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X RAYS FROM NORMAL GALAXIES

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1. INTRODUCTION

The study of the X-ray properties of normal galaxies as a class was made possible by the launch of the *Einstein Observatory* in November 1978 (Giacconi et al. 1979). Before then, with the exclusion of the bright X-ray sources associated with Seyfert nuclei (Elvis et al. 1978, Tananbaum et al. 1978), only four galaxies had been detected in X rays: the Milky Way, M31, and the Magellanic Clouds (see Helfand 1984a, and references therein). The *Einstein* X-ray observations of well over 100 galaxies have been reported in the literature to date, and data on a similar number can still be found in the *Einstein* data bank. Some galaxies were detected with enough detail to allow a study of their X-ray morphology, spectra, and individual sources and to make comparisons with optical, infrared, and radio data. For all the galaxies, values of the X-ray flux, or even upper limits to this flux in the case of nondetections, can be used to explore average sample properties. These observations have shown that normal galaxies of all morphological types are spatially extended sources of X-ray emission with luminosities in the range of $\sim 10^{38}$ erg s^{-1} to 10^{42} erg s^{-1}. Although this is only a small fraction of the total energy output of a normal galaxy, X-ray observations are uniquely suited to study phenomena that are otherwise elusive. These include the end products of stellar evolution (supernova remnants and compact remnants) and a hot phase of the interstellar medium, discovered in bright early-type galaxies. This review gives an up to date and hopefully complete account of these *Einstein* results and of the published results from the European *EXOSAT* and Japanese *Ginga* satellites. Spiral and elliptical galaxies are reviewed separately, since

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their X-ray properties differ and suggest different origins for their X-ray emission.

2. THE X-RAY EMISSION OF SPIRAL GALAXIES

2.1 *Sources of X Rays*

Spiral galaxies are extended and complex X-ray sources with total luminosities in the *Einstein* band ($\sim$0.2–3.5 keV) of $\sim 10^{38}$ erg s^{-1} to a few 10^{41} erg s^{-1} (Fabian 1981, Long & Van Speybroeck 1983, Fabbiano 1984, 1986a). Observations of the Milky Way and of the Local Group galaxies (e.g. see Fabian 1981, Helfand 1984a,b) suggest that a good fraction of this X-ray emission is due to a collection of individual bright sources, such as close accreting binaries with a compact companion and supernova remnants, with luminosities ranging from $\sim 10^{35}$ erg s^{-1} up to a few 10^{38} erg s^{-1}. Stars also emit coronal X rays with luminosities of 10^{28} erg s^{-1} to 10^{33} erg s^{-1} (Vaiana et al. 1981). However, except perhaps at the lowest energies and in some starburst regions, stars do not contribute significantly to the total X-ray emission, since the X-ray to optical ratios measured in spiral galaxies (Long & Van Speybroeck 1983, Fabbiano & Trinchieri 1985) are larger than those expected from a normal stellar population (Topka et al. 1982, Helfand & Caillault 1982), and since the average X-ray spectrum of spiral galaxies appears harder than that of the stellar emission [$kT > 2$ keV in galaxies (Fabbiano & Trinchieri 1987); $kT \sim 0.5$–1 keV in stars (Helfand & Caillault 1982)]. Nuclear sources, either connected with star formation activity or with nonthermal Seyfert-like activity, can also be present and contribute various amounts to the X-ray emission. In this paper, however, we do not discuss "classical" Seyfert-type galaxies, where the emission is totally dominated by the nucleus (e.g. Elvis et al. 1978). Neither diffuse X-ray emission from inverse Compton scattering of the radio electrons off the optical-infrared photons nor synchrotron emission is likely to contribute significantly to the total X-ray emission (Fabbiano et al. 1982). A more likely source is diffuse thermal emission from a hot phase of the interstellar medium, heated by supernovae, and this is discussed later in this review.

2.2 *X-Ray Observations of the Local Group*

It is not surprising that the most detailed work on individual X-ray sources in galaxies and their identifications has been done as a result of the *Einstein* observations of Local Group galaxies (distance ≤ 1 Mpc). This work has been reviewed comprehensively by Helfand (1984a). Here I summarize the main results and review the more recent work not included in Helfand's paper. Table 1, adapted from Helfand (1984a), summarizes the results on the X-ray sources detected and identified with objects belonging or likely to belong to these galaxies. Although this summary offers a way to intercompare the different galaxies in the Local Group, the reader should take care in using it because of the different limiting sensitivities and completenesses of the different surveys. In particular, the Magellanic Clouds have been surveyed down to limiting luminosities for point-source detection of 10^{34}–10^{35} erg s^{-1}, whereas the other galaxies have limiting luminosities closer to 10^{37} erg s^{-1}.

In the Large Magellanic Cloud (LMC) most of the detected and identified sources are supernova remnants (see also Long & Helfand 1979, Helfand & Long 1980, Helfand 1982, 1984b, Tuohy et al. 1982, Mathewson et al. 1983, 1984, 1985, Cowley et al. 1984), of which three are Crab Nebula–like and one definitely contains a pulsar (Clark et al. 1982, Seward et al. 1984, Chanan et al. 1984). Studies of this sample of remnants has provided new insight on the supernova rate, the pulsar birthrate, and the evolution of the remnants (see Helfand 1984a, and references therein). One fourth of the sources found in the Small Magellanic Cloud (SMC) are likely to be supernova remnants. The X-ray population of the Clouds also includes a number of massive young Population I close accreting binaries, to which belong the brightest X-ray binaries known in the pre-*Einstein* era (Clark et al. 1978), and a number of still unidentified fainter sources with $L_X \sim 10^{34}$–10^{36} erg s^{-1} (e.g. Long et al. 1981a, Bruhweiler et al. 1987). The latter authors speculate that these sources in the SMC may be analogous to the wide Be-neutron star binaries that are found in the Galaxy (White et al. 1982, Tuohy et al. 1988), or that they could be normal O and B stars whose X-ray luminosity might have been enhanced by a factor of $\sim 10^4$ because of the low metallicity of the SMC.

Supernova remnants instead constitute a less important component of the X-ray sources detected in the two spiral systems M31 (Figure 1) and M33, which appear to be dominated by binary X-ray source candidates. One should remember that the luminosity threshold for these galaxies is higher than in the Clouds (see above), and that at least in the edge-on M31 the soft X-ray emission of supernova remnants might be affected by interstellar extinction, so it is not possible to draw a strong conclusion from this result. However, seven remnants with $L_X > 10^{37}$ erg s^{-1} are found in the LMC, while only two identifications with supernova remnants have been reported for M31 in this luminosity range, and possibly one for M33 (Long & Van Speybroeck 1983, Long et al. 1981b). The pointlike X-ray sources detected in M33 appear to be associated with young Population I indicators, with the exception of a strong nuclear source that is discussed later (Long et al. 1981b, Markert & Rallis 1983, Trinchieri et al. 1988).

Table 1 X-ray sources in Local Group galaxies

Galaxy	Type	Total L_X (erg s^{-1})	No. of sources	Interlopers[a]	SNR	Binaries (young Pop I)	Binaries (older population)	Unidentified in galaxies	References[f]
LMC[b]	Ir I	6.6×10^{38}	102(52)	~46(~19)	32(21)	7(6)	2(2)	~15(~4)	1, 4, 5, 6
SMC	Ir I	6.1×10^{37}	57	~14	~12	1	0	~30	1, 5, 7, 8, 9
M31	Sb	3.6×10^{39}	117	~6	2	~26	~23GC+~60[c]	—	1, 5, 10, 11, 12
M32	E2	5.4×10^{37}	1	—	—	—	1	—	2, 5, 12
M33	Sc	1.1×10^{39}[d]	17	~3	1	~12	0	—	1, 5, 13, 14, 15
IC 1613	Ir I	—	0	—	—	—	—	—	1, 5
NGC 6822	Ir	1×10^{37}	2	~1	~1	—	—	—	1
NGC 205	E5	$<9 \times 10^{36}$	0	—	—	—	—	—	1
U Mi	E	$\leq 3.2 \times 10^{35}$	3	—	—	—	—	$\leq$3	1
Maffei 1	E?	1×10^{39}	$\leq$3	—	—	—	—	extended	1
Milky Way	~Sc	$\sim 3 \times 10^{39}$	~125[e]	—	~10	~40	8GC+~67[c]	—	3, 5, 16

[a] These are either background or foreground sources not belonging to the galaxies.
[b] Numbers in parentheses are from the complete X-ray-flux-limited sample.
[c] GC are globular cluster sources.
[d] This includes the bright nuclear source.
[e] Approximate number of galactic X-ray sources with $L_X > 10^{35}$ erg s^{-1}.
[f] References: (1) Markert & Donahue 1985, and references therein; (2) G. Trinchieri, private communication, 1988; (3) Fabian 1981; (4) Long et al. 1981a; (5) Helfand 1984a; (6) Cowley et al. 1984; (7) Seward & Mitchell 1981; (8) Inoue et al. 1983; (9) Bruhweiler et al. 1987; (10) Van Speybroeck et al. 1979; (11) Long & Van Speybroeck 1983; (12) Crampton et al. 1984; (13) Long et al. 1981b; (14) Markert & Rallis 1983; (15) Trinchieri et al. 1988; (16) Helfand 1985.

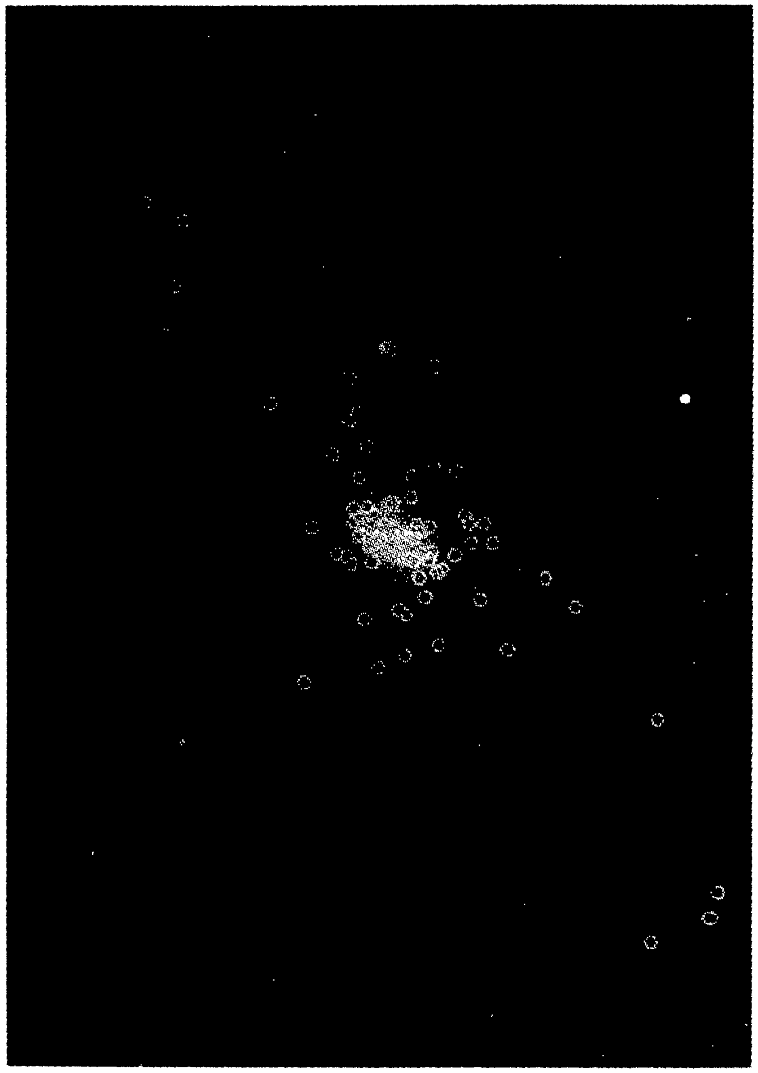

Figure 1 The circles show the positions of the X-ray sources of M31, superimposed onto an optical photograph (courtesy of L. Van Speybroeck). Notice the clustering of sources in the bulge.

One of these sources (M33 X-7) has a variable light curve that is consistent with a 1.8-day eclipsing binary period, similar to those of some massive galactic X-ray binaries (Peres et al. 1989). In M31 (Van Speybroeck et al. 1979, Van Speybroeck & Bechtold 1981, Long & Van Speybroeck 1983; see Helfand 1984a) most of the X-ray sources are instead likely to belong to an older stellar population. The luminosity of these sources is in the range of that of Galactic low-mass binaries, and some variability has been reported (Van Speybroeck & Bechtold 1981, McKechnie et al. 1984), consistent with the hypothesis of their being powered by accretion onto a compact object. Of these X-ray sources in M31, 19 have been identified with globular clusters tabulated by Sargent et al. (1977) and Battistini et al. (1980), and 4 more sources could also be associated with globular clusters (Crampton et al. 1984); ~30 sources are associated with the disk and the spiral arms; 19 pointlike sources plus a number of confused sources are detected in the inner bulge, within 2′ (400 pc) of the nucleus; and 22 additional sources lie in the outer bulge. The average X-ray spectrum of the bulge sources is similar to those of low-mass X-ray binaries in the Galaxy (Fabbiano et al. 1987b, Makishima et al. 1989). Only a few sources have been detected in the less massive members of the Local Group, but this is not surprising if the X-ray source formation rate is somehow linked to the mass or to the stellar content of a galaxy (see later).

Table 1 also gives an approximate estimate of the X-ray source content of the Galaxy (from Helfand 1984a; see also Fabian 1981). These estimates undoubtedly suffer from the unavoidable biases of all Galactic observation—namely, the difficulties in estimating distances and membership in a given stellar population or galactic structure, and the obscuration of softer X-ray sources (among which are the supernova remnants) by the interstellar medium in the Galactic plane. Even if we keep in mind all the necessary cautions, however, a comparison of the different entries of Table 1 suggests differences in the X-ray source composition in galaxies of different morphology. In particular, it appears that there is a shift from X-ray sources belonging to the young Population I to X-ray sources belonging to an older stellar population, going from the later-type galaxies (LMC, SMC, and M33, which are dominated by the spiral arm and disk stellar component) to the earlier-type ones (the Milky Way and definitely M31, with prominent bulges and a large number of globular clusters). Helfand (1985) shows that the percentage per unit mass of sources belonging to the spiral arm population increases with the morphological type in Local Group galaxies, going from bulge-dominated to disk-dominated galaxies; conversely, the percentage of bulge-type sources and globular cluster sources decreases with morphological type. Moreover, in M31 and the Galaxy the brightest X-ray sources belong to the older stellar population, while the opposite is observed in the Clouds and in M33. Another effect, first pointed out by Clark et al. (1978) (who ascribed it to the lower metallicity of the accreting gas), is the higher luminosity of the X-ray binary sources in the Clouds (see also Long & Van Speybroeck 1983, Crampton et al. 1984, Helfand 1984a). This effect could be responsible for the enhancement of the detection of young Population I sources in later-type galaxies. Alternatively, the reason could lie in an intrinsic higher mass for the accreting compact object: In particular, two of the four best black hole candidates are found in the LMC [LMC X-1 and LMC X-3 (Hutchings 1984; see Helfand 1985)].

Detailed comparisons have been made between the different X-ray source populations of the two most massive members of the Local Group: the Galaxy and M31 (Van Speybroeck & Bechtold 1981, Long & Van Speybroeck 1983, Battistini et al. 1982, Crampton et al. 1984). In particular, Long & Van Speybroeck (1983) remarked that M31 appears to have both a larger population of bulge sources and a larger and more luminous population of globular cluster sources than does the Galaxy. These results should be explainable in terms of the differences between these two galaxies: M31 has a larger population of globular clusters [$\sim$600 (Crampton et al. 1985) versus 180 in the Galaxy (Harris & Racine 1979)]. Crampton et al. (1984) remark that the fractions of X-ray-emitting globular clusters in the two galaxies are similar, and that the higher X-ray luminosities seen in the M31 globular clusters may simply reflect the fact that M31 contains more globular clusters and that the X-ray-bright ones, which are also the optically brightest and more condensed, lie on the high-luminosity tail of an overall distribution that is similar to the one in the Galaxy. Other authors (Long & Van Speybroeck 1983, Huchra et al. 1982, Battistini et al. 1982) have debated whether these M31 globular clusters are peculiar, and whether a metallicity–X-ray luminosity effect is possible. The bulge of M31 has a central concentration of $\sim$20 sources within $\sim$400 pc that appear more luminous on average than a similar number of sources in the outer bulge (Van Speybroeck et al. 1979). If these sources are distributed spherically, they would constitute a structure unlike any seen in the Galaxy, where only a few sources are seen in a similar volume (Long & Van Speybroeck 1983). These authors, however, suggest the alternative that the bulge X-ray sources in both galaxies might form similar, flattened barlike structures (see also Van Speybroeck & Bechtold 1981). The coincidence of this enhanced source distribution in M31 with a reported hole in the distribution of optical novae led Vader et al. (1982) to suggest that these sources could be the result of the evolution of a dead cataclysmic variable population that had long since undergone its nova phase. More recent observations, however, have dispelled the notion of a nova hole in M31 (Ciardullo et al. 1987). These authors suggest that the enhanced X-ray source content and the high specific nova rate that they find in the bulge of M31 could both be connected with the disruption of globular clusters in the bulge, which would then release the binaries that had formed in their cores. Although controversial (van Paradijs & Lewin 1985, Vader et al. 1982), a similar mechanism has been suggested by Grindlay (1984, 1985) for the formation of low-mass binaries in the Galaxy.

The results discussed so far are concerned with the detectable individual source content of the Local Group galaxies. However, below the single source threshold, it is still possible to detect the integrated emission of the fainter, individually undetectable sources and of any truly diffuse component, such as a hot phase of the interstellar medium. This type of emission has been reported in the Galaxy, where it accounts for $<10\%$ of the integrated emission of the resolved sources in the 2–10 keV range [the "Galactic ridge" (e.g. Worrall et al. 1982, Warwick et al. 1985, Koyama et al. 1986)]. A soft diffuse X-ray background ($E < 0.284$ keV), which is likely to be of Galactic origin, has also been observed (e.g. McCammon et al. 1983, Marshall & Clark 1984). A soft (0.25 keV) X-ray survey has revealed the presence of diffuse emission in the LMC (Singh et al. 1987). This emission has also been seen in the *Einstein* survey and has a total X-ray luminosity of 3×10^{38} erg s^{-1} (D. Helfand, private communication, 1988). The only other galaxy of the Local Group for which diffuse emission has been reported to date is M33 (Trinchieri et al. 1988), where the diffuse component accounts for $\sim 1/3$ of the total nonnuclear emission (which is not surprising given the much higher source detection threshold of these observations) and can be separated into a spectrally hard ($kT > 2$ keV) and a soft ($kT < 1$ keV) component. The hard component could be due to the integrated contribution of several lower luminosity compact accreting systems and young supernova remnants; the soft component is most likely due to the integrated emission of stellar coronae, with a possible contribution from a hot phase of the interstellar medium.

2.3 *Detailed Observations of Bright Spiral Galaxies*

Only a few very bright X-ray sources can be detected in the *Einstein* images of more distant galaxies, which typically appear as extended X-ray emission regions (e.g. Fabbiano & Trinchieri 1987). However, there is reason to believe that most of the X-ray emission of these galaxies is due to sources akin to those detected in the Local Group. A comparison of the fraction of the X-ray emission resolved in individual bright sources versus that which appears diffuse is consistent with the bulk of the emission originating from individual sources below threshold: More distant galaxies, with higher point-source thresholds, have a relatively larger "diffuse" emission than do less distant galaxies (Fabbiano 1988a). Moreover, the X-ray spectra of these galaxies, although ill defined, are consistent with the hard spectra expected from binary X-ray sources (Fabbiano & Trinchieri 1987, Trinchieri et al. 1988, Fabbiano 1988b).

Only a very few of the sources detected in spiral galaxies can be chance superpositions of background or foreground objects, given the statistics of the serendipitous *Einstein* source detections (Gioia et al. 1984; see Fabbiano & Trinchieri 1987). Most of these sources are therefore in the galaxies, often in the spiral arms, and their X-ray luminosities can be very high indeed. They are typically well above the Eddington limit for accretion onto a 1-$M_\odot$ compact object, which is $\sim 1.3 \times 10^{38}$ erg s^{-1}, and can be as bright as a few $\times\ 10^{39}$ erg s^{-1}. These sources have been detected in a number of spirals, including M83, M51, NGC 253, NGC 4631, NGC 6946, M101, and M81 (Long & Van Speybroeck 1983, Fabbiano & Trinchieri 1984, 1987, Trinchieri et al. 1985, Palumbo et al. 1985, Fabbiano 1988a), and eight bright sources have also been reported in the central starburst region of M82 (Watson et al. 1984). We exclude bright nuclear regions from the present discussion and concentrate instead on the more puzzling galactic sources. One of the most extreme cases is that of a source reported in M100 with an X-ray luminosity of $\sim 10^{40}$ erg s^{-1} (Palumbo et al. 1981). However, a very recent analysis of the same data by this reviewer, and of a subsequent longer exposure with the same high resolution, suggests that this source might be spurious: It is not detected in the longer exposure, and it is only marginally detected as an *extended* feature in the first observation. A similarly luminous source, however, is detected in NGC 4631 (Fabbiano & Trinchieri 1987). About 36 sources more luminous than $\sim 2 \times 10^{38}$ erg s^{-1} have been reported to date, 16 of which are more luminous than 10^{39} erg s^{-1}.

What are these sources? In one case the answer is simple: One of these sources is SN 1980K, which was detected in NGC 6946 $\sim$35 days after maximum light (Canizares et al. 1982b). The variability reported for some bright sources in M101 suggests pointlike objects [possibly bright accretion binaries (Long & Van Speybroeck 1983)]. If these sources are mostly complex emission regions, we would be faced with several bright sources (e.g. 10^{37} erg s^{-1}) in volumes with typical dimensions of a few hundred parsecs to a kiloparsec (Fabbiano & Trinchieri 1987). These sources are not typically in bulges, where such crowding could be expected [e.g. M31 (see earlier discussion)]. If these sources are truly single objects, they could indicate the presence of massive black holes in these galaxies. It is possible, however, that the distances of some galaxies might have been overestimated, which would make these sources appear more luminous than they are in reality. For instance, estimates of the distance of NGC 4631 range from 12 Mpc (Sandage & Tammann 1981) to 3 Mpc (Duric et al. 1982); using the lower estimate, the luminosity of the source reported by Fabbiano & Trinchieri (1987) as $\sim 1.4 \times 10^{40}$ erg s^{-1} would become $\sim 9 \times 10^{38}$ erg s^{-1}. However, this still exceeds the Eddington luminosity of an accreting neutron star.

The observations of the Local Group suggest differences in the X-ray sources in galaxies of different morphological type. However, differences also seem to occur in galaxies of similar morphology. An example is given by a comparison of the X-ray properties of the two Sb galaxies M31 and M81 (Fabbiano 1988a). The latter shows a number of individual X-ray sources, all more luminous than the most luminous sources of M31, and it is highly unlikely that this is due to an overestimate of the distance of M81. With the present data it is impossible to discriminate between an intrinsically more luminous X-ray source population in M81 or a more numerous population with the same luminosity function as that of M31. An overall comparison between these two galaxies also shows that M81 is overluminous in both X-ray and radio continuum emission, and to a lesser extent in far-infrared emission, relative to their optical luminosities. This suggests differences in the star formation history of these two galaxies, which resulted in a more efficient production of X-ray, cosmic ray, and far-infrared sources in M81. All these results are very tantalizing and show the importance of future sensitive X-ray observations in furthering our understanding of the global properties of spiral galaxies and of the detailed physical properties of their stellar remnants.

The presence of bulge (and globular cluster) X-ray sources on the one hand, and of often very bright X-ray sources associated with the spiral arms and H II regions on the other, is immediately demonstrated by the X-ray images of the Local Group and of other relatively nearby galaxies. The close resemblance between the radial profile of the X-ray surface brightness of a few face-on spirals and that of the optical light of their exponential disk suggests the presence of a third component of the X-ray emission, one associated with the stellar population of the disks (see Fabbiano 1986a). This effect was first seen in M83 (Figure 2; Trinchieri et al. 1985) and then in M51 (Palumbo et al. 1985) and possibly NGC 6946 (Fabbiano & Trinchieri 1987) and M81 [Fabbiano 1988a; see also M33 (Trinchieri et al. 1988)]. In particular, the X-ray profile in M51 is significantly different from the Hα profile (where the arms are very prominent) and follows the exponential disk distribution, as do the radio continuum and the CO profiles (Figure 3). These observations open interesting possibilities for our understanding of the origin of low-mass X-ray binaries. The nature of these sources, which constitute $\sim$60% of the Galactic sources and which are also called "galactic bulge sources" and "Population II" sources in the X-ray literature (e.g. van den Heuvel 1980, Helfand 1984a), is one of the open problems of "classical" X-ray astronomy. Suggestions on their origin have included capture of neutron stars in the Galactic bulge (van den Heuvel 1980), remnants of disrupted globular clusters (Grindlay 1984, 1985), or the evolved remnants of low-mass binary systems in the Galactic disk (e.g. Gursky 1976, Rappaport et al. 1982, Nomoto 1984, van den Heuvel 1984, and references therein). The observations of external galaxies morphologically similar to the Milky Way suggest that at least a good fraction of these sources may originate from the evolution of binary systems belonging to the disk stellar population, rather than from dynamical evolution (Fabbiano 1985a, 1986a, Trinchieri

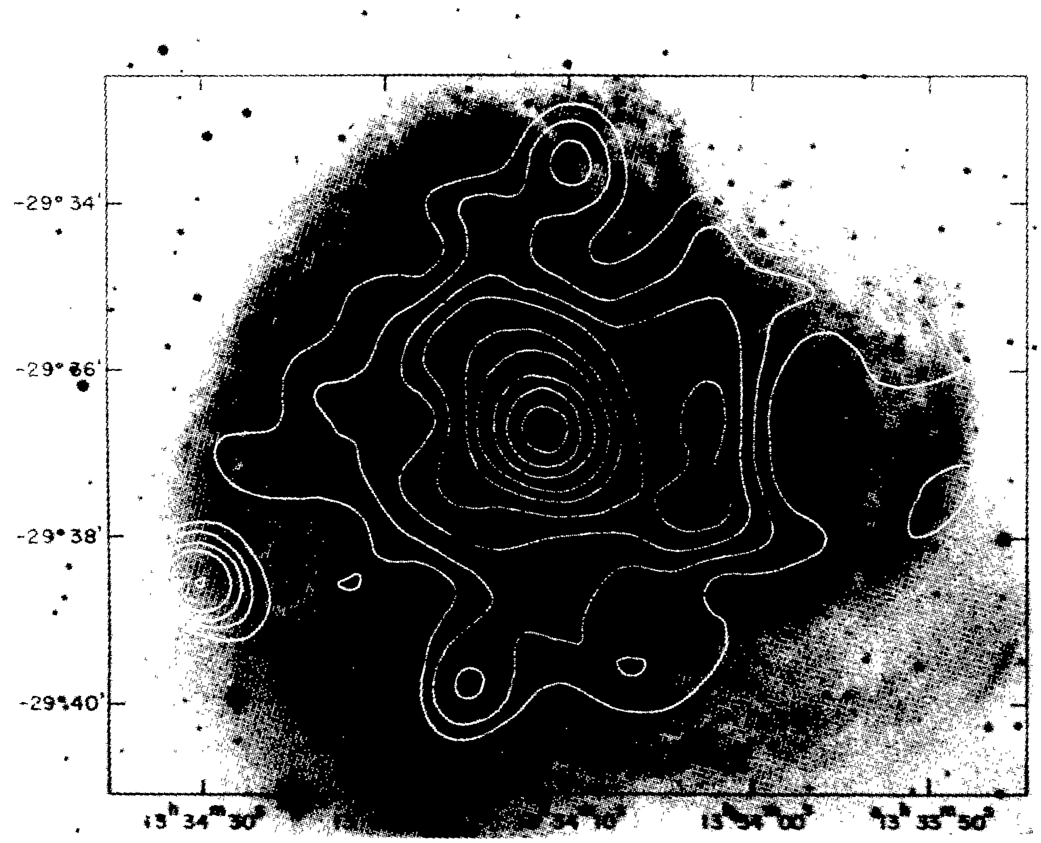

Figure 2 The *Einstein* HRI (high-resolution imager) X-ray map of M83 (Trinchieri et al. 1985). X-ray emission can be seen from most of the optical disk. A bright source is visible on a spiral arm.

et al. 1985). However (Fabbiano 1985a, 1986a), there is a relative excess of X-ray emission over the disk emission in the innermost disk region seen in both M83 and M51 (Trinchieri et al. 1985, Palumbo et al. 1985), which, if we scale by distance and dimensions, roughly coincides with what has been called the X-ray Galactic bulge. This excess emission could either (*a*) indicate an intrinsically brighter population of X-ray sources, analogous to the bright "bulge" Galactic sources, (*b*) point to an enhanced past episode of star formation in the inner disk, in contrast perhaps with steady star formation in the disk as a whole (e.g. Vader et al. 1982), or (*c*) suggest the presence of an additional component of the X-ray binary source population, which could be related to the disruption of globular clusters (Grindlay 1984, 1985).

However, there is one case in which the X-ray surface brightness profile clearly does not follow the optical light but instead follows quite well the radio continuum profile: NGC 253 (Fabbiano 1988b). Enhanced radio and X-ray emission is observed in the inner disk of NGC 253, and I discuss

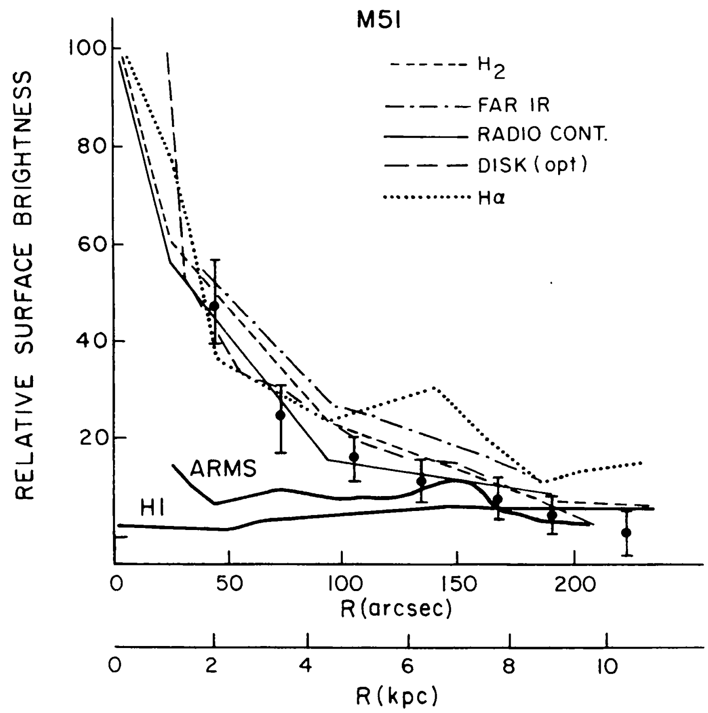

Figure 3 Radial profile of the X-ray surface brightness of M51 [the points (Palumbo et al. 1985)], together with radial profiles at other wavelengths from Scoville & Young (1983) and Klein et al. (1984).

in the next section the implications of this and other observations for a connection between X-ray sources and radio continuum emission.

Another source of X-ray emission, besides the contributions of individual sources, has been predicted in spiral galaxies. This is the thermal emission of the interstellar medium, heated by supernovae, which release $\sim 10^{42}$ erg s^{-1} in the galaxy. It has been suggested that hot gaseous coronae, or galactic fountains, could be produced and should be visible in soft X rays in the *Einstein* range (e.g. Spitzer 1956, Cox & Smith 1974, Bregman 1980a,b, Corbelli & Salpeter 1988). There is evidence of soft thermal diffuse emission both in the Galactic plane and in the LMC (e.g. McCammon et al. 1983, Marshall & Clark 1984, Singh et al. 1987), and perhaps in M33 (Trinchieri et al. 1988). A search for this type of emission in more distant galaxies has been made by Bregman & Glassgold (1982) and McCammon & Sanders (1984). The former searched two edge-on galaxies, NGC 3628 and NGC 4244, for coronal emission and set limits of 10^{39} and 2×10^{38} erg s^{-1}, respectively, on the X-ray luminosity of a gaseous halo; the latter instead analyzed a large face-on galaxy, M101, and concluded that the limits on the diffuse X-ray emission require that the temperature of any hot gas that is radiating $\geq 10\%$ of the average supernova power be less than $10^{5.7}$ K, and that hot bubbles occupy at most 25% of the region between 10 and 20 kpc from the galactic center. Subsequently, Cox & McCammon (1986) have used these measurements to constrain the density of the interstellar medium of M101 and the characteristics of the population of supernova remnants evolving in the disk. The lack of intense diffuse soft X-ray emission could imply that most of the supernova energy is radiated in the unobservable far-ultraviolet (Cox 1983). The only reported instance of this type of soft X-ray emission in a spiral galaxy is in the edge-on NGC 4631, where this component could have an X-ray luminosity of 5×10^{39} erg s^{-1}, which represents $\sim 13\%$ of the total emission in the *Einstein* band (Fabbiano & Trinchieri 1987).

Shostak et al. (1982) interpret an arc-shaped structure aligned with a ridge of radio continuum emission in NGC 1961 as evidence of a shock-heated interstellar medium that is being stripped by a hot intergalactic medium. However, without clear spectral confirmation, this interpretation is not unique: Enhanced star formation resulting from the interaction could also be responsible for the excess emission (e.g. Fabbiano et al. 1982; see next section). Similarly, a plume of extended emission emanating from NGC 4438, a spiral galaxy in the Virgo cluster, is reported by Kotanyi et al. (1983) as evidence of ram pressure sweeping of the interstellar gas from the disk of the galaxy. This plume, however, seems to emanate from the bright nucleus of this galaxy and could perhaps be similar to the gaseous plumes detected near the starburst nuclei of NGC 253 (Fabbiano & Trinchieri 1984) and M82 (Watson et al. 1984). I discuss these later in this review.

2.4 *Average Sample Properties and Correlations With Other Wavebands*

Although the *Einstein* images of some galaxies allow us to study them in detail and so reach some understanding of their X-ray emission components, most of the data are not of this high quality. Some 50 spiral galaxies were surveyed as part of the original *Einstein* observing program, and the results of these observations have been used to study the average properties of the sample and to explore correlations with the emission at other wavebands. This sample is not statistically complete; however, it can be regarded as representative of "normal" spiral galaxies of different morphologies and absolute magnitudes (Fabbiano & Trinchieri 1985). These galaxies have X-ray luminosities ranging between 10^{38} erg s^{-1} and 10^{41} erg s^{-1}, which are linearly correlated with their emission in the optical *B* band. This correlation is similarly tight for early-type bulge-dominated spirals and for late-type disk/arm-dominated galaxies: For all of them the ratios of monochromatic (2 keV) X-ray to optical (*B*) flux densities cluster around 10^{-7}. This result suggests that the X-ray emission is mostly due to sources constituting a constant fraction of the stellar population, in agreement with the conclusion of the detailed X-ray observations discussed above, which show that the X-ray-emitting population is likely to be dominated by binary X-ray sources (Long & Van Speybroeck 1983, Fabbiano et al. 1984b, Fabbiano 1984, Fabbiano & Trinchieri 1985). Even Sa galaxies follow this correlation, which suggests that their X-ray emission is due to the same type of sources responsible for the general emission of spiral galaxies and does not require an additional large gaseous emission component, such as is seen in bright elliptical galaxies (see later in this review).

Correlations have also been found between the X-ray emission and other variables, including the radio continuum, the near-infrared H band, and the far-infrared *IRAS* emission (Fabbiano & Trinchieri 1985, Fabbiano et al. 1988). These correlations are all very tight in late-type galaxies. In the subsample of bulge-dominated galaxies, however, the correlations between radio continuum and/or far-infrared luminosities with any of the other emission bands show a considerable amount of scatter and sometimes also a shift in zero point. In particular, for a given X-ray luminosity, there is a clear deficiency of radio continuum emission when bulge-dominated spirals are compared with disk/arm-dominated galaxies, whereas no differences are seen in the X-ray and optical (B) correlations. Since most of the optical and near-infrared emission of early-type spirals is dominated by the emission of the bulge (Kent 1985), these differences suggest that the radio continuum and the far-infrared are mainly related to the stellar population of the disk, whereas the X rays originate in both the disk and the bulge components. The latter conclusion is in agreement with the results of the X-ray observations of M31, which were discussed earlier.

Fabbiano & Trinchieri (1985; see also Fabbiano et al. 1984b) find that the correlation between X-ray and B-band emission is stronger than those between X-ray and either H-band or the $B-H$ color, which are both indicators of older stellar content and/or galaxy mass (e.g. Whitmore 1984). This result suggests that the X-ray sources belong predominantly to the blue-emitting stellar Population I. A link with the youngest Population I, to which the massive binary X-ray sources belong, is suggested in particular by a comparison between spiral galaxies with "normal" average colors and galaxies with blue peculiar colors, indicative of extensive and recent star formation activity (see Larson & Tinsley 1978). For a given optical luminosity, the X-ray luminosity is enhanced in relatively bluer galaxies (Fabbiano et al. 1982, 1984b, Fabbiano & Panagia 1983). These results also have implications for the nature and evolution of the low-mass X-ray binaries, which represent a very large component of the X-ray emission of the Milky Way: In particular, they suggest that most of these sources are likely to belong to the old Population I and possibly originate from the evolution of native binary systems, rather than having a dynamical origin. These conclusions are supported by the presence of an exponential disk in the X-ray emission of face-on spiral galaxies, as discussed earlier (see Fabbiano 1985a). Of all the correlations studied in late-type spirals, only two—the X-ray/B and the radio/far-infrared—imply strict proportionality between the emission at the two different wavelengths; the others follow power laws with exponents significantly different from unity. Trying to understand which correlations are intrinsically stronger, and therefore more directly connected to the underlying phenomena we wish to discover, and why not all the correlations scale simply with luminosity can give us new insight on the stellar components and evolution of spiral galaxies. Implications for the initial mass function (IMF), the average dust content of the disks, and the presence of compact star-forming regions are reviewed and discussed by Fabbiano et al. (1988). In particular, these correlations suggest the preferential occurrence of obscured starburst components in the more luminous galaxies.

An interesting possibility, raised both by single-galaxy studies and by statistical comparisons, is that of a connection between X-ray and radio continuum emission in spiral and irregular galaxies (Fabbiano et al. 1984b, Fabbiano & Trinchieri 1985, 1987, Palumbo et al. 1985, Fabbiano 1988b). This connection could be through recent star formation, but it is possible that there could be a more direct link between X-ray sources and cosmic-ray production (Fabbiano & Trinchieri 1985, Fabbiano et al. 1988). In particular, there is strong evidence of particle acceleration in X-ray binaries: Relativistic jets have been detected in the massive X-ray binary SS 433 and have been suggested to explain the radio morphology of the low-mass binary Sco X-1 (Geldzahler et al. 1981, Hjellming & Johnston 1981, Watson et al. 1983); and gamma-ray emission has been reported from the X-ray binaries Cyg X-3, Her X-1, and Vela X-1, suggesting intense cosmic-ray production (Samorski & Stamm 1983, Dowthwaite et al. 1984, Protheroe et al. 1984). Although strong, the X-ray/radio correlation has a power law exponent different from unity. Fabbiano & Trinchieri (1985), assuming proportionality between the sources of cosmic rays and the X-ray-emitting population, suggested that this result could imply a luminosity dependence of the intensity of the magnetic field of spiral galaxies. However, the proportionality between radio and far-infrared emission suggests that the sources of cosmic-ray electrons are a constant fraction of the stars responsible for heating the dust to far-infrared temperatures, and therefore that the nonlinear X-ray/radio correlation could be the result of these obscured regions contributing relatively less to the X-ray emission than to the radio and far-infrared emission (Fabbiano et al. 1988).

Although limited to relatively small samples, these comparisons have shown the potential of a multifrequency approach to the study of global galaxy properties. Their extension to larger and better defined samples, through systematic searches of the *Einstein* data bank (e.g. D. Burstein et al., in preparation, 1989) and through future X-ray observations, will be needed to confirm some of the present results and to gain a more general understanding of the structure and evolution of spiral galaxies.

3. STARBURST ACTIVITY AND LOW-ACTIVITY NUCLEI

3.1 *Widespread Starburst Activity in Peculiar Galaxies*

It was mentioned in the previous section that bluer "starburst," often-interacting galaxies tend to have enhanced X-ray emission compared with galaxies having redder, more normal colors (Fabbiano et al. 1982, 1984b, Stewart et al. 1982). The X-ray emission of these galaxies tends to originate from spatially extended regions, excluding a purely nonthermal nuclear origin, and their X-ray spectra exclude on average very soft emission, which suggests that the X-ray emission is not dominated by the thermal emission of a gaseous halo (Fabbiano et al. 1982). There are, however, exceptions to this second statement: The interacting pair NGC 4038/9 (the Antennae) possibly has a softer component of the X-ray emission that is of gaseous origin (Fabbiano et al. 1982, Fabbiano & Trinchieri 1983), and a similar component has been suggested in Arp 220 (Eales & Arnaud 1988); gaseous emission has been suggested to occur in ring galaxies (Ghigo et al. 1983), although there is no proof of its existence; and such emission has been reported in spiral-rich compact groups (Bahcall et al. 1984). Detailed observations of nearby galaxies with starburst nuclei show extended gaseous components emanating from the nuclear regions (e.g. Watson et al. 1984, Fabbiano & Trinchieri 1984, Fabbiano 1988b).

The bulk of the X-ray emission of these galaxies can be understood in terms of a number of young supernova remnants and massive X-ray binaries (with X-ray luminosity possibly enhanced by the low metallicity of the accreting gas) similar to those observed in the Magellanic Clouds (Fabbiano et al. 1982, Stewart et al. 1982). Although this explanation is not applicable in general (Fabbiano et al. 1982), the integrated coronal emission of the young stellar population [see Vaiana et al. (1981) for typical values] may dominate in very young starbursts, where the ultraviolet *IUE* spectra suggest the presence of a very large number of OB stars (Moorwood & Glass 1982, Fabbiano & Panagia 1983). Recently, Ward (1988) has reported a correlation between the Brackett-γ line emission from a sample of starburst nuclei and their X-ray emission, which is interpreted in terms of a relationship between the number of ionizing photons produced by the OB stars and the associated X-ray binary population, as estimated by Fabbiano et al. (1982). These authors, by comparing the observed radio and X-ray luminosities of their sample of peculiar galaxies with the expected output of a population of supernova remnants and X-ray binaries, also point out that the nonthermal radio emission from supernova remnants is not likely to account for the entire observed radio power, and thus that a different radio emission mechanism is required, as had already been observed by Biermann & Friecke (1977) in their study of Markarian galaxies.

3.2 *Starburst Nuclei*

There are galaxies in which the starburst activity is confined to the nuclear regions. The first reported instance of X-ray emission from this type of nucleus is that of NGC 7714 by Weedman et al. (1981), who associate this emission with the type of activity discussed above, as opposed to Seyfert-type nonthermal activity. A number of starburst nuclei, often embedded in an otherwise normal spiral galaxy, have been studied in X rays. They include the Galactic center region (Watson et al. 1981), M82 (Van Speybroeck & Bechtold 1981, Watson et al. 1984, Biermann 1984, Kronberg et al. 1985, Schaaf et al. 1989, Fabbiano 1988b), NGC 253 (Van Speybroeck & Bechtold 1981, Fabbiano & Trinchieri 1984, Fabbiano 1988b), M83 (Trinchieri et al. 1985), M51 (this nucleus also contains a Seyfert component, which does not dominate the X-ray emission; Palumbo et al. 1985), NGC 6946 and IC 342 (Fabbiano & Trinchieri 1987), and NGC 3628 (G. Fabbiano et al., in preparation, 1989). A common characteristic of the emission spectra of these nuclei is the intense far-infrared component (see Figure 9 of Fabbiano & Trinchieri 1987, and references therein), indicative of dusty nuclear regions heated by newly formed early-type stars. The X-ray-emitting regions are seen to be extended whenever observed with high-enough spatial resolution, and in M82 there is evidence of a population of bright individual sources (Watson et al. 1984). Typical X-ray luminosities of these nuclear regions are in the 10^{39} erg s^{-1} range, except for the Galactic center region, which is ~ 1000 times less luminous. To explain this emission requires, in different cases, different amounts of evolved sources (supernova remnants and X-ray binaries) superimposed on the integrated stellar emission from a young stellar population. The X-ray spectra of two of these nuclei, NGC 253 and M82 (Fabbiano 1988b, Schaaf et al. 1989), are intrinsically absorbed, consistent with the presence of a dusty emission region. In M82, in particular, it is possible that two different spectral components are present: a softer one, possibly dominated by the newly formed stars and by the interstellar medium shock heated by the frequent supernovae; and a harder one, which could be due to either binary X-ray sources with large intrinsic absorption cutoff or inverse Compton emission resulting from the interaction of the infrared photons in the nucleus with the relativistic electrons responsible for the radio emission. The latter mechanism was invoked by Kruegel et al. (1983) to explain the apparent excess X-ray luminosity of M82 when compared with NGC 253, but it had been dismissed by Watson et al. (1984; see also Fabbiano & Trinchieri 1984) on the basis of a spatial comparison of the X-ray, radio, and far-infrared emission. Schaaf et al. (1989), however, argue that it cannot be excluded that inverse Compton effects are responsible for a sizable fraction of the X-ray emission. It is clear that future observations at higher spectral resolution will be essential for distinguishing thermal and nonthermal emission components.

Line-of-sight extinction affects differently the optical B-band and the X-ray emission in the *Einstein* band, depending on the "hardness" of the X-ray spectrum. Using this effect, Trinchieri et al. (1985) constrained the maximum allowable extinction in the nuclear region of M83 by comparing the observed X-ray to optical flux ratio with the expected ratio for early-type stars. Any other assumption on the source of X-ray emission would lead to a smaller upper bound on A_V. The limits on the extinction thus calculated for M83 and for IC 342 (Fabbiano & Trinchieri 1987) are of order $A_V < 13$ mag, typically smaller than the mid-infrared estimates [35 mag in M83 (Lebofsky & Rieke 1979) and 15 mag in IC 342 (Becklin et al. 1980)]. This result suggests a nonhomogeneous distribution of the dust in the nuclear region, in agreement with the picture of Becklin et al. (1980), based on a similar discrepancy between the 10-μm infrared extinction and that estimated to the stars seen in the near-infrared.

Perhaps the most unexpected result from the *Einstein* observations of these nuclei has been the discovery of extended emission components, suggestive of gaseous outflows from the nuclear regions, in the edge-on galaxies M82, NGC 253 (Figure 4), and (more recently) NGC 3628. In M82, a correspondence between the region of extended X-ray emission ($\sim 90''$ radially from the nucleus) seen in the *Einstein* high-resolution imager (HRI) and the Hα filaments was first noticed by Van Speybroeck & Bechtold (1981). Watson et al. (1984) then suggested that this X-ray "halo" is likely to be thermal emission of shock-heated gas escaping the nuclear region. They point out that only 2% of the energy released by supernovae in the nucleus, exploding at a rate of 0.2 yr^{-1} over a time scale of 10^7 yr, is needed to heat the gas to X-ray temperatures. In NGC 253 the presence of an extended source, positionally coincident with a region of noncircular motions (Demoulin & Burbidge 1970), was also first reported by Van Speybroeck & Bechtold (1981). Fabbiano & Trinchieri

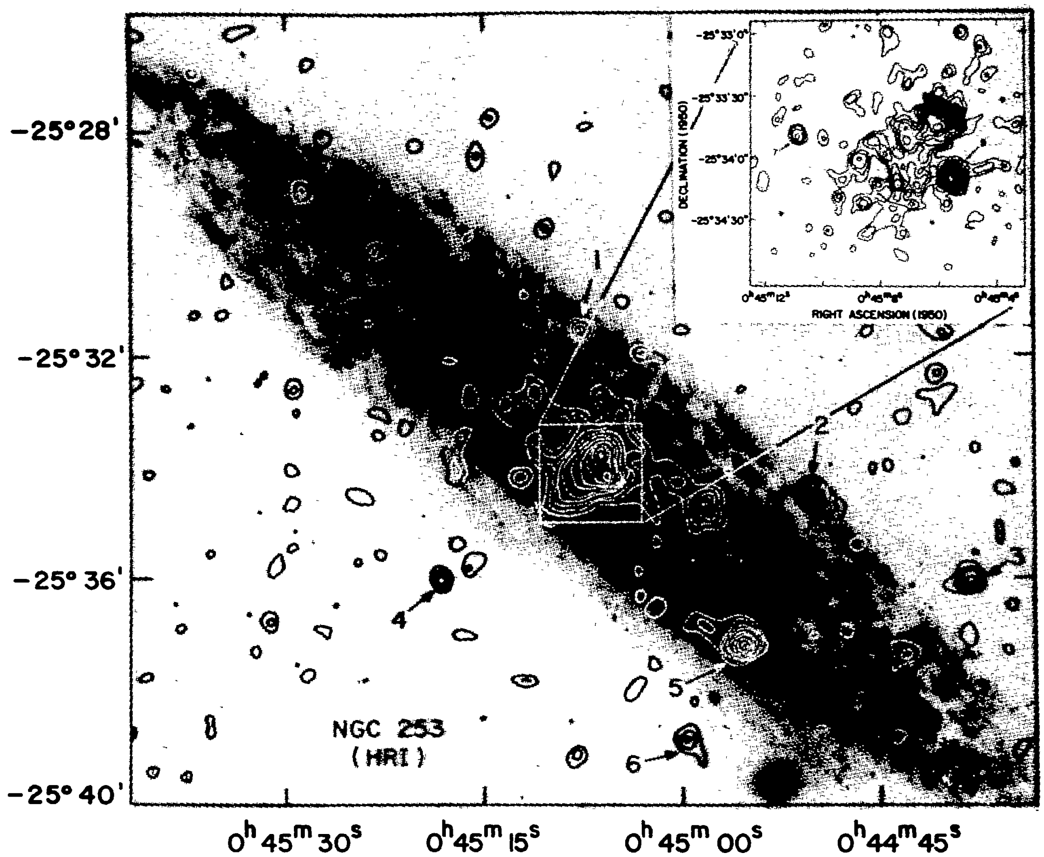

Figure 4 The *Einstein* HRI contour map of NGC 253, smoothed with a 7″ Gaussian. The insert shows a higher resolution map of the nuclear region. Here the shaded oval represents the nuclear starburst region seen in the radio and infrared. A plume of X-ray emission can be seen extending along the southern minor axis, and this was interpreted as evidence of hot outflowing gas (see Fabbiano & Trinchieri 1984, and references therein).

(1984) studied this nuclear region and identified both an emission region associated with the starburst nucleus proper and a "jet-like" feature, or "plume" of emission, extending for ~60″ along the southern minor axis. They suggested that the latter feature could be due to a bipolar nuclear outflow, similar to the one seen in M82, collimated by the galaxy disk and seen in projection along the minor axis. Fabbiano & Trinchieri further proposed that the northern side of the outflow would not be visible because the soft X-ray photons would be absorbed by the interstellar medium in the disk of NGC 253. The subsequent report of an OH line emission plume from the dusty northern side (Turner 1985) confirms this picture. Optical work on the emission line gas velocity fields in these two galaxies is also in agreement with the proposed gaseous outflows (McCarthy et al. 1987, Bland & Tully 1988). Theoretical models of this phenomenon have been offered by Chevalier & Clegg (1985) and Tomisaka & Ikeuchi (1988). Analyzing the lower resolution, but more sensitive, *Einstein* Imaging Proportional Counter (IPC) images of these two galaxies, Fabbiano (1988b) found evidence of diffuse X-ray emission at large radii in the northern side of NGC 253, which could be related to the nuclear outflow; in M82, on the other hand, there is clear evidence of an X-ray halo that is elongated along the minor axis and extends as far as ~ 9 kpc from the nucleus (see also Kronberg et al. 1985). This halo is not likely to be bound to the galaxy, and the hot gas may be leaving the system at a rate that could be as high as 0.7 $M_\odot$ yr^{-1}. These estimates are now uncertain, since neither the gas volume filling factor nor its emission temperature is really known. However, taken at face value, they would imply a maximum lifetime of 7×10^8 yr for the starburst, since the mass present in the nuclear region is $\sim 5 \times 10^8$ $M_\odot$ (Rieke et al. 1980), unless either the outflowing gas, cooling at large radii, flows in again in a galactic fountain or fresh gas from the intergalactic medium flows in to fuel the nucleus. Relatively short lifetimes ($< 2 \times 10^9$ yr) are also suggested by the OH data for the starburst at the nucleus of NGC 253 (Turner 1985).

Fabbiano (1984) remarked that these gaseous outflows should be visible in X rays in many galaxies, since starburst or low-activity nuclei are quite common (Keel 1983). With the present data it is impossible to distinguish them from the underlying disk emission in face-on galaxies such as M83 and M51 (Trinchieri et al. 1985, Palumbo et al. 1985); they should, however, be obvious in edge-on galaxies. Very recently, a reanalysis of the *Einstein* data of the edge-on galaxy NGC 3628 in different energy bands has shown an elongated soft emission region associated with the nucleus, suggestive of this phenomenon. The presence of a gaseous plume has been confirmed by subsequent optical observations (G. Fabbiano et al., in preparation, 1989). Different authors have pointed out that these outflows, if generally associated with violent star formation activity, could be responsible for the formation and enrichment of a large part of the gaseous intracluster medium (Heckman et al. 1987, Fabbiano 1988b). In particular, if a relatively small galaxy like M82 can expel of the order of 1 $M_\odot$ yr^{-1}, a primordial large elliptical system could expel 1000 times this amount. Therefore, some 1000 such systems in a cluster, undergoing violent star formation over a period of 10^8 yr, could produce the $\sim 10^{14}$ $M_\odot$ of gas that are now found in clusters of galaxies (Jones & Forman 1984). This type of scenario has been modeled by Mathews (1988a).

3.3 *Low-Activity Nuclei*

The sample of "normal" spiral galaxies observed with the *Einstein* satellite was selected to exclude known Seyfert nuclei, but some of these galaxies host nuclei with low-level activity not directly related to star formation. These galaxies include M51, whose nuclear region is, however, extended in X rays and therefore dominated by a starburst or by a hot gaseous component (Palumbo et al. 1985); M81, which hosts a small Seyfert nucleus (Peimbert & Torres-Peimbert 1981, Shuder & Osterbrock 1981) detected in X rays as a pointlike source (Elvis & Van Speybroeck 1982, Fabbiano 1988a); and two more galaxies, M33 and NGC 1313, for which the evidence of nuclear activity rests only on the X-ray data (Long et al. 1981b, Markert & Rallis 1983, Gottwald et al. 1987, Fabbiano & Trinchieri 1987, Trinchieri et al. 1988, Peres et al. 1989). A bright nuclear region ($L_X \sim 1.5 \times 10^{40}$ erg s^{-1}) was also observed in M100; however, this nucleus appears extended or complex (Palumbo et al. 1981). Other galaxies with relatively low-luminosity nuclei, although more luminous than the ones just mentioned, were surveyed to study their nuclear emission (e.g. Maccacaro & Perola 1981, Maccacaro et al. 1982). In at least one of these, the X-ray emission is extended and therefore not dominated by the nucleus [NGC 1365 (Maccacaro et al. 1982)].

The nucleus of M81 appears as an unresolved source in the *Einstein* images, with a luminosity $L_X \sim 1.6 \times 10^{40}$ erg s^{-1} (Elvis & Van Speybroeck 1982, Fabbiano 1988b). Variability of this source in the 2–10 keV range over a 5-month time scale has been reported by Schaaf et al. (1989). Fabbiano (1988b) reports that the *Einstein* IPC spectrum appears to be soft and intrinsically absorbed. This X-ray spectrum is reminiscent of the soft spectral components reported in QSO and bright active nuclei (e.g. Elvis et al. 1985, Arnaud et al. 1985, Pounds et al. 1986, Wilkes & Elvis 1987); an extrapolation of this spectrum to the UV suggests that there is enough photoionizing continuum to excite the optical emission lines, whereas this continuum would be missing for a more conventional ($\alpha_E \sim 0.7$) spectral power law (Bruzual et al. 1982). By using an accretion disk model (Bechtold et al. 1987, Czerny & Elvis 1987) to interpret this emission, one can constrain the mass of the central black hole to the range $\leq 10^{4\text{–}5}\, M_\odot$ and the accretion rates to values $\leq 10^{-(4\text{–}5)}\, M_\odot\, yr^{-1}$ (Fabbiano 1988b). This nucleus could therefore be just a low-luminosity specimen of a normal active galactic nucleus. The nucleus of M33 and the unresolved source in NGC 1313 are a factor of 10 less luminous than the nucleus of M81 and have similar spectral characteristics, within the fitting uncertainties (Trinchieri et al. 1988, but see also Gottwald et al. 1987, Fabbiano & Trinchieri 1987). The nucleus of M33 is also variable in X rays (Markert & Rallis 1983), most dramatically in the soft X-ray band (Peres et al. 1989). However, very little or no indication of activity is seen in optical and radio observations of these last two nuclei (von Kapp-her et al. 1978, Glass 1981, Gallagher et al. 1982, O'Connell 1983, Rubin & Ford 1986, J. Gallagher, private communication, 1987). One could speculate (Fabbiano 1988b) that these nuclei might represent a new type of source, possibly the radio-quiet counterpart of sources like the nucleus of 3C 264, which similarly shows no sign of optical activity (Elvis et al. 1981, Fabbiano et al. 1984a). If this is so, it is quite appropriate for these sources to be found in spiral galaxies, in analogy with what is observed in radio-loud and radio-quiet optically active nuclei (Miller 1985).

4. ELLIPTICAL AND S0 GALAXIES

4.1 *Discovery and Properties of the Hot Interstellar Medium*

The absence of tracers of a cold interstellar medium (ISM) in most early-type galaxies (e.g. Sandage 1957, Gallagher et al. 1975, Faber & Gallagher 1976) has prompted the construction of models to explain the removal of the gas shed from stars during their evolution (Mathews & Baker 1971, Bregman 1978, White & Chevalier 1983), which at the present rates would amount to $10^{9-10}\ M_{\odot}$ in a Hubble time in galaxies with an optical luminosity of $10^{10-11}\ L_{\odot}$ (e.g. Faber & Gallagher 1976). Now, X-ray observations have revealed this long-sought interstellar medium.

A hot gaseous halo had been known for some time to be associated with the Virgo cluster and M87 (Kellogg et al. 1975, Mitchell et al. 1976, Malina et al. 1976, Serlemitsos et al. 1977, Gorenstein et al. 1977, Fabricant et al. 1978, Lea et al. 1979, Canizares et al. 1979), but the presence of a hot gaseous medium in more normal ellipticals was revealed for the first time by the *Einstein* survey of the Virgo cluster (Forman et al. 1979). Five early-type galaxies in Virgo were detected in X rays in this first paper, with X-ray luminosities of $5–70 \times 10^{39}$ erg s^{-1}, over a factor of ~ 100 less luminous than M87. The X-ray image of one of them, M86, which has a large velocity relative to the Virgo cluster mean, was particularly important for establishing the gaseous nature of the emission. The X-ray isophotes of this galaxy appear significantly asymmetric with respect to the optical image (see Figure 7 of the *Annual Reviews* paper of Forman & Jones 1982), which suggests the presence of a gaseous halo of $\sim 6 \times 10^{9}\ M_{\odot}$ that experiences ram pressure stripping in its approach to the cluster core (Forman et al. 1979; see also Fabian et al. 1980, Takeda et al. 1984, Forman et al. 1984b). Another galaxy in Virgo, NGC 4472 (Figure 5), was later found to have a similar X-ray morphology (Forman et al. 1985, Trinchieri et al. 1986). Forman et al. (1979) also concluded that the hot gas detected in the Virgo galaxies had to be indigenous, since the cooling time of the intracluster medium is too long to make accretion onto the galaxies possible.

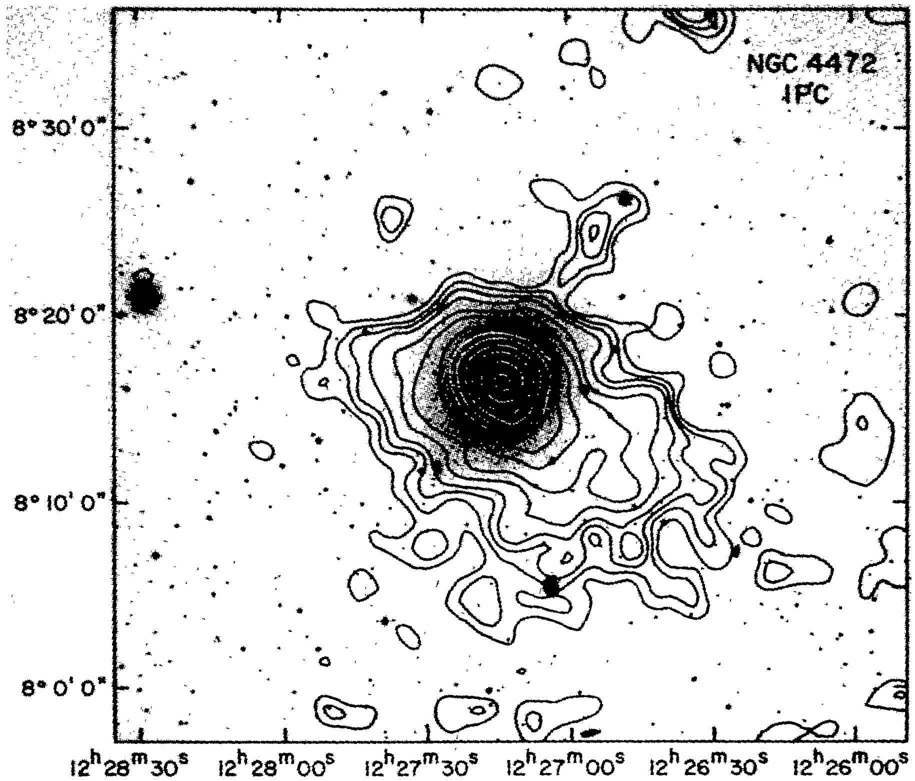

Figure 5 The *Einstein* IPC X-ray map of NGC 4472. Notice the asymmetric halo.

Subsequent X-ray observations and data analysis led to the detection of many more early-type galaxies in Virgo, in poor clusters and groups, and in the field, showing the ubiquity of their X-ray emission [Kriss et al. 1980, 1983, Biermann et al. 1982, Biermann & Kronberg 1983, Nulsen et al. 1984, Dressel & Wilson 1985, Forman et al. 1985, Trinchieri & Fabbiano 1985, Mason & Rosen 1985 (who report *EXOSAT* observations), Killeen et al. 1986, Trinchieri et al. 1986, Canizares et al. 1986, 1987, Killeen & Bicknell 1988a]. Typical X-ray luminosities in the *Einstein* band range from 10^{39} to 10^{42} erg s^{-1}, except for group or cluster-dominant galaxies, which tend to be more luminous (in the 10^{43} erg s^{-1} range). The sources detected with better signal to noise are clearly extended, with radii of ~40–70 kpc, generally comparable with those of the stellar distribution. This spatial extent is not in itself proof of the gaseous nature of the emission, because none of these galaxies is close enough to allow the spatial resolution of single X-ray sources with the *Einstein* instruments, as in the case of nearby spirals. Moreover, the radial distributions of the X-ray and optical surface brightnesses in those galaxies for which both profiles are available tend to follow each other, at least if one excludes the outermost radii, where the uncertainties in the field background subtraction and possible environmental effects could affect the profiles and perhaps the inner core regions (Figure 6; Trinchieri 1986, Trinchieri et al. 1986, Killeen & Bicknell 1988a). However, other convincing indications were found for the presence of a hot gaseous component in at least the brightest galaxies.

One indication is given by the spectral characteristics of the X-ray emission, which in those galaxies bright enough to be so analyzed can be fitted with fairly low emission temperatures [$kT \sim 0.5$–2.0 keV (Forman et al. 1985, Trinchieri et al. 1986, Killeen & Bicknell 1988a)]. This is in contrast with the bright spiral galaxies, which have harder spectra, consistent with the presence of a population of binary X-ray sources and young supernova remnants [$kT > 2$ keV (Fabbiano & Trinchieri 1987)]. Another indication is given by a comparison of the global X-ray and optical properties of early- and late-type galaxies surveyed with the *Einstein* satellite. This comparison shows that the X-ray and optical luminosities of elliptical and S0 galaxies follow a steeper correlation ($\alpha \sim 1.6$) than does

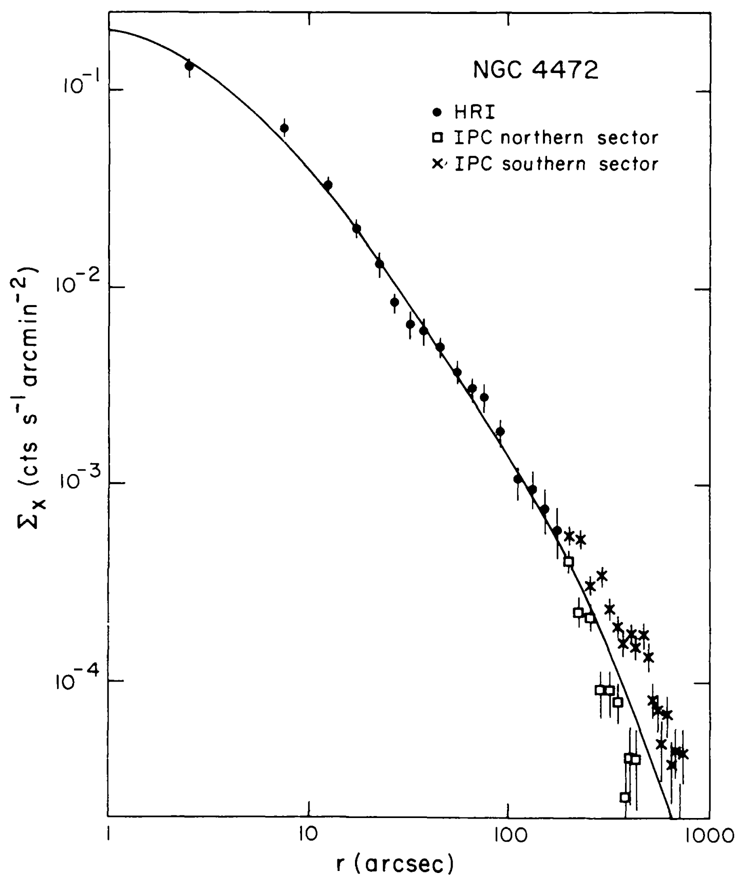

Figure 6 Radial profile of the X-ray surface brightness of NGC 4472 [the points (Trinchieri et al. 1986)] together with the optical profile from King (1978)]. Note the north-south asymmetry at large radii.

the linear one observed in spirals, which suggests that a different emission mechanism or at least an additional emission component is present in early-type galaxies (Fabbiano 1984, Forman et al. 1985, Trinchieri & Fabbiano 1985, Canizares et al. 1987). Those galaxies more luminous in X rays for which we have some spectral information are also those generally presenting excess emission relative to the relationship of the spirals (Figure 7). Therefore, this "excess" X-ray emission can be attributed to a hot gaseous component.

Once the presence of a hot gaseous component in bright early-type galaxies has been established, we would like to know how much hot gas is present in galaxies of different optical and X-ray luminosities.

How much of the X-ray emission of early-type galaxies is due to the hot

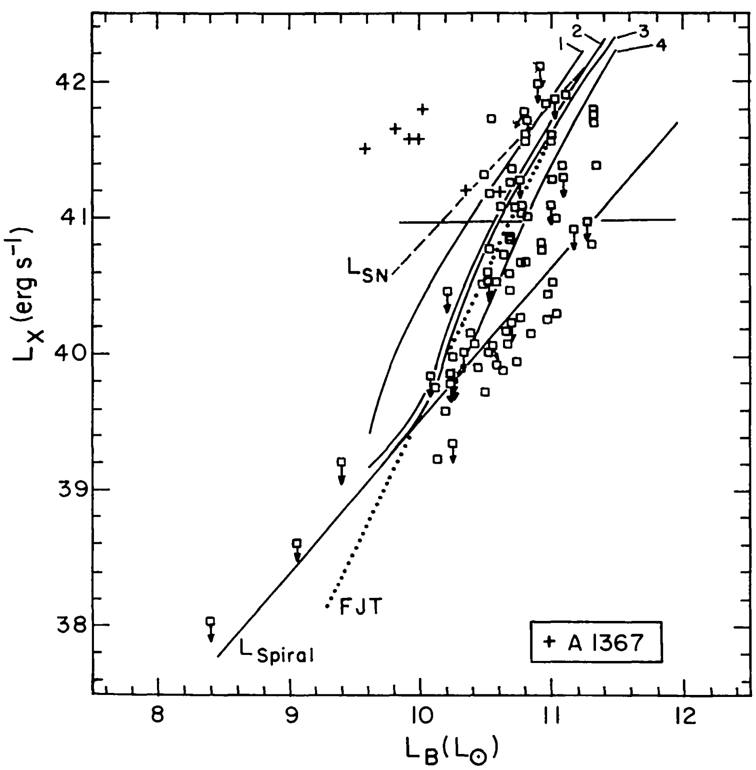

Figure 7 X-ray (in erg s^{-1}) and optical (in solar units) luminosities of E and S0 galaxies observed in X rays (from Canizares et al. 1987). The crosses are the galaxies in A1367 discussed by Bechtold et al. (1983). The solid line ($L_{\rm Spiral}$) is the best-fit line of early-type spirals from Fabbiano et al. (1988); the horizontal solid line delimits the maximum X-ray luminosity of spiral galaxies. The dashed line ($L_{\rm SN}$) is the estimate by Canizares et al. (1987) of supernova heating of the halos; the dotted line (FJT) is the estimate by Forman et al. (1985) (see Section 4.2); and the curves labeled 1, 2, 3, and 4 are the models of Sarazin & White (1988) for massive halos and supernova heating, supernova heating without massive halos, massive halos but no supernova heating, and no massive halos and no supernova heating, respectively.

gaseous component and how much can instead be ascribed to a population of evolved galactic sources, similar to those found in late-type galaxies, is still a matter of debate. Forman et al. (1985; see also Jones 1987, Forman & Jones 1988) conclude that all of the emission of early-type galaxies with absolute blue magnitude $M_B \leq -19$ is due to gaseous halos. Trinchieri & Fabbiano (1985), Canizares et al. (1987), and Fabbiano et al. (1989) note, however, that the data require the presence of a gaseous component only in the more X-ray-luminous galaxies, whereas the emission of galaxies less luminous than $\sim 10^{40.5\text{–}41}$ erg s^{-1} (these galaxies can be optically very bright, with $M_B \sim -22$) can be easily explained with a population of accreting low-mass binary sources. These different conclusions are partly due to the different choices of benchmarks for the expected contributions of discrete X-ray sources, and they illustrate the uncertainties inherent in the present data. Forman et al. (1985) used the *Einstein* X-ray observations of Cen A [NGC 5128 (Feigelson et al. 1981)] as a benchmark. However, the complexity of the X-ray emission of Cen A makes the evaluation of its "binary" component uncertain. Trinchieri & Fabbiano (1985) and Canizares et al. (1987) based their estimate on an extrapolation of the X-ray properties of the bulge of M31, which is dominated by pointlike sources, and of its globular cluster system (Van Speybroeck et al. 1979, Van Speybroeck & Bechtold 1981, Long & Van Speybroeck 1983). This choice has been criticized by Forman & Jones (1988), who remark that the bulge of M31 could be peculiarly bright in X rays. However, the stellar content of this bulge is indistinguishable from that of well-studied elliptical galaxies such as NGC 4472 (Oke et al. 1981, Faber 1983, Bohlin et al. 1985), and therefore it represents our best nearby and well-studied example of such a system (Canizares et al. 1987). More recently, Fabbiano et al. (1989) have performed a direct comparison of the global X-ray and optical luminosities of ellipticals and S0s with those of early-type spirals and found that only in galaxies with X-ray luminosities greater than 10^{41} erg s^{-1} is there a departure from a linear relationship between X-ray and optical luminosities, such as that observed in spirals, which then requires an additional, nonstellar emission component (see Figure 7).

An uncontroversial way to resolve this issue would be to perform a spectral analysis of early-type galaxies of different luminosities, since the spectral signatures of binary X-ray sources and gaseous halos differ. In particular, the X-ray spectrum of the bulge of M31 is typical of low-mass binary X-ray sources (Fabbiano et al. 1987b, Makishima et al. 1989) and differs from those of bright early-type galaxies. This analysis was attempted by Canizares et al. (1987) but proved inconclusive because of the poor statistics of the data. The resolution of this issue will have to wait for future, more sensitive X-ray observations.

There is a consensus, however, that the hot gaseous component dominates the X-ray emission of the more luminous galaxies. The X-ray data can then be used to derive the physical properties of this gas, such as central density, cooling time, and total mass. For the brightest galaxies, radial profiles of density and cooling time can also be derived. Two approaches have been followed (e.g. Fabian et al. 1981, Canizares et al. 1983, 1987, Fabricant & Gorenstein 1983, Stewart et al. 1984a, Forman et al. 1985, Thomas et al. 1986, Trinchieri et al. 1986, Killeen & Bicknell 1988a). One is to use an "onion skin" technique to deproject the X-ray surface brightness and to infer the gas density distribution directly from the data. The other is to assume a parameterization of the form

$$S_X(r) = S_X(0) \times [1+(r/a_X)^2]^{-3\beta+1/2} \qquad 1.$$

for the X-ray surface brightness profile (where r is the radial distance from the centroid of the X-ray surface brightness distribution, and a_X is an X-ray core radius) and then from here derive the deprojected electron density profile $n_e(r)$ [and therefore the gas density $\rho_{gas}(r)$] under the assumption that the gas is isothermal, i.e.

$$n_e(r) = n_e(0) \times [1+(r/a_X)^2]^{-3\beta/2}. \qquad 2.$$

Fits to the X-ray data generally give $\beta \sim 0.4$–0.6 [i.e. a radial dependence of the X-ray surface brightness of the type $S_X(r) \propto r^{-(1.4-2.6)}$ and of the electron density $n_e(r) \propto r^{-(1.2-1.8)}$], although departures from simple power laws and from spherical symmetry are common (see Figure 6). The parameter a_X is less well defined but could be of the order of a few kiloparsecs or less.

Estimates of the gas parameters made by Canizares et al. (1987; see also Forman et al. 1985, Trinchieri et al. 1986, Thomas et al. 1986) give typical central densities of ~ 0.1 cm^{-3}, central cooling times ranging between 10^6 and 10^8 yr, and gas masses ranging between 10^{11} and $10^8 M_\odot$ for galaxies detected in X rays. The amount of hot gas detected in bright galaxies is therefore consistent with the amount expected assuming the present gas injection rates over a Hubble time (Forman et al. 1985), although this could be a coincidence, since the mass shed by the first generations of stars might have been larger than the present rate (Renzini & Buzzoni 1986, Jones 1987, Loewenstein & Mathews 1987a). However, upper limits on the gas masses can be as low as 10^6 $M_\odot$, showing a deficiency of hot interstellar medium in the less luminous galaxies. It should also be noted that the density and mass estimates given above are likely to be upper limits for these galaxies, since the X-ray emission of these galaxies could contain a sizable contribution from the "discrete source" component.

4.2 *Physical Status of the Halos*

Many authors have tried to understand the present status and the evolution of hot gaseous halos by comparing the X-ray observations with different theoretical scenarios. The temperature of the halos suggests the need for heating in addition to that supplied to a static halo by the same gravitational field experienced by the stars (e.g. Fabbiano 1986a). The high X-ray luminosities and corresponding large gas densities of some galaxies rule out the existence of galactic winds (Mathews & Baker 1971, Faber & Gallagher 1976, MacDonald & Bailey 1981, White & Chevalier 1983) because the mass supply from normal stellar processes falls several orders of magnitude short of that required to replenish such a wind (Nulsen et al. 1984, Forman et al. 1985, Sarazin 1986, Loewenstein & Mathews 1987a, Sarazin & White 1988). Moreover, the radial dependence of the gas density ($\rho_{\rm gas} \propto r^{-1.5}$ on average) is flatter than that expected of a wind [$\rho_{\rm gas}$(wind) $\alpha\, r^{-2}$ (Forman et al. 1985)]. All of this points to the need for a confining mechanism.

There are two indications that the halos are "hotter" than the stars. One is given by a comparison between the temperature inferred from the X-ray spectral fits [$T \sim (5.8\text{–}23) \times 10^6$ K, with best fits of $\sim 1.2 \times 10^7$ K] and that predicted under the assumption of thermal equilibrium with the stellar component. For typical line-of-sight velocity dispersions of $\sigma \sim 150\text{–}300$ km s^{-1} (e.g. Whitmore et al. 1985), and under the assumption of isotropy, the latter would be given by $T = \mu m_{\rm p} \sigma^2/k \sim 1.4\text{–}5.4 \times 10^6$ K, which is less than the best-fit temperature and probably near or below the lowest allowed by the data (Mathews & Baker 1971; see also Fabbiano 1986a, Killeen & Bicknell 1988a). The other indication is given by the radial dependence of the gas density as compared with that of the stellar light. Since the X-ray and optical surface brightness profiles tend to follow each other, and since the X-ray bremsstrahlung emission measure is a function of $n_{\rm e}^2$, it is easy to see that $\rho_{\rm gas}^2 \sim \rho_{\rm stars}$. If the gas and the stars are two isothermal spheres experiencing the same gravitational potential, this implies that $T_{\rm gas} \sim 2T_{\rm stars}$ (Cavaliere & Fusco-Femiano 1976; see Killeen & Bicknell 1988a). However, other heating mechanisms in addition to the motion of the mass-losing stars are readily available. They include supernova heating and gravitational heating. The latter would result from the dense gas cooling radiatively and then falling in the potential well in accreting "cooling flows" (Mathews & Baker 1971, MacDonald & Bailey 1981, Nulsen et al. 1984, White & Chevalier 1984, Sarazin 1986, 1987a,b, Thomas et al. 1986, Mathews & Loewenstein 1986, Canizares 1987, Fabian et al. 1987a, Canizares et al. 1987, Loewenstein & Mathews 1987a, Sarazin & White 1987, 1988, Umemura & Ikeuchi 1987, Vedder et al. 1988).

Nonthermal heating by the relativistic electrons in radio sources (e.g. M87) and heating by conduction from the surrounding intracluster medium have also been suggested (Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Rosner & Tucker 1989). Once heated, the gaseous halos must be confined within their emitting volumes. This can be achieved by the pressure of an external medium (e.g. Fabian et al. 1980, Binney & Cowie 1981, Forman et al. 1984b, White & Chevalier 1984, Vedder et al. 1988), by radiative cooling (e.g. MacDonald & Bailey 1981, White & Chevalier 1984), and by gravity (e.g. Bahcall & Sarazin 1977, Mathews 1978, Nulsen et al. 1984, Forman et al. 1985; see Canizares et al. 1987).

Figure 7 shows different model predictions compared with the X-ray/optical scatter diagram of early-type galaxies. In first approximation the functional dependences of the models are easy to understand: In the supernova-dominated model the X-ray and optical luminosities would be linearly related because the supernova energy input is proportional to the stellar luminosity for a constant supernova rate (Tammann 1974); in the gravitational-cooling flow model the X-ray and optical luminosities would be related as $L_X \propto L_B^{1.5-1.7}$ because the X-ray luminosity will be proportional to the stellar mass loss rate and to the square of the stellar velocity dispersion ($L_X \propto \dot{m}\sigma^2$) and $\dot{m} \propto L_B$, while the Faber-Jackson relation (1976; also Tonry 1981) gives $L_B \propto \sigma^{3-4}$ (White & Chevalier 1984, Nulsen et al. 1984, Sarazin 1986, 1987a, Canizares et al. 1987). Sarazin & White (1988), however, find that models can deviate somewhat from these simple approximations, because in parts of the models the temperature can be fairly low, so that the X-ray luminosity is not as simply related to cooling. If supernova heating is the dominant source of energy, the gas could be confined by a combination of radiative cooling and external pressure; if gravitational heating prevails, gravity would confine the gaseous halos (Canizares et al. 1987). In Figure 7 is also plotted the $L_X \propto L_B^2$ line of Forman et al. (1985) for hydrostatic halos accumulated in the galaxy potential over a Hubble time. This model, however, does not take into account cooling and heating mechanisms, or at least assumes that they balance closely (Sarazin 1987a). Moreover, it assumes the same emitting volume for all the galaxies, since the volume also figures in the emission measure (Fabbiano 1986a).

One common characteristic of these predictions is that they can easily explain only the more X-ray-luminous galaxies. The supernova-dominated models, in particular, predict X-ray luminosities in agreement with the upper envelope of the scatter diagram. Therefore, for many galaxies either the supernova rate is significantly lower than Tammann's (1982) estimate or the bulk of supernova energy is dissipated or radiated outside the X-ray band. Gravitational-heating models also predict large X-ray luminosities.

Smaller luminosities could be obtained if the mean stellar mass loss rate were smaller than that used in the calculations, or if a considerable fraction of $\dot{m}$ were not incorporated into the accretion flow or were removed from the flow by thermal instabilities before the flow had reached the center of the galaxy, although in the latter case the reduction is not dramatic (Thomas 1986, Thomas et al. 1986, Fabian et al. 1987a, Canizares et al. 1987, Sarazin & White 1988, Vedder et al. 1988, C. L. Sarazin & G. A. Ashe, submitted for publication, 1988). Moreover, the models cannot account for the observed scatter in the data. This scatter and the possibility that hot halos do not dominate the X-ray emission of the less X-ray-luminous galaxies (see the previous section) might be related to the effect of ram pressure stripping (Forman et al. 1984a, Sarazin & White 1988, Vedder et al. 1988) or to the presence of winds or partial winds (MacDonald & Bailey 1981, White & Chevalier 1984, Sarazin & White 1987; see also Loewenstein & Mathews 1987a, Umemura & Ikeuchi 1987) in some of the galaxies. A. Renzini (preprint, 1988) argues against cooling flows and in favor of winds for the low-X-ray-luminosity galaxies because the rate of stellar mass return is too high to reconcile the cooling flow model with the observed X-ray luminosities.

Pressure confinement has been invoked (Forman et al. 1985) to explain the presence of the very bright coronae in Abell 1367 reported by Bechtold et al. (1983), which (as shown by Figure 7) would be over two orders of magnitude more luminous than early-type galaxies of comparable optical luminosity in the field and in Virgo. Canizares et al. (1987) disagreed with this explanation on the basis that the density of the cluster medium of A1367 is similar to that of Virgo (Forman et al. 1979, Bechtold et al. 1983). More recently, Vedder et al. (1988) developed steady-state cooling flow models for early-type galaxies and concluded that similar galaxies with similar gas content should have similar X-ray luminosities regardless of their location, since the external pressure around a galaxy would not affect the luminosity of the gas within the galaxy, but rather its temperature, and it would only affect the X-ray surface brightness near the outside of the galaxy. However, if conduction is important, heat could flow from the cluster to the galaxy and increase the X-ray luminosity (C. Sarazin, private communication, 1988).

The X-ray/optical correlation does not allow one to discriminate between the different models. However, there are two other observational constraints that need to be satisfied: the radial distribution of the halos, and their emission temperature. Comparison with models of the observed surface brightness profiles have been attempted by various authors, usually by using "average" profiles, which disregard the asymmetries and departures from power laws that are sometimes observed at large radii (see

Trinchieri et al. 1986). Since these events could be due to interaction with the environment, this approach might appropriately describe an undisturbed early-type galaxy. Sarazin (1986; see also Sarazin 1987a,b, Loewenstein & Mathews 1987a, Sarazin & White 1988) pointed out that if heating and cooling balance locally in a halo, and if the heating of the gas per unit mass is independent of position, then $\rho_{\text{gas}}^2 \propto \rho_{\text{stars}}$, and thus the X-ray and optical surface brightness profiles would then follow each other, as observed (Trinchieri et al. 1986, Killeen & Bicknell 1988a). Cooling flow calculations, however, in the absence of conduction heating and under the simplest assumption that the gas is a one-phase medium, generate models that typically have total luminosities that are too large (see above) and have a central peak of the X-ray emission that is not observed (Thomas 1986, Thomas et al. 1986, Loewenstein & Mathews 1987a, Sarazin & White 1988, Vedder et al. 1988). Modifying the models by allowing "sinks" of mass from the flow to prevent accretion at the cores, or even cooling outflows, produces profiles in closer agreement with the observations (Thomas 1986, Thomas et al. 1986, White & Sarazin 1987a,b,c, Vedder et al. 1988, C. L. Sarazin & G. A. Ashe, submitted for publication, 1988). It is also possible that many different phases are present in the cooling gas (Nulsen 1986, Thomas et al. 1987). At present the data do not allow us to discriminate readily between different models with different inputs of supernova energy, dark massive halos, and external pressure. Different models, however, produce different temperature profiles (e.g. Sarazin & White 1987, Vedder et al. 1988), and future X-ray observations will be able to give us an answer. I discuss in the next sections the constraints on the mass of the galaxies imposed by this type of model fitting.

4.3 *Cooling Flows*

As discussed above, with the exclusion of the static halo scenario of Forman et al. (1985), most models for the gaseous halos involve cooling flows to the galaxy cores. The presence and the amount of these flows have been objects of debate, chiefly because observational evidence at wavelengths other than the X ray is not clear-cut. Although a full discussion of this subject is beyond the scope of this review, I summarize here the aspects that are more relevant for the halos of elliptical galaxies. These flows have been suggested because the cooling times implied by the X-ray data for the central regions of most observed galaxies, and in some cases for most of the galaxy volume, are considerably shorter than the Hubble time (Nulsen et al. 1984, Trinchieri et al. 1986, Sarazin 1987a, Canizares et al. 1987). In the absence of other sources of heat, therefore, the gas in a volume element will cool and accrete subsonically in pressure-driven flows toward the center of the galaxy potential (e.g. Silk 1976, Fabian &

Nulsen 1977, Cowie & Binney 1977, Mathews & Bregman 1978). Derived mass accretion rates range from a few to $\sim 1000\ M_\odot\ \mathrm{yr}^{-1}$ for dominant cluster galaxies (Fabian et al. 1981, Mushotzky et al. 1981, Canizares et al. 1982a, Lea et al. 1982, Stewart et al. 1984a,b, Arnaud et al. 1984, Matilsky et al. 1985, Canizares et al. 1988) to $\sim 1\ M_\odot\ \mathrm{yr}^{-1}$ for normal ellipticals (Nulsen et al. 1984, Trinchieri et al. 1986, Canizares et al. 1987).

Although there is evidence for cooler gas in optical filaments and emission-line regions associated with cluster cooling flows and with the central regions of some early-type galaxies [e.g. Fabian et al. 1984b (and references therein), 1985, 1987b, Demoulin-Ulrich et al. 1984, Hu et al. 1985, Phillips et al. 1986, Crawford et al. 1987], the main problem of this scenario has been with finding incontrovertible evidence of star formation, which should be both substantial (given the mass cooling rates) and happening at all radii (Stewart et al. 1984a, Nulsen et al. 1984, Fabian et al. 1984b, 1987a, Nulsen & Carter 1987, White & Sarazin 1987b,c, 1988). Star formation with a normal IMF might be taking place in some galaxies (Silk et al. 1986, Romanishin 1987, Johnstone et al. 1987, Burstein et al. 1988, Bertola 1988); however, in most cases the galaxies' colors and 2.3-μm CO absorption index suggest that only low, or very low, mass stars may be forming (Fabian et al. 1982, Sarazin & O'Connell 1983, Fabian et al. 1984a, Arnaud & Gilmore 1986, Johnstone et al. 1987, O'Connell & McNamara 1988). This unusual IMF has been justified on the grounds that the large pressure in the flows will decrease the Jeans mass (Jura 1977, Fabian et al. 1982, Sarazin & O'Connell 1983), but the inconsistency of this explanation with the formation of massive stars in dense molecular clouds has led some authors to invoke additional sources of heat in the halos (e.g. Silk et al. 1986). Heating by conduction, in particular, has been suggested for galaxies in clusters (Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Rosner & Tucker 1989), but it might only apply for a very limited range of physical parameters (e.g. Bregman & David 1988). This is very much an open field of investigation, and there is no doubt that it will continue to be pursued from both an observational and a theoretical point of view.

Another way of testing some of the cooling flow theories is to try to find evidence of a colder interstellar medium in early-type galaxies and then compare these observations with the X-ray data. Canizares et al. (1987) searched for possible correlations between the X-ray emission and either the optical emission line (e.g. Phillips et al. 1986, Véron-Cetty & Véron 1986; see also Sadler 1988) or the H I emission (e.g. Knapp et al. 1985, Wardle & Knapp 1986), that could suggest a direct connection between the hot and the cooler interstellar medium, but they found none. However, the subsets of galaxies considered in each case are rather small and, at least for the H I, are dominated by nondetections. This lack of correlation would be consistent with the suggestion that the H I could have been accreted as a result of close encounters between galaxies (e.g. Knapp et al. 1985). However, Bregman et al. (1988) report the discovery of 1.5×10^8 $M_\odot$ of neutral hydrogen in NGC 4406 that they believe might be created within a cooling flow, and a similar conclusion has been reached by Huchtmeier et al. (1988) from their detection of CO emission from NGC 4472. The neutral hydrogen in NGC 4406 is centrally peaked, and there is no evidence for rotational support, as is often found in elliptical galaxies, where the H I tends to lie in rotationally supported extensive rings that are thought to be of external origin (e.g. van Gorkom et al. 1986). For completeness, it should be mentioned that Nulsen et al. (1984) have suggested that rotationally supported H I rings, not necessarily aligned with the galaxy's rotation axis, could be excreted from a cooling flow as a way of dissipating angular momentum.

Work on the *IRAS* data has shown that cool dust is present in early-type galaxies (Jura 1986, Wrobel et al. 1986, Thronson & Bally 1987). A possible, although not strong, correlation was reported between the far-infrared and the X-ray emission (Jura 1986, Knapp 1988, Kim 1988) that suggested a link between the hot and the cold interstellar medium in these galaxies, possibly through a common origin for the dust and the hot gas from stellar ejection. In particular, Jura (1986) concluded that the cold far-infrared-emitting dust should exist in pockets separated from the hot X-ray-emitting gas; otherwise, the dust would be destroyed by thermal sputtering in a short time. This might be evidence for the existence of a multiphase interstellar medium, which has been suggested in the framework of cooling flow modeling of the X-ray halos (e.g. Thomas et al. 1987).

In a recent series of papers, Mathews (1988a,b,c) has explored the constraints provided by the observational mass-to-light ratios to the mass of optically dark stars, originating from cooling flows in the cores of elliptical galaxies, and from these to the IMF and the history of winds and cooling inflows in the interstellar medium. He concludes that a component of dark stars in the cores is unlikely to be more massive than 30 times the core mass of luminous stars (Mathews 1988c) and suggests that the IMF of stars in elliptical galaxies is significantly flatter than the Salpeter IMF. In this scenario strong winds have expelled from the galaxies the mass shed by stars in early times, creating the intracluster medium, while present-day ellipticals are likely to be closed systems (Mathews 1988a). A. Renzini (preprint, 1988) also points out the presence of winds in young galaxies, given the enhanced supernova rate, and suggests that these winds might still be prevalent in the less X-ray-luminous ellipticals.

4.4 *The Mass of Early-Type Galaxies*

X-ray observations have been used to measure the mass of early-type galaxies (previous reviews on this subject include Canizares 1987, Sarazin 1987b, Fabian & Thomas 1987, Fall 1987, Trimble 1987). These measurements are based on the assumption that the X-ray emission is thermal bremsstrahlung from hot gaseous halos, and that the gas traces the potential but does not contribute to it significantly. This is a reasonable assumption (Forman et al. 1985), since $M_{gas}/M_{stars} < 7\%$ if one assumes that $M_{stars}/L_{stars} = 6$ (Faber & Gallagher 1979). Three approaches have been used: The first has been to measure the binding mass within a certain radius, under the assumptions of hydrostatic equilibrium and spherical symmetry. This method was first applied to M87 and has more recently been used to estimate the mass of less X-ray-luminous galaxies. The second approach has made use of more detailed modeling to match theoretical predictions to the observed X-ray surface brightness profiles. Finally, Fabian et al. (1986a) have devised a method to estimate lower limits to the *total* mass of a galaxy. In the following I discuss the results of these three types of analyses, with an eye to examining the assumptions made and the limitations of the current data.

The discovery of the extended thermal X-ray source in the Virgo cluster centered on M87 prompted the first attempts at estimating the binding mass of an early-type galaxy within radii well away from the optical core, to which optical measurements have been restricted. The first estimates, based on the assumption of the gas being in hydrostatic equilibrium in the galaxy potential at a temperature $T \sim 3 \times 10^7$ K, suggested very large binding masses, between 10^{13} and $\geq 10^{14}\ M_\odot$ (Bahcall & Sarazin 1977, Mathews 1978). However, Binney & Cowie (1981) showed that the X-ray data then available could also be fitted with a model of pressure-confined cooling atmosphere surrounding a low-mass galaxy. The observations of M87 with the *Einstein* IPC, which produced an image and spatially resolved spectral information, have led to more accurate measurements of the binding mass and have confirmed the earlier suggestions of the presence of a massive dark halo (Fabricant et al. 1980, Fabricant & Gorenstein 1983). In particular, Fabricant & Gorenstein (1983) could exclude a radial dependence of the temperature of the gaseous halo consistent with Binney & Cowie's model and found that the integral mass-to-light ratio (M/L) of M87 in solar units must increase from 5–15 at a radius of 1′ [$\sim$4.4 kpc (from the optical data of Sargent et al. 1978)] to over 180 at 20′ ($\sim$87 kpc), which implies that a dark massive halo is present. They derived a total mass $M \sim 3$–$6 \times 10^{13}\ M_\odot$ within 60′ ($\sim$260 kpc) from the core. Similar parameters were found for other central galaxies in clusters, including

NGC 1275 in Perseus (Fabian et al. 1981, Branduardi-Raymont et al. 1981) and NGC 4696 (Matilsky et al. 1985), the dominant galaxy of the Centaurus cluster. An apparently isolated galaxy, identified as the counterpart of a serendipitous X-ray source [1E0116.3−0116 (Maccagni et al. 1987)], and central galaxies in poor clusters (Kriss et al. 1983, Canizares et al. 1983, Biermann & Kronberg 1983, Malumuth & Kriss 1986) have also been reported to have similar X-ray luminosities (a few 10^{43} erg s^{-1}) and M/L ratios.

The equation used by Fabricant et al. (1980) to estimate the binding mass of M87 was derived from the equation of hydrostatic equilibrium in combination with the ideal gas law, under the assumption of spherical symmetry, and is given below:

$$M(<r) = -(r_{\rm gas} kT_{\rm gas}/G\mu m_{\rm H})(d\log\rho_{\rm gas}/d\log r + d\log T_{\rm gas}/d\log r), \qquad 3.$$

where G is the gravitational constant, and $\mu m_{\rm H}$ is the mean gas particle mass (μ is taken to be 0.6, and $m_{\rm H}$ is the mass of the hydrogen atom).

Equation 3 shows that the measurement of the binding mass depends on four variables: the radius within which the mass is estimated, the gas temperature at this radius, and the logarithmic gradients of both temperature and gas density at the same radius. Each of these variables is a potential source of uncertainty. While the observations of M87 yielded enough signal to noise to allow a relatively well-constrained mass estimate, the same unfortunately is not true when this method is applied to early-type galaxies not at the center of clusters. These galaxies typically are ~ 100 times less luminous than and at least as distant as M87, and therefore their radial profiles and especially temperature information are not as well constrained. Forman et al. (1985) pointed out that the assumption of hydrostatic equilibrium for these galaxies is reasonable even in the presence of cooling flows because these flows would be largely subsonic. They derived M/L ratios ranging from ~ 10 to 90 for a sample of 13 galaxies by assuming that the X-ray emission is due to an isothermal gas at $T = 1.2 \times 10^7$ K, adopting as $r_{\rm gas}$ the outermost radius at which X-ray emission could be detected, and using an average fitted value for the density gradient. Taken at face value, this result would suggest that dark extended halos are a common feature of early-type galaxies. A supporting argument given by these authors for the widespread presence of massive dark halos is the suppression of galactic winds (see the previous section). However, radiative wind suppression in the inner regions and an external pressure from a surrounding intracluster or intergalactic medium (e.g. Fabian et al. 1980, White & Chevalier 1984) could also be responsible for the retention of the hot interstellar medium (Canizares 1987, Canizares et al. 1987). The temperature in this case should increase at the outer radii. Temperature profiles are needed to exclude this possibility (Sarazin & White 1987, Vedder et al. 1988). Forman et al. (1985) performed a spectral fit of the X-ray image of NGC 4472 in three radial annuli and concluded that the data are consistent with isothermality. However, a sharp increase of the temperature at the outer radii, as required by the pressure-confined models, is also possible, given the large uncertainties of the fit. Moreover, Trinchieri et al. (1986) suggest a complex spectrum for this X-ray source, which would thus increase the uncertainties on the fitted temperature.

Subsequent work (Trinchieri et al. 1986; see also Fabbiano 1985b, 1986a,b, Canizares 1987) has shown that the uncertainties of this type of mass measurement can be large. In particular, detailed analysis of the *Einstein* data of six elliptical and S0 galaxies, which are among those detected with higher signal to noise in the sample of Forman et al. (1985), shows both departures from spherical symmetry, which can be ascribed either to interlopers in the field or to the interaction with the surrounding medium, and peculiar variations of the gas density gradient at the outermost radii. Even ignoring some of these effects, the uncertainties of the gas temperature and of its gradient are such that mass estimates differing by up to a factor of 10 are possible for a single galaxy (Figure 8). Jones (1987) and Forman & Jones (1988) have pointed out that the assumption of isothermality is justified in galaxies with a gravitationally bound hot halo (e.g. Norman & Silk 1979; however, see the discussion above about nongravitational confinement). The uncertainties in the IPC spectral fits, however, are such that the range of possible temperatures is still very large, even if one were to assume isothermality (Trinchieri et al. 1986; see Figure 8). Within these uncertainties, the X-ray measurements are generally consistent with the mass estimates from optical velocity dispersion. Therefore, large dark halos are allowed by these data but not required by this analysis. The use of less luminous galaxies or of Sa galaxies will introduce an additional uncertainty that cannot be resolved with the present data. This is the possibility that most of the X-ray emission is due to the evolved stellar component and not to a hot gaseous medium (Fabbiano & Trinchieri 1985, Trinchieri & Fabbiano 1985, Canizares et al. 1987, Fabbiano et al. 1989), thus invalidating the whole approach. In this regard, as remarked by Knapp (1987; see also Fall 1987), it may be significant that the masses of the Sombrero galaxy (an Sa) and of NGC 5128 (Cen A), estimated from H I rotation curves (Bajaja et al. 1984, van Gorkom 1987), are significantly smaller than the estimates of Forman et al. (1985). Although the H I measurements stop at radii smaller than those used for the X-ray measurements, the discrepancy would imply in both cases that the rotation curves, which are flat in the H I measurements, would then rise steeply between the H I and X-ray radius. This effect might be real [a radial increase of the

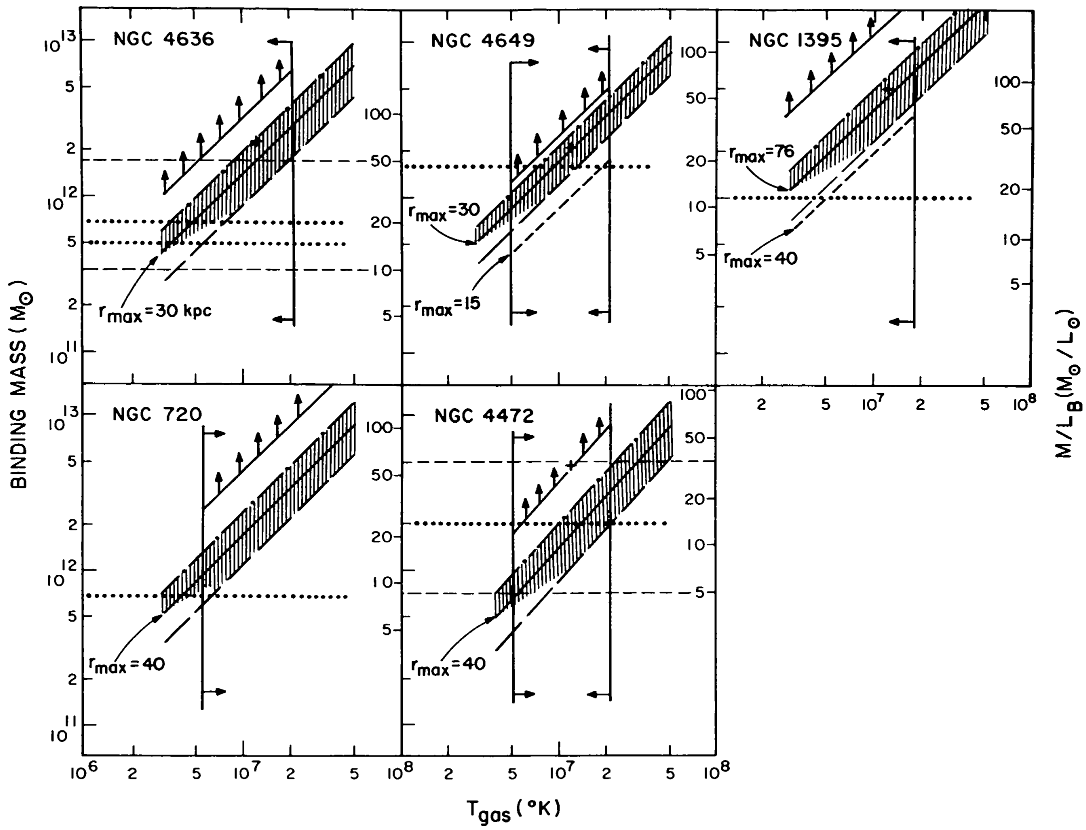

Figure 8 Mass estimates and related uncertainties for five early-type galaxies (adapted from Trinchieri et al. 1986). The shaded areas are the allowed regions from Equation 3, as in the above paper; the central solid line is the estimate for an isothermal halo; and the dashed and dot-dashed lines are the estimates for halos with moderate radial dependences of the temperature ($T \sim r^{0.5}$ and $T \sim r^{-0.5}$, respectively). The vertical lines restrict the temperature ranges to the values obtained by the spectral fits of the X-ray data (at the 90% confidence level). The diagonal short-dashed lines are isothermal estimates of the binding mass for more conservative choices of the halo outermost radii, which exclude regions where the radial surface brightness profiles depart from a power law (see Trinchieri et al. 1986). The horizontal dashed and dotted lines are mass-to-light ratio determinations from optical velocity dispersions (see Trinchieri et al. 1986, and references therein). The diagonal lines with upward-pointing arrows are the lower limits to the total binding mass (and mass-to-light ratios) calculated following Fabian et al. (1986a, Equation 4 herein) for the less conservative estimates of the outer radii (larger r_{max}); if one uses the smaller r_{max} values, these estimates will be displaced downward.

circular velocity occurs in M87 if the halo is gravitationally confined (Binney & Cowie 1981, Sarazin 1987b)], but it could also indicate some problem with the X-ray estimate, since rotation curves generally tend to flatten out at large radii (Knapp 1987).

A different approach to mass measurements relies on a comparison of the observed radial profile of the X-ray surface brightness with model predictions. The method generally followed is to assume a potential that describes the stellar radial distribution and the observed stellar velocity dispersion and then to generate, under various assumptions, the X-ray (gas) surface brightness profile (and/or temperature), to be then compared with the data. This approach was used on M87 and poor clusters (e.g. Mathews 1978, Binney & Cowie 1981, Stewart et al. 1984a, Canizares et al. 1983). In particular, Stewart et al., using the *Einstein* spectral and spatial data of M87, chose a family of models, which describe the radial mass distribution, in agreement with the optical data and with the X-ray data of Fabricant & Gorenstein (1983). Model fitting of less X-ray-luminous, normal early-type galaxies gives less clear results. Using ad hoc models, Trinchieri et al. (1986) showed that the observed gas distributions do not necessarily require the presence of dark halos; Canizares et al. (1987) concluded similarly that the observed correlation between X-ray and optical luminosities does not put strong constraints on the existence of massive halos; and Vedder et al. (1988) pointed out that the only visible effect of massive halos would be in the temperature profiles, which cannot be measured with the *Einstein* data. Sarazin & White (1987, 1988) instead conclude that cooling flow models, possibly without supernova heating but with massive halos, better reproduce the data, although they stress the large uncertainties of their result. A similar conclusion had been reached by Thomas (1986), who applied a cooling flow model to NGC 4472. However, the X-ray isophotes of this galaxy are not circular at large radii, which suggests interaction with the intracluster medium. The binding mass within 40 kpc, which is the radius up to which the "undisturbed" gas distribution should extend in this asymmetric halo (see Trinchieri et al. 1986), is in very good agreement both with the estimate of Trinchieri et al. (1986) and with optical estimates. Killeen & Bicknell (1988a) have estimated the binding mass of NGC 1399, using both model comparison and Equation 3, and conclude that the determination is rather uncertain and does not exclude M/L values in agreement with optical measurements: Thus the presence of a large massive halo, although allowed, is not required. A different approach has been followed by Mathews & Loewenstein (1986), Loewenstein & Mathews (1987a; see also Loewenstein & Mathews 1987b), and Umemura & Ikeuchi (1987), who have studied the time history of gaseous halos in early-type galaxies and find luminosities in agreement with the data only in the presence of dominant dark halos.

Instead of relying on a measure of the binding mass within a certain observed radius, Fabian et al. (1986a) devised a method for estimating a lower limit to the *total* binding mass. Their method is based upon three assumptions: (*a*) that the gas within the observed radius is confined by a hydrostatic outer atmosphere, (*b*) that the halo is convectively stable, and (*c*) that the pressure gradient is always negative. With these assumptions they obtain the equation

$$M(r_\infty) \geq 5r_0kT_0[1-(P_\infty/P_0)^{2/5}]/2G\mu m_{\rm H}(1-r_0/r_\infty), \qquad 4.$$

where r_0 is the outermost detected radius of the halo, P_0 and T_0 are the gas pressure and temperature at this radius, and r_∞ and P_∞ are the outer radius of the halo and the gas pressure at this radius, respectively. From this equation, and using the outermost radii (r_0) and best-fit values of temperatures from the literature, they derive mass-to-light ratios for a sample of early-type galaxies, which lead them to conclude that there is overwhelming evidence for large massive halos in these galaxies. However, the same uncertainties apply here as in the calculation of the binding mass from Equation 3. Using the five galaxies for which the binding mass had been measured by Trinchieri et al. (1986) and temperature estimates that take into account the uncertainties of the spectral fits, together with the values of r_0 derived in that paper, I have calculated lower limits to the mass with Equation 4. They are shown in Figure 8. For two of the galaxies (NGC 4649 and NGC 4472) these limits do not require particularly large M/L ratios in excess of those inferred from optical measurements. For the other three galaxies (NGC 4636, NGC 1395, and NGC 720), however, values of $M/L > 20$ are clearly required. Therefore, there is evidence for large dark halos in some normal elliptical galaxies at least, unless the three basic assumptions of Fabian et al. do not apply. This might be the case for galaxies experiencing considerable external forces, as, for example, is the case for M86, which could be ram pressure confined (Fabian et al. 1980; see also Fabian et al. 1986a). Also, as remarked by the latter authors, if there is a significant confining pressure due to intracluster or intragroup gas, the lower mass limit may not apply to the galaxy but to the group as a whole.

Considering these results, I believe that, purely on *observational* grounds, there is still insufficient evidence to prove that dark massive halos are a general feature of early-type galaxies, although there is evidence of their existence in cluster dominant galaxies and perhaps in some of the most X-ray-luminous normal ellipticals. The use of X-ray data to measure the mass of these galaxies is very promising, but future more sensitive X-ray observations are needed to get a more definite answer.

Assuming that dark halos are a common feature of early-type galaxies, one may ask the question if all galaxies have similar dark halos. Forman et al. (1985) suggested that this may be the case, and moreover that the ratio between total and luminous mass in early-type galaxies could be the same as those of clusters and groups (Blumenthal et al. 1984). This would indicate that the dark matter of clusters might just be the superposition of single galaxy halos. It is also possible that normal ellipticals might be less massive than group or cluster dominant galaxies. In particular, Mathews (1978) remarked that the presence of an extended luminous X-ray halo in M87 and the absence of comparable X-ray emission from NGC 4472, which is also in the Virgo cluster and is optically more luminous than M87, argued for an exceptional massive component in the latter (see also Forman et al. 1984a).

One can investigate further this issue, insofar as the data will allow it, by plotting the mass-to-light ratios of different galaxies (including dominant galaxies in clusters and groups, and normal early-type galaxies) as a function of the ratio between their X-ray and optical luminosities, which is a measure of their gaseous content. This is shown in Figure 9*a*. There is a suggestion of a possible correlation in this plot (if one disregards the large uncertainties on each point) in the sense that cD galaxies, which retain a larger amount of hot gas, may be more massive than normal ellipticals, and therefore different galaxies might have different amounts of dark matter relative to their luminous matter. It is interesting that there is no correlation of the central stellar velocity dispersions with the X-ray to optical ratio, in the same range of ratios (Figure 9*b*), consistent with the dark matter being in extended halos so as not to disturb the stellar component. However, galaxies with X-ray to optical ratios consistent with those of spirals ($L_X/L_B < 10^{30}$ erg s^{-1} $L_{\odot}^{-1}$; this corresponds to a monochromatic flux ratio of $10^{-6.5}$), which therefore might not be able to retain gaseous halos, tend to have smaller central velocity dispersions. Given the paucity of points in Figure 9*a*, however, and the large error bars, the possibility that all early-type galaxies have similar mass-to-light ratios cannot be discounted either. Also, these ratios depend on the measured extent of the X-ray emission and therefore are technically lower limits (see Forman et al. 1985). What has to be explained in this case is why there is a systematic difference between the X-ray luminosities of different types of galaxies, some of which are at the same distance (in Virgo) and were observed with comparable sensitivity. In particular, why can dominant galaxies in clusters retain far larger gaseous halos than those in poor groups, which are still more successful in this endeavor than general field or nondominant cluster galaxies? And, even in the nondominant cluster galaxies, why can galaxies with similar optical luminosity or central velocity dispersion have such a large range of X-ray luminosities (Canizares et al. 1987, Sarazin & White 1988)? Although other interpretations, invoking dynamical stripping of galaxies orbiting the cluster, cannibalism, or past enhanced accretion, are certainly possible (e.g. Fabian et al. 1981, Takeda et al. 1984, Stewart et al. 1984b), it is possible that different amounts of dark matter in otherwise similar galaxies might ab initio be responsible for these results.

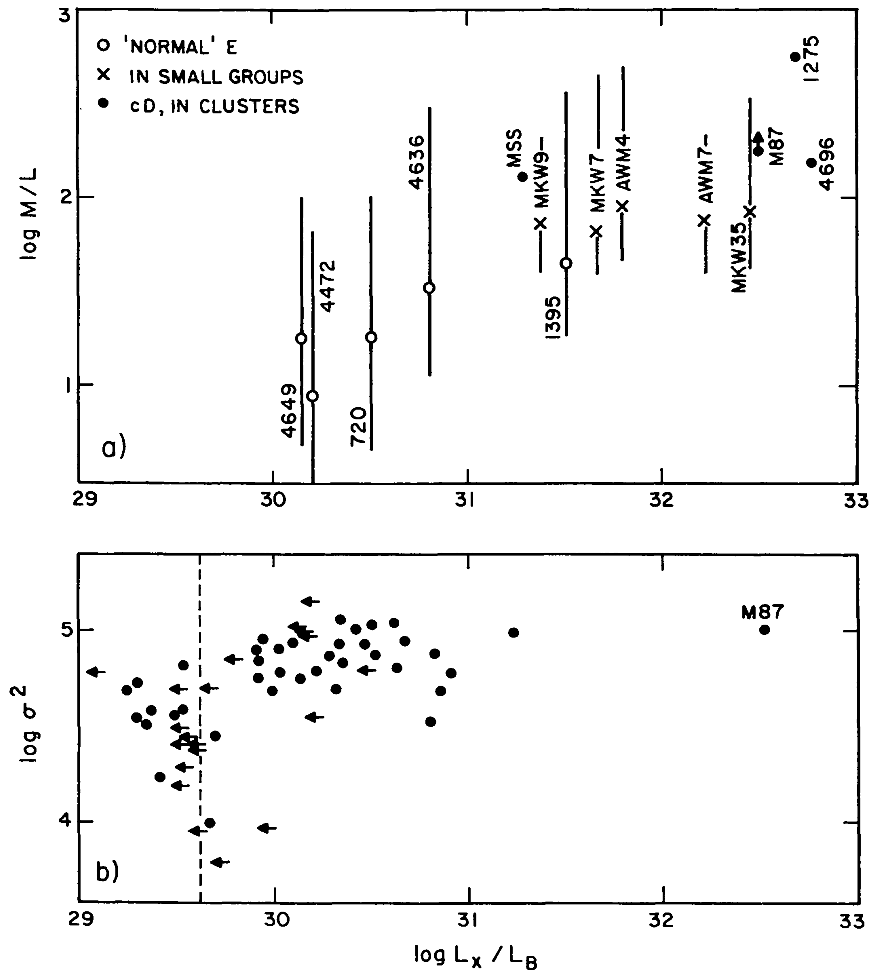

Figure 9 (*a*) Mass-to-light ratio (in solar units) versus the ratio of the X-ray (in erg s^{-1}) to the optical (in $L_\odot$) luminosity for "normal" elliptical galaxies and for group and cluster dominant galaxies (see text for references). MSS is the galaxy found by Maccagni et al. (1987) in the serendipitous *Einstein* survey. (*b*) Square of the central stellar velocity dispersion versus the X-ray to optical ratio. The vertical dashed line represents the average ratio for spiral galaxies. The M87 velocity dispersion is from Sargent et al. (1978), and the other velocity dispersions are from Whitmore et al. (1985). X-ray data are from the compilations of Canizares et al. (1987) and Matilsky et al. (1985).

And finally, getting onto even more speculative ground, we can ask, what would the nature of this dark matter be? One possibility is that of exotic particles, as in the cold dark matter scenario (e.g. Blumenthal et al. 1984; see also Forman et al. 1985). Another possibility is that the dark matter is composed of ordinary stellar remnants or low-mass concentrations, as suggested by Fabian et al. (1986b, 1987a) in the framework of the cooling flow scenario [but see White & Sarazin (1987b) as a dissenting voice: the distribution of the matter deposition from cooling flows may be more similar to the light distribution than to extended massive halos].

4.5 *Radio Sources and Gaseous Halos*

The importance of hot gaseous halos for both fueling nuclear radio sources through accreting cooling flows and confining extended radio lobes has long been recognized (e.g. Cowie & Binney 1977, MacDonald & Bailey 1981, Norman & Silk 1979). A correlation found between radio power and X-ray emission of central cluster galaxies gave empirical evidence of the first phenomenon; the effectiveness of the intracluster gas in confining the radio sources was demonstrated by detailed comparisons of radio and X-ray data (Burns et al. 1981, Forman & Jones 1982, Valentijn & Bijleveld 1983, Jones & Forman 1984, Harris et al. 1984, Feretti et al. 1984a, Morganti et al. 1988, Valentijn 1988). Similar comparisons show that the hot interstellar medium of more isolated early-type galaxies is also effective in confining the radio sources and is likely to play a role in their origin (Biermann & Kronberg 1983, Stanger et al. 1984, Dressel & Wilson 1985, Stanger & Warwick 1986, Thomas et al. 1986, Fabbiano et al. 1987a, 1989, Killeen et al. 1986, 1988). The extended hot gaseous halos can also be responsible for the depolarization observed at long radio wavelengths (e.g. 49 cm) in the bridges of double-lobed powerful radio galaxies (Strom & Jägers 1988).

If one excludes the more "active" specimens (e.g. 3CR galaxies, Cen A, For A), early-type galaxies tend to have relatively faint radio emission confined within their cores. These radio sources in some cases have clearly the same morphology as the more powerful radio galaxies and could therefore be considered physically similar to them and related to nuclear activity (e.g. Ekers & Ekers 1973, Bieging & Biermann 1977, Condon & Dressel 1978, Ekers & Kotanyi 1978, Hummel et al. 1983, Birkinshaw & Davies 1985, Fabbiano et al. 1987a, 1989). Correlations between the radio power and the X-ray luminosity of small samples of relatively radio-faint early-type galaxies suggested a possible link between the hot interstellar medium and the nuclear activity, since the X-ray emission of these galaxies is typically dominated by the extended thermal component (Dressel & Wilson 1985, Fabbiano et al. 1987a; see also Trinchieri 1988). More recently, Fabbiano et al. (1989) have compared the X-ray and radio continuum properties of the larger sample of early-type galaxies studied by Canizares et al. (1987) and report a correlation between the radio "core" power and the X-ray to optical ratio. The latter is a measure of the excess X-ray emission over the linear correlation observed in spiral systems and thus can then be considered as a direct indicator of the gaseous component (see previous discussion). This correlation therefore reinforces the connection between the hot interstellar medium and the nuclear radio sources and points to accreting cooling flows as the fuel.

The hot interstellar medium can also play an important role in the formation of extended radio structures. Fabbiano et al. (1989) notice that in their sample of early-type galaxies, very extended radio lobes, such as those of Cen A (NGC 5128) and For A (NGC 1316), tend to be associated with galaxies with relatively small X-ray to optical ratios. By contrast NGC 1399, which has a comparable core component, and therefore a comparably powerful central engine, but a larger X-ray to optical ratio, has the radio lobes well contained within its optical body. This result suggests that the gaseous halos also play a fundamental role in disrupting the radio jets and confining the extended radio structures. This conclusion had been previously reached by de Ruiter & Parma (1984), who observed significant distortions of the less extended sources in maps of radio galaxies of low to moderate power, suggesting interaction and bending of the jets by the interstellar medium. It has also been addressed in theoretical papers by Soker & Sarazin (1988) and Norman et al. (1988; see also Killeen & Bicknell 1988b). Fabbiano et al. (1989), in particular, demonstrate that the equation of Soker & Sarazin (1988) for the critical luminosity of the radio source, below which the jet is likely to be disrupted by shocks at the sonic radius of a galaxy cooling flow, correctly predicts the typical radio power of a few 10^{29} erg s^{-1} Hz^{-1} at 5 GHz below which extended lobes are not found (Colla et al. 1975, Jenkins 1982, Feretti et al. 1984b, Fabbiano et al. 1989). Once the jets have been disrupted, the thermal pressure of the hot gas is typically effective in confining the less powerful radio lobes well within the galaxies (see also Stanger & Warwick 1986, Killeen et al. 1988).

5. GALAXIES AND THE X-RAY BACKGROUND

The extragalactic X-ray background was discovered in 1962 in the same rocket flight that led to the discovery of the first extrasolar source of X-rays, Sco X-1 (Giacconi et al. 1962). Since then a great deal of effort has been spent trying to understand if this radiation is due to the integrated contributions of different classes of discrete sources or if diffuse processes are responsible for it (see Boldt 1987, Giacconi & Zamorani 1987). Based on the four galaxies then known to emit X rays (Milky Way, M31, and the Magellanic Clouds), Silk (1973) estimated that normal galaxies would contribute $\sim 10\%$ to the X-ray background. This estimate was then revised downward to less than $\sim 1\%$ (Rowan-Robinson & Fabian 1975, van Paradijs 1978, Worrall et al. 1979; see Fabian 1981) for a variety of reasons. One is the assumption that the X-ray luminosity of normal galaxies, which is dominated by the low-mass binary sources, would not be correlated with the optical luminosity but with some function of the galaxy mass (Rowan-Robinson & Fabian 1975); however, we now know that this is not so, as discussed earlier in this review. Other reasons are the effect of the redshift on the spectrum of the galactic sources (van Paradijs 1978), and the failure to detect a volume-limited sample of galaxies with the *HEAO-1* satellite (Worrall et al. 1979). However, this survey observed galaxies that are all of very low optical luminosity and as such cannot be considered representative of normal galaxies as a whole (Fabian 1981, Elvis et al. 1984).

Based on the X-ray to optical ratios of normal galaxies observed with the *Einstein* Observatory (Fabbiano & Trinchieri 1985, Trinchieri & Fabbiano 1985), Giacconi & Zamorani (1987) estimated instead that the integrated emission of normal galaxies contributes $\sim 13\%$ of the 2-keV extragalactic X-ray background (see also Setti 1985). If one includes in this estimate the contribution of low-activity nuclei present in a fraction of these galaxies and the effect of starburst activity, it could be significantly larger: Elvis et al. (1984) estimate that the low-activity nuclei could contribute $\sim 20\%$ of the X-ray background in the absence of evolution; and Weedman (1987), using X-ray to optical ratios measured in starburst galaxies (Fabbiano et al. 1982) and the 60-μm luminosity function derived from the *IRAS* survey, finds that in the absence of evolution these galaxies could account for $\sim 13\%$ of the 2-keV background (see also Giacconi & Zamorani 1987). If one assumes that starburst activity was much more pronounced in the past (Bookbinder et al. 1980, Stewart et al. 1982), starburst galaxies could be responsible for the bulk of the background (Giacconi & Zamorani 1987, Weedman 1987). Although this possibility is rejected by Giacconi & Zamorani because it would predict a surface density of 21–23 mag galaxies inconsistent with optical searches, the presence of a large amount of dust in these systems, suggested by the *IRAS* data, leaves this a still viable option (Weedman 1987).

Even if galaxies contribute substantially to the 2-keV X-ray background, their contribution to the X-ray background in a harder spectral range is uncertain and rests upon the spectral characteristics of their X-ray emission (van Paradijs 1978, Giacconi & Zamorani 1987, Weedman 1987). The spectra of spiral galaxies are consistent with a relatively hard X-ray emission ($kT > 2$ keV; Fabbiano & Trinchieri 1987), and X-ray binaries can have hard X-ray spectra (with $kT \sim 20$ keV). Moreover, a hard spectral component may be present in the starburst galaxy M82 (Fabbiano 1988b, Schaaf et al. 1989). However, it is unlikely that the galactic contribution would be substantial above 10 keV, especially considering that the spectra of faraway galaxies would be redshifted. The soft X-ray spectrum of the nucleus of M81 (Fabbiano 1988a) introduces an additional source of uncertainty to the estimate by Elvis et al. (1984) of the contribution of low-activity nuclei to the 2–10 keV X-ray background, since most of the X-ray luminosity of these sources could be emitted in a softer energy range.

On the other hand, we do not know how common and how bright the optically quiet X-ray-active nuclei, such as those of M33 and NGC 1313, are (see earlier in this paper). Their inclusion could raise the estimate of the galactic contribution to the X-ray background, although their X-ray spectra (Fabbiano & Trinchieri 1987, Trinchieri et al. 1988) suggest that even this type of source should contribute mainly in the soft energy range. Future X-ray observations will help to constrain the spectral range in which galaxies may contribute to the extragalactic X-ray background and will give us a better estimate of the contribution of low-activity nuclei.

6. THE FUTURE

What we have learned so far about the X-ray properties of normal galaxies has been the result of limited exploratory observations. Future X-ray satellites, with increased sensitivity and higher spatial and spectral resolution, will be essential for answering the many open questions resulting from the present work and for expanding and deepening our knowledge of these systems. The German X-ray satellite *ROSAT*, which is scheduled to be launched in 1990, will increase the number of galaxies mapped in X rays with a good sensitivity to low-surface-brightness features, and the Japanese *ASTRO-D* (to be launched in 1993) will allow the study of galactic spectral properties with a tenfold increased spectral resolution (but only 2′ spatial resolution). The next major US X-ray astronomy endeavor, *AXAF*, with its subarcsecond spatial resolution and good spectral resolution, will allow the study of the luminosity function of X-ray sources in nearby spiral galaxies down to limiting luminosities at least 100 times smaller than present ones, and it will be able to detect single early-type stars in the Magellanic Clouds. Spectral parameters or X-ray colors will be measured for these sources and should help in establishing their nature (e.g. black hole candidates vs. X-ray pulsars; see White & Marshall 1984). With *AXAF* and the European *XMM*, with its larger collective area and sensitivity to low-surface-brightness features, the astronomical community will be able to address some of the outstanding questions on the X-ray properties of elliptical galaxies. These include firmly establishing the nature of the X-ray emission in the less X-ray-luminous galaxies, i.e. if it comes from a collection of binary X-ray sources or from a hot gaseous halo; measuring temperatures, temperature gradients, and metallicities of these halos; studying their interaction with the surrounding medium; and, finally, measuring with good accuracy the mass of these galaxies. It will also be possible to establish the luminosity functions and the spectral characteristics of individual X-ray sources in different spiral galaxies and thus to investigate the nature and evolution of these sources in different environments. With the plenitude of X-ray data to come from these missions, this may well be the last review that can cover the entire topic of X rays from normal galaxies.

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