X-RAYS FROM GALAXIES AND CLUSTERS OF GALAXIES: OBSERVATIONS AND PHENOMENOLOGY

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ABSTRACT. X-Ray observations of galaxies and clusters can, in principle, trace the binding mass in these systems. I review some of the relevant work. The mass of hot gas in rich clusters is comparable to or exceeds the mass in visible stars. This proportion of gas to stellar material could be universal, although there is no direct evidence that it must be. Studies of the distribution of the gas indicate the presence of dark matter in the envelopes of some dominant cluster galaxies, most notably M87. The M/L_B values increase with radius to values of $\sim$ 400-600 $M_\odot/L_\odot$. Uncertainties in the temperature distribution of the gas have hampered these analyses and have made it difficult to draw definitive conclusions about the binding mass in clusters. Recent work on Coma suggests that M/L is falling with radius and the total M/L for the cluster may be as low as $\sim$ 120. Studies of early type galaxies show that many contain hot gas with temperatures $\sim 10^7$ K. There is evidence for the existence of cooling flows, and gravity rather than supernovae may be the dominant source of energy that heats the gas. The deduced binding masses for several bright galaxies are uncertain because of the unknown temperature profiles. Values of $M/L_B \simeq 20 - 30$ within $\sim$ 30 - 40 kpc are indicated if one assumes isothermality, but values as low as 5 and as high as 100 are allowed. With better models one may be able to reduce these uncertainties.

I. INTRODUCTION

X-ray observations have a very direct and clear relevance to the study of dark matter. X-rays from clusters and many galaxies are emitted by hot gas, and the X-ray surface brightness is directly related to the density of the gas (for some recent reviews see Forman and Jones 1982, Fabian, Nulsen and Canizares 1984, Sarazin 1985). The gas is a collisional fluid in hydrostatic equilibrium (or nearly so), so it traces the gravitational potential. Thus X-ray observations give us, in principle, an ideal method for tracing the binding matter in galaxies and clusters.

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II. CLUSTERS OF GALAXIES

a. Morphology

Qualitatively, the X-ray images of rich clusters show a variety of morphologies reflecting the variety of underlying potentials. The extensive work of Jones and Forman (1984; also Forman and Jones 1982) shows that some potentials are rather irregular whereas others are very regular, symmetric and well developed. An important class of systems has nearly circular X-ray surface brightness contours that are sharply peaked and centered on a dominant (often a cD) galaxy. This is evidence for a concentrated, spherically symmetric potential well.

b. Quantity of Hot Gas

Before looking at these potentials more quantitatively to deduce what we can about dark matter, I want to consider the matter that is not dark, namely the X-ray emitting gas, and explore its contribution to the luminous mass of the universe. Jones and Forman (1984) have derived the mass in hot gas within a radius of 3 Mpc for a large number of clusters (I use $H_o = 50$ km s^{-1} Mpc^{-1} throughout). They obtain values of 0.3-5 x 10^{14} $M_\odot$. (see also Abramopoulos and Ku 1983, who make somewhat different assumptions). An important caveat is that, although some clusters are observed to such large radii, most clusters are not. More typically the measured surface brightness profiles extend only to $\sim$ 1 Mpc or less (recall that the X-ray emissivity of a gas is proportional to the square of the density, which makes the densest regions in the centers much brighter than the outer parts), and so the estimates of total masses to larger radii require extrapolations. Recently Henriksen and Mushotzky (1985a) have noted the model dependence of the mass estimates and the internal inconsistencies of the isothermal model usually assumed (see also earlier work by Cavaliere and Fusco-Femiano 1976, 1978 and Cavaliere 1979). An additional uncertainty comes from the possible clumping of gas in the more irregular clusters.

Bearing in mind these uncertainties, which could easily amount to factors of 2-4, one can take as a rule of thumb that within rich clusters the mass in X-ray emitting gas is roughly comparable to or even exceeds the mass in stars. For fifteen clusters I obtained values of $M_{gas}/L_V \sim 3 - 40\ M_\odot/L_\odot$. Here I used values of M_{gas} within 3 Mpc from Jones and Forman (1984) and from Abramopoulos and Ku (1983), as corrected to 3 Mpc by Rothenflug and Arnaud 1985, and values of total L_V from Oemler (1974) and Dressler (1978) ignoring differences in their extrapolation techniques. Rothenflug et al. (1984) have looked at two dozen clusters, and they conclude that if one takes only L_V within 3 Mpc then M_{gas}/L_V increases with the luminosity of the cluster as $\sim L_V^{0.6}$. Because of the uncertainties in both M_{gas} and L_V and in their distribution within clusters, which could depend systematically on cluster luminosity and type, one must treat this intriguing suggestion with caution, although it bears further attention (it is related to the question of whether the total mass to luminosity ratio increases with the scale of the system [Blumenthal et al. 1984]).

Mushotzky (1984) and Rothenflug and Arnaud (1985) have shown that for 22 clusters the X-ray emitting gas has an iron abundance that is approximately half solar. This is important for questions of enrichment and evolution, which I will not address. Rothenflug and Arnaud (1985) and Rothenflug et al. (1984) argue that the approximate proportionality between gas mass and virial mass, but not luminosity, together with the apparently constant iron abundance is consistent with the suggestion that the virial mass is composed of stars or star remnants which produced the iron in the past. Again, the observations are subject to systematic uncertainties, but the relations deserve further study.

One can now ask whether the rough correspondence between gas and stellar mass is a property only of rich clusters or is it more general? Could there be comparable quantities of gas in poor groups or even around field galaxies (there is much less gas inside field galaxies as discussed below)? If there were, it could more than double the inventory of baryonic matter in the universe over that estimated from stars alone (e.g. see Blumenthal et al. 1984; Faber this meeting).

The answer is that although a universal relation between stellar and gas masses is certainly not demonstrated, neither can it be ruled out. In fact, X-ray emitting gas has been detected in poor clusters, but only those with reasonable high central galaxy densities and (not coincidentally) a central dominant galaxy (see Kriss, Cioffi and Canizares 1983, Bahcall 1982). For example the poor cluster AWM4 has richness -1 and contains $\sim 5 \times 10^{12}$ $M_\odot$ of gas within 0.5 Mpc, which is comparable to its stellar mass.

Presumably, less dense poor clusters and groups could have comparable amounts of gas but have escaped detection because they have very low X-ray surface brightness. We have recently completed a study of the Pegasus I cluster, which is a loose, spiral rich system (Canizares et al. 1985). Although the X-ray image is dominated by the two central elliptical galaxies, there is evidence for diffuse intracluster gas with a mass of $\sim 3.5 \times 10^{11}$ $M_\odot$ within a radius of $\sim$ 250 kpc. This is only $\sim$ 20% of the estimated stellar mass in the cluster. But the central regions of the cluster are just barely detected above the instrumental and diffuse background. The deduced mean gas density is $\sim 2 \times 10^{-4}$ cm^{-3}, which is a factor of $\sim$ 3-5 lower than that of the least dense detected rich cluster. Therefore it is very likely that the gas is still more extensive but too diffuse to be seen. If the gas fills the $\sim$ 1-2 Mpc region occupied by the galaxies its total mass could easily be comparable to the stellar mass.

In summary, the evidence suggests that at least some poor clusters contain roughly the same proportion of hot gas relative to stars as do rich clusters (see also Rothenflug and Arnaud 1985). One can say still less about more isolated galaxies, although there is some recent evidence for possible circum-galactic material in a few cases (see below). That stars constitute one-half or less of the luminous matter in the universe remains an intriguing possibility.

c. Total Binding Mass

I will now turn to the more central question of the determination of binding masses from X-ray data. The operative equation is that of hydrostatic equilibrium,

$$\frac{dP}{dr} = - \mu mG\ M(<r)n(r)/r^2 \tag{1}$$

which can be combined with the perfect gas law to give

$$M(<r) = (-k/\mu mG)[d\ln(n)/d\ln(r) + d\ln(T)/d\ln(r)]T(r)r. \tag{2}$$

Here P is gas pressure, r is radius, μm is the mean mass per particle, n is the gas density, M(<r) is the binding mass within r, T is the temperature. The value of n(r) can be deduced with reasonably few assumptions from X-ray measurements with imaging detectors, like the IPC on the Einstein Observatory (e.g. see Fabricant, Lecar and Gorenstein 1980). There is generally much less information about the radial dependence of the temperature, which clearly complicates the application of Equation 2. The standard procedure has been to use plausible models for T vs. r; typical assumptions are that the gas is isothermal, adiabatic or polytropic (see Sarazin's contribution to this meeting). These models can be constrained by measurements of mean temperatures and, in a few cases, by measurements of temperatures at several radii or of temperature sensitive emission lines.

By far the most successful application of Equation 2 has been to the M87 in the Virgo cluster (Fabricant, Lecar and Gorenstein 1980, Fabricant and Gorenstein 1983, Stewart et al. 1984). The X-ray image and an extensive set of spectral measurements constrain both the total binding mass and the distribution of mass with radius. The mass within $\sim$ 200 kpc is $\sim 2 \times 10^{13}$ $M_\odot$. The implied average value of M/L_B is $\sim$ 200, and the very sharp concentration of light requires that M/L increase with radius. Furthermore, the binding mass must have a core radius of $\sim$ 10-30 kpc (if it has one at all), so it is clearly associated with M87 rather than with the cluster as a whole (a model of Binney and Cowie [1981] that attributed most of the mass to the cluster does not fit the data [Fabricant and Gorenstein 1983, Stewart et al. 1984]).

There is, of course, reason to believe that the approximately central location of M87 in Virgo and its low relative velocity helped it to acquire this large mass. The more isolated or less centrally located galaxies discussed below do not show extensive X-ray halos.

Data on other dominant cluster galaxies suggest that they too have dark, massive halos, although in no other case is the temperature data as complete as it is for M87. Matilsky, Jones and Forman (1985) derive a mass of $\sim 2 \times 10^{13}$ $M_\odot$ within 200 kpc for NGC4696 in the Centaurus cluster. The dominant galaxies in poor clusters, which I mentioned earlier, are similar (Kriss, Cioffi and Canizares 1983). Using the assumption of isothermality of the X-ray gas, one derives mean values of M/L_B of 70-100. In these cases the central galaxy contains typically $\sim$ 30% of the light in the cluster and the local M/L_B increases to

400-600 at a few hundred kpc (see Fig. 1; I assumed B-V = 0.7 to convert L_V to L_B). The uncertainties in the temperature distributions cause uncertainties in the deduced mass distributions (see below), but the results are probably good to within a factor of 2-3, as are the trends in M/L vs. radius, (which cover an order of magnitude).

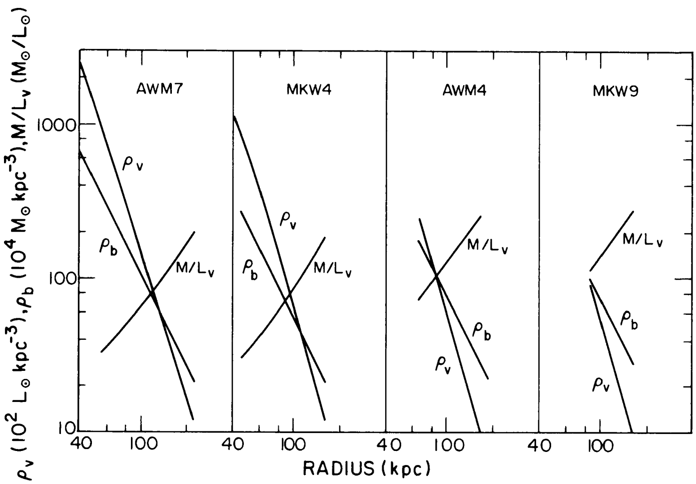

Figure 1. Density of light and binding mass deduced from the X-ray observations of four poor clusters with dominant galaxies, and the resulting M/L_V (from Kriss, Cioffi and Canizares 1983).

Several rich clusters have been studied in more detail in attempts to probe triaxial potentials (e.g. see Channan and Abramopoulos 1984, Fabricant, Rybicki and Gorenstein 1984, Fabricant et al. this meeting). Again the lack of temperature measurements is always a difficulty. For example, Figure 2 shows mass determinations for A2256 assuming either adiabatic or isothermal gas -- the values differ by factors of 2-3 (Fabricant, Rybicki and Gorenstein 1984). Nevertheless, the ellipticity of the potentials is demonstrated in these analyses.

Very recently, Henriksen and Mushotzky (1985b) and Cowie (1985) have tried to examine more carefully the model assumptions that go into analyses of this sort in the hopes of improving the accuracy of the mass determinations (there will be no improvement in the quality of the data for several years). Cowie has made a self-consistent fit to the X-ray data (assuming a polytropic gas model) and the optical velocity dispersions in the Coma cluster. Out to $\sim$ 1 Mpc, where the X-ray surface brightness profile is still measureable, he obtains a total virial mass of $\sim 10^{14}$ $M_\odot$ and a total M/L_B of $\sim$ 200. Two interesting results are first, that within this radius the gas mass is an increasing fraction of the virial mass and second, that M/L falls monotonically with radius, in marked contrast to the cases described above involving dominant galaxies. These results become even more extreme if one extrapolates to larger radii. At 4 Mpc the virial mass has increased by less than a factor of 2, and 30% of it is in the form of hot gas.

The mean M/L_B for the non-luminous component is only $\sim$ 120. The real question is how good is the extrapolation? The fits to the data require polytropic models with indices that differ from 1 (isothermal) and 5/3 (adiabatic), but these have no clear physical interpretation. So although these results are very provoking, they may not yet be the last words on the subject.

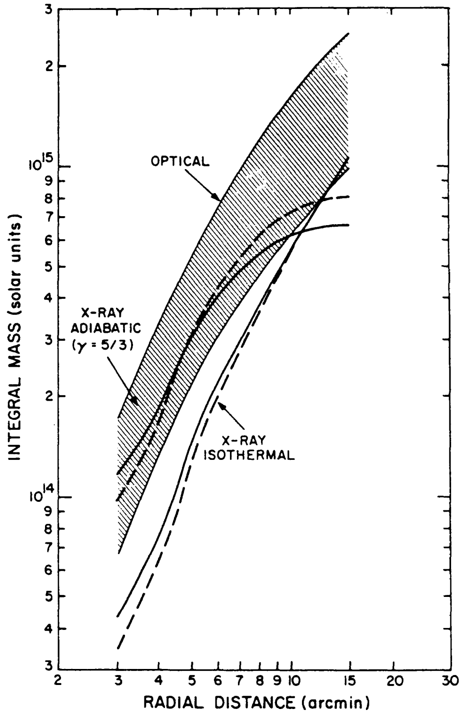

Figure 2. Integrated binding mass of cluster A2256 deduced from the optical galaxy counts and from the X-ray surface brightness distribution. The X-ray estimates are for oblate (dashed line) or prolate (solid line) geometries and for isothermal or adiabatic gas models, as indicated. For H_0 = 50 kms^{-1} Mpc^{-1}, the scale is 100 kpc arc min^{-1}. (From Fabricant, Rybicki and Gorenstein 1984).

d. Cooling Flows

I will conclude my discussion of observations of clusters with a few words about cooling flows, which involve pressure driven accretion flows of X-ray emitting gas that cools in the dense central regions of many clusters. This topic will be dealt with in greater detail by Fabian and Sarazin (this meeting) and I will return to it in the context of elliptical galaxies (see also reviews by Fabian, Nulsen and Canizares 1984, Sarazin 1985).

Here I just want to emphasize that there is ample evidence for the existence of cooling flows in clusters of galaxies. This evidence includes X-ray images with high central surface brightnesses that directly imply short cooling times and, less directly, low central temperatures. It includes X-ray spectra, both broad band and in a few cases X-ray emission line measurements, that indicate the presence of cool gas over a range of temperatures. And it includes optical studies of Hα emission from filaments that are condensing out of the flow (see recent work by Hu, Cowie and Wang, 1985). To whatever extent the details of the cooling flows are open to question, I think their existence in a great many clusters is not.

III. Early Type Galaxies

a. Global Properties

An increasing body of evidence accumulated over the past several years has now established that many early type galaxies contain hot, X-ray emitting gas (Forman et al. 1979, Bierman, Kronberg and Madore 1982, Bierman and Kronberg 1983, Nulsen, Stewart and Fabian 1984, Dressel and Wilson 1985, Forman, Jones and Tucker 1985, Trinchieri and Fabbiano 1985, Stanger and Schwarz 1985). In contrast, spiral galaxy X-ray emission at ∿ 1 keV is all attributable to discrete sources (Fabbiano and Trinchieri 1985).

Figure 3 shows the X-ray and optical luminosities of ∿ 60 early type (E and SO) galaxies. Notice that none of the upper limits is restrictive; the data suggest that all elliptical galaxies brighter than $L_B = 10^{10}$ $L_{\odot}$ ($M_B = -19.5$) have X-ray luminosities above 10^{39} erg s^{-1}. Trinchieri and Fabbiano (1985) have argued that the X-ray emission of the lower luminosity galaxies, and possibly of all those along the lower envelope of the distribution, may be dominated by discrete sources, but Forman, Jones and Tucker (1985) state that the discrete source contribution will be important only for the least luminous systems.

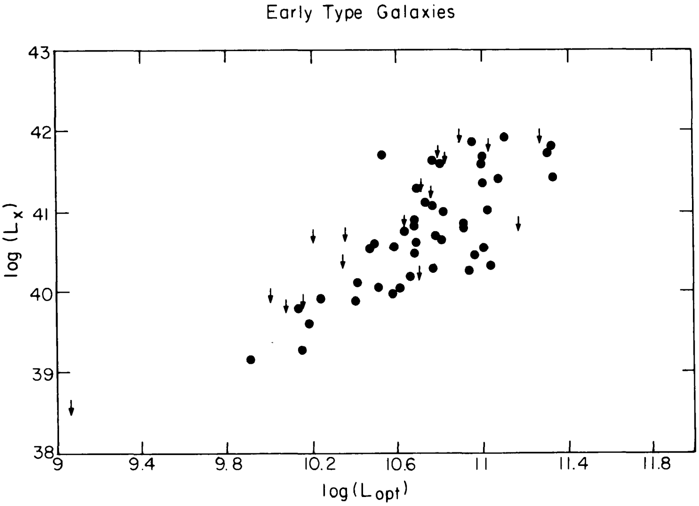

Figure 3. X-ray vs. optical luminosity for a sample of E and SO galaxies, (From Canizares, Fabbiano and Trinchieri 1986).

For the X-ray luminous galaxies, there is ample evidence that the emission is from hot gas (Forman, Jones and Tucker 1985, Trinchieri and Fabbiano 1985). This is based on spectra of about a dozen galaxies, which appear thermal with temperatures of $\sim 10^7$ K, on a few cases of distorted surface brightness contours indicating that the galactic gas is being pushed or stripped by an external medium, and on a series of other arguments including the consistency of the hot gas picture and the inability of a simple discrete source model to give the observed non-linear L_x vs. L_{opt} distribution.

b. Evidence for Cooling Flows

As pointed out by Nulsen, Stewart and Fabian (1984), the mere detection of the ellipticals in X-rays rules out a hot galactic wind that blows throughout the galaxy, as suggested by Mathews and Baker 1971 to explain what used to be the absence of gas in ellipticals (see also McDonald and Bailey 1981 and White and Chevalier 1984). This is because a sonic wind would flow away too quickly to maintain the required density of gas within the galaxy, and replenishment by stellar mass loss would be too small by one to two orders of magnitude. Nulsen et al. argued in favor of cooling flows in these galaxies (in agreement with an earlier speculation of mine; Canizares 1981), and there is good evidence that these do exist.

All the early type galaxies with sufficient data show the very high central X-ray surface brightness that implies short cooling times, as required for a cooling flow. For example, Figure 4 shows the deduced gas densitites and cooling times for NGC4636 and NGC4649 (Trinchieri, Fabbiano and Canizares 1986). The cooling times are less than a Hubble time throughout the galaxy, which indicates that a steady state cooling flow should have been established (see Fabian, Nulsen and Canizares 1984). A second piece of evidence is the existence of Hα filaments in many elliptical galaxies (c.f. Caldwell 1984, Demoulin-Ulrich, Butcher and Boksenburg 1984). These could be the galactic counterparts of the filaments seen in cluster cooling flows, as mentioned earlier. One direct piece of evidence that exists for some clusters but not for early type galaxies is X-ray spectral evidence of cooler gas. Such data are simply not available.

One thing to note is that a steady-state cooling flow powered by supernovae at the estimated rate of 0.22 per 100 years per 10^{10} L_B (Tammann 1982) overproduces the X-ray luminosity, and it does not give the correct dependence of L_x on L_{opt} (see Figure 2, White and Chevalier 1984 and Sarazin, this meeting). On the other hand, if the supernova energy input were lower, then a gravity-dominated cooling flow could roughly reproduce the observations (see Canizares, Fabbiano and Trinchieri 1986). In that case one would expect $L_x \sim \dot{M}(<\Delta\phi>_m + \varepsilon)$, where $\dot{M}$ is the mass loss rate of stars in the galaxy, $<\Delta\phi>_m$ is the mean gravitational potential properly weighted according to fraction of mass injected and ε is the specific energy due to thermalization of the gas by the stars. If one takes $\dot{M} \sim 1.5$ $M_\odot$ yr $^{-1}$ $(10^{10}$ $L_\odot)^{-1}$ (Faber and Gallagher 1976) and computes the potential in terms of the galaxy velocity dispersion σ, one obtains a relation between L_x and L_{opt} σ^2.

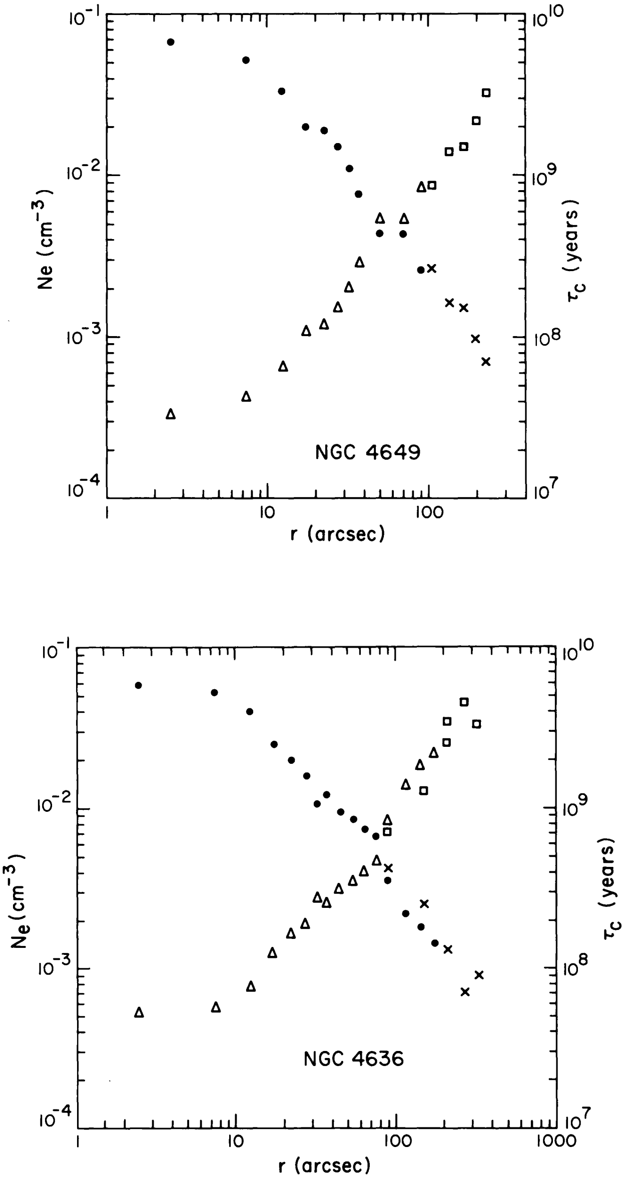

Figure 4. The electron densities and cooling times estimated from the X-ray surface brightness profiles of two early type galaxies. (From Trinchieri, Fabbiano and Canizares 1986).

This is shown in Figure 5 for two assumptions about the mass distribution in the galaxy (see Canizares et al. 1986 for details). At high values of $L_{opt}\sigma^2$ most of the luminosity will be emitted as X-rays, whereas at lower values, where the curve is shown dashed, it could emerge in the UV. There is a striking correspondence between the data and the simple model, which has assumptions but no free parameters. A more detailed cooling flow model is discussed by Fabian (this meeting).

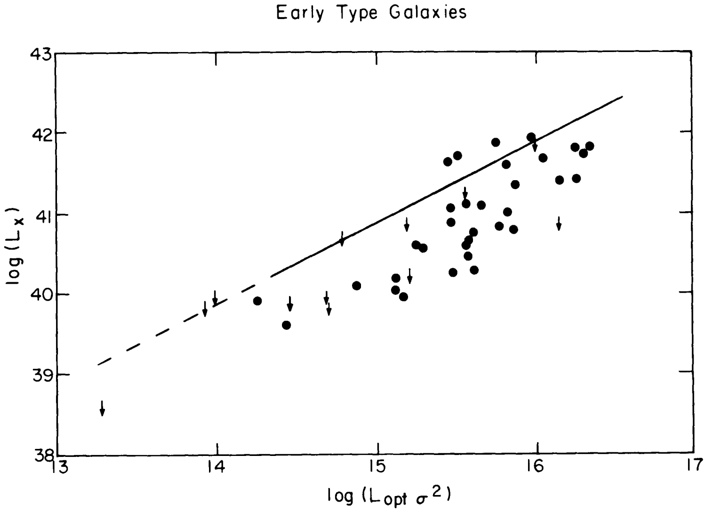

Figure 5. X-ray luminosity (in erg s^{-1}) vs. the product of optical luminosity and the square of the line-of-sight velocity dispersion (in units 10^4 $L_\odot(kms^{-1})^2$) for a sample of galaxies. The curve is the expectation for the simple gravity dominated cooling flow model discussed in the text for a typical galaxy potential. (From Canizares, Fabbiano and Trinchieri 1986). The dashed portion of the curve corresponds to cooling flows with temperatures below the X-ray band.

c. Dark Matter in Early Type Galaxies

As in the clusters, the X-ray emitting gas in early type galaxies can be used to probe their gravitational potentials and could reveal the presence of dark matter in the form of galactic halos (Forman, Jones and Tucker 1985). Let me first note however, that the observations that galactic winds have been suppressed is not in itself a sufficient argument in favor of massive halos. It is true that the observed mean gas temperatures of $\sim 10^7$ K exceed the critical temperature for wind formation (Bregman 1985, Forman, Jones and Tucker 1985, also McDonald and Bailey 1981), which is $\sim 10^6$ K for a reasonable galaxy without halo. But the addition of a plausible halo ten times more massive (but with a density that falls as the square of the radius) only raises the critical temperature by a factor of three, which in itself is not sufficient to suppress the wind (see Canizares, Fabbiano and Trinchieri 1986). The observed fact that the wind is suppressed is therefore not due to energetics but is instead probably a dynamical effect: the very short cooling time in the core of the galaxy is sufficiently small relative to the flow time that a wind is not established (see Mathews and Baker 1971). At large radii, external pressure may play a role.

The evidence for massive halos must come from Equation 1, which in units relevant for galaxies can be written as

$$M(<r) = 10^{12}(r/30\ \mathrm{kpc})(T/10^{7}\ \mathrm{K})[-d\ln(n)/d\ln(r) - d\ln(T)/d\ln(r)]M_{\odot}. \quad (3)$$

As was true for clusters, the first logarithmic derivative is the quantity that is easiest to determine from the imaging observations. For most galaxies studied in sufficient detail, the X-ray surface brightness roughly follows the optical surface brightness out to the faintest optical isophotes (Trinchieri and Fabbiano and Canizares 1986; Forman, Jones and Tucker 1985). This implies a gas density that falls roughly as $r^{-1.5}$ over much of the galaxy. However, the most interesting application of Equation 3 is at the largest radii where there are clear departures from this relation for some galaxies. For example, in the case of NGC4472 which lies in a subgroup of the Virgo Cluster, the X-ray isophotes (see Figure 6) suggest strongly that the outer part of the galactic gas is being pushed by an ambient medium (compare to the still more extreme case of M86 in Virgo, where the ambient medium is apparently stripping off much of the galactic gas [Forman et al. 1979]). This gives different density profiles in different directions, and it also suggests that dynamical effects might disturb the assumption of hydrostatic equilibrium at the largest radii. Another example is NGC4636 in the outskirts of Virgo. The X-ray image of this galaxy shows a faint ring of excess emission at the largest radii (Stanger and Schwarz 1985, Trinchieri and Fabbiano and Canizares 1986). Unfortunately, instrumental effects cannot be completely ruled out as the cause of this feature. If it is real it suggests some interaction of galaxy gas with circum-galactic material (and may indicate that this galaxy has a partial wind in addition to its cooling flow). In any event the conservative approach is to evaluate Equation 3 at radii inside these disturbances. NGC4649 exhibits yet another behavior: its X-ray surface brightness roughly follows the optical out to a radius of ∿ 2' and then falls considerably more steeply.

Also as for clusters, the biggest difficulty in determining the binding mass from Equation 3 is the uncertainty in the temperature and its profile at the largest radii. Mean temperatures have been measured for about ten galaxies (Forman, Jones and Tucker 1985, Trinchieri, Fabbiano and Canizares 1986). These can be used directly if one assumes that the gas is isothermal out to the radius in question. Such an assumption is valid if conduction operates efficiently throughout the galaxy, although there is as yet no detailed model for such a quasi-static isothermal atmosphere (one difficulty is maintaining the pressure at the outer boundary). Cooling flow models also give roughly isothermal temperature profiles (White and Chevalier 1984).

Figure 7 shows the application of Equation 3 to the data of three galaxies with the full range of possible assumptions (Trinchieri, Fabbiano and Canizares 1986). The radii have been chosen conservatively, as noted above, and several choices of possible temperature gradient are indicated. We can be quite sure of the low temperature limit because cooler gas could not easily be detected by the Einstein instruments. The very high temperatures simply become implausible given the indicated mean temperatures of ∿ 10^7 K and a desire to limit M/L to values smaller than the mean for rich clusters. Figure 7 also shows the values deduced by Forman, Jones and Tucker 1985, who do assume isothermality at a characteristic temperature of 1.2 x 10^7 K. Note that they generally chose to apply Equation 3 at larger radii and used a mean value of dln(n)/dln(r) derived from a fit over the whole galaxy. For comparison, the horizontal lines in the figures mark the range of masses deduced from the central stellar velocity dispersions by Davies (1981), Tonry and Davis (1982) and Katz and Richstone (1985).

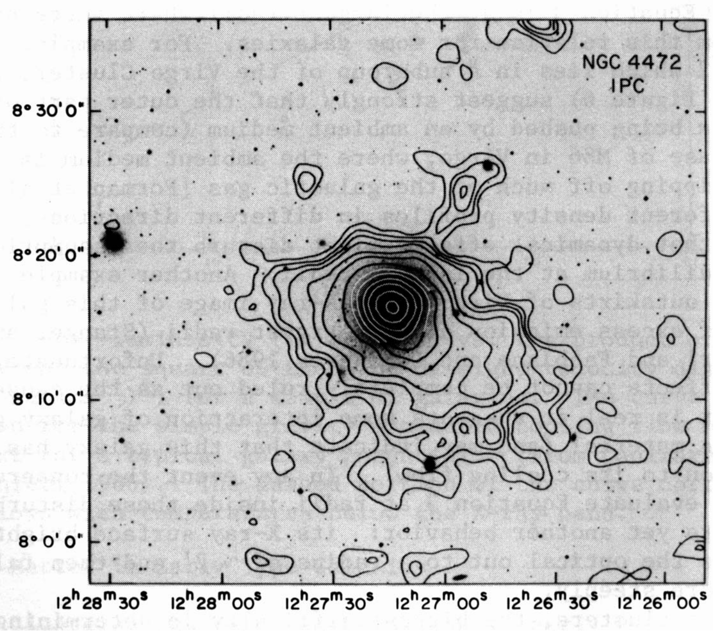

Figure 6. Isophotes of constant X-ray surface brightness superimposed on an optical image of NGC4472, showing the asymmetry at large radii. (From Trinchieri, Fabbiano and Canizares 1986).

One can see that conservative assumptions give an order of magnitude uncertainty in the deduced values of binding mass (or M/L). This situation could improve considerably if we had good physical models of the gas which could be fit to the surface brightness profiles and constrained by the measured mean temperatures (eg. see Fabian's contribution to this meeting). The lowest values of M/L_B allowed by all the data range from the value ∿ 5 one might attributed to the stars (Faber and Gallagher 1979) to ∿ 20. The values of 10-20 suggested by the optical data are quite acceptable. It is worth noting that the difficulty of interpreting stellar velocity dispersions is at least as great as those described here for the X-ray data (e.g. see the range of M/L values deduced by Katz and Richstone [1985] for NGC4636 in Figure 7). If the temperatures at the chosen radii are near to the mean value for each galaxy then the M/L_B would be $\gtrsim$ 20-30, and with the large uncertainties, values of $\gtrsim$ 100 are allowed (Forman, Jones and Tucker 1985). With the right theoretical tools and, eventually, better data one can expect X-ray observations to provide very detailed maps of the galactic gravitational potentials.

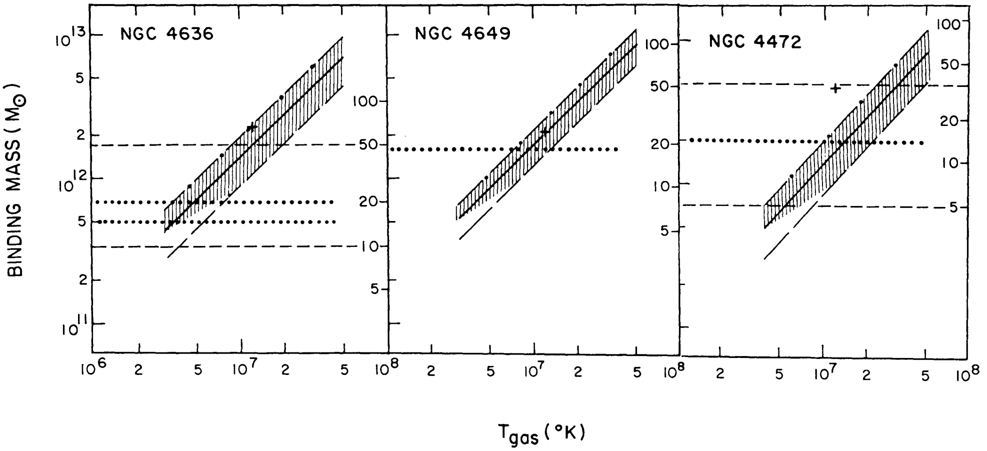

Figure 7. The range of binding masses within R_{max} deduced from the X-ray surface brightness profiles of three early type galaxies as functions of the temperature and temperature gradient at R_{max}. The solid line corresponds to α = dlnT/dlnr = 0, while the upper and lower lines correspond to α = -0.5 and α = 0.5, respectively. The values of R_{max} are 30 kpc for NGC4636 and NGC4649 and 40 kpc for NGC4472. The crosses represent the values from Forman, Jones and Tucker (1985) for T = 1.2 x 10^7 K and slightly different radii. The horizontal lines mark optical results from Davies (1981), Tonry and Davis (1981) and Katz and Richstone (1985). (From Trinchieri, Fabbiano and Canizares 1986).

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DISCUSSION

DAVIS: Most of us would agree that the limitations on these observations are the lack of information on temperatures and temperature gradients. Could you tell us whether AXAF or other satellites are likely to improve this situation?

CANIZARES: There will probably be some improvement already from ROSAT. We could have done better with EINSTEIN if we'd known what to look for during the lifetime of the satellite. Certainly, AXAF will help. It will give us the ability to make spatially resolved spectral observations with x-ray CCDs. But I don't know how many systems we will be able to study. The observations are difficult, because the surface brightnesses are very low.

P. QUINN: In the mass-radius curves you showed you were finding a few x 10^{12} $M_\odot$ inside r ≃ 30 kpc. I'd like to ask Vera Rubin whether these values are high compared to masses of spirals.

RUBIN: They are upper limits on the range of masses for spirals.

REES: Can you say something about the total amount of heavy elements? Is it still true that the heavy element abundance can only be measured in the cores of clusters, or can one now state a higher lower limit to the total amount of heavy elements present?

CANIZARES: All of the information on heavy element abundances comes from integrated spectra observed with instruments with large fields of view; such observations are heavily weighted toward cluster cores. In all systems which have been observed, the data are consistent with heavy element abundances of about half the solar value. But there is no information about abundances in individual elliptical galaxies, and no information about the outskirts of even very rich clusters.

REES: But if one is having a hard time making the heavy elements, can one just fit the core of a cluster, so that the total mass of heavy elements is not too large?

CANIZARES: I think so. If you can find a good way of segregating the heavy elements in the core, your assumption is consistent with the observations.

GUNN: I find it very striking that the x-ray luminosity so nicely follows the optical luminosity, in view of the fact that the x-rays come from gas. The power-law dependences of the gas distribution and the x-ray emission are entirely different. But there is evidence now that elliptical galaxies have a higher proportion of globular clusters than do later-type galaxies, and that the globular cluster distributions in ellipticals have larger core radii than the galaxies. Could the x-rays from elliptical galaxies entirely be due to emission from globular cluster x-ray sources?

CANIZARES: The evidence for thermal emission is that the spectrum is thermal, rather than the harder spectrum you see from compact sources. Another problem with your suggestion is that the number of globular clusters in a galaxy could not be linearly proportional to the luminosity L, since we find $L_x \propto L^{1.6}$.

BINNEY: You said that many ellipticals have been detected. Does that include ellipticals in places like the Coma Cluster which have an appreciable intergalactic medium?

CANIZARES: No. The surface brightness of the cluster itself makes the measurement of individual galaxies difficult. The existing limits on the x-ray emission from galaxies in clusters don't really tell us much about whether the galaxies have their own gas or not. There have been reports of detections of galaxies in A1367 by Bechtold et al., but we have reexamined the data and are not convinced that you can detect galaxies against the cluster background. And in no case has anyone set a limit on the x-ray emission from a galaxy in a cluster that is lower than the luminosities observed for more isolated galaxies.

BINNEY: I think this is crucial for the question asked by Jim Gunn. If the x-ray emission were really from globular cluster sources, it would also be present in galaxies in clusters.

SCHECHTER: In all the images you've looked at, have you seen any evidence for halos without galaxies? I.e., have you seen any isolated diffuse sources?

CANIZARES: Not that I know of.

SCHECHTER: But, for example, Ed Turner needed offset mass distributions. And one might imagine that there are halos floating around that failed to form galaxies within them. Moreover, in some scenarios one could have failed galaxies, i.e., halos that didn't accumulate galaxies. These things might be in the vicinity of galaxies that we do see, so it makes some sense to look at existing exposures.

CANIZARES: That is being done. But in every case out of the 500 or so that have been looked at where there is an extended source, there is a rich cluster of galaxies with $z \lesssim 0.3$ which perfectly well explains the emission. So I don't see any evidence for empty halos at this point.

LAKE: I think it would be hard to find an empty halo. The cooling times you see involve flows of 1 - 10 $M_\odot$ per year. If you don't have any supernovae to heat the gas, then over a Hubble time you are surely going to make a galaxy of mass 10^9 - 10^{10} $M_\odot$ at the center.