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ABSTRACT

The X-ray emission from luminous clusters of galaxies is dominated by thermal bremsstrahlung from an intergalactic medium. The central density of the gas is strongly correlated with the X-ray surface brightness. The X-ray surface brightness $S(\sigma)$ of many clusters is well modeled by a law of the form $S(\sigma) \alpha S(o) (1 + r^2/a^2)^{-3\beta+1/2}$ with $\beta \sim 0.66$. However this model does not fit the X-ray spectral or optical galaxy counts well. In clusters with cooling flows in their center there is a strong correlation between the cooling rates of X-ray emitting material and optical $H\alpha$ emission. It is not clear, at present, what percentage of the virial mass of the cluster is in hot gas but if $\beta = 0.66$ the values can be of order 1/2. Spatially resolved X-ray spectroscopy is necessary to determine this value with any accuracy.

At the end of the HEAO era there were several broad conclusions one came to regarding X-ray emission from clusters of galaxies. For luminous clusters, $L_X > 10^{44}$ erg sec, the bulk of the 2-30 keV luminosity is due to thermal bremsstrahlung emission from hot gas, kT > 3 keV, with roughly half solar abundances of iron. One of the major discoveries due to the Einstein Observatory was that a significant fraction of these luminous clusters have a temperature inversion in their centers. This results in a large fraction of the 1/2 - 3 keV flux originating in a very small component whose average temperature is considerably less than the mean for the cluster as a whole. However the bulk of the total bolometric X-ray luminosity is still due to the hotter gas.

For the luminous clusters there are strong correlations between bulk X-ray and optical properties. The X-ray luminosity L_x and temperature T are strongly correlated with the central density of galaxies in the cluster N_0, with $L_x \propto N_0^{3.5}$ and $kT \propto N_0$ (Mushotzky 1984). This result implies that the mean gas density ρ is roughly linearly related to the central galaxy density and that the effective cluster size is independent of the temperature. However, the presence of cooling flows in clusters destroys the correlation between the central gas density ρ_0 and central galaxy density N_0. (For the small sample of objects without a cooling flow, that have ρ_0 measured by the Einstein IPC, and measured N_0 the relationship is consistent with being linear).

The X-ray luminosity is strongly related to cluster richness but there is a wide range of luminosities in each richness class. However, one correlation that had been expected from theoretical studies to have been the strongest, that between cluster X-ray temperature and optical velocity dispersion, is quite poor. If we take the ratio of optical velocity dispersion to X-ray temperature, $\beta = \mu\sigma_v^2/kT$, we find that the observed values of β do not peak around a mean value but seem to be distributed smoothly from .5 to 2.0 (Figure 1). This wide distribution is rather unexpected but was hinted at in the earliest X-ray data (when it was noticed that Perseus with a velocity dispersion of 1420 km/sec has a lower X-ray temperature than Coma with a velocity dispersion of 905 km/sec).

There are also strong relations between various X-ray properties. The X-ray luminosity is related to the X-ray temperature by $L_x \propto T^{2.7}$. However, other properties, such as the presence of a cooling flow, the Fe abundance, and the X-ray size, seem to have little or no correlation with each other.

The Einstein Observatory imaging data showed that the X-ray surface brightness distribution of luminous clusters is remarkably homogeneous and is well fit by the simple relation which we shall call a "β model"

$$S(r) = S(o)\ (1 + r^2/a_x^2)^{-3\beta+1/2} \qquad (1)$$

with $\langle\beta\rangle \sim .66 \pm .10$ and $\langle a_x\rangle = .24 \pm .10$ Mpc (Jones and Forman 1984). The central surface brightness S(o) varies over 2 orders of magnitude from $\sim 5 \times 10^{-4}$ IPC cts/arc-min^2 sec to $\sim 5 \times 10^{-2}$ (Figure 2). The central surface brightness is extremely well correlated with the central density with $S(o) \propto \rho_0^{1.65}$. This range in surface brightness and density is constrained at the low end by the IPC background of $\sim 5 \times 10^{-4}$ cts/sec min^2 and at the high end by the

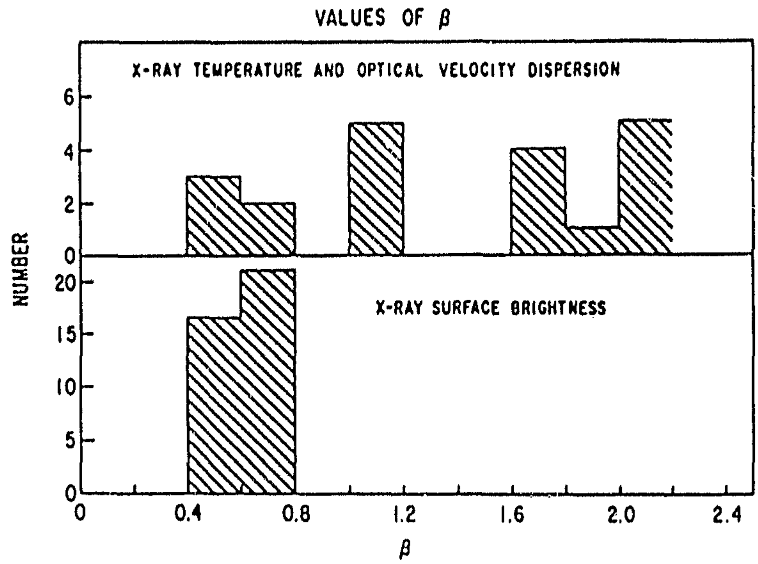

Figure 1 - Histogram of the values of β derived from X-ray temperatures and optical velocity dispersions (Mushotzky 1984) and those from X-ray surface brightness measures (Jones and Forman 1984).

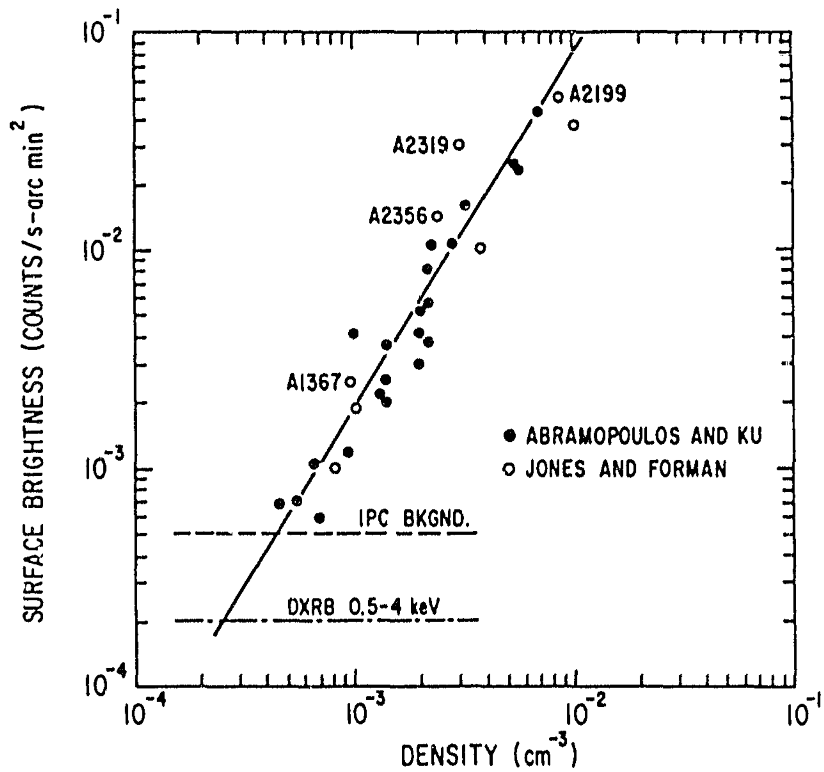

Figure 2 - Correlation of the X-ray surface brightness with central density solid line is best fit $S \propto \rho^{1.65}$.

time scale against cooling. Since $\tau_{cool} \sim \frac{6.7 \times 10^7 T_8^{1/2}}{\rho_o}$ years, if $\langle T_8 \rangle \sim .6$ and if $\rho_o > 5 \times 10^{-3}$ cm^{-3}, the cluster will start to cool in less than the Hubble time. The clusters with $S(o) \sim 5 \times 10^{-2}$ have $\rho(o) \gtrsim 8 \times 10^{-3}$. Thus it is unlikely, if clusters are truly quite old, $\tau > 7 \times 10^9$ years, that there would exist clusters whose central density at the present time is greater than 10^{-2} cm^{-3} or whose central surface brightness is greater than 7×10^{-2} IPC ct/sec min^2.

The imaging data have also allowed detailed consideration of the interaction between the gas in galaxies and the gas in the cluster for low luminosity clusters. For clusters such as Abell 1367, Virgo etc., where the central density is $\sim 5 \times 10^{-4}$ cm^{-3} and the temperature is ~ 2 keV, the pressure in the interstellar medium of a "normal" galaxy (using our galaxy as a guide) is equal to that in the intracluster medium, even inside one core radius. Thus for these low luminosity clusters one expects to see, and has seen (Fabian, Schwarz and Forman 1980), the interaction between galactic and intergalactic gas. The lack of spatially resolved X-ray spectra, however, has made understanding of this interaction difficult.

The existence of cooling flows in clusters has been inferred from both spectroscopic observations of the core of the cluster and surface brightness maps. The spectral data have shown that some clusters have emission lines due to O, Fe L, Si and S (Canizares et al. 1982; Lea, Mushotzky and Holt 1982; Mushotzky et al. 1981) and must arise in gas of $T < 1.2 \times 10^7$ °K, much cooler than the integral cluster temperature. The surface brightness maps (Fabian et al. 1981; Stewart et al. 1984) show that some clusters have a surface brightness which rises much more steeply near the middle than is possible for an isothermal hydrostatic gas. The mass flow (solar masses per year of cooling gas) inferred from both the imaging and spectroscopic data are usually in rough agreement and imply for the several examples cooling rates of more than 100 M_o/yr. This result has been nicely confirmed by optical observations of cool gas emitting Hα lines near the centers of several clusters (Cowie et al. 1983; Heckman 1981). The Hα flux seems to be linearly related to the m inferred from X-ray data and indicates that ~ 1 Hα photon is emitted by each atom of the cooling gas (Figure 3). However, the Hα data show interesting structure which, so far, seems absent from the X-ray data.

If the β models are correct then the values of β derived from the surface brightness measurements should agree with those derived from the ratio of X-ray temperature to optical velocity dispersion, since $\beta = \mu m_H \sigma^2/kT$ (Cavaliere 1979). However, the values of β inferred from the X-ray surface brightness distribution and the ratio of optical velocity dispersion to X-ray temperature are not necessarily in agreement (Figure 1). It is possible that the optical velocity dispersions and/or the X-ray temperatures from

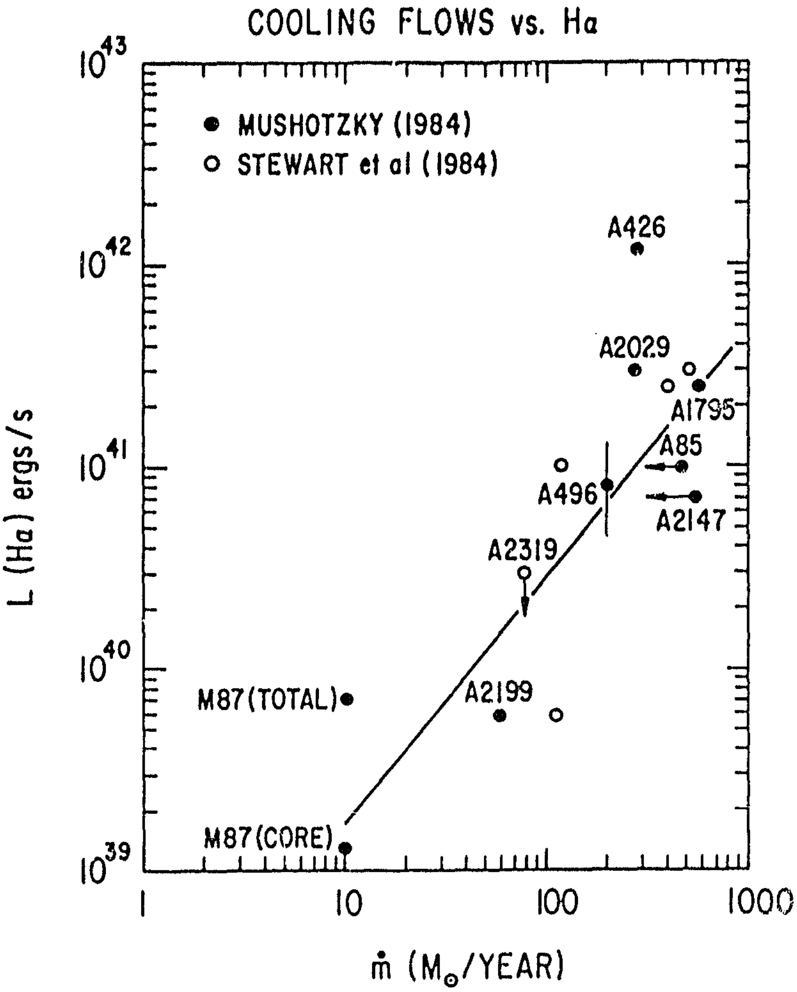

Figure 3 - Correlation of luminosity in Hα vs. cooling rate in flow determined from X-ray data. Line has a slope of one and is fit by eye to the data.

which β are inferred are poorly determined. Recent work has indicated that there can exist velocity substructure in clusters; that is the galaxies are not virialized (Beers et al. 1983). If this is the case it is not clear what should be the relationship between σ_v and T_o. Alternatively, as indicated by the existence of "two-component" X-ray emission (Mitchell and Mushotzky 1980), there may exist X-ray spectral structure and thus the measured T_x from a large beam experiment such as HEAO-1 may not be relevant to the optical data. Only much more optical and spatially resolved X-ray data can answer this question.

The "simple" β values used to analyze the data so far have assumed that the gas was isothermal. If the gas is not isothermal the published values of β are irrelevant. For example if the gas is isothermal, and we use a King model to describe the galaxy distribution and assume that the potential is better described by the galaxy counts rather than the gas distribution the density distribution is

$$\rho(r) = \rho(o)\ (1 + r^2/a^2)^{-3\beta/2} \qquad (2)$$

where a is the galaxy core radius.

If the gas is not isothermal but polytropic with polytropic index γ

$$\rho(r) = \rho_0 \left[1 - \frac{3}{2}\left(\frac{\gamma-1}{\gamma}\right) \beta \ln\left(1 + (r/a)^2\right]^{1/\gamma-1}\right. \qquad (3)$$

for a range of γ and β the surface brightness law predicted from a polytropic model is difficult to distinguish from an isothermal β model. However the temperature profile

$$T(r) = T(o) \left[1 - \frac{3}{2}(\gamma - 1/\gamma)\beta \ln\left(1 + (r/a)^2\right)\right] \qquad (4)$$

is quite different. The total amount of mass in the cluster gas predicted by these models is also very different. It is not even clear that this type of model is correct; a may not be the correct scale length of the gas and if the galaxies are not virialized, β may not be a relevant parameter.

There are several other problems with the isothermal β models. Because of the implied shallow density law the total inferred mass in gas is quite large. If we assume $\beta = .66$, and that the virial mass has a King distribution and integrate out to 3 Mpc then the ratio of mass in gas, M_{gas}, to virial mass, M_v, is

$$M_{gas}/M_v \sim .04\, \rho_{-3}\, (\sigma_{1000})^{-2} \qquad (5)$$

where ρ_{-3} is the central density of the gas in units of 10^{-3} per cm^3 and σ_{1000} is the line of sight velocity dispersion in units of 1000 km/sec. Many rich, luminous clusters have this ratio > .25 (Figure 4) and some, like A1795 have a ratio > .4. Thus the β models imply that a large fraction of the virial mass is in the X-ray emitting gas (and therefore in the form of baryons). Since this gas is enriched in Fe these huge gas masses imply more than $1 \times 10^{12}\ M_0$ in Fe in some clusters. It seems quite difficult to obtain such huge masses of metals.

The β models also require that the gas and galaxy core radii be strongly correlated (Cavaliere 1979). As we see in Figure 5 the X-ray and optical core radii have different distributions; a sample with the X-ray values having a broader (Columbia groups King model fits) or narrower (CFA groups β model fits) distribution than the optical core radii (Bruzual and Spinrad 1978) or harmonic radii (Hickson and Adams 1979). In addition, for individual clusters (Figure 5b) we see that the X-ray and optical sizes are <u>not</u> strongly correlated. This indicates to me that one or more of the basic ideas underlying the β models is wrong.

Recent detailed studies of the HEAO-1 A2 X-ray spectra of clusters (Henriksen, Mushotzky and Szymkowiak 1984) show that

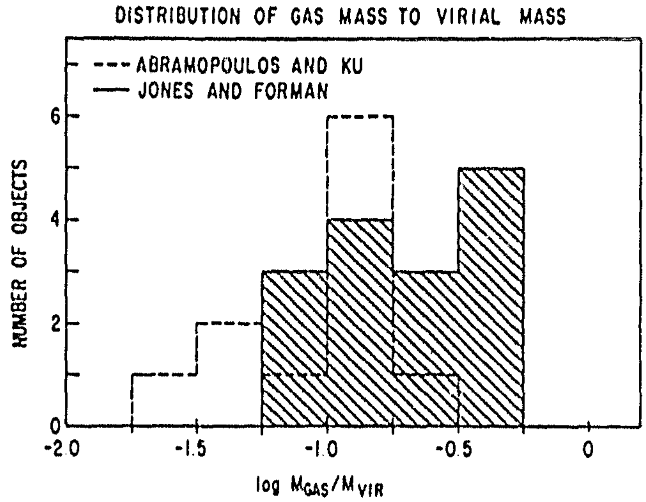

Figure 4 - Histogram of the ratio of the mass in gas to the virial mass for King model (unshaded) and β model (shaded) fits to X-ray imaging data.

polytropic models provide better fits for some clusters than isothermal models. In particular for the two brightest clusters in the sample, Perseus and Coma, we can constrain both the central temperature and the polytropic index. For Coma $T_0 = 18 \pm 2$ keV and $\gamma = 1.55 \pm .1$ while for Perseus $T_0 = 9.1 \pm 1.5$ keV and $\gamma = 1.25 \pm .11$. In both cases isothermal models, $\gamma = 1$, are ruled out at > 95% confidence. In these models one also derives the emission measure. If we assume a density profile these data allow determination of the central density and core radius.

The fact that polytropic models fit the spectral data better than isothermal models indicates that the gas is probably not isothermal. However the integrated spectrum is not very sensitive to the polytropic assumption. For example regulated accretion models which are not polytropic (Cowie 1980) fit the Perseus data equally well.

One must go to the equations of hydrostatics and use the gas parameters $\rho(r)$ and $T(r)$ to get a true picture of the cluster. One thus needs spatially resolved spectra beyond 1 core radius. This is the single greatest need at present to model clusters.

If we use the equation of hydrostatic equilibrium and assume spherical symmetry (Fabricant, Lecar and Gorenstein 1980) then the gravitational mass inside a radius R which will confine the X-ray emitting gas is

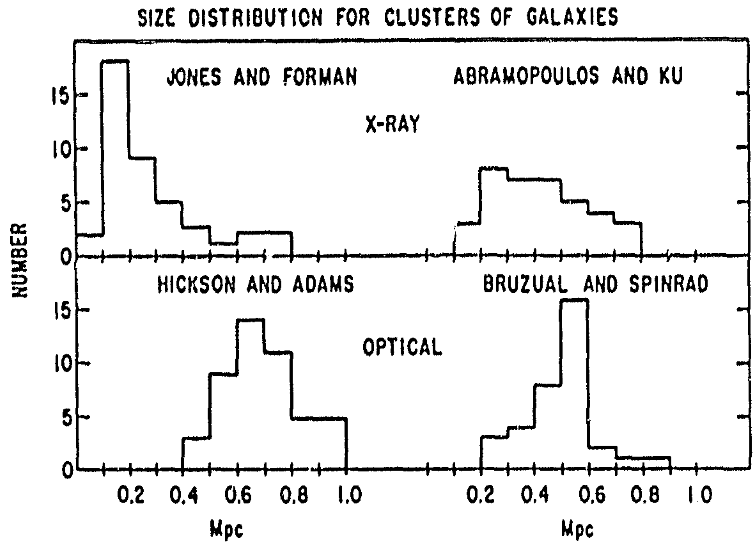

Figure 5a. Histograms of the X-ray and optical sizes determined by various authors.

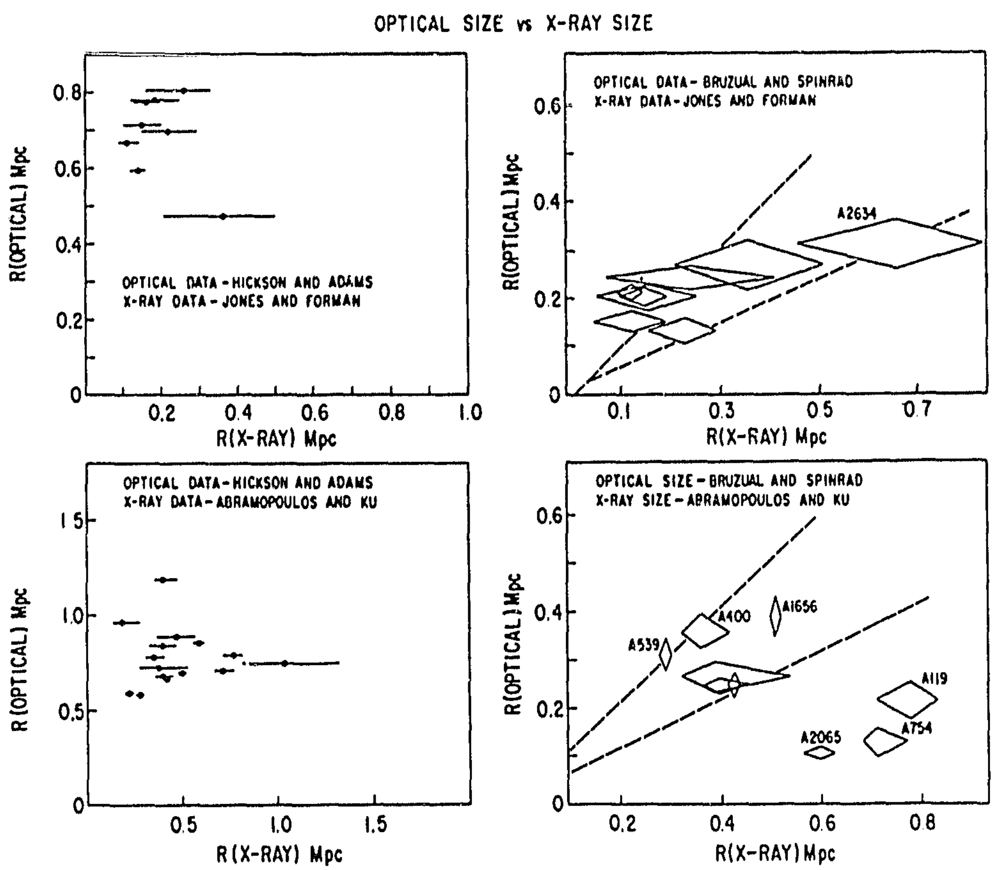

Figure 5b. Correlation of X-ray and optical sizes. Note the general lack of agreement.

$$M(<R) = \frac{KTR}{G\mu m} \left(\frac{d \log \rho}{d \log R} + \frac{d \log T}{d \log R}\right) . \quad (6)$$

If the gas is polytropic and has a power law density distribution (Kriss, Cioffi and Canizares 1983) $\rho(r) = \rho(o)\ r^{-Q}$ then

$$M(<R) = \frac{(Q\gamma)\ kT(o)}{\mu m H G} R^{(Q - Q\gamma+1)} . \quad (7)$$

For polytropic indices γ and Q values such that $Q(1-\gamma) < 0$ this can result in considerably less mass in the gas than in the isothermal models depending on the value of the central temperature, T(o).

While the HEAO-1 data show that, within a factor of 4 at the present epoch, most luminous clusters have the same Fe abundance, we have little information on the spatial distribution of the Fe in the cluster or on the correlation of Fe abundance with any cluster property. Our knowledge of other elemental abundances is even worse. The abundances of Si and S for a few clusters (Mushotzky 1984) are known to be within a range (.3 - 2.0) of solar, while for one object (M87 in Virgo) there is an indication of an overabundance of oxygen relative to iron (Canizares et al. 1982). To solve the cluster metal problem e.g. the origin of the heavy elements, we need to know the relative abundances of the elements to accuracy of better than ~ 20%, so that different nucleosynthesis models can be tested and the IGM in clusters compared to stellar populations in our galaxy. Such accuracy requires both higher sensitivity and better energy resolution than is obtainable from mechanically collimated standard proportional counters.

In addition comparison of the metal abundances in different "types" of clusters will place strong constraints on models of the origin of the gas. If for example the "unevolved" clusters have the same metal abundance as those "evolved" high luminosity systems for which we have the most data, then the IGM must be enriched early in the lifetime of the system and the early cluster potential must be deep enough to trap the metal enriched products of supernova explosions. Alternatively, if the reverse is true, the metals might have been removed from galaxies by stripping and must remain trapped (Norman and Silk 1979; Sarazin 1978) in galaxies for a long time.

The cluster metal problem is also intimately connected with the "β" problem (the problem of the cluster potential). The mass of the cluster gas out to 3 core radii for a $\gamma = 1$, $\beta = .66$ model is 2.75 times larger than a $\gamma = 1.4$, $\beta = 1$ model (roughly $4 \times 10^{14}\ M_0$ for a rich cluster). Thus if all this material is enriched in heavy elements, we have to understand how $4 \times 10^{14}\ M_0$ could possibly have been processed through stars when there are only $\sim 2 \times 10^{14}\ M_0$ of stars still around.

Thus despite the great progress in our understanding of clusters in the HEAO era, we are still left with several fundamental problems:

1. What is the form of the cluster potential?
   a. What is the mass in gas?
   b. What is the mass in baryons of the cluster?

2. How did the metals get produced?
   a. When did they get injected?
   b. How were they created?

3. How do clusters evolve?
   a. Relationship between gas and galaxies
   b. Correlation between form and other properties

4. How are cooling flows generated?
   a. Detailed understanding of flow
   b. Relationship to central massive galaxy and clusters
   c. Where does the matter go?

5. How do the dynamical parameters inferred from optical data such as velocity dispersion or central density relate to X-ray parameters such as temperature, density and luminosity?

X-ray spectroscopy is vital to solving all of these problems, in particular spatially resolved X-ray spectra.

In addition, the recent discovery of hot X-ray emitting gas in elliptical galaxies (Forman et al. 1979; Fabian, Schwarz and Forman 1980; Bechtold et al. 1983; Biermann and Kronberg 1983; Nulsen et al. 1984) raises the possibility that X-ray observations of these systems will pose the same types of questions as observations of clusters did. At present we only know that these systems are probably cool, $kT < 2$ keV, and probably small, $r < 20$ kpc. If we use a simple form of Equation 6 (with constant T and a King model for ρ) then the X-ray data imply a mass $M(<R) \sim 3\ KTR/\ \mu m_H G \sim 5 \times 10^{11}\ M_0$ inside 10 kpc, consistent with the virial mass of these systems inferred from optical measurements. However, because of their lower temperatures, different metallicity, higher angular momentum, different evolutionary history and different ratio of gas mass to virial mass, X-ray observations of gas in elliptical systems should prove to be a completely new field.

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