X-RAY HALOS IN GALAXIES AND CLUSTERS OF GALAXIES: THEORY

Craig L. Sarazin*
Department of Astronomy, University of Virginia,
Charlottesville, VA 22903 and
Joint Institute for Laboratory Astrophysics, University of
Colorado and National Bureau of Standards, Boulder, CO 80309

ABSTRACT. X-ray measurements provide an excellent method to determine the amount and distribution of the dark matter in clusters. Unfortunately, accurate temperature profiles, necessary to this method, are currently not available. However, if the intracluster gas is assumed to have a monotonically decreasing temperature, one finds that the dark matter is strongly concentrated to the cluster center, and has a mass which only exceeds the known baryonic mass by a factor of about three. On a second topic, cooling flows are shown to be a very common feature of cluster central and normal elliptical galaxies. The cooling gas is probably ultimately converted into low mass stars.

1. INTRODUCTION

In this paper, two topics will be reviewed. First (Sec. 2), I will discuss the use of x-ray measurements to derive mass profiles for clusters of galaxies and individual galaxies, and I will report on some recent applications of this method to clusters. Second (Secs. 3 and 4), I will discuss the cooling flows which appear to be a common feature of ellipticals at the centers of clusters as well as relatively isolated elliptical galaxies. I will argue that the cooling gas is consumed by low mass star formation. If very low mass stars are formed, this could contribute to "dark matter" halos around galaxies.

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*1985-86 JILA Visiting Fellow; permanent address, University of Virginia.

J. Kormendy and G. R. Knapp (eds.), Dark Matter in the Universe, 183–199.

2. MASS DETERMINATIONS AND HYDROSTATIC EQUILIBRIUM

2.1. Method

Masses for individual galaxies and clusters can be derived by assuming that the x-ray emitting gas is in hydrostatic equilibrium with the gravitation field. This is a reasonable assumption as long as the cluster is stationary (the gravitational potential does not change on a sound-crossing time), other forces (magnetic fields, etc.) are not important, and gas motions are significantly subsonic.

Under these circumstances, the gas obeys the hydrostatic equation and the total mass can be determined from the variation of pressure and density. This method has a number of advantages over the use of stars (in galaxies) or galaxies (in clusters) as test particles to determine the gravitational potential. First, the gas is a collisional fluid, and the particle velocities are isotropically distributed. On the other hand, stars in galaxies or galaxies in clusters are collisionless, and uncertainties in the distribution of particle orbits can significantly influence the derived mass distribution (see, for example, Tonry 1983). Second, the statistical errors associated with mass determinations for clusters from the gas distributions are much smaller than those based on galaxy distributions, as there are only $\sim 10^2$ bright galaxies in a rich cluster. Third, better statistics in the x-ray measurements means that it is considerably easier to avoid background contamination, and to resolve possible uncertainties due to subclustering (Geller and Beers 1982). Fourth, x-ray mass determinations are not very sensitive to the shape of the galaxy or cluster (Strimpel and Binney 1979; Fabricant, Rybicki, and Gorenstein 1984).

The first applications of x-ray distributions to derive mass distributions were by Bahcall and Sarazin (1977) and Mathews (1978) in M87. The method has been developed extensively by Fabricant, Gorenstein, and collaborators (Fabricant, Lecar, and Gorenstein 1980; Fabricant and Gorenstein 1983; Fabricant, Rybicki, and Gorenstein 1984). Ideally, one would measure the spatially and spectrally resolved x-ray surface brightness of the cluster or galaxy $I_\nu(\vec{b})$, where $h\nu$ is the x-ray photon energy and $\vec{b}$ is the projected position relative to the center. This would be inverted to give the local x-ray emissivity $\varepsilon_\nu(\vec{r})$, where $\vec{r}$ is the position relative to the cluster center. This deconvolution is stable because the observed x-ray images of regular clusters or galaxies are quite smooth. To deconvolve the projected surface brightness one must assume that the actual gas distribution is spherical or spheroidal (Strimpel and Binney 1979) or, more generally, has an axis of symmetry in the plane of the sky (Fabricant, Rybicki, and Gorenstein 1984). However, the resulting mass distributions are not affected strongly by the shape. For a spherical cluster, the Abel integral inversion for $\varepsilon_\nu(\vec{r})$ is:

$$\varepsilon_\nu(\vec{r}) = -\frac{1}{\pi}\,\frac{d}{dr^2}\int_{r^2}^{\infty}\frac{I_\nu(b)\,db^2}{(b^2-r^2)^{1/2}} \quad . \qquad (1)$$

The x-ray emissivity of a hot plasma depends on its electron density n_e, its temperature T, and its abundances (Sarazin and Bahcall 1977)

$$\varepsilon_\nu = n_e^2 \Lambda_\nu \text{ (T, abundances)} \quad . \tag{2}$$

Heavy elements mainly produce discrete line features in x-rays; the strength of these features determines the heavy element abundances. The x-ray continuum is exponential $\varepsilon_\nu \propto \exp(-h\nu/kT)$, and thus the spectral shape of the emissivity $\varepsilon_\nu(r)$ determines T(r), while its normalization gives $n_e(r)$. Then the hydrostatic equation gives the total mass M(r) interior to r as

$$M(r) = - \frac{k\ T(r) r}{\mu\ m_p\ G} \left\{ \frac{d\ \ell n\ n_e}{d\ \ell n\ r} + \frac{d\ \ell n\ T}{d\ \ell n\ r} \right\} \quad , \tag{3}$$

where μ is the mean molecular weight. It is important to note that the mass depends only weakly on $n_e(r)$ (only on its logarithmic derivative), but depends strongly on the temperature T(r).

2.2. Applications to Galaxy Clusters

The Einstein x-ray observatory produced x-ray images of clusters with excellent spatial resolution, but the imaging detectors had rather poor spectral resolution. Moreover, the telescope was sensitive only to x-ray photons with energies $h\nu \lesssim 4$ keV, while the typical x-ray cluster has a temperature kT ~ 7 keV. Since the exponential thermal bremsstrahlung spectrum is flat for $h\nu \lesssim kT$, the Einstein x-ray images do not give much information on the run of temperatures in the intracluster gas. On the other hand, since the instrumental response of Einstein was very insensitive to the temperature, excellent gas density distributions $n_e(r)$ were determined (Jones and Forman 1984). Unfortunately, the mass in equation (3) is mainly affected by the temperature distribution.

2.2.1. Isothermal Models. In order to resolve this uncertainty in the temperature distribution, one approach has been to assume a simple "polytropic" equation of state connecting the temperature and density $T \propto n_e^{\gamma-1}$, where $\gamma = 1$ means the gas is isothermal, while $\gamma = 5/3$ means the gas is adiabatic (isentropic). Some examples of these mass estimates include Fabricant, Rybicki, and Gorenstein (1984) and Vallée (1981).

The assumption that the gas is isothermal leads to a particularly simple density distribution for the gas. If the total mass has a density distribution given by an "analytic King" model $\rho_{tot} \propto \left(1+(r/a)^2\right)^{-3/2}$ (King 1962) where a is the cluster core radius, and has an isotropic velocity distribution with a one-dimensional velocity dispersion σ, then the isothermal gas distribution is

$$n_e(r) = n_e(0) \left[1 + \left(\frac{r}{a}\right)^2\right]^{-3/2\ \beta} \tag{4}$$

where

$$\beta \equiv \frac{\mu\, m_p\, \sigma^2}{kT} \qquad (5)$$

(Cavaliere and Fusco-Femiano 1976; Bahcall and Sarazin 1978).

Equation (4) provides an excellent fit to the observed surface brightnesses of most clusters, with a typical value of $3\beta/2 \approx 1$ or $\beta \approx 2/3$ (Jones and Forman 1984). The quality of these fits suggests that the gas may indeed be isothermal; in that case, the temperature can be determined by a global (not spatially resolved) x-ray spectrum of the cluster. Then, the total and gas masses can easily be found. These determinations give somewhat smaller total cluster masses than optical (virial) analyses, and give somewhat higher gas masses than most pre-*Einstein* analyses.

On the other hand, there are several arguments which suggest that the isothermal model cannot be consistently applied to gas distributions in clusters (Henriksen and Mushotzky 1985a; Henriksen 1985; Mushotzky 1985). The first problem is that when β is derived from x-ray temperatures (derived from global spectra) and optical galaxy velocity dispersions, larger values are generally found, with $\beta \approx 1.2$ being typical (Mushotzky 1985). A second problem with the isothermal model is that, for $\beta \approx 2/3$, the gas is more extended than the assumed total mass. In the outer parts of the cluster, the gas density actually dominates the total density, and thus it is inconsistent for the gas density and total density to have different distributions. Third, the HEAO-1 A-2 global x-ray spectra of some of the best studied clusters (for example, Coma; Henriksen and Mushotzky 1985b) cannot be fitted by emission from gas at a single temperature.

2.2.2. *Global X-ray Spectra and Monotonic Temperature Gradients*. Excellent global (not spatially resolved) x-ray spectra exist for bright clusters from the HEAO-1 A-2 detectors. These can generally not be fitted by emission at a single temperature (Henriksen 1985). These spectra can be used to determine how much gas (or, more precisely, how much $n_e{}^2V$, where V is volume) is present at each gas temperature T, but they cannot tell us where this gas is located in the cluster. On the other hand, the *Einstein* x-ray images give us $n_e(r)$ (which can be integrated to give $n_e{}^2V$), but give no information on temperatures. However, *if we assume that T decreases monotonically with radius*, we can match these two determinations of $n_e{}^2V$ and derive T(r).

Such analyses have been done for the Coma and Perseus clusters by Henriksen (1985), Henriksen and Mushotzky (1985b), and Cowie (1985). While the method described above is nonparametric (it involves direct determinations on $n_e{}^2V$ from the x-ray spectra and images), these authors parameterized the distributions by assuming a polytropic equation of state $T \propto n_e^{\gamma-1}$.

Since the observed gas densities vary at large distances like an isothermal sphere ($n_e \sim r^{-2}$), while these determinations require that the gas temperature decreases, the total density will always decrease with radius more rapidly than the gas density. Since the total density is the sum of the gas density, the galaxy density, and the dark matter density, these mass determinations indicate that the dark matter is concentrated to the cluster center. For Coma, this method gives a dark matter distribution which is more centrally concentrated than that of the galaxies, which is in turn more centrally condensed than that of the x-ray emitting gas. Values of the mass-to-light ratio for the entire cluster of $M_{tot}/L_V \approx 100$ (H_0/50 km/s/Mpc) are found, with the hot gas contributing about 30% of the total mass.

This leads to a picture for the dark matter in clusters which is considerably different than has previously been given. First, the ratio of dark mass to visible baryonic mass would only be two or three, not the ten or twenty sometimes assumed. Moreover, if the dark matter is more centrally concentrated than the visible baryonic matter, it would seem reasonable to assume that it has undergone dissipation. These properties of the cluster dark matter, taken alone, would suggest a baryonic origin, perhaps in substellar condensations or black holes.

The major uncertainty in these analyses of cluster mass profiles is the assumption that the temperature decreases monotonically outwards. While this seems quite plausible, and simple infall or galaxy ejection models for the origin of the intracluster gas usually produce such monotonic temperature gradients, there is no compelling physical argument requiring a monotonic temperature gradient. Since cooling and thermal condition timescales are long in the outer parts of clusters, the gas temperature profiles are probably determined by uncertain conditions at the time of cluster formation.

With AXAF, it will be possible to simultaneously determine the density and temperature profiles in clusters, without assuming a monotonic temperature variation. Until that is possible, these results on the dark matter distribution in clusters must be viewed as tentative.

3. COOLING FLOWS ONTO CENTRAL CLUSTER GALAXIES

3.1. Evidence for Cooling Flows and Rates

At the centers of many rich and poor clusters of galaxies, the gas density is high enough ($n_e \gtrsim 3 \times 10^{-3}$ cm^{-3}) that the intracluster gas can cool over a Hubble time. Thus, we expect gas to cool and flow into the centers of many clusters. Evidence that this is indeed occurring includes the detection of peaks in the soft x-ray surface brightness at the cluster center, central densities and temperatures implying cooling times shorter than the Hubble time, and central temperature inversions ($dT/dr > 0$). The strongest evidence comes from the detection of soft x-ray line emission from low ionization stages produced at temperatures of 10^6-10^7 K coming from the cluster center. An excellent review of cooling flows has been given by Fabian, Nulsen, and Canizares (1984). A survey of cooling flows by Stewart *et al.* (1984b) shows that the cooling rates range from 10-1000 $M_\odot$/yr. About 30 clusters are known with cooling rates on this order.

The cooling rate is inferred directly from the x-ray luminosity of the central surface brightness peak in x-ray emission from the cluster, where the cooling time t_{cool} is less than a Hubble time. The flow velocity, which is expected to be $\sim r/t_{cool}$, is very subsonic except possibly at the very center of the flow, and the thermal energy of the gas is considerably larger than the change in the gravitational potential. Under these circumstances the gas cools isobarically, and the luminosity is

$$L_{cool} \approx \frac{5}{2} \frac{\dot{M}}{\mu m_p} kT$$

$$\approx 1.7 \times 10^{44} \text{ ergs/s} \left(\frac{\dot{M}}{100\ M_\odot/\text{yr}}\right) \left(\frac{T}{8 \times 10^7 \text{K}}\right) \quad . \qquad (6)$$

In many cases, extended optical line emitting filaments (emitting Balmer and Lyman lines, and [O II], etc.) are seen near the centers of these cooling flows (Cowie et al. 1983). The line luminosities are consistent with roughly the same cooling rates through the temperature range $T \sim 10^4$ K as at x-ray temperatures, and the inferred gas pressure in the line emitting filaments are similar to those expected in the cooling flows.

3.2. Accretion by Central Galaxies

In essentially every case of a cluster with a cooling flow, there is a central dominant galaxy located at the center of the flow (Jones and Forman 1984). In most cases, the central galaxy is a radio source, and there is a correlation between $\dot{M}$ and the radio luminosity. Now, these central galaxies cannot cause cooling flows. Since the velocity dispersion of the galaxy is small compared to the cluster velocity dispersion or the sound speed in the intracluster gas, a central galaxy has only a very small influence on the density of the gas and cannot initiate cooling. However, once the gas has cooled so that its sound speed is comparable to the galaxy velocity dispersion, the cooling flow will be focused onto the central galaxy if it moves slowly enough so the gas can cool before the galaxy moves away.

Thus, the fact that cooling flows and central dominant galaxies are strongly correlated means either that they both result from a common cluster property (e.g., high central density) or that cooling flows produce central dominant galaxies.

3.3. Fate of the Cooling Gas

If the cooling rates derived from the x-ray observations are correct, and the cooling flows are long-lived, and gas is not expelled from the central galaxies, a considerable mass M_{acc} will be accreted

$$M_{acc} = 10^{12}\ M_\odot \left(\frac{\dot{M}}{100\ M_\odot/\text{yr}}\right) \left(\frac{t}{10^{10}\ \text{yr}}\right) \qquad (7)$$

where t is the age of the cooling flow. This mass is comparable to the mass of the central galaxy. What has happened to all this accreted gas?

Observations indicate that M_{acc} is not present in the form of H I or H II (Cowie *et al.* 1983; Burns, White, and Hayes 1981). It might be present in H_2, because CO observations have not been done for many cD galaxies. This much mass could not have been accreted by a central black hole, because the galaxy central velocity dispersion would be dramatically elevated and because the energy released by the accretion would vastly exceed the luminosities of these galactic nuclei. This much gas cannot be going into high mass star formation, because the galaxies would be bluer and have higher supernova rates than are observed.

3.4. Low Mass Star Formation

The cooling gas could be forming low mass stars $M_* \lesssim 1\ M_\odot$. While I cannot give a convincing argument as to why low mass star formation should be favored in cooling flows, the following argument is, at least, suggestive (Jura 1977; Fabian, Nulsen, and Canizares 1982; Sarazin and O'Connell 1983). As the gas cools, it becomes thermally instable, and slightly denser, cooler clumps will cool more rapidly. Presumably, these clumps form the observed optical emission line filaments. Now, as they cool further they will eventually become gravitationally unstable, if their mass exceeds the Jeans mass M_J. For static, nonmagnetic, isothermal spherical gas cloud, this is (Spitzer 1978)

$$M_J = 1.2 \left[\left(\frac{kT}{\mu m_p}\right)^4 \frac{1}{G^3 P}\right]^{1/2}$$

$$\approx 0.54\ M_\odot\ \mu^{-2} \left(\frac{T}{10\ K}\right)^2 \left(\frac{P}{10^{-9}\ \text{dynes cm}^{-2}}\right)^{-1/2} . \qquad (8)$$

Now, the temperatures in molecular clouds in the cooling flows are probably somewhat lower than those in clouds in the disk of our galaxy. On the other hand, the ambient pressure in the cooling flows is $\sim 10^{-9}$ dynes/cm^{-2}, which is 10^3-10^4 times larger than that in the disk of our galaxy. Thus, in cooling flows $M_J \sim 1\ M_\odot$, whereas it is $\sim 100\ M_\odot$ in our galaxy. Since it is difficult to assemble a protostellar cloud with a mass exceeding M_J (it would collapse first), M_J may form an upper limit to the mass of star formation.

Is there any evidence for ongoing low mass star formation in cooling flow galaxies? The best known example is NGC 1275 in the Perseus cluster. It looks, from its surface photometry, like a typical giant elliptical galaxy, but over most of the optical extent its spectrum is dominated by A stars (Minkowski 1968; Rubin *et al.* 1977). Similarly, the cD in A1795 and PKS 0745-191, the central dominant galaxy in a southern x-ray cluster, have A-F star spectra (McNamara, O'Connell, and Sarazin 1985; Fabian *et al.* 1985). Thus these galaxies, which have several of the highest cooling rates observed, contain young stars with masses of 1-3 $M_\odot$.

3.4. Distribution of Stars Formed From Cooling Flows

If one takes the total accreted mass in a Hubble time for clusters with large cooling rates, and divides it by the total optical luminosity of the central galaxy, mass-to-light ratios of ~10 $M_\odot/L_\odot$ are found. Since the Jeans mass in the cooling flow is ~1 $M_\odot$, which is about the mass of the luminous stars in ellipticals, it is possible that all of the observed stars in these central galaxies were formed from the cooling flows. Ignoring for the moment the evolution of the cooling rate and the galaxy stellar distribution, one would predict that stars are now forming with a distribution which is similar to the observed luminosity of the galaxy (de Vaucouleurs' or Hubble law).

Alternatively, it might be the very low mass star formation is favored in cooling flows, with masses $<0.1\ M_\odot$. These stars would be invisible optically. If the cooling rates were larger in the past, these "black dwarfs" might form the "dark matter" halos which have been observed around several central cluster galaxies (see the papers by Canizares and by Fabian in this volume). In that case, the distribution of newly formed stars ought to mimic the distribution of mass in the dark halo, with $\dot{M}(r) \sim r$.

It is very important to determine the distribution of the newly formed stars within the cooling flow, or equivalently, the variation of $\dot{M}(r)$ in the flow. As gas cools, forms clumps, and is converted into stars, the rate at which hot, diffuse gas is flowing into the galaxy center will decrease. Such a reduction in $\dot{M}(r)$ with decreasing r will appear as a flattening in the x-ray surface brightness peak associated with the cooling flow. Thus, the x-ray surface brightness profiles can be used to derive the variation of $\dot{M}(r)$ with r, if the gas is assumed to be in steady-state inflow (Fabian, Nulsen, and Canizares 1984; Stewart *et al*. 1984a; White and Sarazin 1985). These analyses show that the x-ray surface brightness profiles require that $\dot{M}(r)$ decrease with decreasing r; hot gas is being removed from the flow and presumably converted into stars even at large radii ~50 kpc from the galaxy center. Unfortunately, White and Sarazin found that the uncertainties in temperature profiles prevented a unique determination of the profiles of $\dot{M}(r)$. AXAF, with its better spectral response, should allow a direct and accurate determination of $\dot{M}(r)$.

3.5. Cooling Flow Models with Star Formation

As an alternative to the direct deconvolution of $\dot{M}(r)$, White and Sarazin (1985) have calculated cooling flow models including star formation. The star formation rate was assumed to be proportional either to the cooling rate, or to the rate of growth of linear thermal instabilities.

These models give the equilibrium distribution of the newly formed stars. These distributions generally are fairly close to the de Vaucouleurs' profile assumed for the background galaxy, suggesting that cooling flows form the optical portions of galaxies.

4. COOLING FLOWS ONTO NORMAL ELLIPTICAL GALAXIES

4.1. Observations

Recent x-ray observations indicate that many early-type galaxies which are not in the cores of rich compact clusters have extended x-ray emission (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985; Nulsen, Stewart, and Fabian 1984). These galaxies have x-ray luminosities of $L_x \sim 10^{39}$-10^{42} ergs/s, and sizes of typically $R_x \sim$ 50 kpc. There is a strong correlation between the x-ray and optical luminosities of the galaxies $L_x \propto L_B^{1.6-2.0}$, where L_B is the blue luminosity. It seems most likely that the x-ray emission is thermal with typical gas temperatures $T \sim 10^7$ K. The gas densities in the inner parts of the coronae exceed 0.01 cm^{-3}, and vary roughly as $r^{-3/2}$. The total gas mass is typically $M_g \sim 10^9$-10^{10} $M_\odot$, and the ratio of gas mass to luminous stellar mass M_* is typically $M_g/M_* \sim$ 0.02. (See the paper by Canizares in this volume.)

4.2. Source of the Gas

These galaxies are sufficiently far from the cores of clusters that it is unlikely that the gas is accreted intracluster gas. It seems most likely that this gas is simply the result of normal stellar mass loss. The present rate of stellar mass loss per unit volume $\dot{\rho}$ can be written as $\dot{\rho} = \alpha_* \rho_*$, where ρ_* is the mass density of stars, and α_* is the inverse of the stellar mass loss timescale. Stellar evolution studies suggest that $\alpha_* \approx 1$-2×10^{-12} yr^{-1}. Thus, if the lifetime of the galaxy is t, the total accumulated gas mass M_g is

$$M_g/M_* \approx 0.01\text{-}0.02 \left(\frac{t}{10^{10}\ \mathrm{yr}}\right) \frac{\langle\alpha_*\rangle}{\alpha_*} \qquad (9)$$

where $\langle\alpha_*\rangle$ is the average value of α_* over the lifetime of the galaxy. Given that the rate of stellar mass loss was considerably higher in the past, the observed mass of gas can easily be produced in this way.

4.3. Dynamics

What is the dynamical state of the gas? Assuming that the gas can be treated as spherically symmetric and homogeneous over scales comparable to the radius from the galaxy center, there would appear to be four possibilities, determined by the rates of heating and cooling in the gas. First, if the gas is heated sufficiently, it could form a wind and blow out of the galaxy (Mathews and Baker 1971). Prior to the discovery of diffuse x-ray emission from ellipticals, galactic winds were generally invoked as a mechanism to remove the gas produced by stellar mass loss, and to explain the absence of significant amounts of H I in these galaxies. This argument no longer appears tenable. The amount of hot gas in ellipticals agrees with the amount expected from stellar mass loss. Thus, the absence of cool gas in ellipticals is due to the fact that most of the gas is hot, and not to the lack of any sort of gas. In fact, x-ray emission from ellipticals is completely incompatible with the presence of a global galactic wind. In a wind, the gas would be removed on the sound crossing time of the galaxy ($\lesssim 10^8$ yr). Unless the stellar mass loss rate was $\sim 10^2$ times larger than expected, the gas density would be $\sim 10^2$ times smaller and the x-ray luminosity $\sim 10^4$ times smaller than is observed.

If neither heating or cooling were important (or if they were in a stable equilibrium), the gas might just accumulate in the galaxy potential well (Forman, Jones, and Tucker 1985). Using the density profiles of Forman et al. and assuming a temperature of 10^7 K, I have calculated the radius r_c at which the cooling time is equal to 10^{10} yr; this lies in the range $r_c \approx (\frac{1}{2} - 1) \times R_x$. Thus, over nearly all the observed gas extent, cooling is very effective. Unless the heating rate balances cooling, the gas would cool and flow into the galaxy center. Even if there were a heating mechanism which balanced cooling, this thermal equilibrium would be very unstable and the gas would form dense, cool clumps which fall into the galaxy center. Given that the cooling time is short, it is unlikely that the gas would just accumulate in the galaxy potential.

Third, the gas might form a cooling flow, in which gas was ejected by stars, cooled, and flowed into the galaxy center (White and Chevalier 1984). Given the short cooling time in the gas and the problems with wind or static models, I believe this must be the correct dynamical model for the gas.

A fourth, hybrid possibility is a "partial wind" (White and Chevalier 1984). Here, gas forms a cooling flow in the inner parts of the galaxy where the gas density is large, but forms a wind in the outer parts of the galaxy where heating can overcome both cooling and the gravitational binding of the gas. Unless the gas in elliptical galaxies is pressure-confined by "intergalactic" gas, it seems likely that a wind would form in the outermost parts of a galaxy. However, the gas density in such a wind would probably be too low to be observed in x-rays (as argued above). Since the observed x-ray halos in ellipticals extend to essentially the full optical extent of the galaxies ($R_x \sim 50$ kpc), any possible partial wind must start very far out in the galaxy.

I conclude that most of the x-ray emitting gas in elliptical galaxies forms a cooling flow.

4.4. Heating of the Gas

4.4.1. Gravitational Heating. Gas ejected from a star is initially moving with the orbital velocity of the star. The distribution of these orbital velocities is determined by the stellar velocity dispersion σ_* (one-dimensional). Thus, the ejected gas is given an energy per unit mass of $3\sigma_*^2/2$. If the gas forms a cooling flow, then subsequent infall through the galaxy gravitation potential will give it a similar amount of energy. Based on numerical calculations, I find that the total gravitational heating is about $3\sigma_*^2$. Let us define an injection temperature T_{inj} such that $kT_{inj}/\mu m_p$ is the energy per unit mass given the gas. Then, for gravitational heating T_{inj} is

$$T_{inj} \approx 1.4 \times 10^7 \text{ K} \left(\frac{\sigma_*}{250 \text{ km/s}}\right)^2 \quad . \tag{10}$$

4.4.2. Type I Supernova Heating. The other major source of heating in the gas is likely to be Type I supernovae. If the rate of mass ejection in supernovae is $\alpha_{SN}\rho_*$ and gas is ejected at a velocity V_{SN}, then the heating per unit mass by supernovae is $(\alpha_{SN}/\alpha_*)\ V_{SN}^2/2$. For the Type I supernova rate of Tammann (1974), I find

$$T_{inj} \approx 6 \times 10^7 \text{ K} \tag{11}$$

although this is very uncertain, in part because of the small number of supernovae used in computing the rate.

Comparing the heating of supernovae and gravitational heating, it seems supernova heating should dominate. However, I will now argue that gravitational heating must dominate in elliptical galaxies, and that the Type I supernova rate must be lower than previously thought.

4.5. X-ray Luminosities

Balancing the heating of the gas with its cooling, the x-ray luminosity must be $L_x = \dot{M}(kT_{inj}/\mu m_p)(\Lambda_x/\Lambda)$. Here, (Λ_x/Λ) is the fraction of the cooling radiation which occurs in the observed x-ray band, which is expected to be very nearly unity if $T \sim 10^7$ K. $\dot{M}$ is the total rate of gas injection by stellar mass loss, which is $\dot{M} = \alpha_* M_* = \alpha_* (M/L_B)_*\ L_B$, where M_* is total stellar mass, $(M/L_B)_*$ is the mass-to-light ratio of the stellar population, and L_B is the blue luminosity of the galaxy. Combining this with equations (10) and (11) gives

$$L_x = L_B \alpha_* \left(\frac{M}{L_B}\right)_* \left(\frac{\Lambda_x}{\Lambda}\right) \left[3\sigma_*^2 + \left(\frac{\alpha_{SN}}{\alpha_*}\right) \frac{V_{SN}^2}{2}\right] \quad . \tag{12}$$

If supernovae dominate the heating, then the second term in brackets is larger. Now, all of the terms in equation (12) except L_B and σ_*^2 are either unity $[(\Lambda_x/\Lambda)]$ or determined by the stellar population of the galaxy $[\alpha_*, (M/L_B)_*, \alpha_{SN}, V_{SN}]$. Thus, if elliptical galaxies of different luminosities have essentially the same stellar population, then we expect $L_x \propto L_B$ if supernova heating dominates. However, the observed relationship between L_x and L_B is steeper, $L_x \propto L_B^{1.6-2.0}$. Moreover, if we take typical values of $\alpha_* \approx 1.5 \times 10^{-12}$ yr^{-1}, $(M/L_B)_* \approx 8\ M_\odot/L_\odot$, and T_{inj} from equation (11), we find $L_x \approx 6 \times 10^{41}$ ergs/s $(L_B/10^{11}\ L_\odot)$. For most galaxies, this greatly exceeds the observed x-ray luminosity. Thus, if supernova heating dominates, neither the observed x-ray-optical correlation nor the observed x-ray luminosities can be explained.

If the heating of the gas is gravitational, then the energy per unit mass is determined by the stellar velocity dispersion σ_*. Now, the velocity dispersion is known to correlate strongly with the optical luminosity of the galaxy, with $L_B \propto \sigma_*^{3-4}$ (Tonry 1981; Faber and Jackson 1976). If gravitational heating dominates, then equation (12) gives $L_x \propto L_B^{1.5-1.67}$, where the higher exponent in the L_x-L_B

relationship corresponds to the lower exponent in the L_B-σ_* relationship (Nulsen, Stewart, and Fabian 1984). If the L_B-σ_* relationship is written as $L_B \approx 10^{11}\ L_\odot\ (\sigma_*/350\ \mathrm{km/s})^{3-4}$, then the x-ray luminosity is

$$L_x \approx 2.8 \times 10^{41} \left[\frac{L_B}{10^{11}\ L_\odot}\right]^{1.5-1.67} \mathrm{ergs\ s^{-1}} \qquad (13)$$

which fits the observed x-ray luminosities reasonably well. The corresponding inflow rate of gas due to stellar mass loss is

$$\dot{M} \approx 1.2 \left[\frac{L_B}{10^{11}\ L_\odot}\right] M_\odot/\mathrm{yr} \quad . \qquad (14)$$

I conclude that the gas in elliptical galaxies is heated primarily by gravitation and not by supernovae, and that the rate of Type I supernovae in ellipticals probably has been overestimated by a factor of at least three.

4.6. Distribution of the Hot Gas

The form of the gas distribution in the cooling flows can be derived from the energy equation in the flow. It is easy to show that these flows are subsonic except possibly very near the center, and thus kinetic energy can be ignored. The change in the enthalpy flux is balanced by the rates of heating and cooling in the gas. The rate of heating is associated with stellar mass loss, and thus is proportional to the stellar density. For an elliptical galaxy, the stellar density increases rapidly toward the galaxy center, roughly as $\rho_* \propto r^{-3}$. This means that heating due to mass loss dominates over convection of enthalpy as the primary means of delivering energy to each volume of the gas. Moreover, subsonic flows are nearly hydrostatic, and the gas must cool in order to flow inward. The result is that the convective energy transport is proportional to the cooling. Under these conditions, the flow nearly satisfies a local energy balance, with heating due to mass loss balancing cooling:

$$\alpha_* \rho_* \frac{kT_{inj}}{\mu m_p} \approx n_e^{\,2}\ \Lambda(T) \qquad (15)$$

where the right-hand side is the cooling rate.

Now, if T_{inj} and T do not vary rapidly, we will have $n_e \propto \rho_*^{1/2}$. Since $\rho_* \sim r^{-3}$ outside the core of an elliptical galaxy, this gives $n_e \sim r^{-3/2}$, basically as is observed. This statement can be made more directly in terms of the optical and x-ray surface brightnesses, I_B and I_x respectively. As long as $T \gg 10^6$ K, the cooling radiation appears in the x-ray band and $n_e^{\,2}\ \Lambda$ is the x-ray emissivity. Let us integrate equation (15) along a line-of-sight through the galaxy. The right-hand side gives I_x, and the left-hand side is proportional to I_B:

$$\alpha_* \left(\frac{M}{L_B}\right)_* I_B \left(\frac{kT_{inj}}{\mu m_p}\right) \approx I_x \quad . \tag{16}$$

Thus, simple cooling flow models predict that the x-ray and optical surface brightnesses vary in proportion to one another, essentially as is observed (Trinchieri 1985).

4.7. Fate of the Cooling Gas

About 1 $M_\odot$ per year of gas will flow into the center of a large elliptical galaxy. We expect this gas will be thermally unstable, and will form optical line emitting filaments, as have been seen in many ellipticals (Caldwell 1982). I believe that this gas must ultimately be consumed through star formation; this may explain the blue population seen in the ultraviolet light of some ellipticals. Finally, some of this gas may flow into the galactic nucleus and power activity there.

This work was supported in part by NSF Grant AST81-20260, and in part by NASA Astrophysical Theory Grant NAGW-764.

REFERENCES

Bahcall, J. N., and Sarazin, C. L.: 1977, Astrophys. J. Lett. **199**, L89.

Bahcall, J. N., and Sarazin, C. L.: 1978, Astrophys. J. **219**, 781.

Burns, J. O., White, R. A., and Hayes, M. P.: 1981, Astron. J. **86**, 1120.

Caldwell, N.: 1982, Yale Ph.D. Thesis.

Cavaliere, A., and Fusco-Femiano, R.: 1976, Astron. Astrophys. **49**, 137.

Cowie, L. L.: 1985, preprint.

Cowie, L., Hu, E., Jenkins, E., and York, D.: 1983, Astrophys. J. **272**, 29.

Faber, S. M., and Jackson, R. E.: 1976, Astrophys. J. **204**, 668.

Fabian, A. C., Nulsen, P. E., and Canizares, C. R.: 1982, Mon. Not. Roy. Astron. Soc. **201**, 933.

Fabian, A. C., Nulsen, P. E., and Canizares, C. R.: 1984, Nature **310**, 733.

Fabian, A. C., Arnaud, K. A., Nulsen, P. E., Watson, M. G., Stewart, G. C., McHardy, I., Smith, A., Cook, B., Elvis, M., and Mushotzky, R. F.: 1985, preprint.

Fabricant, D., and Gorenstein, P.: 1983, Astrophys. J. **267**, 535.

Fabricant, D., Lecar, M., and Gorenstein, P.: 1980, Astrophys. J. **241**, 552.

Fabricant, D., Rybicki, G., and Gorenstein, P.: 1984, Astrophys. J. **286**, 186.

Forman, W., Jones, C., and Tucker, W.: 1985, Astrophys. J. **293**, 102.

Geller, M. J., and Beers, T. C.: 1982, Publ. Astron. Soc. Pac. **94**, 421.

Henriksen, M. J.: 1985, Univ. of Maryland Ph.D. Thesis.
Henriksen, M. J., and Mushotzky, R. F.: 1985a, Astrophys. J. **292**, 441.
Henriksen, M. J., and Mushotzky, R. F.: 1985b, preprint.
Jones, C., and Forman, W.: 1984, Astrophys. J. **276**, 38.
Jura, M.: 1977, Astrophys. J. **212**, 634.
King, I. R.: 1962, Astron. J. **67**, 471.
Mathews, W. G.: 1978, Astrophys. J. **219**, 413.
Mathews, W. G., and Baker, J. C.: 1971, Astrophys. J. **170**, 241.
McNamara, B., O'Connell, R. W., and Sarazin, C. L.: 1985, preprint.
Minkowski, R.: 1968, Astron. J. **73**, 842.
Mushotzky, R. F.: 1985, in Proc. Conf. on Non-thermal and Very High Temperature Phenomena in X-ray Astronomy, edited by G. Perola and M. Salvati, in press.
Nulsen, P. E., Stewart, G. C., and Fabian, A. C.: 1984, Mon. Not. Roy. Astron. Soc. **208**, 185.
Rubin, V., Ford, W., Peterson, C., and Oort, J.: 1977, Astrophys. J. **211**, 693.
Sarazin, C. L.: 1985, Rev. Mod. Phys., in press.
Sarazin, C. L., and Bahcall, J. N.: 1977, Astrophys. J. Suppl. **34**, 451.
Sarazin, C. L., and O'Connell, R. W.: 1983, Astrophys. J. **268**, 552.
Spitzer, L. Jr.: 1978, Physical Processes in the Interstellar Medium (New York: Wiley), p. 283.
Stewart, G. C., Canizares, C. R., Fabian, A. C., and Nulsen, P. E.: 1984a, Astrophys. J. **278**, 536.
Stewart, G. C., Fabian, A. C., Jones, C., and Forman, W.: 1984b, Astrophys. J. **285**, 1.
Strimpel, O., and Binney, J.: 1979, Mon. Not. R. Astron. Soc. **188**, 883.
Tammann, G. A.: 1974, in Supernovae and Supernova Remnants, edited by C. B. Cosmovici (Dordrecht: Reidel), p, 155.
Tonry, J. L.: 1981, Astrophys. J. Lett. **251**, 1.
Tonry, J. L.: 1983, Astrophys. J. **266**, 58.
Trinchieri, G.: 1985, preprint.
Trinchieri, G., and Fabbiano, G.: 1985, Astrophys. J. **296**, in press.
Vallée, J. P.: 1981, Astrophys. Lett. **22**, 193.
White, R. E., and Chevalier, R. A.: 1984, Astrophys. J. **280**, 561.
White, R. E., and Sarazin, C. L.: 1985, preprint.

DISCUSSION

KORMENDY: Regarding the discussion of cooling flows: In a high-resolution photometric survey that I have been making with the Canada-France-Hawaii Telescope, I find that elliptical galaxies very often have dust near their centers. There is a strong correlation between the presence of dust and the detection of x-ray emission.

SARAZIN: I'm very interested to hear of such a correlation, because there's another new result that ties into this. Mike Jura has recently examined the IRAS data base, and found that x-ray emitting galaxies have infrared emission from their centers. He argues that they must contain 10^9 $M_\odot$ of molecular hydrogen to produce the amount of infrared emission he sees.

YAHIL (to KNAPP): Wouldn't we see CO from these 10^9 $M_\odot$ of H_2?

KNAPP: If CO is present, and if the ratio of CO emissivity to H_2 mass is the same as in the Galaxy, then observations of the necessary sensitivity are possible. To date, less than half-a-dozen ellipticals have been observed carefully, and none of them shows CO emission. But this number is too small to restrict the argument Craig just presented.

If I may ask a related question: Can dust possibly survive in a cooling flow?

SARAZIN: If Jura is right about the amount of infrared emission from these ellipticals, then I think the grains must come out in planetary nebulae and never get mixed into the hot gas. Otherwise they would certainly be destroyed.

KNAPP: But John Kormendy just said that dust is observed and is well correlated with the presence of x-rays.

SILK: I do not find the argument for exclusively low-mass star formation in cooling flows to be very compelling, for the following reason. The infall rate at a given radius is effectively taken to be the mass of a shell of gas divided by the local cooling time scale. However, if the cooling gas forms any massive stars, the resulting supernovae will heat the gas. This could reduce the rate of infall to the extent that adoption of even a solar neighborhood initial mass function might be consistent with the observed colors of galaxies at the centers of cooling flows.

SARAZIN: It seems to me that the required supernova rate would be much too high. The cooling luminosity of the cooling flow in the Perseus Cluster is more than 3×10^{44} erg s^{-1}. For supernovae to provide the majority of this energy and seriously lower the cooling rate, the supernova rate would have to be ten per year. NGC 1275 has been sufficiently observed that I very much doubt that it could have one supernova per month.

OSTRIKER: My question is a variant on the last one. If I consider isolated galaxies, where the x-ray luminosity is low, I find an approximate upper bound on the supernova rate of less than one every 300 years if a cooling flow is to be produced. I'm assuming an energy of 10^{51} ergs per supernova. This supernova rate is less than the rate people actually observe.

SARAZIN: That's right, it's about 1/3 of the rate found by Tammann. But remember that these rates for E and SO galaxies are based on a total of only nine observed supernovae.

GUNN: Craig, if the cooling time for the gas in galaxies is short compared to the Hubble time, then you have to look for some equilibrium situation. Why then would you expect the amount of gas present to be the total amount output by the stars over a Hubble time?

SARAZIN: The cooling time becomes equal to the Hubble time just at the outer edge of the flow. The mass is mainly coming from the outer edge, because the gas density is dropping off as $1/r^{3/2}$. This argument is uncertain by a factor of two or three. If you do the integral properly, then you find that you can have a steady-state distribution with a reasonable current gas inflow rate.

GUNN: But then you run into the problem that most of the gas is not where most of the stars are. The stellar density drops as $1/r^3$. Are the distributions of gas and stars consistent?

SARAZIN: Yes. If gas is coming out of stars, then you measure the x-ray luminosity due to the cooling of the gas, while the amount of heat input is just proportional to the mass being shed by the stars. In a steady state, these two ought to agree. So you expect that the x-ray surface brightness is proportional to the optical surface brightness. But because the x-ray surface brightness depends on the square of the density, the gas density will go as the square root of the stellar density, as observed.

TUCKER: Two points. (1) In addition to the supernova heating mentioned by Joe Silk, there is another source of heating, namely the relativistic electrons associated with the radio sources known to be present in most galaxies with cooling flows. If this energy source is included, the accretion rates can be reduced by two orders of magnitude or more. (2) I would like to point out that a steady state model cannot explain the large amount of gas observed to be present in x-ray halos. The observations require that the halos store up the mass lost by stars over the lifetime of the galaxy, not just over a cooling time. You must use a non-steady model, in which case you can get $L_X \propto L_B^2$ for supernova heating.

SARAZIN: All we know about the gas in cooling flows is that it is cold. We have never seen it actually flow into the center. It is possible to have enough heating to make up for the extra cooling near the center, so that the gas is in thermal equilibrium. But this situation is violently thermally unstable. The gas would clump and fall into the center on a time scale which is at least as short as the cooling time. So you end up with a cooling flow anyway.

WHITE: When you analyze the cooling flows for structure, you just assign a unique temperature and density to each point. At the same time you say that there is a thermal instability occurring which is forming stars. I wonder whether the clumpiness in the gas can seriously affect the solution.

SARAZIN: That's the point I was making when I talked about consistently determining the cooling rates. Both Ray White and I, and Andy Fabian and colleagues, do the calculation by putting in gas at a range of temperatures at each radius, in order to include the effect of cooling.

SANDERS: If a substantial fraction of stars in cD galaxies form from gas in cooling flows, these stars should lie on essentially radial orbits. One might expect the stellar velocity distribution to be extremely anisotropic. Might this not be apparent in the observed dependence of velocity dispersion on projected radius?

SARAZIN: Yes, if the stars formed from comoving lumps in a radial cooling flow, the orbits would indeed be radial. However, it is possible that star-forming clouds might have a significant velocity dispersion. For example, the cooling rate is very high between 10^6 K and 10^4 K. Clouds of gas should cool isochorically through this range, and then be repressurized by shocks. These shocks, which probably produce the observed optical emission-line filaments, could give the star-forming lumps a significant amount of transverse velocity, and result in less radial stellar orbits.