# REVISITING THE MASS OF THE COMA CLUSTER FROM X-RAY OBSERVATIONS

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I re-examine mass estimates of the Coma cluster from pre-*ASCA* X-ray spectral observations. A large range of model dark matter distributions are examined, under the assumptions of hydrostatic equilibrium and spherical symmetry, to determine the widest possible allowed range on the total mass of the cluster. Within a radius of 1 Mpc, the total cluster mass is tightly constrained to be $(6.2 \pm 0.9) \times 10^{14}\, M_\odot$ and the ratio of luminous baryonic matter to total matter lies between 13% and 17%. Within a radius of 3 Mpc the total mass is $(1.3 \pm 0.5) \times 10^{15}\, M_\odot$ and the luminous matter fraction is 20%-40%. I find that the "universal" dark matter density profile proposed by Navarro, Frenk, and White,[11] based on N-body simulations of a standard cold-dark-matter dominated Universe, predicts a steep temperature gradient within the core of the cluster that is a poor fit to the Coma data and can be rejected at greater than 99% confidence.

## 1 Introduction

Determination of the total masses of galaxy clusters is of great interest because of what these measurements can tell us about the amount, nature, and distribution of dark matter. The ratio of luminous to dark matter, which provides a lower limit to the baryon fraction, appears to be considerably higher in rich clusters of galaxies than that allowed by Big-Bang nucleosynthesis in a flat ($\Omega = 1$) $\Lambda = 0$ Universe. The Coma Cluster, because it is nearby and well observed, stands as an important laboratory for studies of this kind.

I was motivated by several factors to revisit measuring the mass of the Coma cluster from X-ray observations. One was to address the reliability and accuracy of X-ray–derived cluster mass estimates, which have been questioned recently.[1] Another was to see if Coma's radial gas temperature profile, which is essential for determining the gravitating mass, showed evidence for a remarkably rapid drop at the cluster outskirts as seen in the cluster Abell 2163 by *ASCA*.[9] The availability of previously unpublished scanning data from the *Ginga* satellite that provides strong constraints on the temperature distribution over spatial scales up to 1° was a further motivation.

In this article I utilize all available pre-*ASCA* temperature data on Coma from *Tenma*,[5] *EXOSAT*,[7] *Ginga*[6] and coded aperture mask data from *Spacelab-2*[12] (see Fig. 1). The *ROSAT* surface brightness profile [2] was used to define

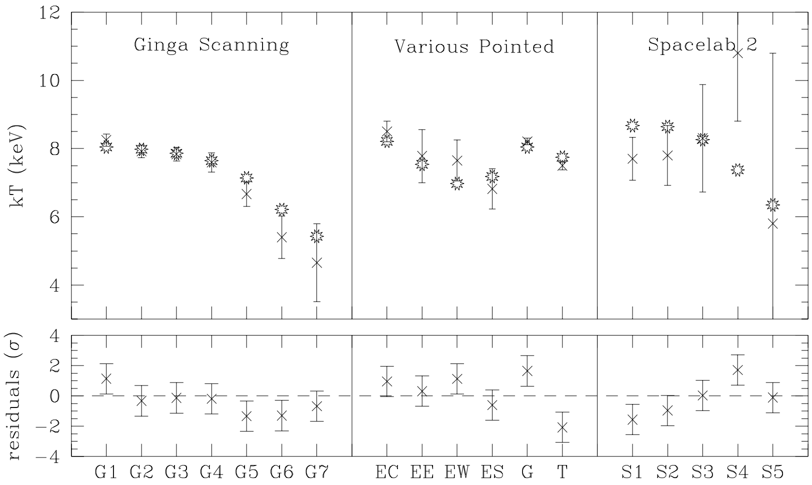


Figure 1: Projected temperatures of the hot gas in the Coma Cluster (top panel) from various sources with one-sigma error bars (*Ginga* scan data on the left part of the plot; *Spacelab-2* data on the right; and pointed data from *Tenma*, *Ginga*, and several *EXOSAT* fields in the middle). The temperature values from the overall best-fit dark matter profile are shown as the starred symbols. The bottom panel shows the residuals between the data and the model.

the gas density profile and the galaxy distribution was taken from Millington and Peach.[10] I determine the cluster mass by constraining the parameters of a dark matter halo function using methods described previously.[4] Briefly, given the *ROSAT* gas density profile and a particular set of parameter values for the dark matter halo, one directly solves for the temperature profile, which is then compared to the observed temperature values using a figure-of-merit function (I employ $\chi^2$ here) to assess the quality of the fit. A value of $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, which yields a distance to Coma of 140 Mpc, is used throughout.

## 2 Parameterized Dark Matter Halos

For the dark matter profile I use the three-parameter functional form given by $\rho_{\rm DM} = \rho_0[1 + (R/R_{\rm DM})^2]^{-\alpha}$ and the allowed ranges of all three parameters are determined. The fits to the data are reasonably good (minimum $\chi^2 = 21.4$ for 15 degrees of freedom; this model is plotted in Fig. 1) and are summarized in Fig. 2. The left panel shows that the allowed values of the scale length $R_{\rm DM}$ and index $\alpha$ are strongly correlated. Formally I can reject a dark matter model that is distributed like the X-ray gas with high significance (>99%

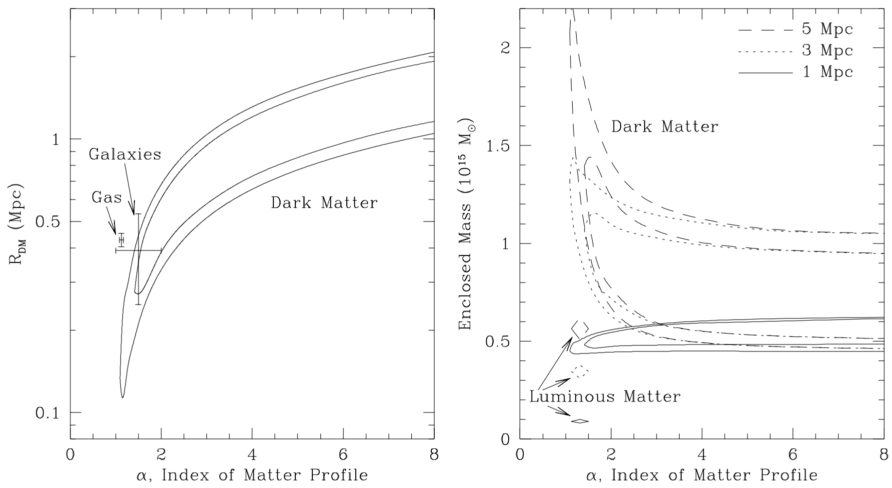


Figure 2: (Left) Allowed ranges (at the 90% and 99% confidence levels) of the scale length of the dark matter distribution ($R_{\rm DM}$) as a function of the power-law index of the matter distribution, $\alpha$. (Right) Allowed ranges (also 90% and 99% confidence levels) of the masses of the luminous and dark matter in the Coma cluster within three fiducial radii as indicated plotted as a function of $\alpha$.

confidence), but a model with the dark matter distributed like the galaxies is allowed, although it is not highly favored. Note that the current data do not constrain the maximum value of $\alpha$ and, in fact, $\chi^2$ continues to drop, albeit very slowly, for even larger values of $\alpha$ than shown.

The total gravitating mass of Coma is well constrained by these fits as shown in the right panel of Fig. 2. Here the masses, integrated within three fiducial radii (1 Mpc, 3 Mpc, and 5 Mpc), were determined based on the allowed ranges of $R_{\rm DM}$, $\alpha$, and $\rho_0$. (Note how the dark matter masses reach asymptotic values at large values of $\alpha$ so, even though $\alpha$ is not constrained at the upper end, my mass estimates are robust.) The total cluster mass (luminous plus dark) as well as the baryon fraction within 1 Mpc and 3 Mpc are quoted in the abstract for the 99% confidence level. The mass within 5 Mpc is $(1.9 \pm 0.9) \times 10^{15}\, M_\odot$ and the luminous matter fraction is 20%–55%.

The temperature profiles we obtain are nearly all convectively stable, i.e., $|\frac{d \ln T}{d \ln \rho}| < \frac{2}{3}$, within the maximum observed extent of the cluster $\sim$3.3 Mpc. The few models that violate this constraint lie between the 90% and 99% confidence contours at low values of $R_{\rm DM}$ and $\alpha$ and thus are statistically less likely to be acceptable solutions anyway. In summary, I find no evidence for steep temperature gradients in Coma that might indicate nonhydrostatic or other exotic conditions.

## 3 "Universal" Dark Matter Halos

Based on their $N$-body simulations of a standard cold-dark-matter dominated Universe, Navarro, Frenk, & White [11] (NFW) find that the radial dark matter density profiles of systems ranging from dwarf galaxies to rich clusters of galaxies can be well described by the simple function $\rho = \delta_c \rho_{\rm crit}/(r/r_s)(1+r/r_s)^2$, where $\delta_c$ is the characteristic overdensity of the halo in terms of the critical density $\rho_{\rm crit}$ and $r_s$ is a characteristic scale radius.

The best fit of this function to the Coma temperature data is obtained for $r_s \sim 0.5$ Mpc and $\delta_c \rho_{\rm crit} \sim 4 \times 10^{-26}$ g cm$^{-3}$. However, this fit is formally unacceptable: the minimum $\chi^2$ of 31.5 for 15 degrees of freedom can be rejected at greater than 99% confidence. The central temperature in the best-fit model is rather high ~16.5 keV but drops rapidly to ~8 keV at $r_s$ and thereafter continues to fall, although more gradually. The steep temperature gradient near the center of the cluster is inconsistent with the observed data for Coma. This also appears to be the case for the rich cluster Abell 2256 where the NFW halo function predicts a considerably steeper temperature profile in the center of the cluster than observed.[8] On the other hand, the NFW function appears to be an acceptable description of the optically-derived average mass profile of galaxy clusters.[3] Further work on the mass distribution of Coma as well as other galaxy clusters is clearly needed in order to resolve this important issue.

## References

1. C. Balland and A. Blanchard, preprint (astro-ph/9510130).
2. U.G. Briel, J.P. Henry and H. Böhringer, *A&A* **259**, l31 (1992).
3. R.G. Carlberg *et al*, *ApJ* **485**, L13 (1997).
4. J.P. Hughes, *ApJ* **337**, 21 (1989).
5. J.P. Hughes *et al*, *ApJ* **327**, 615 (1988).
6. J.P. Hughes *et al*, *ApJ* **404**, 611 (1993).
7. J.P. Hughes, P. Gorenstein and D. Fabricant, *ApJ* **329**, 82 (1988)
8. L. Kopman *et al*, *ApJ* **470**, 102 (1996).
9. M. Markevitch *et al*, *ApJ* **456**, 437 (1996).
10. S.J.C. Millington and J.V. Peach, *MNRAS* **221**, 15 (1986).
11. J.F. Navarro, C.S. Frenk and S.D.M. White, *ApJ* **462**, 563 (1996).
12. M.P. Watt *et al*, *MNRAS* **258**, 738 (1992).

This research was partially supported by NASA LTSA Grant NAG5-3432.