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The Physical Implications of an Isothermal Model

for the Hot Intracluster Medium

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ABSTRACT

We have used X-ray fluxes from HEAO-1 A2 and Einstein Imaging Proportional Counter (IPC) observations of clusters of galaxies to constrain the parameter β in the isothermal surface brightness profile ($S = S_0 (1+(r/a)^2)^{-3\beta+1/2}$). β is found primarily to have values between .50 and .75 for 15 clusters. Eight of these objects have values of β previously measured using imaging observations. For these clusters good agreement is found with the values reported here implying that this profile is a good description of the surface brightness out to 8 - 10 core radii. The total gas mass and radial distribution (assuming spherical symmetry) within the cluster resulting from the isothermal model imply an extended halo of hot gas which has 30 - 60% of the virial mass for some clusters. This seems to contradict a fundamental assumption in the derivation of the isothermal model, that the matter responsible for the potential is distributed like a "King" (β = 1) profile and that the gas is either not a significant contributor to the cluster mass, or it must have the same distribution as the unseen mass. Application of this model

to the X-ray data tells us that neither assumption about the gas is true.

Isothermal model fits to the data consistently give β less than 1, implying that the gas component is more extended than the galaxy component. However, using available optical data, we find no correlation between the HWHM of the gas and galaxies and there is no evidence of the narrow range of acceptable pairs of these parameters which is predicted by the model using the observed range in β. Also no significant correlation is found between the gas core radius and the optical HWHM; parameters which must be equal for this model to be self-consistent. These inconsistencies cast doubt upon physical interpretations based on the isothermal model even though it is useful as an empirical description of the X-ray surface brightness.

Subject headings: galaxies: clusters of galaxies: intergalactic medium: X-ray sources

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I. INTRODUCTION

Less than a decade ago, spectroscopic studies of the diffuse X-ray source in clusters of galaxies produced compelling evidence that the X-rays were produced by thermal bremsstrahlung from a hot gas (Serlemitsos et al. 1977). The initial models assumed that the gas was a self-gravitating isothermal sphere since it seemed that the gas and galaxy masses were comparable. However, since the gas mass was believed to be roughly 10% of the mass necessary to bind the cluster (Lea et al. 1973), models were developed in which the gas was trapped in the potential well formed by the unseen binding mass of the cluster (Bahcall and Sarazin 1978; Cavaliere and Fusco-Femiano 1976). A model often used in the analysis of X-ray imaging data, the "β" model, (Jones and Forman 1984; Ku et al. 1983; Gorenstein et al. 1979) was formulated under the assumption that the unseen matter is distributed like the galaxies (Rood et al. 1972) and that this radial distribution is roughly given by the King (King 1966) approximation to an isothermal sphere. The latter assumption is based primarily on studies of the Coma cluster and may not apply to clusters in general (Chincarini 1979).

In this paper, we will use HEAO-1 A2 and Einstein IPC observations of 15 clusters of galaxies to measure the isothermal β model parameters. These parameters will then be compared to those derived from model fits to the X-ray images. We will then address the physical constraints imposed on this model by the existing optical data, the implied gas mass, and the gas contribution to the binding cluster mass.

II. DESCRIPTION OF THE ISOTHERMAL MODEL

The Einstein Observatory was used extensively to measure the X-ray surface brightness of clusters of galaxies. Much of these data have been modeled (Ku et al. 1983; Jones and Forman 1984, hereafter JF) using the surface brightness profile

$$S/S_0 = (1 + (r/a)^2)^{-3\beta + 1/2} \qquad (1)$$

described by Cavaliere and Fusco-Femiano (1976), in which β, a, and S_0 are free parameters. The special case of a self-gravitating isothermal sphere, β fixed at 1, was fit to a sample of clusters by Abramopoulos and Ku (1983) (hereafter AK). This is a physically unreasonable situation if the gas mass is only 11% of the virial mass, as determined by these authors, since the gas mass would not be large enough to be self-gravitating and would have to respond to the total cluster potential.

In this model, β is the ratio of the energy of the galaxies to that of the gas, $\beta = \mu m_H V^2/kT$, where V is the line of sight velocity dispersion of the galaxies, kT is the temperature of the gas, and the parameter a is the X-ray core radius. The value of β and core radius derived from fits to the data determine the relative extension of the galaxy and gas components:

$$\beta = 0.1/[\log((h/a)^2 + 1)] + .17, \qquad (2)$$

where h is the half width at half maximum (HWHM) of the X-ray surface brightness and a is the HWHM of the galaxy counts. The form of the gas density profile is

$$\rho/\rho_0 = (1 + (r/a)^2)^{-3\beta/2} \qquad (3)$$

III. METHOD OF ANALYSIS

The clusters analyzed here are those which have published fluxes from large ($3^o \times 1.5^o$) and small ($1^o \times 1^o$) field of view experiments. The total X-ray luminosities (L_T) in the 2 - 10 keV energy range (Mckee et al. 1980; Piccinotti et al. 1982) have been measured for 40 clusters using the HEAO-1 A2 detectors ($3^o \times 1.5^o$ FOV). In addition, .5 - 3 keV luminosities within the central region of the cluster (L_r) have been measured with the Einstein Observatory's Imaging Proportional Counter (Giacconi et al. 1979). The observed values of L_r used here are from the surveys of JF (who give the luminosity within .5 Mpc of the cluster center) and AK (who give the luminosity within 1.5 Mpc). The ratio of the luminosities L_T/L_r depends only on β, a, and the temperature (choice of the outside radius of the gas has only a weak effect on the resulting luminosity ratio). The measured ratio can be corrected for the relative difference in bremsstrahlung emission in the respective bandpasses of the IPC and HEAO-1 detectors using the known temperatures of these clusters (Mushotzky 1984). The temperature used in this correction is derived from modeling the spectrum with a single component bremsstrahlung continuum plus Fe-K line emission. The correction ranges from 3% for clusters whose temperature is 8 keV to 26% at kT = 4 keV. Thus, for cooler clusters, such as A2199, an uncertainty in the temperature would produce a more significant uncertainty in L_T/L_r.

Utilizing the data in AK, we derive values of β not previously determined for 7 clusters. The luminosity ratio and the core radius for each cluster is plotted in Figure 1 which gives contours of β for a large range in both (L_T/L_r) and a. The error bars in the luminosity ratio combine the random counting error given by AK, a 7% systematic error in the IPC due to uncertainties in the background subtraction (Fabricant, Rybicki, and Gorenstein 1984), and the errors in the published HEAO-1 fluxes. The error in the core radius is given by AK. Correcting their core radii to a model with β equal to .6, using equation (2), allows us now to determine β from Figure 1. It is necessary to apply this correction to the core radii since this parameter is dependent on β and has been overestimated in AK who fixed β at 1.0 in the model fitting procedure. However, relatively large errors in a only give small changes in β (Figure 1).

IV. RESULTS

a. Values of β

The values of β (given in Table 1), which we have determined for these clusters, range from .50 - .75 and are peaked around .6. This is typical of the range of β derived from fitting the surface brightness from the IPC data alone. Figure 2 shows a determination of β for the clusters in JF using the same method. Since these authors fit the isothermal surface brightness profile to the radial profiles and allow β to vary, we can compare our independent determinations of β for 8 clusters. Table 1 contains values of β for each cluster. In most cases, very good agreement is found. The only significant disagreement is for A2199 which has a large temperature correction factor. The close agreement implies that the isothermal model provides a good empirical description of the surface brightness over most of the cluster, as seen by the large field of view HEAO-1 detectors.

To determine quantitatively how much of the cluster is described by this profile, it is necessary to examine the integrated surface brightness in more detail. Figure 3 shows the integrated surface brightness as a function of radius. In the outer part of the cluster, the gas density has a radial dependence given by a power law with index proportional to -3β. Since this is a strongly decreasing function of radius, the isothermal surface brightness, which is proportional to the density squared along the line of sight, rapidly decreases in the outer region. The total flux then increases very slowly as more cluster is observed. This is shown in Figure 3 in the dramatic flattening of the curves at 8 - 10 core radii. Since the values of β determined using the total cluster emission agree well with previous determinations, we infer that the surface brightness profiles must give a good description of the region of the cluster which contains most (90%) of the surface brightness. Alternatively, the "edge" of the gas can be considered to be the point at which the applicable surface brightness model gives 90% of the observed large beam flux. The significance of choosing 90% is that it allows for a 10% error in the relative normalization of the HEAO-1 and IPC fluxes. This is reasonable since the uncertainty in the flux determination for the IPC is estimated at 7% (Fabricant, Rybicki, and Gorenstein 1984) and for HEAO-1, the background fluctuations due to unresolved sources are typically 5-10% of the cluster fluxes. Thus the combined uncertainty is about 10%.

b. Mass of Gas

Knowing the approximate extent of the gas allows us to calculate the mass of the gas, within the context of the isothermal assumption. The mass of gas is calculated from the density profile, given by Equation (3), using the integration limits derived above. Table 1 contains the calculated gas mass and its fraction of the virial mass. For comparison with previous determinations of the ratio of gas to virial mass by AK, we use the virial mass calculated from integration of the King profile (with a central density given by $\left(\frac{9V_{11}^2}{4\pi G\mu M_p a^2}\right)$ out to 10 core radii. The virial mass is calculated here for the clusters in the sample of JF. The central density is corrected for use of the space velocity dispersion and the core radius is corrected to a (King) model with $\beta = 1$. However, we stress that the error associated with the velocity dispersion in the central region is large and that the virial mass calculated in this way is not well determined. It is also important to note that the ratio of the masses is proportional to the Hubble constant to the -3/2 power; thus a factor of 2 underestimate in this parameter leads to a factor of 2.8 overestimate of the ratio of gas to virial mass. In addition this must be considered a model dependent result since there exists no compelling evidence that the binding mass distribution in clusters is generally described by a King profile (though this is an assumption of the β model).

The mass of the cluster gas is proportional to $4\pi a^3 \rho_0$ and the integration over radius: $\int x^2 (1 + x^2)^{-3\beta/2} dx$ where $x = r/a$. The integrals are solved by numerical integration and the limits of the integration are the estimated size of the cluster gas. As discussed in the previous section, this is typically 8 - 10 core radii. Those clusters with large core radii (> .25 Mpc) and flat density profiles (β < .7) give the largest gas masses. This is the case with A1795 in which the gas mass is 61% of the virial mass. For many clusters, the masses derived from this density distribution are a significant fraction of the inferred virial mass. Recently published mass determinations based on the isothermal model which establish the gas mass to be typically 11% of the virial mass (AK) underestimate the ratio of gas to virial mass required by this model. These authors compare the gas mass within 5 core radii to the virial mass within this same region. It is important to note that the virial mass, assuming it is distributed like the galaxies (specifically like a King profile), falls off much more quickly than the gas mass. This is clearly seen in Figure 4 which gives the integrated mass within successive core radii out to a radius of 15a. Both the β = 1 model, applicable to the galaxies, and the β = .6 profile are seen to increase rapidly within 5 core radii. It is outside of this region where the β = 1 profile flattens while the β of .6 model substantially increases in mass. While 5 core radii contain most of the galaxy mass, only a fraction of the gas mass is within this region; thus the actual gas mass in the cluster is seriously underestimated by considering only this inner region. There is no evidence that 5 core radii should be a cutoff point since the galaxies are seen to extend to 8 - 10 core radii in some clusters (Kent and Gunn 1982) and a result of the isothermal model fits to the data (see IVa), is that the gas component is more extended than the galaxies. If the gas did extend just to 5 core radii then the integrated surface brightness profiles would give only 50 to 80% of the observed large beam X-ray flux. Thus it is necessary for the cluster gas to extend 8 - 10 core radii. In light of this, the masses in Table 1 of this paper, which take into account the mass in the outer regions of the cluster, more accurately reflect the mass of the gas relative to the virial mass and its distribution within the cluster for the isothermal "β" model. We also note that the gas masses are similiar to those of JF who calculate the mass within 3 Mpc (~ 12 core radii) of the cluster center.

The fact that the hydrostatic isothermal model predicted a gas "halo" for

Coma was pointed out by Gorenstein et al. (1979). In their analysis, adiabatic as well as isothermal models were able to adequately describe the data which encompassed a small field of view (r < 25') at soft X-ray energies (.5 - 2 keV). Based on our determinations, which use data which extends out to 180', we can conclude that if these clusters are isothermal then the surface brightness characterization requires that: (1) the gas be more extended than the galaxies, which leads to the ratio of visible light to total mass decreasing with radius (Stewart et al. 1984) and (2) the gas is a substantial fraction of the virial mass for many clusters as was found previously for 0340-538 (Ku et al. 1983).

c. Optical Structure

The interpretation of β assumes that the density distribution of the galaxies is well represented by an isothermal sphere. This result has not been confirmed for clusters in general. In fact, an optical survey of rich clusters by Geller and Beers (1982) finds that many clusters are asymmetric or have substructure and that very few look like isothermal spheres. It is important to note that the β model was developed at a point in cluster analysis when the optical properties of clusters (primarily Coma) were better determined than the X-ray properties. Thus, the King approximation to an isothermal sphere, which described the galaxy counts in Coma was used as a fundamental starting point for the developement of a model for the X-ray emission. Originally, the scale length in the β model fits to the X-ray data, the X-ray core radius, was fixed at the HWHM of the galaxy counts (Cavaliere 1978). The fact that in practice the core radius is currently left as a free parameter reflects that during the HEAO era, high quality X-ray data became available for a large sample of clusters while comparable optical data was not available. Recent optical work allows us to now check the self-consistency of this approach to the analysis of the X-ray data by comparing constraints imposed by the optical data.

The X-ray and galaxy density distributions have a clearly defined relationship in the isothermal model. The best fit X-ray core radius must be equal to the optical HWHM for the model to be self consistent. In Figure 5, we show the best fit X-ray core radius and the optical HWHM for 17 clusters (those clusters common to both the Jones and Forman sample and the Geller and Beers sample). We have measured the optical HWHM from the contour maps published by Geller and Beers. The error bars for this parameter in Figure 5 follow from the 1 sigma errors given with the contours. As the figure shows, the size of the error is significant. This is due primarily to the low number of galaxies in some of the clusters and the uncertainty in the background subtraction. Even given the large errors, one can readily see that few of the clusters fulfill the condition for self-consistency, that the x-ray core radius equals the optical HWHM. A linear correlation analysis shows that these two paramaters are not strongly correlated (r=.28). Graphically, this condition is shown in Figure 5, where the line represents equal scale length determinations, and it is clear that the few clusters are seen to be consistent with the line at the 1 sigma level. A similiar result using published optical scale lengths was found by Mushotzky (1984).

A model independent characterization of the emission scale length, the HWHM, is also not well correlated (r = .26) in the X-ray and optical. Using the published values of β, the X-ray core radius, and equation (2), the HWHM for the gas component is calculated and plotted in Fig. 6 for 25 clusters (8 in AK and 17 in JF that are in Geller and Beers). The lack of a strong correlation does not support the general conclusion based on the isothermal model fits to the data that the X-ray emission is systematically more extended than the optical (β is less than 1.). If the components had this simple relationship, one might expect to at least see a weak correlation on the scale of the HWHM, since the observed range in β predicts a well defined range of acceptable pairs of X-ray and optical HWHM.

Furthermore, the relatively small dispersion in β from X-ray surface brightness analysis is not verified by determinations using the velocity dispersion and central temperature. The latter method shows a distribution in β which includes many clusters with $\beta > 1$ (Mushotzky 1984); a case in which the gas is less extended than the galaxies. Though this may be consistent with the optical measurements, this is not seen in the imaging X-ray analysis. The conflicting values of β have a number of possible explanations which are beyond the scope of this paper.

V. DISCUSSION

The isothermal model has been applied to much of the imaging and spectral data. The validity of the physical interpretation of the results is doubtful since the existing optical data does not seem to confirm that the model is self consistent. Another major inconsistency is associated with the isothermal gas mass. The model implies gas masses which are a significant fraction of the binding mass, and have a flatter density distribution than the assumed binding mass. Yet, in the derivation of the model the contribution of the gas to the total cluster mass is neglected. We conclude then, that the model is a useful empirical description of the data, but not necessarily a physically relevant one. We suggest that this model does not uniquely describe the data. In fact, non-isothermal models such as that described by Cavaliere and Fusco-Femiano

(1978) can also produce the observed small to large beam flux ratios. However, the increased number of parameters in this model (polytropic index, β, central temperature, and core radius), allow for very little constraint on the parameters using the flux ratios presented in this paper. This particular model, though useful in illustrating an alternative to the isothermal model, is still lacking in generality, particularily in its use of a fixed cluster potential. In a future paper, we will advocate a more general approach to the analysis of the X-ray data which is independent of assumptions concerning the distribution of galaxies or the binding cluster mass.

VI. SUMMARY

The following important points have been raised in this paper:

(1) Application of the isothermal model to measurements of the ratio of large to small beam fluxes from clusters of galaxies gives values of beta less than 1. This is consistent with the results from X-ray imaging data. We interpret this to imply that the gas extends out to 8 - 10 core radii, ~ 2-3 Mpc.

(2) The cluster scale lengths found using X-ray observations do not agree well with those determined optically. In the derivation of the surface brightness from the assumed cluster potential and galaxy density distribution, the scale length is the same. This is not found for the 25 clusters analyzed here.

(3) The isothermal gas mass can be as large as 60% of the virial mass for some clusters. This contradicts the fundamental assumption that the cluster potential is determined by an unseen mass which is given by the King approximation to an isothermal sphere. If the gas mass is a significant fraction of the total cluster mass and is given by a flatter density distribution than this mass, it must be included in the assumed cluster potential.

We conclude that the isothermal model is a non-physical model though it has proven to be a useful empirical characterization for clusters. We advocate the application of non-isothermal models in an attempt to arrive at cluster models which may be more physically self-consistent.

TABLE 1

Values of Beta and Cluster Virial and Gas Masses

Cluster	β^1	β^2	Gas Mass[3]	% Virial Mass
A85	.60-.67	.60-.65	1.7	9
A119	.56-.59	------	6.5	52
A401	.60-.72	------	4.4	18
A426	.56-.62	.55-.60	4.1	20
A496	.60-.70	------	0.64	--
A644	.58-.65	------	3.8	--
A754	.56-.60	------	8.5	43
A1656	.57-.63	------	3.3	30
A1795	.60-.73	.65-.80	3.8	61
A2029	.48-.60	.63-.83	5.9	63
A2142	⩾.70	------	3.2	15
A2199	.50-.55	.63-.73	1.6	47
A2256	.65-.67	.68-.78	8.2	29
A2319	.58-.65	.63-.73	8.9	--
A2657	.40-.50	.50-.57	1.1	--

Footnotes:

1) This paper

2) From Jones and Forman (1984)

3) In units of 10^{14} solar masses

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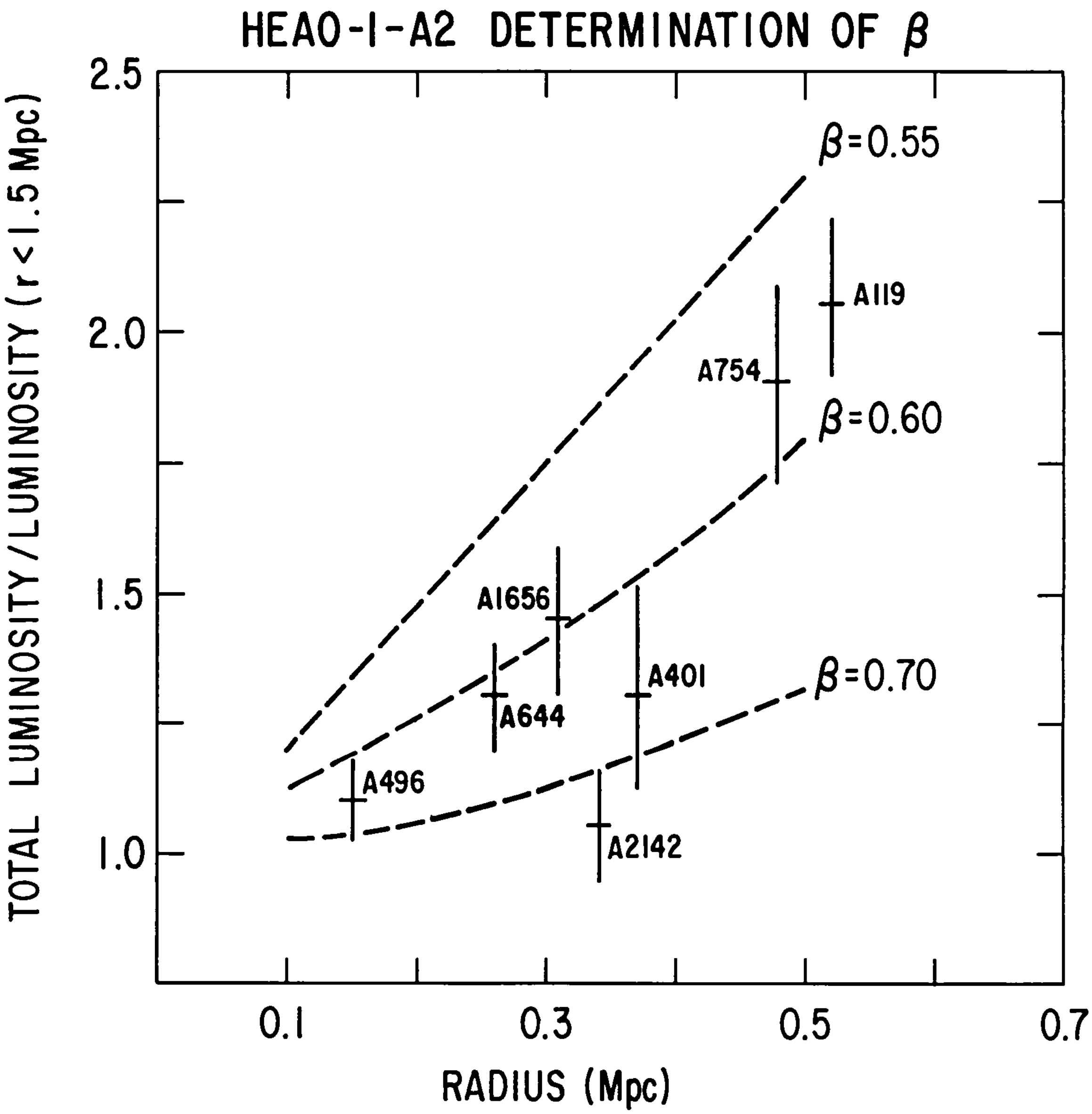

Figure 1: The parameter β in the isothermal surface brightness profile $S/S_0 = ((1 + (r/a)^2)^{-3\beta+1/2}$ measured using HEAO-1 A2 and Einstein IPC Observations The vertical error bars combine the systematic errors of both detectors in addition to the counting errors quoted by Abramopoulos and Ku (1983) The horizontal error in the core radius is from these authors.

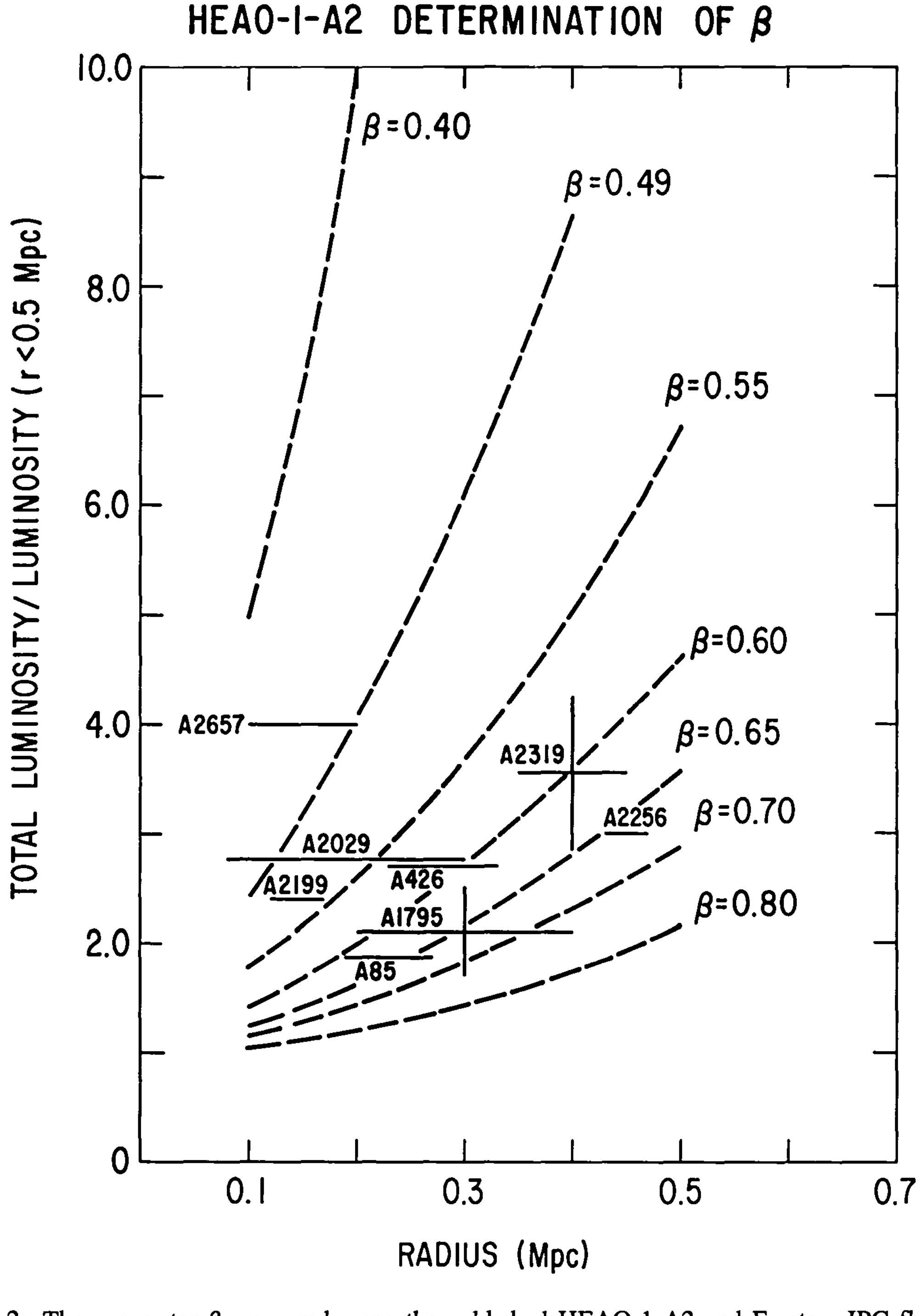

Figure 2: The parameter β measured using the published HEAO-1 A2 and Einstein IPC fluxes. The sample error bars combine the systematic uncertainty of the HEAO-1 A2 detector and the error in the IPC flux to give the error in the flux ratio The IPC fluxes, core radii, and their associated errors are from Jones and Forman (1984)

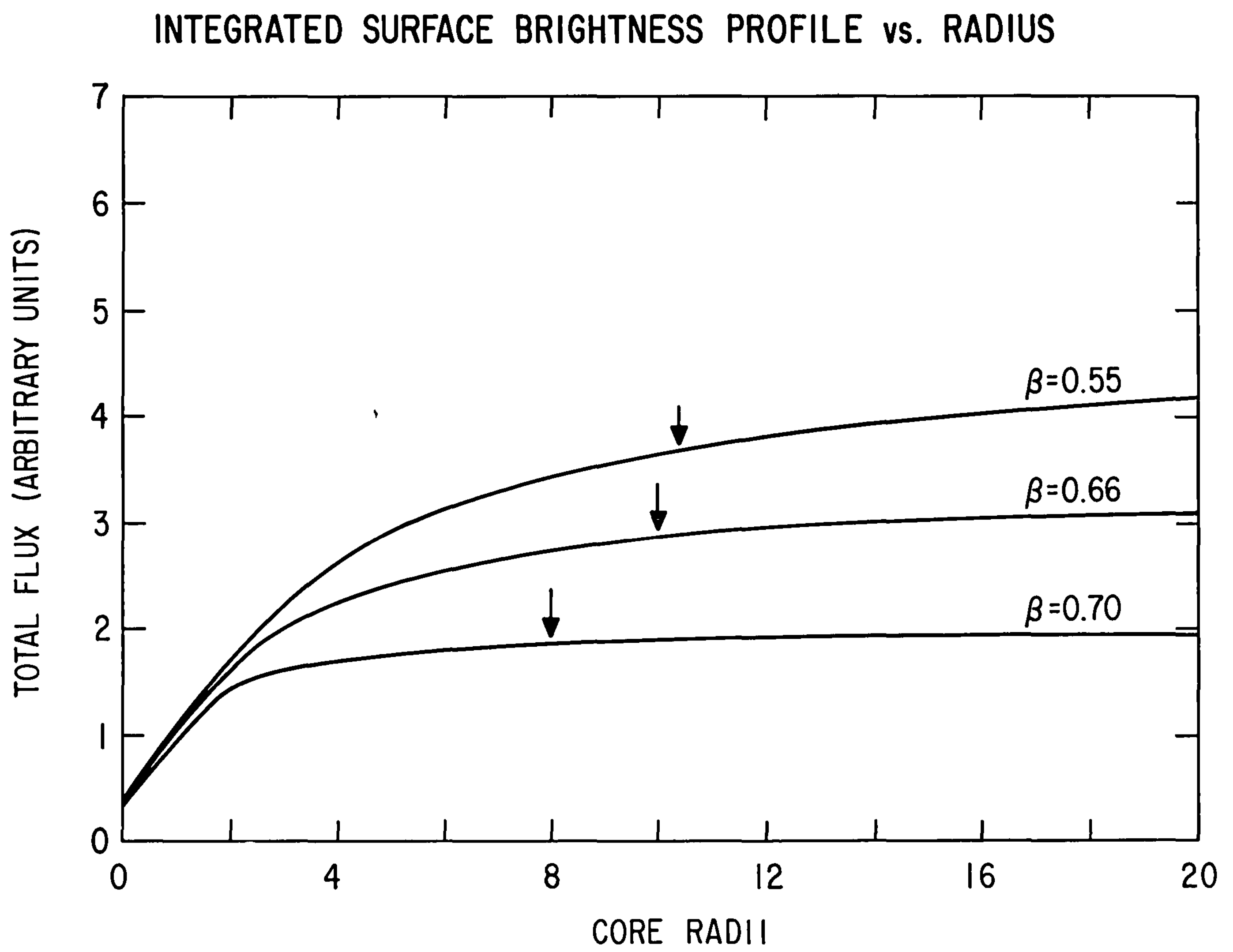

Figure 3 The total flux obtained from integrating the surface brightness profile $S/S_o = (1 + (r/a)^2)^{-3\beta+1/2}$ out to the specified radius (in units of core radius a) for a value of β The verticle arrows indicate the nominal cluster "edge" (90% of the total cluster flux). This determination is discussed in section IV of the text

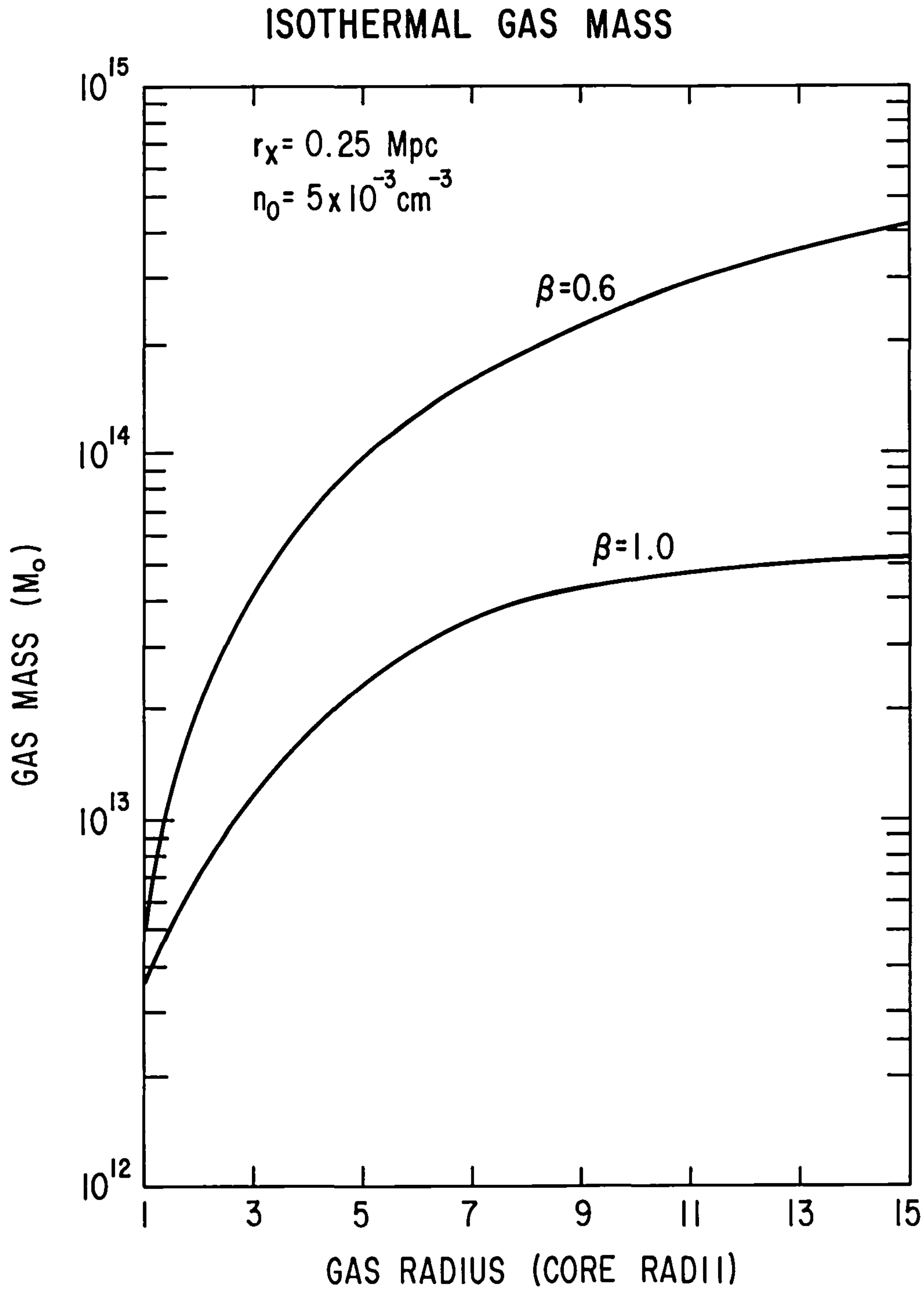

Figure 4 The mass of X-ray emitting gas is calculated under the assumption of isothermality The total gas mass (in solar masses) within a specified number core radii is shown for the β = 6 model, and for the case of a King profile (β = 1)

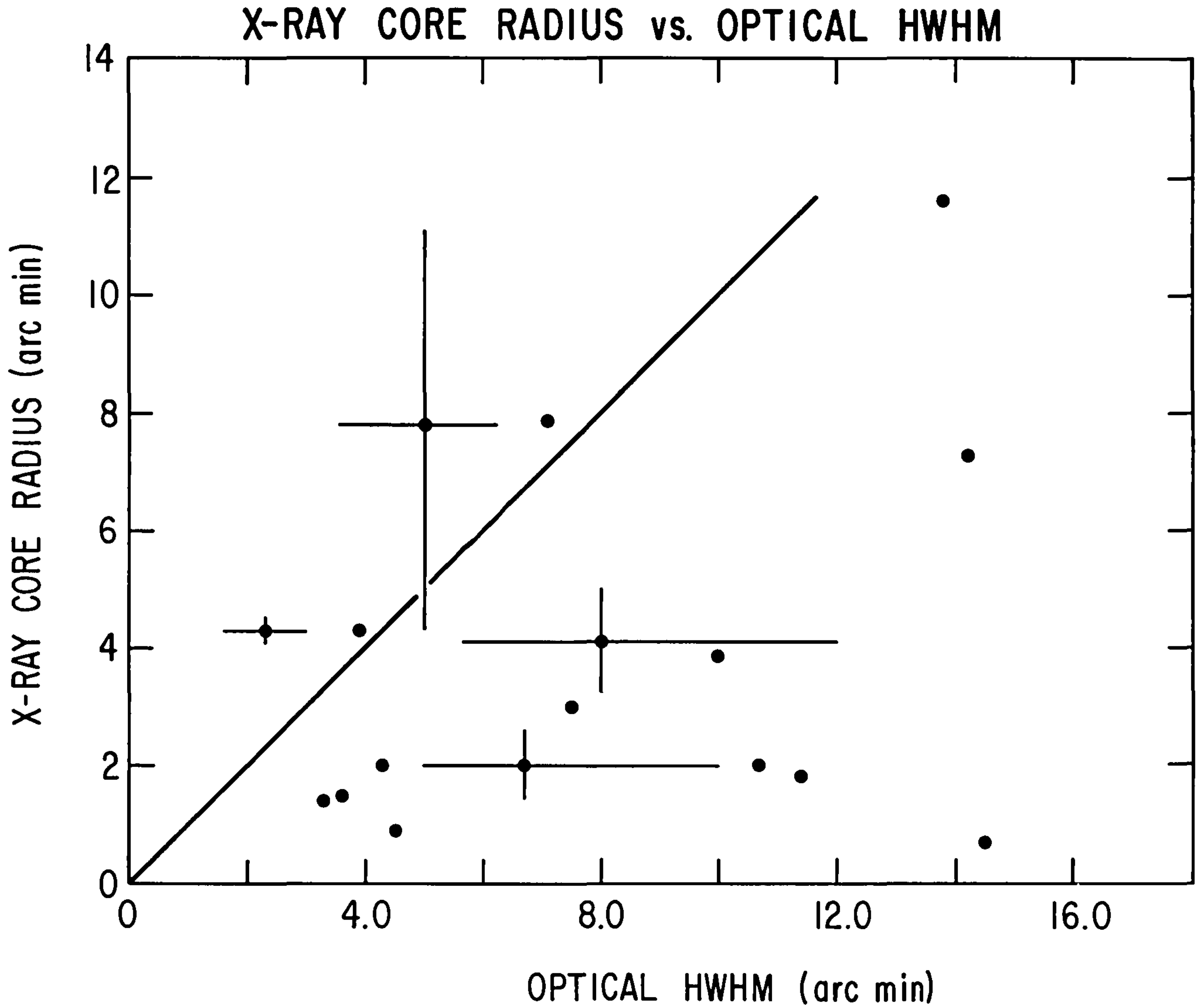

Figure 5 The characteristic scale length of the isothermal model is determined from the X-ray data and the optical data The condition for self-consistency, that the two determinations give the same value, is indicated by the line Sample error bars are given

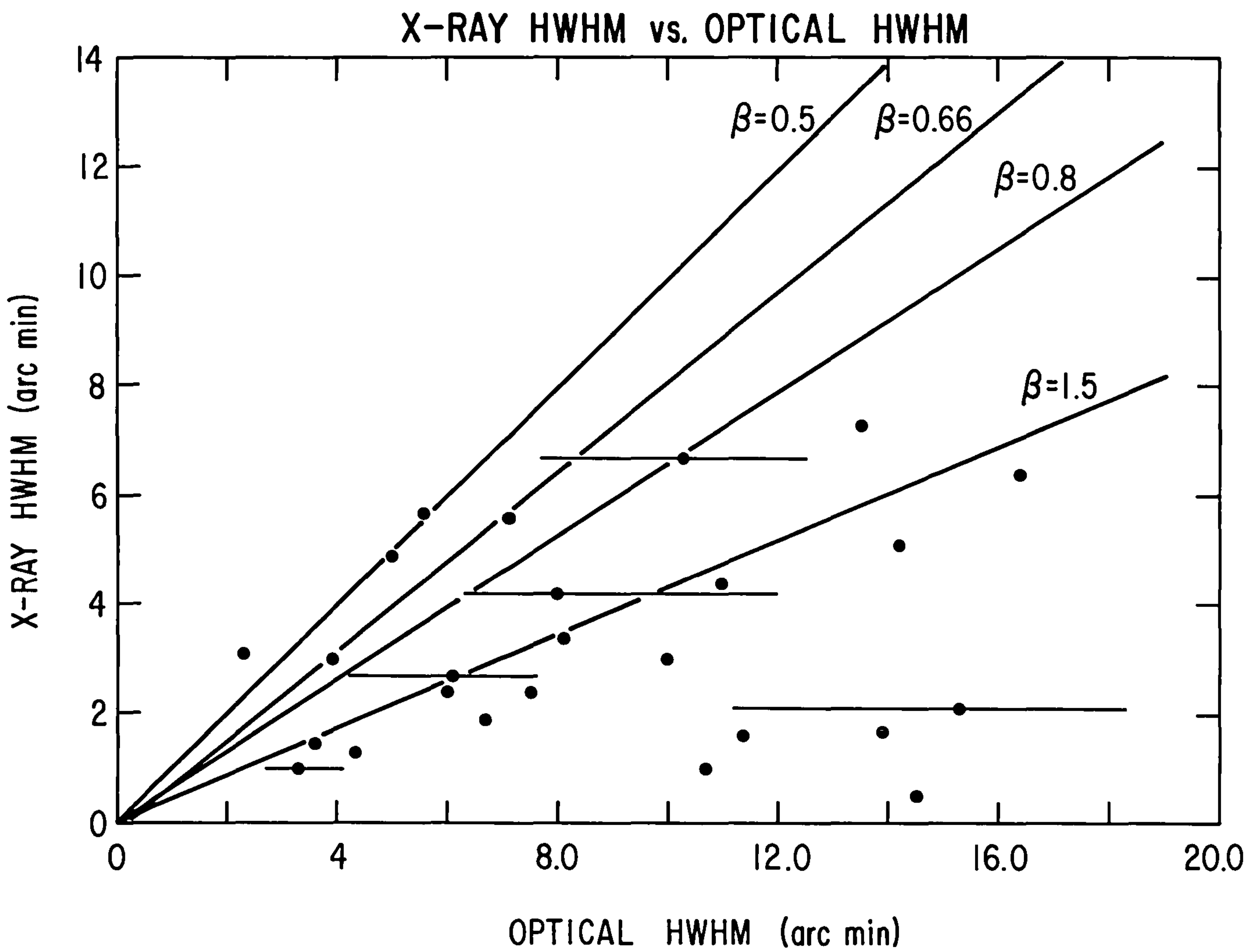

Figure 6 The X-ray Half Width at Half Maximum (HWHM) and the optical HWHM is shown for 25 clusters. A value of β specifies a given linear relationship between the two HWHM The range in β typically observed (5 - 75) predicts a narrow cone of observed pairs of HWHM The isothermal model predicts that these clusters should lie in the cone Even with the large errors in the HWHM, few clusters seem to satisfy the prediction

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15 Supplementary Notes

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