Hot Gas and Halos in Elliptical Galaxies

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Abstract

We review recent progress in understanding the evolution of hot interstellar gas in the halos of elliptical galaxies. The enormous spread in x-ray luminosity $L_x$ for galaxies of similar $L_B$ is driven by non-homologous variations in the physical size of the hot interstellar medium, $L_x \propto L_B^2 (r_{ex}/r_e)^{0.6}$, where $r_{ex}$ and $r_e$ are the half-luminosity radii in x-rays and optical radiation. This relation may have been established as the ellipticals formed in small groups of galaxies. By combining ROSAT with older Einstein data we derive the distribution of total mass $M_{\text{tot}}(r)$ in NGC 4472 which, for $0.1 \leq r/r_e \leq 1$, is identical to the expected stellar mass $M_e(r)$. This means that stellar mass to light ratios can be determined from x-ray observations! It also means that the widely used “mass dropout” assumption must be incorrect in this important part of the cooling flow. Recent ROSAT determinations of temperature profiles in ellipticals show a curious maximum in the gas temperature at $\sim 3 \ r_e$ and global mean gas temperatures that are about twice the virial temperature of the stars. These results are totally unlike those predicted by standard models of galactic cooling flows. However, cooling flow solutions can be brought into agreement with observed interstellar temperature and density profiles if they begin with an additional massive component of “circumgalactic” gas, assumed to fill the outer galactic halos beyond most of the stars. This old hot gas, first heated during the epoch of galaxy formation, continues to flow into the stellar parts of ellipticals today, combining with gas expelled from evolving stars. The dual origin of hot interstellar gas further complicates recent discussions of abundances in the hot interstellar gas.

Subject headings: X-rays, halos, galaxies, ellipticals

1. Introduction

Gravitational confinement of hot, x-ray emitting interstellar gas provided the earliest evidence for massive halos in early type galaxies (Bachall & Sarazin 1977; Mathews 1978; Forman, Jones, & Tucker 1985). The ratio of interstellar to stellar baryonic components, 3 - 10 percent, is similar to that in typical spiral galaxies. Dynamically this gas must be quiescent, near hydrostatic equilibrium. If the observed interstellar gas were free-falling in the galactic potential it could not be replenished fast enough from stellar mass loss to maintain the gas mass observed. If the hot gas were participating in a supersonic galactic wind, the gas density and x-ray luminosity would be very much less than observed. Therefore, the hot gas must be close to static equilibrium. Hydrostatic equilibrium is also supported by the short sound-crossing time to the effective radius, $t_{sc} \sim 10^8$ yrs. The total mass within radius $r$ can be determined from the condition for hydrostatic equilibrium,

$$M_{\text{tot}}(r) = \frac{kT(r) r}{G \mu m_p} \left( \frac{d \log \rho}{d \log r} + \frac{d \log T}{d \log r} + \frac{P_{\text{mag}}}{P} \frac{d \log P_{\text{mag}}}{d \log r} \right).$$

The total mass is sensitive to the leading coefficient which involves the gas temperature $T(r)$ determined from the x-ray spectrum. The logarithmic derivatives describe the radial variation of the total pressure. The (negative) gas density derivative is generally the largest and can be rather accurately determined from the x-ray surface brightness distribution. Typical temperature gradients are smaller and only weakly influence $M_{\text{tot}}(r)$. Very little is known of the variation of magnetic pressure $P_{\text{mag}} = B^2 / 8\pi$. However, since $(P_{\text{mag}}/P)(d \log P_{\text{mag}}/d \log r)$ is expected to be negative, if this term were important and not considered in the hydrostatic equilibrium, then $M_{\text{tot}}$ would be underestimated. Determinations of the total mass $M_{\text{tot}}(r)$ in elliptical galaxies clearly indicate the universal presence of dark matter halos. For those ellipticals that are members of rich clusters having hot, high pressure cluster gas, the partial confinement of interstellar gas by the ambient cluster gas cannot simulate the effect of dark halos; $M_{\text{tot}}(r)$ can still be determined from hydrostatic equilibrium in this case too provided the logarithmic gradients in the equation above can be accurately determined.

While much was learned about elliptical galaxies from Einstein observations, more recent high quality x-ray observations with ROSAT and ASCA have
revealed unanticipated aspects of the hot interstellar gas that are inconsistent with older theoretical models. In the following brief review we discuss some of these recent developments and their possible implications. We show that the sizes of the x-ray images, now well-determined for about a dozen ellipticals, account for the strong scatter in x-ray luminosity among ellipticals having similar optical luminosity. We have also realized that interior to an effective radius in NGC 4472 and 4649 the hot gas pressure is balanced by the stellar potential, with little or no influence from dark matter; this allows a determination of the stellar mass to light ratio directly from x-ray data. Of particular interest are the strange maxima in the interstellar gas temperature, peaking near $r \sim 3 r_e$, and the generally high value of the mean gas temperature in ellipticals, about twice the equivalent temperature of orbiting stars $T_\star$. We show below that this temperature profile cannot be produced by normal mass loss from evolving galactic stars, instead most of the hot gas currently observed in elliptical galaxies may have been stored in the outer dark halo regions since the formation of these galaxies by mergers and tidal truncations in small groups of galaxies. But many details are still incompletely understood. It remains a mystery, for example, why few if any x-ray images show the isophotal flattening expected from the global rotation of galactic stars as observed in essentially all ellipticals.

We begin with a brief review of the nature of galactic cooling flows.

2. Cooling Flows in Elliptical Galaxies

In the standard explanation, to be modified below, the hot interstellar gas in ellipticals is the accumulation of normal mass loss from a dominant population of old galactic stars. Many lines of evidence suggest that the stars in large ellipticals are very old, formed in nearly coeval bursts of star formation (Bender 1997). The gaseous envelopes expelled from these normally evolving stars collide with the ambient gas, shock, and dissipate the orbital energy of the parent stars. Evidently, the efficiency of this dissipation accounts for the high gas temperature in ellipticals and explains why it is roughly comparable to the virial temperature of stellar orbits $T_\star \sim 10^7$ K. Although the hot gas could be heated further by Type Ia supernovae, this cannot be very important since the iron abundance in the interstellar gas would greatly exceed that observed. If the hot gas is in quiescent equilibrium, it is easy to show under these assumptions that the x-ray luminosity should vary roughly as the square of the optical luminosity, $L_x \propto L_B^2$ (e.g. Tsai & Mathews 1995) and this dependence has been observed (e.g. Eskridge, Fabbiano & Kim 1995) but with very large cosmic scatter.

Why is hot gas in ellipticals referred to as “cooling flows”? The observed x-rays are clear evidence that the hot gas is losing energy. However, as energy is lost by radiation, the gas sinks deeper into the galactic potential and receives additional energy by compression in the atmosphere of hot gas. The net result, quite ironically, is that the gas in the “cooling flow” doesn’t cool until its density is so high that $Pd\tau$ heating is no longer able to compensate radiative losses. Under these circumstances the gas temperature profile in a galactic “cooling flow” is nearly constant with galactic radius. Since all ellipticals exhibit some amount of rotation, the final stage of cooling is likely to be into a disk rotating at the local circular velocity. In the absence of strong supernova heating or other disturbances, the cooling flow velocity is negative and highly subsonic throughout the cooling flow except immediately before the final cooling catastrophe where the flow passes through a sonic surface and shocks against the cooled gas already present. Since the stellar mass loss varies with time (see below), the flow continuously evolves and never reaches steady state.

3. X-ray and Optical Image Sizes Correlate with $L_x/L_B$

In spite of the overall correlation $L_x \propto L_B^2$, ellipticals with similar $L_B$ can have x-ray luminosities $L_x$ that range over factors of 30 - 100. This large scatter has been discussed for many years but no intrinsic property of the galaxies had been found that correlated with residuals from the $L_x$, $L_B$ correlation. However, we have recently shown that these residuals are related to the sizes of the x-ray images. As the number of ellipticals that are spatially resolved in x-radiation slowly increases, the wide disparity in their x-ray image size $r_{x\alpha}$ has become evident (Loewenstein 1996). Ellipticals that are centrally dominant in small galaxy groups – NGC 5044 or 1399 – have enormous clouds of hot gas extending far beyond their optical images. Other less endowed ellipticals – NGC 4374 or 4649 – have x-ray images that are truncated at or
near their optical radius $r_e$. Ellipticals are thought to have formed by galactic mergers in small galaxy groups. Their close dynamical proximity in group environments also promotes tidal exchanges of halo material (Merritt 1985; Bode et al. 1994) and probably also of hot gas. Motivated by this conjecture, Mathews & Brighenti (1997b) plotted $r_{ex}/r_e$ against residuals in the $L_x, L_B$ plot and found a strong correlation. A distance-independent representation of this correlation, $(L_x/L_B) \propto (r_{ex}/r_e)^{0.6 \pm 0.3}$, is shown in Figure 1. Although the significance of this result is not fully understood, it is likely that the vast range of x-ray sizes is related to disparities in the final allocation of halo material resulting from mass-exchange interactions in group environments. If this explanation is correct, information about hot gas production in the early history of ellipticals must still be retained in currently observed ellipticals. We think that this is indeed the case.

4. Evolutionary Models of Galactic Cooling Flows

To allow for the stellar origin of the gas, the standard equations of gas dynamics expressing conservation of mass, momentum and energy must be embellished with source and sink terms representing the input of gas from orbiting stars, the possible heating by Type Ia supernovae, and cooling of the gas by radiation losses (e.g. Brighenti & Mathews 1996). The steadily decreasing rate that mass is supplied from an old single-burst stellar population varies as $\alpha_*(t) \rho_*(r)$ where $\alpha_*(t) = \alpha(t_n)(t/t_n)^{-1.3}$ s$^{-1}$ (Mathews 1989) and $t_n = 13 - 15$ Gyrs is the current age of the population. The value of $\alpha_*(t_n)$ corresponds to about 1.5 $M_\odot$ yr$^{-1}$ for a galaxy having total stellar mass $M_{st} = 10^{12} M_\odot$. The gas moves in a galactic potential described by a King or de Vaucouleurs stellar system immersed in a massive dark halo. Since intercluster gas in rich clusters is rich in iron ($[Z/Z_\odot] \approx 0.3$), it has usually been assumed that galactic winds driven by Type II supernovae were common early in the history of elliptical galaxies (David et al. 1990; 1991). For this reason, evolutionary cooling flow calculations often begin with an essentially gas-free galaxy at some early time $t \approx 1$ Gyr when it is assumed that that galactic winds subsided; thereafter the interstellar gas is provided by stellar mass loss.

The results of a typical evolutionary calculation of this sort for a non-rotating E0 galaxy on the fundamental plane are shown in Figure 2 (from Brighenti & Mathews 1996). The gas temperature variation $T(r)$ follows the stellar temperature $T_*(r)$ which is found by solving the Jeans equation in the combined stellar-dark halo potential. Of particular interest is the small but nevertheless significant difference shown in Figure 2 between the projected soft x-ray surface brightness distribution $\Sigma_x(R)$ (in the Einstein band) and the observed x-ray profile $\Sigma_{x,obs}(R)$ which for some well-observed galaxies is very similar to the stellar surface brightness distribution $\Sigma_*(R)$ (Trinchieri et al. 1986). The computed x-ray surface brightness is too centrally peaked. The traditional means of correcting this discrepancy has been to remove hot gas from the flow, removing more gas closer to the galactic center (Fabian & Nulsen 1977; Stewart et al. 1984; White & Sarazin 1987a, 1987b, 1988; Thomas et al. 1987; Sarazin & Ashe 1989; Bertin & Tonizzio 1995). This “mass dropout” introduces an arbitrary adjustable function of galactic radius into the theoretical model, allowing $\Sigma_x(R) \propto \Sigma_{x,obs}(R)$ at least for small $R$. The physical justification for this approach has been the notion that thermal instabilities rapidly remove hot gas throughout cooling flows, not just at the central regions. Only low mass stars are assumed to form in these unstable condensations since a normal population of young stars is inconsistent with the red optical spectrum observed in most ellipticals. Although the resulting cooling flow models are improved with the “mass dropout” assumption, dropout has not been supported by detailed hydrodynamical calculations. Malagoli et al. (1990) and Hattori & Habe (1990) showed that thermally unstable regions undergo motions due to buoyant forces that introduce shear and Rayleigh-Taylor instabilities, effectively destroying the instability. Moreover, high quality x-ray observations in a few bright ellipticals are inconsistent with the “mass dropout” assumption (see below). The total x-ray luminosity $L_x(t_n)$ for the model shown in Figure 2 falls among the observed data in the $L_x, L_B$ plot but this can hardly be regarded as a verification of the theory since the scatter in this diagram is so large.

More realistic models than that shown in Figure 2 must consider the influence of galactic rotation on the evolution of hot interstellar gas. Rotation is also expected to lessen the slope of the computed x-ray surface brightness distribution since the gas cools toward a disk configuration and does not flow entirely to the center of the galactic potential. Even for the
most luminous ellipticals, where galactic flattening of the stellar component is due to anisotropic stellar orbits, some significant rotation is always observed, \( v_{e,rot} \sin i \approx 50 – 100 \) kpc. Less luminous ellipticals rotate even faster, having rotationally flattened optical images, and typically have stellar disks and evidence for youthful stars (Davies 1997; Scorza and Bender 1995). Brighenti & Mathews (1996; 1997b) have computed the evolution of rotating cooling flows in both slowly and rapidly rotating ellipticals. \( L_e \) is found to decrease markedly with increasing rotation. A large disk \( r_{disk} \sim r_e \) of hot gas forms as shown in Figure 3, even in slowly rotating ellipticals. If such cooling gaseous disks formed into stars less massive than 8 \( M_\odot \) (since SNII are not observed), stellar disks like those observed in disky, rapidly rotating ellipticals can be created from cooling flow gas. But this theoretical model may be incomplete since there is no evidence for either x-ray or stellar disks in massive ellipticals.

5. Recent ROSAT and ASCA Observations

Recent observations of elliptical galaxies with the ROSAT and ASCA satellites have provided qualitatively new information about the iron abundance, gas temperature and density distributions in galactic cooling flows. As a consequence, a much different interpretation has emerged in which most of the hot gas is not supplied by stellar mass loss but instead is left over from the epoch of galaxy formation. In principle the iron abundance in the hot gas can be found from observations of the complex of FeL lines at \( \sim 1 \) keV. In practice, however, there is a wide range of observed values depending on the data reduction procedure and instrument used. For example, the iron abundance for NGC 4472 quoted by Awaki et al. (1994), \( z_{Fe}/z_{Fe\odot} = 0.63 \), is about half that of Buote & Fabian (1997), \( z_{Fe}/z_{Fe\odot} = 1.18 \), although both groups were using ASCA data. Some, but not all, of this variation is due to significant differences in the adopted iron abundance for the sun or solar system (Ishimaru & Arimoto 1997). Much discussion has focused on the low values of the gas iron abundance relative to the iron abundance observed in the stellar spectrum (Arimoto et al 1997); questions have been raised about the accuracy of the FeL iron determination (Renzini 1997). The abundance discrepancy is so large that the iron contribution from SNIa to the interstellar gas must be very low indeed (e.g. Loewenstein et al. 1994). There is also some considerable uncertainty in the stellar iron abundances, particularly since it has been realized that the relative abundances are non-solar. The most recent contribution to this discussion, an extensive re-observation of NGC 4636 with ASCA, has resulted in iron abundances that are consistent with stellar values (Matsushita et al. 1997). Nevertheless, in view of the many uncertainties and the prospect that much of the hot gas does not come from galactic stars, we shall not discuss comparisons of computed and observed cooling flow abundances here.

One of the least expected recent findings has been the high gas temperatures and strange radial temperature profiles in galactic cooling flows. If the gas temperature \( T \) is plotted as function of normalized radius \( r/r_e \) for the six bright, well-resolved ellipticals observed by ROSAT – NGC 507, 1399, 4472, 4636, 4649, and 5044 – a consistent non-isothermal temperature profile is apparent. In each case the gas temperature is close to \( T_e \) near the center then rises to a maximum of about 1.5 - 2 \( T_e \) at \( \sim 3 \) \( r_e \) and slowly decreases at \( r > 3 \) \( r_e \) (Brighenti & Mathews 1997a). This \( T(r) \) has been confirmed by ASCA observations for several of these ellipticals. The region of positive \( dT/dr \) within 3 \( r_e \) \( \sim 15 – 30 \) kpc is not a natural result of conventional theoretical models (cf. Figure 1). In these models the dominant stellar potential in this region of the galaxy provides enough compressive heating to keep the inflowing gas nearly isothermal. In addition, Davis & White (1996) have shown for a larger sample of ellipticals that the average gas temperature is \( \langle T \rangle \approx 1.5 – 2 T_e \), consistent with the peaking temperature profile of the six resolved galaxies. In the absence of SNIa heating, gas expelled from stars cannot have mean temperatures greater than \( T_e \) which characterizes the potential well within the stellar system. However, gas with temperature \( T \sim 2 T_e \) can be bound to the outer dark halos.

6. A Model for NGC 4472 Including Circumgalactic Gas

Inspired by the serious qualitative differences between the observed gas temperature profiles and those expected from simple cooling flow models like that shown in Figure 1, we decided to explore new types of evolutionary models using the observed properties of NGC 4472 as a guide. While NGC 4472 lies at the center of a Virgo subcluster, its global gas tem-
perature and density profiles are very similar to those of other, more isolated ellipticals such as NGC 4636. We proceed in two stages. First, the radial distribution of the total stellar and dark mass in NGC 4472 can be found by using the assumption of hydrostatic equilibrium. Then the usual evolutionary cooling flow equations can be solved over the Hubble time, using the known galactic potential, to see how well the solutions can recover the gas and temperature variations observed in NGC 4472 today.

In Figure 4a we combine Einstein HRI (Trinchieri et al 1986) and ROSAT HRI+PSPC (Irwin & Sarazin 1996) data for the gas (number) density and temperature distributions. Then we fit these with the analytic curves shown and solved the hydrostatic equation for \( M_{\text{tot}}(r) \) plotted with a solid line in Figure 4b. It is particularly gratifying that the hot gas is confined by the stellar potential in the region \( 0.1 \, r_e \lesssim r \lesssim r_e \). In this region the total mass determined from the x-ray gas agrees almost exactly with the de Vaucouleurs profile for the stellar mass \( M_*(r) \), normalized by the stellar mass to light ratio determined by van der Marel (1991). Discounting a conspiracy of errors, this excellent agreement implies a multitude of conclusions: (1) the x-ray determined gas temperature is correct, (2) van der Marel’s stellar mass to light ratio is correct and constant out to \( r_e \), and (3) “mass dropout” cannot be important in this large region of the cooling flow otherwise \( M_{\text{tot}} \) would be less than \( M_*(\text{Gunn & Thomas 1996}) \). In \( r \lesssim 0.1 r_e \) we see that \( M_{\text{tot}} < M_* \); this could be due to dropout but, if real, may be a result of large self-generated magnetic fields that are expected to concentrate near the galactic core (Mathews & Brighenti 1997a). Similar \( M_{\text{tot}}(r) \) determinations for NGC 4649 and 4636 are discussed by Brighenti & Mathews (1997a).

Using the total mass distribution \( M_{\text{tot}}(r) \) from Figure 4b, we solved the cooling flow equations in the normal way, letting an initial gas-free galaxy evolve from \( \sim 1 \, \text{Gyr} \) to \( t_n = 13 \, \text{Gyrs} \). The objective is to reproduce the density and temperature profiles actually observed in NGC 4472. The results of this calculation, shown as dotted lines in Figure 5, are seen to differ significantly from the observations. The computed gas density profile is too steep at all radii and the gas temperature is about half the observed value at \( r \gtrsim r_e = 8.6 \, \text{kpc} \). In seeking agreement with the observations we varied the parameters and altered the assumptions in rather radical ways. The usual mass dropout model only improved the slope of the gas density profile near the galactic center with no improvement elsewhere and the deviation from the observed \( T(r) \) was worsened. Making the stellar mass loss rate or the thermal emissivity of the hot gas increase (unphysically) with galactic radius had surprisingly little influence on the final cooling flows at time \( t_n \). Increasing the supernova rate produced a huge iron abundance (four times solar) and only heated the gas modestly until a galactic wind sets in. Galactic winds are undesirable since \( L_x \) drops far below the value observed for NGC 4472.

After these and other similar explorations, success in fitting the observed density and temperature was only possible if the galaxy is filled with hot gas when the calculation is begun. The dashed lines in Figure 5 show the resulting interstellar gas density and temperature when the calculation is begun with a total hot gas mass of \( M_{\text{hot}} = 1.5 \times 10^{12} \, M_\odot \) (much of which flows out during the subsequent evolution) all initially at temperature \( T = 1.2 \times 10^7 \, \text{K} \). At the end of the calculation when \( t = t_n = 13 \, \text{Gyrs} \), only about 60 percent of the gas within \( r_e \) comes from the stars. If the gas from the stars is totally neglected throughout the evolution (dash-dotted line in Figure 5) the gas temperature is too large, but reducing \( \alpha_*(t_n) \) by a factor of two improves the fit somewhat (solid lines).

We conclude that the hot gas in galaxies like NGC 4472 cannot have originated solely from mass loss from the currently observed stellar system. Instead large masses of hot gas must have been present at early times and a significant fraction of this ancient gas is retained by present day ellipticals. Evidently, all large ellipticals have this circumgalactic gas since \( \langle T \rangle > T_* \) is generally observed (Davies & White 1996). Since the circumgalactic gas is hotter than the stars, its scale height in the galactic potential is also greater; this explains the relatively flat observed x-ray surface brightness distribution \( \Sigma_x(R) \) and obviates the need for “mass dropout.” It is likely that the circumgalactic gas was heated by shocks in the secondary infall against the Hubble flow and by Type II supernova explosions of massive stars. The presence of old circumgalactic gas filling the distant halo regions of present-day ellipticals will provide important new information about the conditions that prevailed during the epoch of galaxy formation.

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Fig. 1.— Variation of $L_x/L_B$ with $r_{ex}/r_e$ for eleven well-resolved elliptical cooling flows.

Fig. 2.— Cooling flow for an $L_B = 5 \times 10^{10} L_{B,\odot}$ elliptical at $t = 15$ Gyrs. Density, temperature and surface brightness are shown for gas (solid lines) and stars (dashed lines) respectively. The sudden transitions at small $R$ are artifacts of the computational grid. $\Sigma_x$ is computed for the band $0.5 - 4.5$ keV and $\Sigma_*$ is arbitrarily normalized.

Fig. 3.— Equator-on x-ray surface brightness distribution $\Sigma(R,z)$ in the central region of a slowly rotating ($v/\sigma = 0.39$) E2 galaxy with $L_B = 5 \times 10^{10} L_{B,\odot}$ after $t = 15$ Gyrs. Two adjacent equally spaced contours are labeled with $\log \Sigma(R,z)$ in ergs cm$^{-2}$ s$^{-1}$ for the $0.4 - 4.5$ keV band.

Fig. 4.— (a) Einstein HRI (filled circles) and ROSAT (open circles) observations of gas density and temperature in NGC 4472; solid lines are analytic fits to data. (b) Distribution of total mass $M_{tot}(r)$ (solid line), stellar mass $M_*(r)$ (dashed line), and hot gas mass $M_g(r)$ (dashed-dot line). (c) Distribution of total mass density $\rho_{tot}(r)$ (solid line) and stellar density $\rho_*(r)$ (dashed line).

Fig. 5.— Gas density and temperature observations of NGC 4472 compared with density and temperature in cooling flow models at $t = 13$ Gyrs with and without additional gas at early times. Dotted lines: cooling flow created only by stellar mass loss; Dashed lines: same cooling flow with hot gas present at early times; Solid lines: same cooling flow with extra initial gas and $\alpha(t_n)$ reduced by 2; Dot-dashed lines: same extra-gas cooling flow with $\alpha(t) = 0$. 
