X-ray Emission from Elliptical Galaxies

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Abstract:
Elliptical galaxies are generally luminous sources of X-ray radiation, and contain large amounts of hot, interstellar gas. In the brighter X-ray galaxies, the inferred masses of hot gas are consistent with those expected given the present rates of stellar mass loss. The required rates of heating of the gas are also roughly consistent with those expected from the motions of gas losing stars. X-ray observations, particularly X-ray spectra, require a low rate of Type Ia supernova heating and chemical enrichment in the gas. In the brightest X-ray galaxies, the cooling times in the gas are short, which suggests that the gas forms steady-state cooling flows. Steady cooling models explain most of the properties of the brighter X-ray galaxies, including their luminosities, the X-ray–optical correlation, their temperatures, and their surface brightness profiles. Although the optical and X-ray luminosities of early-type galaxies are strongly correlated, there is a large dispersion in this correlation. The origin of the emission in the X-ray faint ellipticals is less certain. All ellipticals appear to have a hard X-ray spectral component due to accreting binary systems. X-ray faint ellipticals also have a very soft X-ray component, which may be residual hot interstellar gas. The X-ray spectra of ellipticals indicate that the abundance of iron is well below the solar value, which implies that the rate of Type Ia supernova contamination is small. The abundances and evidence for gradient gradients suggest that stellar abundance gradients and inflow of the gas affect the X-ray spectra.

1. Introduction
One of the most important discoveries of the Einstein X-ray Observatory was that normal elliptical are generally strong X-ray sources (Forman et al. 1985; Trinchieri & Fabbiano 1985). The X-ray emission indicates that these galaxies contain extensive atmospheres of hot, diffuse interstellar gas. Prior to this discovery, it was generally believed that early-type galaxies were gas-poor systems (Faber & Gallagher 1976). Surveys of elliptical galaxies based on Einstein data include Nulsen et al. (1984), Forman et al. (1985), Canizares et al. (1987), and Fabbiano et al. (1992). A number of Ginga observations of early-type galaxies are analyzed in Awaki et al. (1991). A recent compilation of ROSAT observations is given in Davis & White (1996). ASCA results on the X-ray spectra of ellipticals described in Awaki et al. (1994), Loewenstein et al. (1994), Matsushita et al. (1994), Mushotzky et al. (1994), and Matsumoto et al. (1996).
2. X-ray Properties

Elliptical galaxies have X-ray luminosities which range over \( L_X \approx 10^{39} - 10^{42} \) erg s\(^{-1}\). (All comparisons to observations in this paper assume a Hubble constant \( H_0 = 50 \) km/s/Mpc, and a distance to the center of the Virgo cluster of 25 Mpc.) There appears to be a strong correlation between the X-ray and blue optical luminosities of early-type galaxies, with \( L_X \propto L_B^{1.6-2.3} \). Figure 1 shows the X-ray and optical luminosities of the early-type galaxies in the survey of Canizares et al. (1987). The filled circles are detections, while the inverted triangles are upper limits on \( L_X \). Obviously, there is considerable scatter about this relation.

The X-ray emission from ellipticals is extended, with typical overall sizes of \( R_X \sim 50 \) kpc. For example, Figure 2 shows the ROSAT X-ray image of NGC 4472 from Irwin & Sarazin (1996). On large scales, the azimuthally-averaged X-ray surface brightnesses \( I_X(r) \) of ellipticals typically decline with radius \( r \) roughly as \( I_X \propto r^{-2} \) (Forman et al. 1985). Very crudely, the X-ray and optical surface brightnesses of ellipticals decline in proportion to one another \( I_X(r) \propto I_B(r) \) (Trinchieri et al. 1986). This relationship holds only very approximately; the X-ray surface brightness profiles of ellipticals often have structure which is not apparent in the optical profiles. Also, this proportionality holds only within a given elliptical. The constant of proportionality varies from galaxy to galaxy, as required by the steeper than linear correlation between X-ray and optical luminosities.

![Figure 1. The correlation of X-ray and optical luminosities of early-type galaxies from Canizares et al. (1987). The filled circles are detections, and the inverted triangles are upper limits. The hatched area gives the range of estimated stellar X-ray luminosities from Forman et al. (1985), Canizares et al. (1987), and Fabbiano et al. (1989). The curve gives the predicted relation for the steady cooling models of Sarazin & Ashe (1989).]
At least for the more luminous X-ray ellipticals, spectral observations indicate that the X-rays are produced by thermal emission from diffuse gas. The spectra imply that the temperature of the gas is typically $T \approx 10^7$ K ($kT \approx 1$ keV) (Forman et al. 1985; Trinchieri et al. 1986). The X-ray surface brightnesses profiles of ellipticals then indicate that the hot gas density declines with radius at large radii roughly as $\rho_{\text{gas}} \propto r^{-3/2}$. The total gas masses required by the X-ray observations are rather uncertain, because this density distribution doesn’t converge and the X-ray images of ellipticals fade into the background at large radii. However, the gas masses are often in the range $M_{\text{gas}} \approx 10^9 - 10^{11} M_\odot$. It is useful to compare the gas masses to the optical luminosities of the galaxies. For the brighter ellipticals, one finds $(M_{\text{gas}}/M_\odot) \approx 0.2(L_B/L_\odot)$. If a stellar mass to light ratio of $\approx 10 M_\odot/L_\odot$ is assumed, then is implies that the gas mass is about 2% of the stellar mass. The hot gas is generally the dominant form of interstellar matter in elliptical galaxies (by mass). The interstellar gas masses in brighter ellipticals are large, but represent a much smaller fraction of the stellar mass than in late-type spiral galaxies.

![Figure 2](image_url). The ROSAT X-ray image of the Virgo elliptical NGC 4472 (Irwin & Sarazin 1996). Contours of the X-ray emission are superposed on a greyscale representation of the optical image.

3. Physical State of the Gas

3.1 Origin of the Gas

The amount of hot gas seen in the brighter X-ray ellipticals is consistent with the amount expected for the present rates of stellar mass loss acting over a significant fraction of the Hubble time. The present rate of stellar mass loss in early-type galaxies is fairly well-determined by stellar evolution theory to be
\begin{equation}\nonumber \left( \dot{M}_s/L_B \right) \approx 1.5 \times 10^{-11} M_\odot \text{yr}^{-1} L_\odot^{-1} \text{ (Renzini & Buzzoni 1986).} \end{equation}

If all of the stellar mass loss is converted into hot gas and the same rates have applied for a time \( t \), the ratio of the mass of hot gas to the optical luminosity would now be \( (M_{\text{gas}}/M_\odot) \approx 0.16(L_B/L_\odot)(t/10^{10} \text{yr}) \), which is quite close to the typical observed value for bright ellipticals.

There are several caveats that need to be given concerning this agreement of the observed and predicted gas masses. First, models for the stellar evolution of elliptical galaxies predict that the stellar mass loss rate was much higher in the past. This and the fact that the gas in clusters of galaxies contains a very large mass of heavy elements suggest that elliptical galaxies have lost substantial amounts of gas in the past. Second, the agreement of the present stellar mass lost rate and the amount of hot gas really only applies to the brightest X-ray galaxies. For the fainter X-ray galaxies in Figure 1, the masses of hot gas are apparently much smaller than from the present rates of stellar mass loss. Third, it is not obvious that all the gas resulting from stellar mass loss will be heated to X-ray emitting temperatures. Finally, elliptical galaxies are seldom very isolated, and large ellipticals near the centers of groups or poor clusters may be accreting ambient gas (Thomas 1986).

### 3.2 Heating of the Gas

Why is the interstellar gas in ellipticals hot? The primary reason is that the stars in elliptical galaxies move at large velocities relative to nearby stars. Thus, gas which is ejected from one star (for example, in a red giant wind or planetary nebula) will encounter gas ejected from other stars at a very high velocity, determined by the stellar velocity dispersion of the galaxy. Collisions between the ejected gas and either gas ejected by neighboring stars or ambient hot gas may thermalize the kinetic energy of motion of the gas. Because this gives an amount of heat which is proportional to the amount of gas injected, it is useful to define the energy per unit injected gas mass as \( 3kT_{\text{inj}}/2\mu m_p \). The resulting heating due to stellar mass loss is then

\begin{equation}
T_{\text{inj}} = \frac{\mu m_p \sigma^2_*}{k} = 6.8 \times 10^6 \text{K} \left( \frac{\sigma_*}{300 \text{km} \text{s}^{-1}} \right)^2, \tag{1}
\end{equation}

where \( \sigma_* \) is the one-dimensional stellar velocity dispersion, and \( \mu \) is the mean mass per particle in the gas in units of the proton mass \( m_p \). This gives a temperature which is comparable to those observed in ellipticals. If the gas in ellipticals forms a cooling flow, there will be additional heating due to infall in the galactic potential and adiabatic compression. Since the stellar velocity dispersion measures the depth of the potential well in an elliptical galaxy, this source of heating is also proportional to \( \sigma^2_* \), and can be viewed as a proportionate increase in equation 1.

In addition to the relatively quiescent stellar mass loss which dominates the injection of mass into the interstellar gas, a small fraction of the gas may be ejected with large kinetic energy by Type Ia supernovae. The heating rate per
unit injected gas mass due to supernovae is

\[ T_{inj} = 3.6 \times 10^7 K \left( \frac{r_{SN}}{0.22} \right) \left( \frac{E_{SN}}{10^{51} \text{ ergs}} \right) \left( \frac{\dot{M}_\ast / L_B}{1.5 \times 10^{-11} M_\odot \text{ yr}^{-1} L_\odot^{-1}} \right)^{-1}. \]  

(2)

Here, \( E_{SN} \) is the average kinetic energy of each supernova ejection, and the rate of supernovae is \( r_{SN} \) per \( 10^{10} L_\odot \) (in blue luminosity) per century. Tammann (1982) gives \( r_{SN} = 0.22 \), but more recent surveys give lower values (e.g., Evans et al. 1989).

Comparing equations 1 and 2, it is clear that supernova heating would dominate in all ellipticals if the supernova rate is as high as that given by Tammann (1982). However, there are many reasons why the X-ray observations of ellipticals are inconsistent with such a high supernovae heating rate. First, this much heating would cause many ellipticals to have winds, which are not observed. Second, the predicted X-ray luminosities would be too large in most cases if this much supernova heating were converted into X-ray emission. Finally, the heavy element abundances in the hot gas in ellipticals would be very high if the supernova rate was high, whereas they are observed to be quite small (§ 7).

### 3.3 Cooling of the Gas

One certain mechanism for energy loss by the hot gas is the emission of the observed X-rays. X-ray emission by a hot, thin plasma is the result of processes involving electron-ion collisions (e.g., thermal bremsstrahlung and line emission), and the emissivity is proportional to the square of the density. One can write the emissivity or the cooling rate per unit volume of the gas as \( \rho^2 \Lambda(T) \), where \( \rho \) and \( T \) are the gas density and temperature, respectively. In order to assess whether this cooling is likely to affect the gas significantly, it is useful to estimate the time required to cool the gas completed if these energy losses are not balanced. The total isobaric cooling time of the gas is given by

\[ t_{cool} = \frac{5}{2} \frac{1}{P} \int_0^\theta \frac{\theta d\theta}{\Lambda(\theta)^{1/3}}, \]

(3)

where \( \theta \equiv kT / (\mu m_p) \). In general, the cooling time increases with radius in an elliptical galaxy. However, for the brighter X-ray ellipticals, the cooling time is shorter than \( 10^{10} \) yr over essentially all of the galaxy (see Table 1 in Sarazin [1990]). The major sources of heating of the gas are associated with its injection (equations 1 and 2 above), and cannot balance continuous cooling. Thus, one expects the gas to cool, and approach steady-state cooling over most of the observed regions of the brighter galaxies.
4. Evolution of the Gas in Ellipticals

There are several reasons why the interstellar gas in ellipticals should evolve over time. First, the time scales for cooling and inflow become longer than the age at large radii, and the gas flows there are presumably time dependent. Second, the rates of stellar mass loss and supernova heating vary with time.

Spherically symmetric, time-dependent hydrodynamical simulations of elliptical galaxies have been made by a number of authors, including Loewenstein & Mathews (1987), D’Ercole et al. (1989), and David et al. (1990). Most of these models assume that elliptical galaxies form in a single short burst of star formation. Many of the models follow the evolution only after this burst. The most important characteristic of these models tends to be the rate of variation of the supernova heating rate compared to the total rate of stellar mass loss. In general, most models have a supernova rate which was higher in the past; this is particularly true if one includes the initial burst of star formation and Type II supernovae.

In the models where the supernova heating rate was very high in the past, the gas initially forms a transonic wind. As the rate of supernovae declines, these models may undergo a period of subsonic inflation. The heating of the gas is insufficient to unbind it from the galaxy, and most of the injected energy goes into increasing the pressure in the gas and causing it to inflate slowly. Finally, once the cooling time becomes shorter than the age of the galaxy, a steady-state cooling flow forms. In this phase, the X-ray luminosity of the galaxy is essentially equal to the total rate of heating of the gas. In § 3.3, we noted that the cooling time is less than the age over essentially the entire observed regions of hot gas in the brighter X-ray ellipticals. Thus, these galaxies are likely to be undergoing steady-state cooling at present.

5. Steady-State Cooling

One-dimensional, steady-state, cooling flow models for the gas in ellipticals have been calculated by Thomas (1986), Sarazin & White (1987), Vedder et al. (1988), Sarazin & Ashe (1989), and others. In these models, the rate of heat input associated with the injection of gas by stellar mass loss equal the rate of emission of the gas as it cools. Thus, the X-ray luminosity for steady cooling is given approximately by

\[ L_X \approx \left( \frac{3kT_{\text{inj}}}{2\mu m_p} \right) \dot{M}_* . \]  

(4)

Steady cooling models give X-ray luminosities which agree with those of the brighter X-ray ellipticals, as long as the supernova heating rate is low.

These models also provide a simple explanation for the steep dependence of the X-ray luminosity on the optical luminosity. If the supernova rate is low, then the injection temperature of the gas varies with the square of the velocity dispersion (equation 1). According to the Fundamental Plane or Faber–Jackson relations, the velocity dispersion of an elliptical increases with its luminosity.
When combined with equations 1 and 4, this leads to $L_X \propto L_B^{1.5-2}$, consistent with the observed relation. In Figure 1, the predicted $L_X-L_B$ relationship is shown for detailed cooling flow models from Sarazin & Ashe (1989).

Steady cooling models give a reasonably good fit to the radial X-ray surface brightness profiles of ellipticals. There is a simple argument which explains this (Sarazin 1986). In steady cooling models, the rate of heating of the gas equals the rate of cooling through the emission of X-rays (equation 4). If this applies locally as well as globally, then the emissivity of the gas equals the local heating rate per unit volume. If one integrates the X-ray emissivity along a line of sight through the galaxy, this gives

$$I_X(r) \approx \frac{3}{2} \frac{k}{\mu m_p} \langle T_{\text{inj}} \rangle \left( \frac{\dot{M}}{L_B} \right) \frac{\Lambda_X}{\langle \Lambda \rangle} I_B(r),$$

where the averages are along the line-of-sight at $r$. The factor $\langle \Lambda_X/\Lambda \rangle$ is a bolometric correction for the fraction of the gas emission in the X-ray band, which is nearly unity. If the velocity dispersion of the galaxy is relatively constant, the $\langle T_{\text{inj}} \rangle$, then equations 1 and 5 imply that $I_X \propto I_B$, approximately as is observed. Also, if one adopts a Hubble law for the optical surface brightness of ellipticals, then this gives $I_X \propto r^{-2}$.

![Figure 3](image-url)  

**Figure 3.** The radial variation of the temperature in NGC 4472 from the ROSAT PSPC X-ray spectrum (Irwin & Sarazin 1996). The curve is a fit to the data.

Finally, the steady cooling models are consistent with the temperatures and temperature variations observed in the brighter X-ray ellipticals. The steady cooling models generally predict that the gas temperatures are relatively constant in the outer regions, and decline toward the center. ROSAT and ASCA spectra show this pattern in all of the bright ellipticals of which I am aware. For example, Figure 3 shows the observed temperature profile of NGC 4472 (Irwin & Sarazin 1996).
6. X-ray Faint Ellipticals

Most of the detailed X-ray properties of ellipticals discussed above are based on observations of the brightest ellipticals. However, it is clear from Figure 1 that there is a range of at least an order of magnitude in the X-ray luminosities of ellipticals with the same optical luminosity. Why is there such a large dispersion in X-ray luminosities? What is the origin of the detected X-ray emission of the fainter ellipticals? Is it thermal emission by interstellar gas as in the brighter ellipticals?

There have been a number of suggestions as to the origin in the dispersion in the X-ray luminosities of ellipticals. D’Ercole et al. (1989) suggested that the faint X-ray ellipticals are at an earlier evolutionary stage and undergoing subsonic inflation (§ 4). However, the specific version of this hypothesis which they advocated required a large supernova heating rate, which may be ruled out by the X-ray spectra of ellipticals and other X-ray data (§§ 3.2, 7).

White & Sarazin (1991) suggested that the X-ray faint ellipticals were mainly located in denser regions, and that the gas in these galaxies had been removed by ram pressure stripping. While there are clear cases of this occurring (e.g., M 86 in the Virgo cluster), the statistical anticorrelation of X-ray luminosity with local density is not very well established (Eskridge et al. 1995).

What is the nature of the X-ray emission in the X-ray faint ellipticals? It might be due to residual diffuse hot ISM, in which case it would have a soft X-ray spectrum, or due to low mass X-ray binaries [LMXRBs], with a hard X-ray spectrum. In Figure 1, the shaded area shows the predicted X-ray luminosities of due to LMXRBs based on a number of different extrapolations from nearby galaxies. Because the stellar populations of bright ellipticals appear to be fairly homogeneous, one expects the $L_X$ contribution of LMXRBs to scale with the optical luminosity $L_B$.

ASCA X-ray spectra of essentially all ellipticals show the presence of a very hard spectral component which is approximately proportional to the optical luminosity of the galaxy (Matsushita et al. 1994; Matsumoto et al. 1996). This hard spectral component is consistent in spectral shape and flux with that expected from LMXRBs. So, it is likely that binary stars are an important source of X-ray emission in X-ray faint ellipticals.

However, ROSAT and ASCA spectra also show evidence for a very soft X-ray spectral component in X-ray faint ellipticals (Fabbiano et al. 1994). This component might be due to diffuse ISM, to stellar corona, or to some unknown cause, although there is some evidence favoring an interstellar origin (Davis & White 1996).

Thus, it seems likely that the X-ray emission of X-ray faint ellipticals is due to several mechanisms, including LMXRBs and residual hot ISM.
7. Abundances in the X-ray Gas

At the temperatures found in elliptical galaxies, much of the X-ray emission is line emission due to heavy elements. Thus, X-ray spectra can be used to determine the abundances in the gas, particularly the abundance of iron. It was expected that the gaseous abundances would be moderately to extremely high, depending on the supernova rate. The heavy element abundances in stars in the central regions of elliptical galaxies are rather high, and Type Ia supernovae may further enhance the abundances. The expected average gaseous iron abundance is then

\[
\frac{(\text{Fe/H})_{\text{gas}}}{(\text{Fe/H})_{\odot}} \approx \left[ \frac{(\text{Fe/H})_{*}}{(\text{Fe/H})_{\odot}} + 1.6 \left( \frac{M_{\text{Fe}}}{0.6 M_{\odot}} \right) \left( \frac{r_{SN}}{0.075} \right) \right],
\]

where \((\text{Fe/H})_{*}\) is the iron abundance in the normal stellar ejecta, and each Type Ia supernova produces a mass \(M_{\text{Fe}}\) of iron. The supernova rate used in equation 6 is at the low end of the suggested rates, so the iron abundances in ellipticals were expected to be \((\text{Fe/H})_{\text{gas}} \gtrsim 3(\text{Fe/H})_{\odot}\), and could reach ten times solar if higher supernova rates apply.

The expected gaseous abundances in ellipticals are also sensitive to stellar abundance gradients and the dynamical state of the gas. The stellar abundance gradients observed in elliptical galaxies will produce gradients in the interstellar abundances, particularly for elements which are not provided mainly by Type Ia supernovae. If the gas is involved in an outflow (e.g., D’Ercole et al. 1989), the heavy elements at any radius will have come from stars interior to that radius, and this will increase the abundances. Conversely, if the gas is involved in an inflow as in a cooling flow, all of the heavy elements come from the outer regions of the galaxy, and the abundances are depressed.

X-ray spectra from ROSAT and particularly ASCA show that the interstellar abundances of iron are quite low, \((\text{Fe/H})_{\text{gas}} \approx 0.1 - 0.5(\text{Fe/H})_{\odot}\) (Awaki et al. 1991; Awaki et al. 1994; Loewenstein et al. 1994; Mushotzky et al. 1994; Matsumoto et al. 1996). In a number of cases, abundance gradients are seen. Such a low iron abundance requires that the rate of Type Ia supernovae mass injection must be very low (equation 6). The low abundances and the presence of abundance gradients suggest that stellar abundances gradients and inflow affect the spectra. However, the observed abundances are so low that external inflow of low abundance gas or incomplete mixing of stellar ejecta into the hot gas may be required. It would be very helpful in this regard if accurate stellar iron abundance gradients could be determined for many of the X-ray bright ellipticals.

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