Astron. Astrophys. 259, L31–L34 (1992)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Observation of the Coma cluster of galaxies with ROSAT during the All-Sky Survey

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Received December 24, 1991, accepted January 23, 1992

Abstract.

The Coma cluster of galaxies was observed with the position sensitive proportional counter (PSPC) during the ROSAT all sky survey. We find evidence for substructure in this cluster. Diffuse X-ray emission is detected from the regions of the NGC 4839 and 4911 subgroups at 6% and 1% of the total cluster emission respectively. There may be emission associated with the NGC 4874 and 4889 subgroups as well. The NGC 4839 group appears to be in the process of merging with the cluster. These X-ray data show that at least some of the groups previously found in projection are in fact physical objects possessing potential wells deep enough to trap their own X-ray gas.

Because of the unlimited field of view of the all sky survey and the low background of the PSPC, we were able to measure the azimuthally averaged surface brightness of Coma out to approximately 100 arcmin, twice as far as was previously possible. Given the validity of our mass models, these new X-ray data imply that within 5 h_{50}^{-1} Mpc the binding mass of the Coma cluster is $1.8 \pm 0.6 \times 10^{15}$ h_{50}^{-1} $M_{\odot}$, and the fraction of cluster mass contained in hot gas is $0.30 \pm 0.14 h_{50}^{-3/2}$. Furthermore, the binding mass is more centrally concentrated than is the X-ray gas.

Key words: Clusters: of Galaxies - X-rays: general - cosmology

1. Introduction

The Coma cluster of galaxies has long been thought to be the archetype of a relaxed virialized cluster in a state of dynamical equilibrium (c.f. Kent and Gunn, 1982). It was the orginal cluster in which what has come to be known as dark matter was discovered (Zwicky, 1933). However, there are conflicting claims that Coma has substructure, which, if present, would show that it may not in fact have virialized. Substructure was claimed by Baier (1984), Fitchett and Webster (1987) and Mellier *et al.* (1988). The structure can be described as a clumping of galaxies around the brightest galaxies in the cluster. On the other hand, Geller and Beers (1982) and Dressler and Schectman (1988), using essentially the same data, claim that there is no statistically significant structure in the Coma cluster. The resolution of this conflict probably lies with the difficulty of identifying structure in projection using a small number of galaxies. The best studies use approximately 1000 objects, and groups are identified on the basis of as few as 20 galaxies. Using radial velocities to help reduce projection effects is not necessarily helpful since the velocity dispersion of the Coma cluster is nearly 1000 km s^{-1} so that a one sigma restriction still gives an acceptance column of 40 Mpc (for $H_o = 50$ km s^{-1} Mpc^{-1} which we use throughout this paper) through an object whose size is typically only 1 Mpc. Radial velocities can be helpful if the substructure comes from groups with smaller velocity dispersions than the main cluster, but not in the general case.

In this paper we report on our analysis of the ROSAT X-ray all sky survey data on the Coma cluster. Studies in X-rays offer two advantages over those done in the optical using galaxies to locate significant substructures. The statistical precision of the data is limited only by observing time, up to the limit imposed by systematics in the detector, and not by a finite number of galaxies. Secondly, X-ray surface brightness enhancements come from potential wells which are needed to hold the extra gas required to generate the enhancement. Hence X-ray images can locate the physical objects producing the potential wells. We show that some of the galaxy density enhancements previously pointed out in Coma are indeed associated with X-ray emission and are therefore likely to be real. Our data suggest that the most significant of these is associated with a small group about 50 arcmin away (corresponding to 2 Mpc) which is in the process of merging with the main cluster. The implication of these results is that Coma is not in a state of dynamical equilibrium, at least to some extent.

Our data can also be used to determine the mass of the Coma cluster, if the state of disequilibrium is not too severe, or if we restrict ourselves to regions that are not contaminated by enhanced emission. Unlike using galaxies as probes of the mass distribution, X-ray observations can in principle be used straightforwardly to determine M(r), since the X-ray emitting plasma is in hydrostatic equilibrium with the cluster potential and is a fluid so that its tangential and radial velocity dispersions are identical. The cluster mass depends therefore only on two parameters which are observable: the radial gas distribu-

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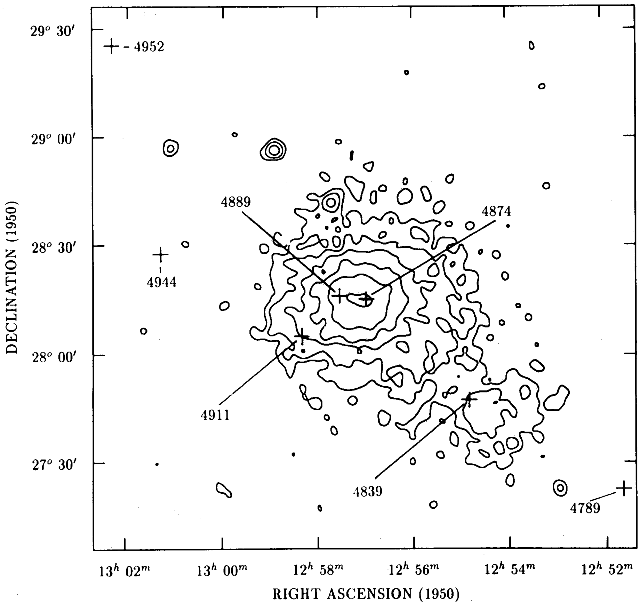

Fig. 1. Contour map of the Coma cluster in the 0.5 to 2.4 keV band. Contours are at 0.05, 0.12, 0.26, 0.43, 0.83, and 1.68 PSPC counts per 20×20 arcsec^2 pixel above a background of 0.016 counts per 20×20 arcsec^2 pixel. For our exposure 1.68 PSPC counts per 20×20 arcsec^2 pixel is 4.1×10^{-13} ergs cm^{-2} s^{-1} arcmin^{-2} in the 0.5 to 2.4 keV band. We also show the positions of some of the bright galaxies in Coma labeled by their NGC numbers.

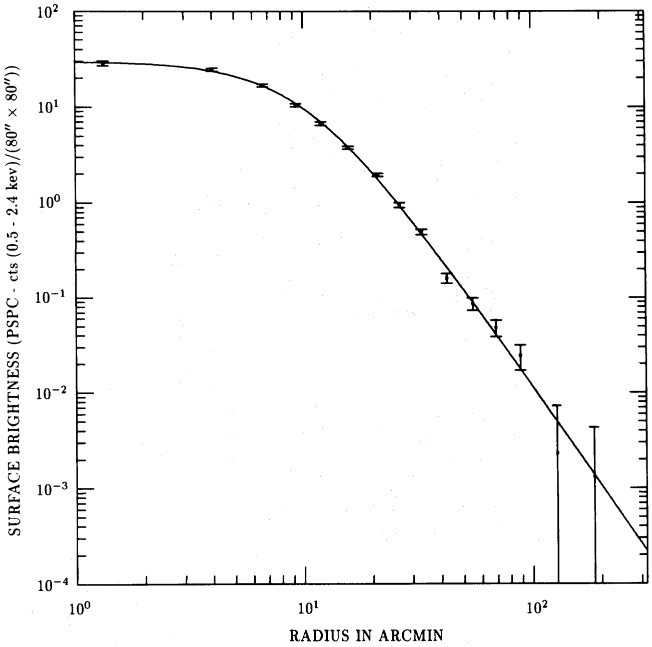

Fig. 2. Azimuthally averaged surface brightness distribution in the 0.5 to 2.4 keV band of the Coma cluster X-ray emission, excluding the NGC4839 group and obvious point sources. The curve is the best fitting β model.

tion $\rho_{gas}(r)$ and the temperature profile T(r) (c.f. review by Sarazin, 1988). With a measured radial extent of the X-ray emission of about 50 arcmin, Hughes (1989) could restrict the mass of Coma within 5 Mpc to $(1.1 - 3.0) \times 10^{15}$ $M_\odot$, even allowing for a large range of general mass distributions. In the Coma image from the ROSAT survey, we can trace the radial X-ray emission out to about 100 arcmin, which leads to a tighter constraint on the cluster mass.

2. Observation and data reduction

Coma was observed for 850 sec with the PSPC in Dec. 1990 during the ROSAT all sky survey. We will restrict our analysis in this paper to the energy band 0.5 to 2.4 keV in order to avoid any local variations of the soft X-ray background. The conversion from the observed counting rate in this band to the unabsorbed ("dereddened") flux in the same band is 2.28×10^{-11} erg cm^{-2} ct^{-1} assuming a temperature of 8 keV and a neutral hydrogen column density of 6×10^{19} cm^{-2} (see below). This conversion includes the vignetting caused by the sky survey scan pattern. The net counting rate of the cluster within 105 arcmin in this band was 10.5 cts s^{-1} which corresponds to a flux of 2.4×10^{-10} erg cm^{-2} s^{-1}.

In Fig. 1 we show a contour plot of the surface brightness distribution for this observation. The raw data have been sampled in 20×20 arcsec^2 pixels and then smoothed with a 2-dimensional Gaussian function with a $\sigma_x = \sigma_y = 2$ arcmin. Although the exposure time was short, and hence the 2-dimensional data are somewhat noisy, we do see a tendency of the position angle of the major axis of the elliptically shaped surface brightness distribution to rotate in a systematic fashion. The position angle is at approximately 80° East of North for the innermost contour, rotates to about 110° for the intermediate contours, and finally points at the extended object near the NGC4839 group at a position angle of about 230°. The IPC image of Coma (Sarazin, 1988; McMillan, Kowalski and Ulmer 1989) shows a similar change in major axis orientation for the first two of these regions. The position angle of the galaxy distribution is approximately constant at 80° (Thompson and Gregory, 1978). We also find emission in the region between the main cluster and the NGC4839 extended source.

The structure at the intermediate and outermost contours is caused mainly by two enhanced regions of X-ray emission near and probably associated with the NGC 4911 and NGC 4839 groups respectively. To quantify this assertion we have determined the net counting rates for these two regions. Annuli with the same inner and outer radii as the enhanced emission region were constructed. Source counts were accumulated from a range of position angles which encompassed the emission region; background, composed of cluster emission and true background, was accumulated from the remaining position angles. The net counting rates determined in this way were 0.13 ± 0.02 and 0.64 ± 0.03 cts sec^{-1} for the NGC 4911 and NGC 4839 regions respectively corresponding to 1.2 ± 0.2 % and 6.1 ± 0.3 % of the total Coma luminosity. The boundaries of the source regions were (inner radius, outer radius, position angle range) = (12.5 arcmin, 25 arcmin, 95° − 135°); and (33 arcmin, 64 arcmin, 200° − 260°) respectively.

Excluding a pie shaped region from position angles 200° to 260° (East of North), centered on the main cluster (in order to avoid the NGC 4839 group), and also excluding obvious point sources out to a radius of 3° (some of which are seen in Fig.1), we obtained the azimuthally averaged surface brightness distribution. The result is shown in Fig. 2 with 1 σ errors after a constant background was subtracted. We performed a fit to this distribution, using a modified isothermal King profile

$S(r) = S_o(1+(r/a)^2)^{(.5-3\beta)}$, where a is the core radius, β is the density slope parameter, and S_o is the central surface brightness. The fit yielded, at a reduced χ^2 of 1.8, a $S_o = 29.9 \pm 2.0$ cts pixel^{-1} corresponding to $S_o = (2.0 \pm 0.13) \times 10^{-2}$ cts sec^{-1} arcmin^{-2} or $(4.6 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} arcmin^{-2}, a $\beta = 0.75 \pm 0.03$ and a core radius of 10.5 ± 0.6 arcmin, corresponding to (0.42 ± 0.024) h_{50}^{-1} Mpc. These errors are at the 68 % confidence level. Although the reduced χ^2 is not particularly good, much of it comes from residual structure identified above which we have not excluded from the fit. The best fit is plotted as solid curve in Fig. 2. Our results are in good agreement with the parameters found by Hughes (1988) for the Einstein IPC data, using the average of all IPC fields, but we can trace the radial surface brightness out to about 100 arcmin which is approximately twice as far as could be done with the Einstein data. Using the formulae in Henry and Henriksen (1986) for deriving the electron density from the observed surface brightness, we find that the central electron density is $n_o = 2.89 \pm 0.04 \times 10^{-3}$ $h_{50}^{1/2}$ cm^{-3}.

The X-ray spectrum of the inner 33 arcmin diameter, this time using the 0.1 to 2.4 keV band, was fit to a Raymond and Smith model. Fixing the metal abundances at 0.22 solar (Hatsukade, 1990), we found an average temperature of $7.8^{+3.8}_{-1.8}$ keV (68% confidence for one interesting parameter), consistent with the Ginga result of 8.2 ± 0.2 keV. The NGC 4839 and 4911 groups have too few counts to permit an accurate temperature measurement, as does the region between the maxima and NGC 4839.

3. Discussion

3.1. X-ray morphology of Coma

The Coma cluster of galaxies appears in the ROSAT survey as an elliptically shaped X-ray source whose orientation is a function of radius, rotating by approximately 150° from the inner to the outer contours. This rotation is likely due to the superposition of X-ray emission from structure in the cluster. In Fig. 1 we indicate bright galaxies in the Coma cluster with Zwicky (1963) magnitudes < 13.75 and radial velocities in the range 5500 to 8500 km s^{-1}. Such bright galaxies are associated with the groups identified from the increased galaxy density in projection. The inner ellipticity might stem from the two subclumps associated with NCG 4874 and NGC 4889 that Fitchett and Webster (1987) and Mellier *et al.* (1988) find in the galaxy distribution in that region. The intermediate ellipticity results from emission from the NGC 4911 subgroup. Finally the outermost elliptical structure visible in Fig. 1 is due to the ongoing merger of the NGC4839 group with the main cluster.

We believe at least this latter enhancement in the galaxy isopleths is a physical group of galaxies because its X-ray properties resemble the properties of isolated groups. An EXOSAT pointing near that position revealed a temperature of $1.9^{+1.7}_{-0.7}$ keV (Edge, 1989), and, from our measurement, the luminosity of the source is 6.1% of the main cluster corresponding to $L_x = 3 \times 10^{43}$ h_{50}^{-2} erg sec^{-1} (assuming a temperature of 1.9 keV). Both parameters are consistent with the X-ray parameters Kriss, Cioffe and Canizares (1983) have determined for 16 poor clusters with central dominant galaxies. The luminosity of the NGC 4911 enhancement indicates that it could be a group as well, but we have no temperature information for it.

Evidence, that the NGC 4839 group is falling towards the main cluster comes from the offset between NGC 4839 and the center of the X-ray surface brightness associated with its group. Similar structure has been observed in A2256 which is also interpreted as a merger of a small group with the main cluster (Briel *et al.*, 1991). The radio maps of NGC 4839 itself, which show evidence for head-tail structure with the tail pointing away from the main cluster (Cordey, 1985; Birkinshaw and Davies, 1985; Venturi, Giovannini, and Feretti, 1990) supports this interpretation. Similar structure in other galaxies in other clusters is taken to indicate the direction of motion in the sense that the radio emission is swept back by the impinging intracluster medium. Such an interpretation would indicate that NGC 4839 is moving toward the main Coma cluster.

3.2. Mass determination

Because of the high temperature of the Coma cluster there is no measured temperature profile T(r). The best approach employed in the past to constrain the binding mass is then to combine the optical and X-ray data. Hughes (1989) has performed this analysis for Coma. He uses binding mass models of the form $\rho_b(r) = \rho_{bo} \times (1 + (r/r_b)^2)^{-n/2}$, King (1966) profiles, and "mass-follows-light". We have examined what additional constraint our data place on the mass of Coma for the first two profiles. We have found that our new X-ray data is more restrictive for these models then the combination of data used by Hughes (1989).

The method that we use assumes that the cluster gas has relaxed to hydrostatic equilibrium. As we discussed above, there are some regions of the Coma cluster where this assumption is not valid due to enhanced emission. We will therefore exclude from our analysis that region where the assumption is least likely to be valid. In particular, we only discuss the data shown in Fig. 2 which excludes emission from the NGC 4839 group. Emission from the other three groups discussed above is not important, as may be seen from Fig. 2. The excess at 21 arcmin is caused by the NGC 4911 group yet it is barely above the curve. Far more important is the total radial extent of the X-ray emission since in what follows we reject all models whose temperatures drop to zero before our observed surface brightness becomes undetectable in the noise, which we take to be at a radius of 100 arcmin.

Briefly, the method consists of assuming a mass distribution and then calculating what temperature distribution would be needed to insure that the inferred X-ray gas distribution (assumed to make a negligible contribution to the total mass) is in hydrostatic equilibrium with that mass. We then accept only those models in which the calculated temperature distribution is not zero inside 100 arcmin, which give the observed average temperatures in the EXOSAT and TENMA beams (8.5 ± 0.5 keV and 7.5 ± 0.2 keV for beams 0.75° and 3° respectively at 90 % confidence, see Hughes, 1989), and which have a higher binding matter density than hot gas density at 100 arcmin. Our data can place tighter limits than does that of Hughes (1989) because we have a more extended hot gas atmosphere which still has the same average temperature as before, so a smaller binding mass is inferred. We find that, for the n = 3, 4, 5, and King models, the core radius must be 5-12, 15-19, all values excluded, and 7-12 arcmin respectively. The total allowed mass range from all the models within 5 h_{50}^{-1} Mpc (the same radius used by Hughes) is $1.8 \pm 0.6 \times 10^{15}$ h_{50}^{-1} $M_\odot$. These values should be compared with those in Fig. 7 and Table 5 of Hughes. The net result is that the uncertainty in the mass of

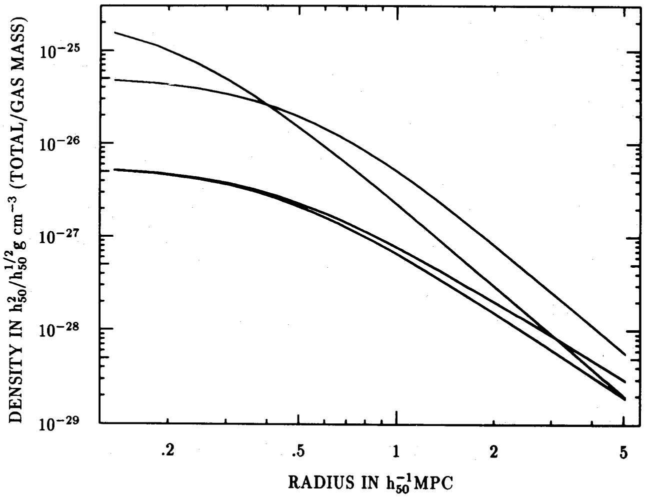

Fig. 3. Comparison of the density of total and hot gas masses. The upper two curves are the models which are fully consistent with the X-ray data and which give the minimum and maximum total enclosed mass at 5 h_{50}^{-1} Mpc. The lower two curves are the envelope of the hot gas density with its error.

the Coma cluster is reduced from a factor of three to a factor of two given the validity of the models.

In Fig.3 we show the mass density of the hot gas and that of the total binding matter for the allowed core radii in the n=3 model. This model gives the largest range of total mass and thus is an indication of the error bounds on the binding matter density. We see that the total mass distribution is more concentrated toward the cluster center than is the hot gas. This result also follows just from the assumption of hydrostatic equilibrium and a monotonically decreasing temperature distribution with radius, given the shape of the gas density distribution (cf Sarazin 1988, p179). Eyles et al. (1991) find a similar result for the Perseus cluster. The more concentrated distribution suggests that the dark matter (which makes up most of the total matter) is baryonic in order for it to dissipate energy and cool to a lower temperature than the hot gas.

In addition to the different shapes of the two matter distributions, the relative fraction of hot to total matter is also interesting. The total hot gas mass within 5 h_{50}^{-1} Mpc is $5.1 \pm 1.5 \times 10^{14}$ $h_{50}^{-5/2}$ $M_{\odot}$. Hence the fraction of cluster mass contained in hot gas is $0.30 \pm 0.14 h_{50}^{-3/2}$. This value is approximately the asymptotic limit at very large radius because the integral of both densities in Fig. 3 flattens within the range of our data. Such a fraction is larger than that contained in the galaxies. Models of biased galaxy formation (Kaiser, 1984; Bardeen *et al.*, 1986) predict more efficient galaxy formation in denser regions of the Universe such as clusters of galaxies. In this context it is difficult to understand why so much of the presumably primordial baryonic material has not be consumed in galaxy formation. Furthermore, if the matter in the Coma cluster is representative of the Universe, then $\Omega_B/\Omega_o \geq 0.3 h_{50}^{-3/2}$ where Ω_B is the fraction of the closure density contained in baryons. Simple models of primordial nucleosynthesis (Walker *et al.*, 1991) need $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ in order to agree with observations, hence $\Omega_o \leq 0.17$ $h_{50}^{-1/2}$.

Acknowledgements. The ROSAT project is supported by the Bundesministerium für Forschung und Technologie (BMFT). JPH thanks Prof. J. Trümper and the ROSAT group for their hospitality while this paper was being written. JPH was supported by NASA Grant NAG5-1256 and NSF Grant INT89 12660. HB was supported by the Deutsche Forschungsgemeinschaft through the research program "Theorie kosmischer Plasmen". We thank A. Cavaliere and R. Scaramella for several interesting ideas at an early stage of this paper, and S.D.M. White for his comments on the manuscript.

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