Chapter 1
The Hot ISM of Elliptical Galaxies: A Brief History

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This chapter reviews the history of the discovery of a hot gaseous interstellar medium (ISM) in normal E and S0 galaxies with the imaging X-ray telescope of the *Einstein Observatory*. It also highlights the ensuing two-decade long debate on the ubiquity and properties of this medium, and on the suitability of X-ray observations for measuring the gravitational mass of early-type galaxies. Fundamental questions explored during this period included: How much of the X-ray emission is truly from a hot ISM? Is this ISM in hydrostatic equilibrium? Can the data constrain the physical and chemical evolution of this hot medium? While the debate went on, a deeper understanding on the evolution of the hot ISM was generated. Some of these outstanding questions have now been solved with the high spatial resolution observations of the *Chandra X-ray Observatory* and with the high signal-to-noise spectra of *XMM-Newton*.

1.1 X-ray Astronomy and the Discovery of Hot Gaseous Halos

The first extended extragalactic X-ray sources were discovered early in the history of X-ray astronomy with the *Uhuru* satellite (Giacconi et al. 1971) in the Virgo (Kellogg et al. 1971) and Coma (Gursky et al. 1971) clusters. These discoveries were extended soon after to several other galaxy clusters (e.g., Forman et al. 1972; Gursky et al. 1972; Kellogg and Murray 1974). Gursky et al. (1971) pointed out that the temperature of a hot gas derived from a fit to a bremsstrahlung model of the X-ray spectrum of the Coma cluster (73×10^6 K $\sim$ 7 keV), would give thermal velocities of 1,050 $\pm$ 90 km s^{-1}, comparable with the velocity dispersion of the galaxies in the cluster (1,470 km s^{-1}). Although observational confirmation that the diffuse emission was indeed the thermal emission of hot plasma had to await later

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measurements (Mushotzky et al. 1978; Fabricant et al. 1978; Lea et al. 1979), it was soon realized that these halos could be hydrostatic, adiabatic atmospheres trapped in the cluster potential. Thus the halos could provide a means for measuring the mass of the associated self-gravitating body (Lea et al. 1973; Gull and Northover 1975; Cavaliere and Fusco-Femiano 1976).

The central Virgo Cluster galaxy, M87, was the first galaxy associated with extended X-ray emission, from a 2–3 keV temperature plasma embedded in a hotter Virgo cluster medium (Lea et al. 1973; Malina et al. 1976; Gorenstein et al. 1977; Mushotzky et al. 1978; Fabricant et al. 1978; Lea et al. 1979; Fabricant et al. 1980). Early modeling of this halo suggested a huge extended halo of dark matter in M87 (Bahcall and Sarazin 1977; Mathews 1978). Fabricant et al. (1980) confirmed this result with stringent observational constraints obtained with the first imaging X-ray telescope, the *Einstein Observatory* (Giacconi et al. 1979).

With the angular resolution and sensitivity allowed by the *Einstein* mirrors, extended emission was discovered in several other early-type galaxies in the Virgo cluster (Forman et al. 1979): the clear displacement of the X-ray isophotes from the optical body of the galaxy in M86 made a strong case for the discovery of a hot gaseous halo, dynamically interacting with the hotter cluster gaseous medium, and suggested that hot halos may be widespread in E and S0 galaxies. This was the beginning of the study of the hot interstellar medium (ISM) of early-type galaxies. Although now we all know that hot X-ray emitting gas is found in E and S0 galaxies, it is worth noting that this was not expected at the time, since the lack of cold ISM in these galaxies had convinced astronomers that winds were likely to occur, dissipating the gaseous stellar ejecta outside the parent galaxy (e.g., Faber and Gallagher 1976; Mathews and Baker 1971). The presence of hot ISM in early-type galaxies could only be discovered with X-ray astronomy.

In summary, *Einstein* observations provided convincing proof of the existence of hot halos in elliptical galaxies:

1. As mentioned above, the images of a few galaxies revealed a displacement of the X-ray isophotes from the stellar body, suggesting a non-stellar source of the X-ray emission (e.g., M86, Forman et al. 1979; NGC4472, see Fig. 1.1 from Trinchieri et al. 1986.)
2. The X-ray spectra of X-ray luminous elliptical galaxies where found to be softer than those of spiral galaxies, suggesting thermal emission from hot coronae (see e.g. Trinchieri et al. 1986 versus Fabbiano and Trinchieri 1987; Kim et al. 1992, Fig. 1.2).
3. The slopes of the correlation between integrated X-ray (L_X) and optical (L_B) luminosity were found to differ between E + S0 and spiral galaxies. In the spiral sample (Fabbiano and Trinchieri 1985), $L_X \sim L_B$, as it would be expected for an X-ray emission dominated by stellar binary sources, which would be a nearly constant fraction of the overall stellar population of the galaxy; instead in the E + S0 sample (Trinchieri and Fabbiano 1985 – TF85), $L_X \sim L_B^{>1}$, suggesting the presence of an additional non-stellar emission component (hot ISM) in some galaxies.

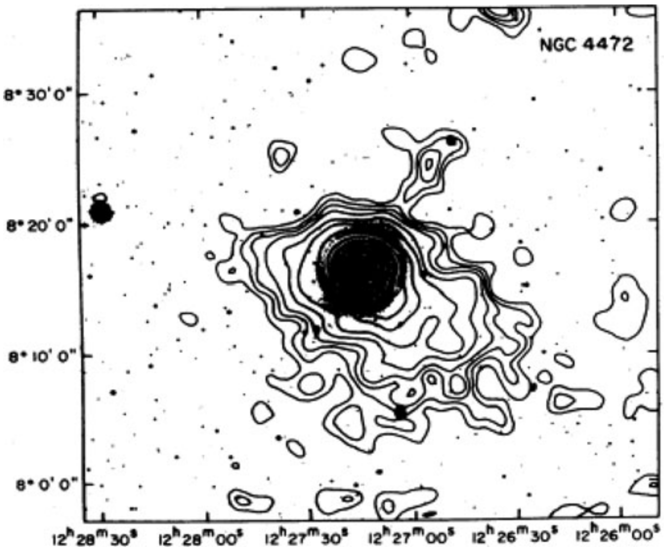

Fig. 1.1 Einstein isophotes of the (0.2–4.0 keV) X-ray emission of the Virgo cluster galaxy NGC 4472, showing a displacement relative to the stellar body of the galaxy (Trinchieri et al. 1986)

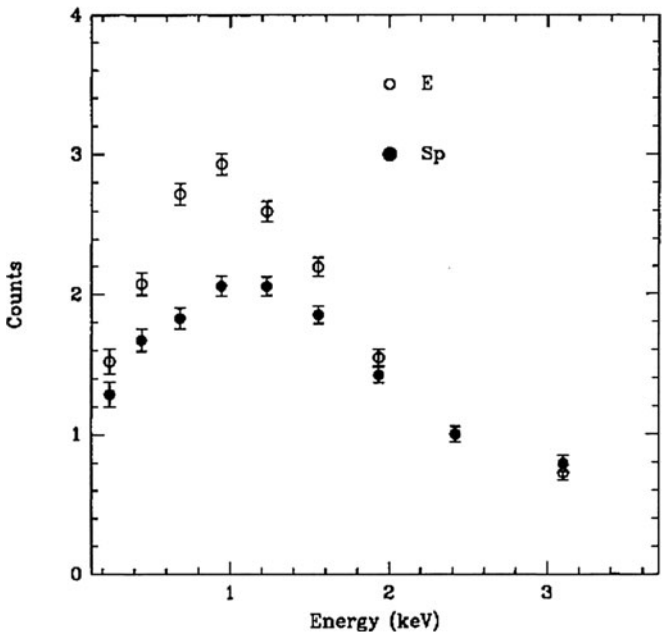

Fig. 1.2 Average X-ray spectral count distributions of the samples of E and Spiral galaxies observed with Einstein (Kim et al. 1992); note the relative excess of counts at the lower energies of the E sample

Although convincing evidence of the existence of hot ISM and gaseous halos in some elliptical galaxies was produced by the *Einstein* observations, it soon became evident that several of these galaxies may not have these hot halos. The detection of extended X-ray emission in Virgo cluster galaxies was not in itself proof of the existence of gaseous halos, because a population of X-ray binaries could not have been possibly resolved with *Einstein* at that distance. These X-ray binary populations were detected in nearby galaxies, such as M31 (see Fabbiano 1989 and references therein). The extent to which the X-ray emission was dominated by a hot hydrostatic halo soon became the subject of intense debate.

In what follows, I will discuss more fully some of the early observations of E and S0 galaxies, and highlight the debate resulting from the *Einstein* and subsequent observations with the *ROSAT* (Truemper 1990) and *ASCA* (Tanaka et al. 1994) X-ray satellites. This discussion provides the background for the more recent *Chandra* (Weisskopf et al. 2000) and the ESA X-ray satellite *XMM-Newton* results, which are only mentioned here when needed, and are more thoroughly discussed in other chapters of this book. A more complete review of the early *Einstein* results can be found in Fabbiano (1989). Here, I will focus the discussion on four topics: Disentangling hot halos from other X-ray emission components (Sect. 1.2); Physical evolution of the hot ISM (Sect. 1.3); Chemical evolution of the hot ISM (Sect. 1.4); and X-ray constraints to galaxy masses (Sect. 1.5).

1.2 The Halo Debate: How Much of the X-ray Emission of E and S0 Galaxies is from a Hot Halo and How Much from X-ray Binaries?

Following the work on M87 mentioned in Sect. 1.1, the discovery of hot gaseous emission in other Virgo elliptical galaxies (Forman et al. 1979) led to an important prospect. *If the X-ray emission of E and S0 galaxies were dominated by hot halos in hydrostatic equilibrium*, these observations could provide a ready means for measuring the masses of the galaxies and detecting the associated dark matter. Forman et al. (1985 – FJT85) presented the results of *Einstein* observations of a sample of early-type galaxies (Sa, S0, E), arguing for hot coronae in hydrostatic equilibrium. Under this assumption, FJT85 derived measurements of the gravitational masses, suggesting widespread substantial dark halos in early-type galaxies.

However, the prevalence of hydrostatic hot coronae in most early-type galaxies could not be proved observationally. The quality of these first X-ray images did not allow disentangling a truly diffuse gaseous emission from the unresolved contribution of populations of low-mass X-ray binaries (LMXBs). Moreover, the associated spectra could not constrain meaningfully multiple emission components.

These were important questions that had to be answered, before the general validity of X-ray mass measurements could be accepted (see also Sect. 1.5).

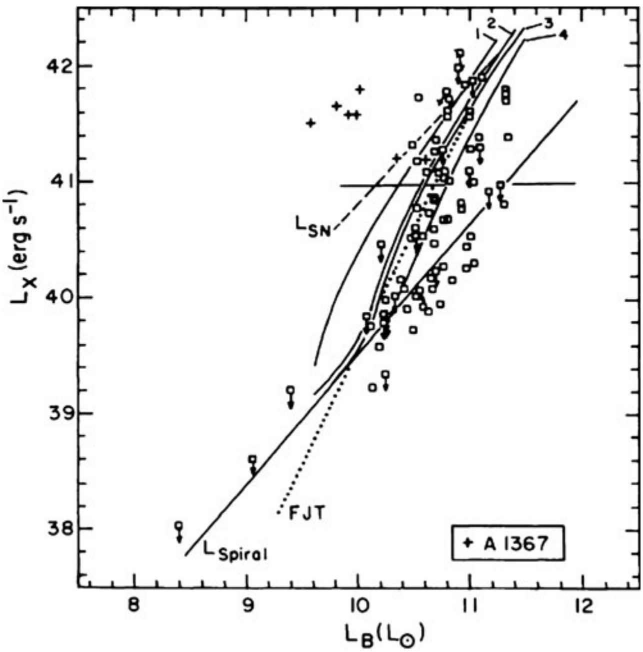

Fig. 1.3 The distribution of early-type galaxies (*squares and crosses*) observed in X-rays with Einstein (see CFT87). The diagonal *solid line* is the TF85 and CFT87 estimate of LMXB luminosity. The *dotted line* represents the FJT85 law of halo emission. The *dashed line* is the CFT87 estimate of energy input from SNe Ia, and curve represent different cooling flow models from Sarazin and White (1988; see also Sect. 3.1)

1.2.1 The L_X–L_B Diagram

A tool used in several of these early studies, and in much later work, was the L_X–L_B diagram. The X-ray (L_X) and B-band luminosity (L_B) are correlated, with a large scatter and a power-law slope steeper than linear (TF85; FJT85; see also Canizares et al. 1987 – CFT87; Fabbiano 1989, Fig. 1.3). The interpretation of this diagram has been central to the 'halo' debate (see also Sect. 1.3). Although the *Einstein* L_X–L_B diagram must be at a certain level the expression of halo evolution and physics (FJT85), it is also 'biased' by the contribution of unresolved LMXB populations.

TF85 first raised the LMXB problem, based on a comparison with the bulge of M31 and the integrated emission properties of bulge-dominated spiral galaxies. In M31 the LMXB population could be easily detected with *Einstein* (Van Speybroeck et al. 1979), leaving no doubt as to the nature of the dominant X-ray emission. Bulge-dominated spirals have L_X/L_B ratios consistent with those of 'X-ray faint' elliptical galaxies. In spirals the X-ray and optical luminosities are roughly linearly correlated, as expected from the integrated contribution of populations of X-ray binaries (Fabbiano and Trinchieri 1985). Based on these results, TF85 (see also review Fabbiano 1989) concluded that integrated LMXB emission– not gaseous halos – is responsible for most or all of the X-ray luminosity of a very substantial fraction of early-type galaxies.

1.2.2 X-ray Spectra

The importance of LMXB emission was confirmed by the spectral characteristics of the emission. Harder X-ray emission, a signature of LMXB populations (see Fabbiano et al. 1987 using M31 as a spectral benchmark), was found by analyzing the average X-ray colors and the coadded spectra of the sample of X-ray faint elliptical galaxies observed with *Einstein* (Kim et al. 1992). Subsequent deeper observations of some of these galaxies with *ROSAT* (Fabbiano et al. 1994) confirmed this result. Later, with the CCD spectra of ASCA, Matsushita et al. (1994) found a clear signature of hard LMXB emission also in halo-dominated galaxies. Interestingly, the spectra of the least X-ray luminous galaxies showed an additionalvery soft emission component (Kim et al. 1992). Pellegrini and Fabbiano (1994) modeled the *ROSAT* spectra, suggesting complex 3-component emission, consisting of LMXBs, some amount of hot ISM, and the integrated X-ray emission of the normal stellar population in these galaxies (Fig. 1.4).

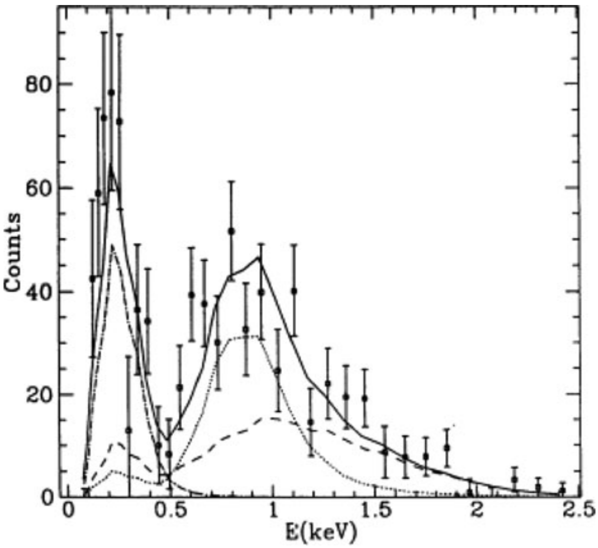

Fig. 1.4 ROSAT X-ray spectrum of NGC 4365, with a 3-component model (*solid line*) including LMXB emission (*dashed*), hot ISM (*dotted*), and a cooler possibly stellar component (*dot-dashed*), from Pellegrini and Fabbiano (1994)

These conclusions, now confirmed with *Chandra* (e.g., Boroson et al. 2011), casted doubts on the presence of dominant hydrostatic coronae in all E and S0 galaxies.

1.2.3 Chandra Images

With the sub-arcsecond telescope of the *Chandra X-ray Observatory*, populations of LMXBs are now ubiquitously detected in the images of elliptical galaxies (see Fabbiano 2006 and refs. therein). These LMXBs in some cases account for the bulk of the X-ray emission, leaving little space for diffuse hot ISM emission (e.g. NGC 3379, NGC 4278; Brassington et al. 2008, 2009; Fig. 1.5).

The debate on the relative fraction of hot ISM and LMXB emission in early-type galaxies has been solved with *Chandra*. This debate, however, has provided a useful framework to reach a deeper understanding of the evolution of early-type galaxies, and their stellar and gaseous components (see also Sects. 1.3 and 1.5).

1.3 Physical Evolution of the Hot Halos: Gravity, Feedback and Interactions

Once the presence of hot ISM and halos – in at least some early-type galaxies – had been established, the observed properties of this hot ISM could be used to constrain its evolution. There is sufficient material from stellar out-gassing to account for the hot halos (FJT85; Faber and Gallagher 1976), if this ISM is trapped by the galaxy gravity. Therefore, the origin of the hot ISM is linked to the evolution of the stellar component of the galaxies. However, the data also suggested that the hot ISM, in X-ray luminous hot-gas-rich galaxiesat least - where this medium was convincingly present -is not in thermal equilibrium with the stellar component. Spectral fits to the *Einstein* data, and the radial behavior of the X-ray surface brightness, indicated temperatures in excess of those implied by the stellar velocity dispersion, suggesting that further heating of the ISM had occurred (see Fabbiano 1989 and references therein).

The sources of energy considered in the early *Einstein* days are Supernova explosions (prevalently SNe Ia, given the old stellar population of elliptical galaxies) and gravity, and to less extent interaction and merging with the surrounding environment and neighboring galaxies. More recently, nuclear/AGN feedback has also been introduced as an important factor in the evolution of the hot halos (see also Sarazin, and Ciotti and Ostriker, this volume).

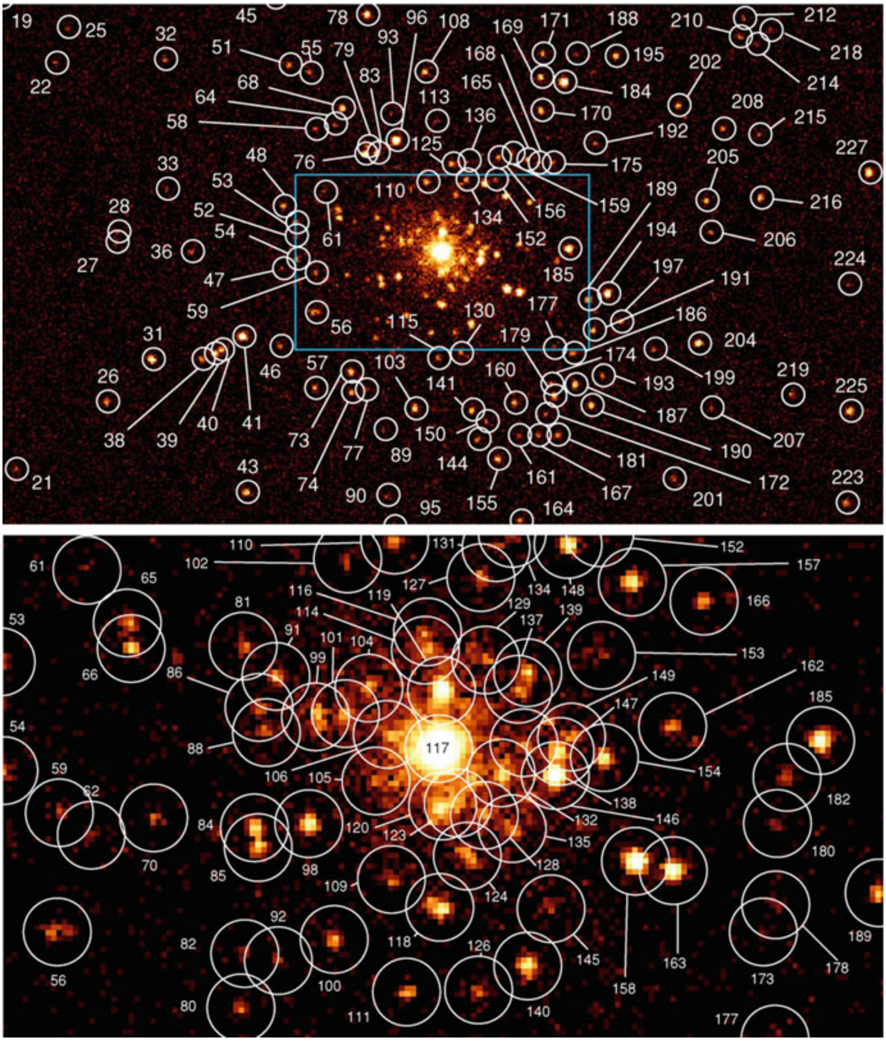

Fig. 1.5 *Chandra* ACIS image of NGC 3379, from Brassington et al. 2008; the bottom panel is an expansion on the blue inner box in the *top panel*; each detected LMXB is identified with a *circle* and a source number. LMXBs account for almost all the X-ray emission of this elliptical galaxy

1.3.1 Supernova and Gravitational Heating

CFT87 (see Fig. 1.3) argued that the distribution of points in the *Einstein* L_X–L_B diagram is roughly bound between two lines: the contribution of X-ray binaries, at the bottom end, and the luminosity that may originate from SN heating at the top. Gravitational heating (see Pellegrini, this volume) is effective, but cannot account for the spread of points in the L_X–L_B diagram.

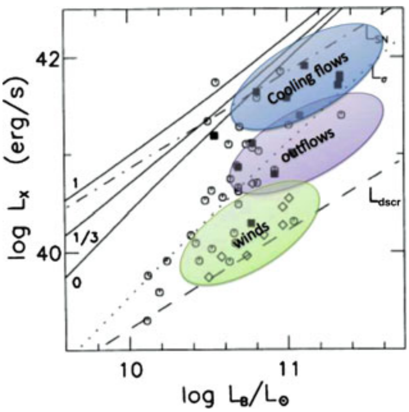

Fig. 1.6 L_X–L_B diagram compared with the evolutionary models of Ciotti et al. 1991. The different physical regimes are indicated by the colored ellipses

Gravitational heating occurs if the hot gas slowly accretes to the center of the galaxies via subsonic cooling flows, caused by faster cooling in the central denser regions of the halos. Gull and Northover (1975) and Binney and Cowie (1981) first pointed out the potential importance of cooling flows for the hot halos of galaxy clusters and M87. This idea enjoyed a vigorous renaissance with the *Einstein* discovery of hot halos in galaxies, where cooling times can be considerable shorter than the Hubble time. Cooling flow models were developed by several authors in the attempt to fit both the data of individual galaxies (e.g. Thomas et al. 1986), and the distribution of points in the *Einstein* L_X–L_B diagram (e.g. Sarazin and White 1988). The Sarazin and White (1988) cooling flow models, plotted in Fig. 1.3, cannot bridge the gap between the two boundary lines even in the absence of dark massive halos and supernova heating; models assuming dark halos and the unescapable supernova heating can only explain the most X-ray luminous galaxies (e.g., Ciotti et al. 1991).

Given all this ready energy input, can we be sure that the halos are in hydrostatic equilibrium? David et al. (1990) modeled the evolution of the ISM of elliptical galaxies with $L_B = 10^{11} L_\odot$, finding an early phase of wind fuelled by SNe II, followed by a long-lasting phase of pure accretion flow resulting in large hot halos within a Hubble time, therefore arguing for 'static' halos. However, more extensive modeling soon after (David et al. 1991; Ciotti et al. 1991) revealed that outflows and wind may be important. David et al. (1991) concluded that except for very high values of the SNe Ia rate most *Einstein* detections are consistent with inflow models. Ciotti et al. (1991) instead reached the opposite conclusion, because in their models the secular variation of the stellar mass loss rate was less steep than that of the supernova rate, in the passive evolution of an old stellar population (see Pellegrini, this volume). The result of this approach is that only the brightest of the galaxies are in inflow/cooling flow, while most of the L_X–L_B diagram would be consistent with outflow models, and the galaxies with the faintest X-ray emission would be in a strong wind phase (Fig. 1.6).

1.3.2 Interactions and Merging

Interactions with the intra-cluster medium and with other galaxies were also suggested as means of alternatively enhancing or reducing the hot halos of galaxies. The hot cluster medium can help confining the hot halos of galaxies (e.g. Vedder et al. 1988; Renzini et al. 1993; Brighenti and Mathews 1998; Brown and Bregman 2000), but can also be effective in ram stripping of these halos (e.g., Forman et al. 1979; Acreman et al. 2003; Sarazin, this volume). Correlations in large samples of galaxies were explored to investigate the importance of this effect, but with inconclusive results. Sarazin and White (1990) reported a correlation between lower X-ray luminosity and a denser environment, suggesting that interactions in clusters may be responsible for the L_X–L_B scatter. However, Mackie and Fabbiano (1997), using the sample of early-type galaxies observed with *ROSAT*, could not confirm this suggestion.

Instead, galaxy merging appears to be an important factor in both galaxy and halo evolution. Recent merging and the related rejuvenation of the stellar populations (causing additional energy input into the ISM) has been connected with smaller or absent hot halos (Fabbiano and Schweizer 1995; Mackie and Fabbiano 1997), a view confirmed by a recent study based on a sample of galaxies observed with *Chandra* (Boroson et al. 2011). Conversely, optical indicators of large gravitational potentials and primordial merging are correlated with the presence of large X-ray halos (e.g., Eskridge et al. 1995; see Kormendy et al. 2009 and refs. therein); these indicators are consistent with the presence of large dark halos in massive systems that have had time to settle into passive evolution, where the hot gaseous halos would be gravitationally confined.

1.3.3 The Effect of Nuclear Super-Massive Black Holes

At the time when people were trying to make sense of the *Einstein* observations of early-type galaxies, it was not yet known that super-massive black holes are present in the nuclei of luminous elliptical galaxies (Magorrian et al. 1998). In fact, Fabian and Canizares (1988) suggested that the absence of cooling-flow-fed AGNs in most elliptical galaxies argued against the ubiquity of nuclear black holes. However, several elliptical galaxies harbor some form of nuclear emission. In the minority of luminous radio galaxies these radio cores are associated with powerful jets and large radio lobes, extending outside the stellar body of the galaxies. In a larger number of galaxies the radio source is faint and confined within the nuclear region. It was speculated that the hot ISM would have a role in causing and shaping these sources (Hummel et al. 1983).

Fabbiano et al. (1987a, 1989) assembled 5 GH observations for a sample of early-type galaxies observed with *Einstein*. Fabbiano (1989), using 84 elliptical and S0 galaxies, found a correlation between core radio power and X-ray to optical ratio, suggesting that the hot ISM could provide the fuel for the nuclear radio sources. Moreover, they noticed that, for a given radio power, extended radio lobes are associated with X-ray fainter galaxies, pointing to the importance of the hot ISM in disrupting radio jets and confining the radio sources. Furthermore, there is a continuum of radio/X-ray properties from radio-faint to radio-loud 3CR galaxies (Fabbiano et al. 1984), suggesting that either radio-faint galaxies are associated with less massive nuclear black holes, or that something impedes cooling flows from accreting onto these nuclei. This was the first inkling of the interplay between nuclear feedback and the hot ISM in early-type galaxies.

The comprehensive multi-variable correlation study of the entire 148 E and S0 sample observed with*Einstein* (Eskridge et al. 1995) confirmed the results of Fabbiano (1989); moreover, these authors find that the *total* radio power of a galaxy is related to the stellar mass (L_B) rather than the presence of hot ISM, and conclude that *'the mass of the black hole is larger in more massive galaxies'* – a result now widely accepted (Magorrian et al. 1998).

AGN feedback has since surfaced as an important energy source. It has been shown in theoretical models that AGN feedback could be strong enough to eliminate hot halos by starting galactic-size winds (e.g. Tabor and Binney 1993; Ciotti and Ostriker 2001). Observationally, with *Chandra* we have set stringent limits on the amount of diffuse emission in some X-ray faint galaxies, demonstrating the presence of winds (Fabbiano et al. 2004; Pellegrini et al. 2007; Trinchieri et al. 2008). However, while it is certain that winds occur, the relative importance of SNe Ia versus AGN energy input is still debatable.

AGN feedback solves the puzzle of the cooling flow interpretation of the *Einstein* X-ray data: the lack of direct observation, in the predicted amount, of the two key consequences of cooling flows: (1) central colder gas, (2) central star formation (e.g. see review McNamara and Nulsen 2007). The morphology and thermal properties of the circum-nuclear hot ISM from *Chandra* observations of some early-type galaxies convincingly prove that AGN feedback is at play (e.g., the circumgalactic hot ring in Cen A, Karovska et al. 2002; the properties of the inner regions of M84, Finoguenov et al. 2008).

1.4 Chemical Evolution of the Halos: Measurements of Metal Abundances and Theoretical Predictions

The physical evolution of the hot halos is closely linked to their chemical evolution, since these halos are enriched in metals by stellar and supernova ejecta. In particular, large hot halos in gravitational equilibrium should have Fe content commensurate to the integrated output of SNe Ia over their lifetimes; in these halos, the Fe to alpha element ratios should be solar or higher, unless inflow of intra-cluster gas, enriched by SNe II-powered winds early in the galaxies lifetimes, alter these values (David et al. 1991; Ciotti et al. 1991; Renzini et al. 1993; Arimoto et al. 1997; Loewenstein and Davis 2010). Since optically thin hot plasmas with temperatures in the range of the emission of halo-dominated galaxies ($\sim$1 keV) should contain emission lines produced by atomic transitions in elements (see Raymond and Smith 1977), the X-ray spectra may be used to set observational constraints to the metal abundance. This was – and still is – not an easy task, as explained below (see discussion in Fabbiano 1995).

The *Einstein* and *ROSAT* proportional counter spectra lacked the resolution to reveal individual emission lines and absorption edges, with the result that one could not distinguish between excess line emission or excess absorption in a spectrum (e.g., Trinchieri et al. 1986); similarly, the data could be fitted equally well with either an isothermal halo with sub-solar metallicity, or with multi-temperature models and higher metal abundance (Buote and Canizares 1994; Fabbiano et al. 1994). Estimating abundances of different elements separately was basically impossible.

The higher spectral resolution CCD detectors of the Japanese *ASCA* satellite (Tanaka et al. 1994) first revealed emission lines in the spectra, although with some blending. The abundances measured from these early spectra in luminous early-type galaxies were sub-solar, and the elemental ratios consistent with solar, suggesting a lack of significant SNe Ia input (Awaki et al. 1994). The spectra of X-ray faint galaxies suggested low-metallicity cooler gaseous components, in addition to hard LMXB emission (e.g., Kim et al. 1996; Iyomoto et al. 1998). Multi-temperature halo models (Buote and Fabian 1998; see also Trinchieri et al. 1994), resulted in higher – nearly solar – abundances, which however are still below the theoretical prediction (Arimoto et al. 1997). Adding proper weighing of the uncertainties in the Fe plasma emission codes to multi-temperature models (Matsushita et al. 2000), resulted in abundances for the X-ray luminous galaxies near the range of the prediction; this study also suggests lower abundances in X-ray faint galaxies, which could be related to the presence of winds.

We have now realized that spatial resolution, together with spectral resolution, may be needed to get more realistic abundance measurements, especially in the case of X-ray faint E and S0s with small gaseous components. By ‘cleaning’ the diffuse emission of the contribution of luminous binaries, and by allowing the separate analysis of different emission regions with *Chandra,* abundances higher than the *ASCA* estimates were found in the elliptical galaxy NGC 1316 (Kim and Fabbiano 2003); interestingly, the *ASCA* estimates were reproduced analyzing the entire emission of the galaxy as a whole, disregarding the information provided by the spatial resolution.

Very high signal to noise data also help, as demonstrated in the case of the *XMM-Newton* observations of the luminous hot halo of NGC 507 (Kim and Fabbiano 2004). In this galaxy, where previous reports gave a range of abundances from sub-solar to near solar (Matsumoto et al. 1997; Kim and Fabbiano 1995; Buote and Fabian 1998; Paolillo et al. 2003; Kraft et al. 2004), the analysis of the *XMM* data revealed that the hot ISM is not isothermal and that the Fe abundance is 2–3 times solar within a radius of 40 kpc from the center of NGC 507, then decreasing at larger distances. A full discussion of the present understanding of the chemical evolution of the halos can be found in the chapters of Pipino and Kim, this volume.

1.5 Can We Measure Galaxy Masses with X-ray Observations?

Having reviewed the debate surrounding the X-ray emission of E and S0 galaxies, we go back here to the issue of using X-ray observations for measuring the mass of these galaxies. As discussed in Sect. 1.1, Fabricant et al. (1980) applied the equation of hydrostatic equilibrium to the X-ray halo of M87 to constrain the binding mass of this galaxy, confirming the presence of an extended dark matter halo. The equation of hydrostatic equilibrium can be expressed as:

$$M(r) = -kT_{gas}/G\mu m_H(d\,log\,\rho_{gas}/d\,log\,r + d\,log\,T_{gas}/d\,log\,r)r$$

Based on this equation, the mass enclosed within the outer detected halo radius is a function of four quantities, which all need to be measured, and for all of which uncertainties need to be estimated. These quantities are the outer radius of the hot halo, the gas temperature at this radius, and the gradients of gas density and temperature at the outer radius.

The above equation was used by FJT85to measure the binding masses of a sample of normal E and S0 galaxies detected in X-rays with *Einstein*. Under the assumption that the X-ray emission of all these galaxies is dominated by hot halos in hydrostatic equilibrium, these measurements led to the conclusion that large amounts of dark matter are associated with these galaxies. But, as discussed in Sects. 1.2 and 1.3, we now know that hot halos do not dominate the X-ray emission of all E and S0 galaxies.

Following on the previous discussion in this chapter, I will revisit the status of these mass measurements, for X-ray luminous and X-ray faint galaxies, separately.

1.5.1 X-ray Luminous Galaxies

Trinchieri et al. (1986) took a critical look at the *Einstein* mass measurements of five X-ray luminous galaxies, where the emission could be dominated by hot halos in or near hydrostatic equilibrium. These authors concluded that, given the quality of the *Einstein* data, taking into account all the sources of measurement uncertainty would lead to inconclusive results even for the most X-ray luminous galaxies (Fig. 1.7). Trinchieri et al. (1986) also expressed concern on the assumption of hydrostatic equilibrium, because asymmetries in the X-ray surface brightness distributions of some of these galaxies suggested strong interaction of the hot galaxy halo with the hotter cluster gaseous medium. Moreover, steep radial profiles in some cases suggested winds or the result of stripping at the outer detectable radii. Subsequently,

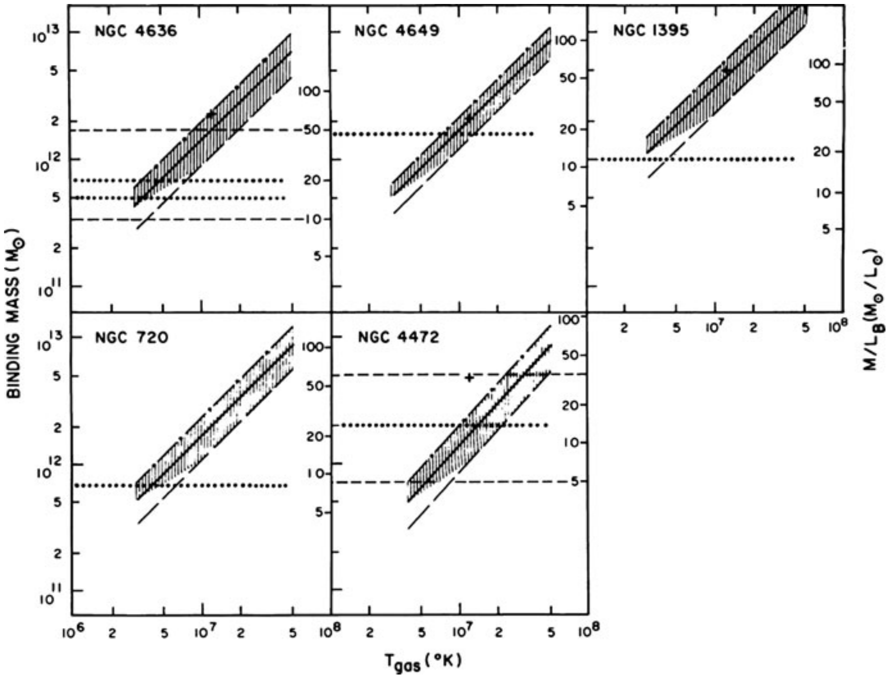

Fig. 1.7 Loci of binding mass allowed by the *Einstein* measurements of five luminous elliptical galaxies (Trinchieri et al. 1986)

Trinchieri et al. (1994), revisited the mass measurement of NGC 4636 with *ROSAT* data, and pointed out additional uncertainties resulting from the possible existence of multi-temperature halos.

Notwithstanding the concerns discussed above, more recent work has confirmed the validity of the X-ray approach to mass measurement – and of the assumption of hydrostatic equilibrium – for X-ray luminous galaxies, even with moderate resolution (10 s to several 10 s of arc-seconds) data. This work is based on deeper X-ray images than those obtained with *Einstein* in clear cases of galaxies with halo-dominated X-ray emission, such as those with L_X/L_B ratios well in excess of the ratios expected from LMXB populations in the L_X–L_B diagram. A good example is given by the *ROSAT*-based measurement of the binding mass of NGC 1399 shown below in Fig. 1.8 (Paolillo et al. 2002).

In NGC 1399 the X-ray isophotes allow the separation of galaxy halo and cluster emission (Ikebe et al. 1996; Paolillo et al. 2002). The X-ray-based *ROSAT* mass profile obtained by Paolillo et al. (2002) is consistent with other X-ray estimates (Rangarajan 1995; Ikebe et al. 1996). More important, this mass profile is also consistent with estimates obtained independently from optical indicators available out to large galactocentric radii (planetary nebulae and GCs, Saglia et al. 2000). This consistency demonstrates that the X-ray mass measurement is correct.

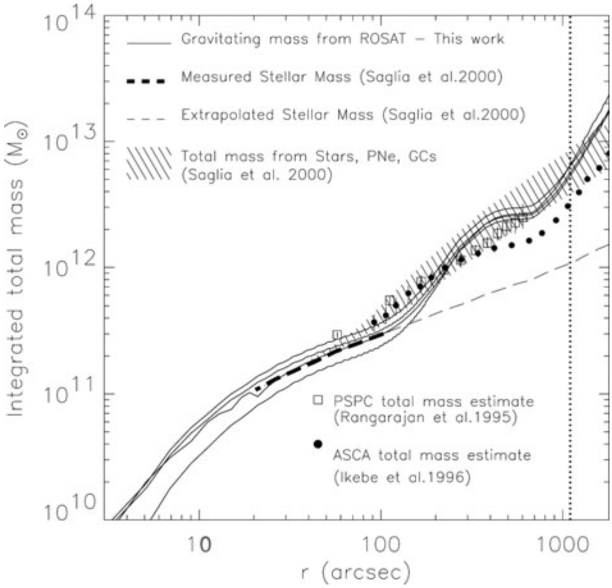

Fig. 1.8 Radial distribution of the enclosed mass in NGC 1399, from different indicators, showing that the X-ray measured mass is consistent with that derived from optical indicators over a large range of radii (Paolillo et al. 2002)

As noted by Paolillo et al. (2003) in the case of NGC 507, the effect of halo/AGN interaction in the central regions of the halos may produce significant departures from equilibrium, so that these regions are best excluded from X-ray mass measurements. However, these are the regions where other non-X-ray measurements are generally available. Therefore, with due caution, deep X-ray observations of luminous hot halos in early-type galaxies are a good means for obtaining mass measurements of these systems, which may be otherwise unobtainable (see Buote and Humphrey, this volume). However, conflicting interpretations of the same data are possible, especially in the case of 'intermediate luminosity' halos (see Buote and Humphrey versus Statler, this volume), all pointing to the significant uncertainties connected with the justification and assumption of hydrostatic equilibrium.

1.5.2 X-ray Faint Galaxies

Instead, moderate angular resolution mass measurements of X-ray faint galaxies are not believable, because it is impossible to disentangle LMXB contamination from halo emission. NGC1316 is a case in question. FJT85 estimated a binding mass of $2.0 \times 10^{12} M_{\odot}$ for this galaxy from the *Einstein* data. This estimate is $\sim$10 times larger than the mass estimated using the radial velocities of planetary

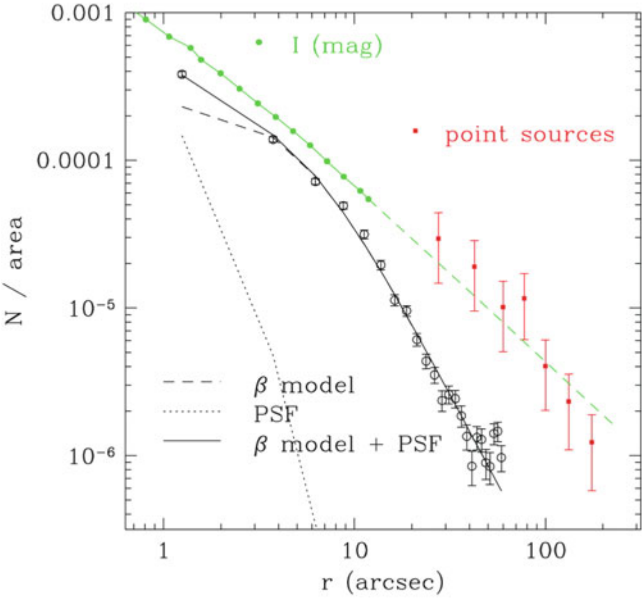

Fig. 1.9 NGC 1316 – radial distribution of stellar surface brightness (*green*), LMXB number counts (*red*), and surface brightness of the hot ISM (*black*), from the *Chandra* measurements of Kim and Fabbiano (2003). This figure shows that the radial distribution of LMXBs is consistent with the optical stellar light, while the gaseous emission has a steeper radial distribution and is concentrated only at the inner radii, see the electronic version for a color version of this figure

nebulae, within a comparable outer radius (Arnaboldi et al. 1998). The *Chandra* observation of NGC1316 (Kim and Fabbiano 2003) revealed that LMXBs dominate the emission at the outer radii out to a radius comparable to that used for the *Einstein* mass estimate, while the hot gas is only detected within less than a 1/3 of this radius (Fig. 1.9); moreover, the temperature of this halo is well constrained with *Chandra* to be ∼0.5 keV, while ∼1 keV was assumed by FJT85.

Therefore, without the sub-arcsecond angular resolution of *Chandra*, and assuming that the X-ray emission is dominated by a halo in hydrostatic equilibrium, the outer radius of the putative hot halo would have appeared mistakenly to be much larger than it is. Moreover, the temperature of this putative halo would have appeared higher because of contamination by the hard emission of LMXBs. All of this would conspire to inflate the mass estimate. Of course in X-ray faint galaxies the halo may not be in hydrostatical equilibrium (see Sect. 1.3), so this method would not be applicable, without appropriate modeling of the halo, even with *Chandra*data (e.g., Ciotti and Pellegrini 2004; Pellegrini and Ciotti 2006).

1.6 Final Remarks

The discovery of hot halos in early-type galaxies was a pivotal result of the first X-ray imaging observatory, *Einstein*. These halos were originally hailed as a new means for measuring the mass of these galaxies and constraining the amount and ubiquity of Dark Matter in the universe. However, the real power of this discovery has been to uncover a new dimension for understanding galaxy evolution. The evolution of the hot halos is the result of a tug of war between the pull of gravity and the push of feedback from stellar evolution (SNe Ia) and AGNs, as well as interactions with the circum-galactic medium and galaxy encounters. This evolution has left observational imprints in both physical properties and chemical composition of the hot gas, which can be exploited to reconstruct the history of both halo and parent galaxy.

The above discussion illustrates that caution must be used when approaching X-ray based mass measurements. In the case of 'dominant' extended hot halos hydrostatic equilibrium may be a good approximation. However, for less X-ray luminous galaxies the halo may be far from equilibrium and also may not dominate the X-ray emission. The analysis of NGC 1316 demonstrates that, for low L_X/L_B galaxies, mass measurements from moderate resolution observations (such as *Einstein*, *ROSAT*, and even *XMM-Newton*) are not to be trusted. For these galaxies, careful analysis of high-resolution X-ray data and hydro-dynamical modeling is required to extract the halo and understand its physical state.

The discovery of these hot halos and the characterization of their properties have been unique contributions of high resolution X-ray telescopes to astronomy. The progress from the first *Einstein* observations to *Chandra* has given us a more complete view of early-type galaxies, including not only their gaseous component, but also their stellar component and their nuclei. To unravel the properties of the hot ISM, we have learnt about the populations of LMXBs in these galaxies, and have now a new tool for studying LMXB evolution. We have also gained a new awareness of the detailed effects of AGN feedback, a key ingredient in the formation and evolution of galaxies in the universe.

This process of understanding has enfolded over the last three decades, and has progressed through discoveries, controversies, setbacks, and more discoveries. While painful at times, this debate has been fruitful, and to me epitomizes the progress of science. I am grateful to have been part of this journey and I am indebted to all other participants, collaborators and competitors, without whom this enterprise would not have been possible.

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