < \log L_B (L_\odot) < 10.9$ ,  $L_X$  values as high as  $\sim 2-3 \times 10^{41}$  erg s $^{-1}$  can be easily reached. So, in the X-ray luminosity values of a large sample of galaxies there should be no trace of the precise shape of the mass profile in the very central regions. This is supported also by the observations that show how all power law galaxies have low  $L_X$  independently of the  $\gamma$  values (Fig. 2), while core galaxies have a large range of  $L_X$  with little variation of  $\gamma$ .

Galactic rotation is an important property of power law galaxies (Sect. 1), and so one might suspect that the simulations mentioned above are not realistic for these galaxies. However, as shown by Ciotti & Pellegrini (1996) and by D’Ercole & Ciotti (1998) with simulations, rotation has minor effects on  $L_X$ . If no type Ia supernova’s heating is assumed (so that the flows are always cooling flows) the effect is larger: a reduction of  $L_X$  by a factor of six is obtained when  $v/\sigma \approx 0.3$ , and a very massive cold disk forms (of mass  $\approx 3 \times 10^{10} M_\odot$ ; Brighenti & Mathews 1996). Even though in this case the effect of rotation goes in the right direction, the observations cannot be fully explained,

because the needed reduction in  $L_X$  is at least of one order of magnitude. Moreover, for  $v/\sigma \leq 0.4$  there are both power law and X-ray bright core galaxies (see Fig. 4), and so the amount of rotation cannot be taken as the general explanation.

A flatter global galaxy shape is another property known to be associated on average to lower  $L_X$  values, from observations (Eskridge et al. 1995). The hot gas is less bound when the mass distribution is flatter, for fixed  $L_B$ , so that an outflow is favoured (D’Ercole & Ciotti 1998). This is the case of galaxies where a disk is present, and might apply preferentially to power law galaxies. Those in the present sample, for  $\log L_B (L_\odot) > 10.4$ , include four S0s, but also three roundish (E0-E2) galaxies. So, again the presence of a disk has an effect that goes in the right direction, but cannot be taken as a general explanation (unless all the above mentioned power law galaxies with rounder shape turned out to be disk galaxies viewed face on).

In conclusion, large systematic variations of the hot gas content resulting from differences of the inner profile shape are not expected, based on numerical simulations; galactic rotation and flattening of the mass distribution are expected to have an effect, but seem to be unable to offer a general explanation. This is consistent with the  $L_X-\gamma$  relation being sharper than the  $L_X-v/\sigma$  one (and the  $L_X-\epsilon$  one, where  $\epsilon = 1 - b/a$  is the projected galaxy ellipticity, Pellegrini et al. 1997).

### 5.2. Effect of the presence of a massive black hole

When dealing with properties connected with the very central regions of early type galaxies, one is naturally brought to consider the effects produced by a central MBH. In fact, on the basis of various kinds of observational evidence, in the past few years it has become commonly accepted that early type galaxies host central massive black holes, possibly remnants of dead or quiescent QSOs (Kormendy & Richstone 1995, Richstone et al. 1998). Why the X-ray emission in early type galaxies is not as high as in classical AGNs, due to accretion of hot gas by the central MBH, is a problem that has been addressed by Binney & Tabor (1995), Fabian & Rees (1995) and by Ciotti & Ostriker (1997). Fabian & Rees suggest that accretion of gas from the surrounding cooling flow has a very low radiative efficiency, and that early type galaxies should typically host low or very low luminosity AGNs. Ciotti & Ostriker suggest that the hot gas can be expelled from the galaxies when a central MBH is present, because the gas flows are found to be unstable due to Compton heating. So, most of the time the galaxies are in a low or medium  $L_X$  state, they are in a high  $L_X$  state only during global inflows, and the large observed scatter in  $L_X$  is reproduced.

In both frameworks it is not clear why power law galaxies are found *only* in the low or medium state, while core galaxies span the whole observed scatter in  $L_X$ . A few solutions, where other ingredients besides the presence of a MBH enter, can be imagined: the shape of the galaxies (triaxial versus axisymmetric) can have an effect on the way accretion proceeds. Or the very MBH properties (such as its mass) could play a role. In any case if a MBH is important in determining  $L_X$ , the conventional approach to the problem of interpreting the X-ray

properties of early type galaxies requires revision; the input ingredients are currently just stellar mass loss, supernova heating, and gas potential energy (see, e.g., Sarazin & White 1988, David et al. 1990, Ciotti et al. 1991). More precisely, since a different amount of hot gas is at the origin of the observed large scatter in  $L_X$  at fixed  $L_B$  (e.g., Matsumoto et al. 1997), one should focus on the relation between central MBH presence and amount of hot gas.

### 5.3. Effect of the environment

F97 present a preliminary evidence that core galaxies tend to be found in dense groups and clusters, while power law ones are preferentially found in the field. This is in line with the fact that core galaxies are on average also boxy/irregular (which has been argued to be a merger signature, or a sign of past accretion and interaction events; Nieto 1989, Barnes 1992) and show more frequently indications of accretion of small satellites such as cores within cores, central counter-rotation, etc. (Lauer et al. 1995). In this scenario, what could be the effects on  $L_X$ ? More generally, what is the effect of the environment on the hot gas content?

An environment denser of intragroup/intracluster gas and of galaxies should act in the sense of producing both extremely X-ray luminous galaxies and galaxies with medium or low  $L_X$ . In fact accretion of external gas is needed to explain the X-ray brightest galaxies of the  $L_X-L_B$  diagram (Renzini et al. 1993, Mathews & Brighenti 1998) while in the X-ray faint ones the hot gaseous halos could have been stripped by ambient gas, if it is sufficiently dense, or in encounters with other galaxies (White & Sarazin 1991). This picture would be consistent with the finding that the larger spread in  $L_X$  is shown by core galaxies, that are preferentially found in high density environments (and this is so even for the sample studied here). Also it has been suggested that MBH presence and galaxy environment might be connected (F97); in this view cores might result from ejection of stars by a coalescing black hole binary during a merging event (Quinlan & Hernquist 1997, Nakano & Makino 1999). So, the association of cores and a large spread in X-ray emission could come from a combination of environmental effects and MBH presence; for example, merging produces triaxiality, and this facilitates the gas to reach the nucleus, and feed the central MBH. Note that just the variety of merging and/or tidal interaction conditions (time of the event during the galaxy history, progenitors' masses and orbits, and so on) might produce a variety of effects on the hot gas content. Numerical simulations are needed to derive more firm conclusions concerning this aspect; the first results show that the effect of perturbing the hot gas flows is in the direction of producing a spread in  $L_X$  (D'Ercole et al. 1999).

While various solutions can be imagined to explain the large range of  $L_X$  shown by core galaxies, again a major problem is why power law galaxies do not reach high X-ray luminosities, even when they are in a range of  $L_B$  values where core galaxies can be very X-ray luminous. Certainly, they do not seem to experience accretion from outside, because they do not even show  $L_X$  values as high as the numerical simulations for the hot gas

evolution predict for them when they are isolated (Sect. 5.1). So, they should reside in the field<sup>4</sup>, or never be the central dominant galaxies in clusters, subclusters and groups. But this seems not to be the case: for example NGC1553, NGC4697 and NGC5198 are also the brightest members of their groups. So, the problem remains of why power law galaxies do not become very X-ray bright, even when they are optically dominant.

## 6. Conclusions

I have investigated the relationship between X-ray emission and shape of the inner surface brightness profile, for a sample of 59 early type galaxies. I have found that:

- The family of core galaxies spans the whole observed range of  $L_X$  values (two orders of magnitude in  $L_X$ ) while that of power law galaxies is confined to  $\log L_X \text{ (erg s}^{-1}\text{)} < 41$ . This dichotomy in the X-ray properties holds even in the  $L_B$  range where the two families coexist.
- The relation between  $L_X$  and the shape of the inner profile is sharp, and is stronger than the relations of  $L_X$  with the other basic properties characterizing the two families of early type galaxies. For example, being a power law galaxy is connected with a low  $L_X$  with no exception, while the same cannot be said for the property of having disk isophotes. So, a global quantity such as  $L_X$  is surprisingly tightly connected with a nuclear galaxy property.
- A linear regression analysis shows that  $L_X \propto L_B$  could be a good description of the  $L_X-L_B$  relation for power law galaxies, while core galaxies deviate from this relation.
- Different possible reasons can be argued for the origin of the dichotomy in the  $L_X$  behavior. The central profile shape itself should not be the main factor, given the results of previous numerical simulations of the hot gas evolution and the absence of a trend of  $L_X$  with the  $\gamma$  values. A higher degree of rotation of power law galaxies could produce an effect, but not large enough, and, much like the possibility of a higher degree of flattening of the mass distribution, does not seem to be a general explanation of the reduction in  $L_X$  for the whole class of power law galaxies.
- It has been suggested that nuclear massive black holes and environmental differences are important for explaining the dichotomy of the inner light profiles; both aspects are likely to influence the hot gas content. While a few explanations can be imagined for the large spread in the X-ray luminosities of core galaxies, a clearly open problem is why power law galaxies never become X-ray bright, even when they are the brightest objects of the groups where they reside.
- If a massive black hole and the environment have a fundamental role in determining  $L_X$ , the problem of interpreting the X-ray properties of early type galaxies becomes much more complex than thought so far, when the input ingredients were just stellar mass loss, supernova heating and gas potential energy.

<sup>4</sup> The power law galaxies with  $\log L_B (L_\odot) \geq 10.4$  of the sample investigated here reside either in the field, or in groups with 3 to 18 members, or in Virgo (NGC4621).

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## References

- Barnes J., 1992, *ApJ* 393, 484  
 Bender R., Surma P., Döbereiner S., Möllenhoff C., Madejsky R., 1989, *A&A* 217, 35  
 Bender R., Saglia R.P., Gerhard O.E., 1994, *MNRAS* 269, 785  
 Beuing J., Döbereiner S., Böhringer H., Bender R., 1999, *MNRAS* 302, 209  
 Binney J., Tabor G., 1995, *MNRAS* 276, 663  
 Brighenti F., Mathews W.G., 1996, *ApJ* 470, 747  
 Ciotti L., D'Ercole A., Pellegrini S., Renzini A., 1991, *ApJ* 376, 380  
 Ciotti L., Pellegrini S., 1996, *MNRAS* 279, 240  
 Ciotti L., Ostriker J.P.O., 1997, *ApJ* 487, L105  
 Cipollina M., Bertin G., 1994, *A&A* 288, 43  
 Crane P., Stiavelli M., King I.R., et al., 1993, *AJ* 106, 1371  
 David L.P., Forman W., Jones C., 1990, *ApJ* 359, 29  
 Davies R.L., Efstathiou G., Fall M., Illingworth G., Schechter P., 1983, *ApJ* 266, 41  
 D'Ercole A., Ciotti L., 1998, *ApJ* 494, 535  
 D'Ercole A., Recchi S., Ciotti L., 1999, *ApJ* in press  
 de Vaucouleurs G., de Vaucouleurs A., Corwin H.G., et al., 1991, *Third Reference Catalogue of Bright Galaxies*. Springer, New York (RC3)  
 Dow K.L., White S.D.M., 1995, *ApJ* 439, 113  
 Eskridge P.B., Fabbiano G., Kim D.W., 1995, *ApJS* 97, 141  
 Fabbiano G., Kim D.W., Trinchieri G., 1992, *ApJS* 80, 531  
 Faber S.M., Tremaine S., Ajhar E.A., et al., 1997, *AJ* 114, 1771 (F97)  
 Fabian A.C., Rees M.J., 1995, *MNRAS* 277, L55  
 Feigelson E.D., Nelson P.I., 1985, *ApJ* 293, 192  
 Ferrarese L., van den Bosch F.C., Ford H., Jaffe W., O'Connell R., 1994, *AJ* 108, 1598  
 Forbes D.A., Franx M., Illingworth G.D., 1995, *AJ* 109, 1988  
 Fisher D., Illingworth G., Franx M., 1995, *ApJ* 438, 539  
 Franx M., Illingworth G., Heckman T., 1989a, *AJ* 98, 538  
 Franx M., Illingworth G., Heckman T., 1989b, *ApJ* 344, 613  
 Fried J.W., Illingworth G., 1994, *AJ* 107, 992  
 Gebhardt K., Richstone D., Ajhar E.A., et al., 1996, *AJ* 112, 105  
 Goudfrooij P., Hansen L., Jorgensen H.E., et al., 1994, *A&AS* 104, 179  
 Irwin J.A., Sarazin C.L., 1998, *ApJ* 499, 650  
 Isobe T., Feigelson E.D., Nelson P.I., 1986, *ApJ* 306, 490  
 Jaffe W., 1983, *MNRAS* 202, 995  
 Jaffe W., Ford H.C., O'Connell R.W., van den Bosch F.C., Ferrarese L., 1994, *AJ* 108, 1567  
 Kim D.W., Fabbiano G., Trinchieri G., 1992, *ApJ* 393, 134  
 Kormendy J., Richstone D., 1995, *ARA&A* 33, 581  
 Kormendy J., Bender R., 1996, *ApJ* 464, L119  
 Lauer T.R., Ajhar E.A., Byun Y.I., et al., 1995, *AJ* 110, 2622  
 Magorrian J., Tremaine S., Richstone D., et al., 1998, *AJ* 115, 2285  
 Mathews W.G., Brighenti F., 1998, *ApJ* 503, L15  
 Matsumoto H., Koyama K., Awaki H., et al., 1997, *ApJ* 482, 133  
 McElroy D.B., 1995, *ApJS* 100, 105  
 Merritt D., 1999, *astro-ph/9906047*  
 Møller P., Stiavelli M., Zeilinger W.W., 1995, *MNRAS* 276, 979  
 Nakano T., Makino J., 1999, *ApJ* in press  
 Nieto J.L., 1989, 2<sup>da</sup> Reunion de Astronomia Extragalactica. *Bul. Academia Nacional de Ciencias de Cordoba* 58, 239  
 Peletier R.F., Davies R.L., Illingworth G., Davis L.E., Cawson M., 1990, *AJ* 100, 1091  
 Pellegrini S., Held E., Ciotti L., 1997, *MNRAS* 288, 1  
 Pellegrini S., Ciotti L., 1998, *A&A* 333, 433  
 Quillen A.C., Bower G.A., Stritzinger M., 1999, submitted to *ApJ*  
 Quinlan G., Hernquist L., 1997, *New Astronomy* 2, 533  
 Renzini A., Ciotti L., D'Ercole A., Pellegrini S., 1993, *ApJ* 419, 52  
 Richstone D., et al., 1998, *Nat* 395, A14  
 Sarazin C.L., White R.E.III, 1988, *ApJ* 331, 102  
 van den Bosch F.C., Ferrarese L., Jaffe W., Ford H.C., O'Connell R.W., 1994, *AJ* 108, 1579  
 van der Marel R.P., 1999, *ApJ* 117, 744  
 White R.E.III, Sarazin C.L., 1991, *ApJ* 367, 476