X-RAY OBSERVATIONS OF M87's HALO

D. Fabricant, M. Lecar and P. Gorenstein
Harvard-Smithsonian Center for Astrophysics,
Cambridge, Massachusetts, USA.

We briefly describe the soft X-ray image of M87 obtained using the imaging proportional counter aboard the Einstein Observatory. These data provide further strong evidence for the existence of a massive halo of dark matter surrounding M87 and allow a much more precise determination of its mass. Two pointing positions of the satellite were analyzed; one centered on M87, the other 63' south and 25' east of M87. The field of view of the imaging proportional counter is 60'x60', and it attains a two dimensional spatial resolution of $\sim$ 1.5' in a spectral range spanning 0.1 to 4.5 keV.

As previous reports had suggested (Gorenstein et al. 1977; Fabricant et al. 1978), the present observations show M87 to be a strong, very extended, thermal X-ray source with a temperature near 2 keV, surrounded by weaker and still more extended emission from hotter gas associated with the Virgo cluster as a whole (Davison, 1978; Lawrence, 1978). We find M87 to have a total 0.5-4.5 keV X-ray luminosity of about 2×10^{43} ergs/sec, and an extrapolated 2-6 keV luminosity of approximately 1×10^{43} ergs/sec. The total mass of gas inferred from the X-ray measurement exceeds 10^{12} solar masses.

Figure 1 is a contour plot of the central region of the X-ray emission. The contour levels are separated by a factor of 2. This is shown principally to demonstrate the near circular symmetry of the source in a central region which is 30' or 150 kpc across (assuming a distance of 18 Mpc to M87).

Figure 2 is the radially binned 0.7-3.0 keV surface brightness profile of M87, with both the instrumental background and the background from the Virgo cluster diffuse emission subtracted. The data beyond 30 arcminutes has been taken from the field to the southeast. It has been assumed that the radial symmetry continues at large radii even though full 360° coverage is not presently available.

From 4 to 40 arcminutes, the surface brightness profile follows a -1.7 power law, but decreases more rapidly at larger radius. The

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 689–693.

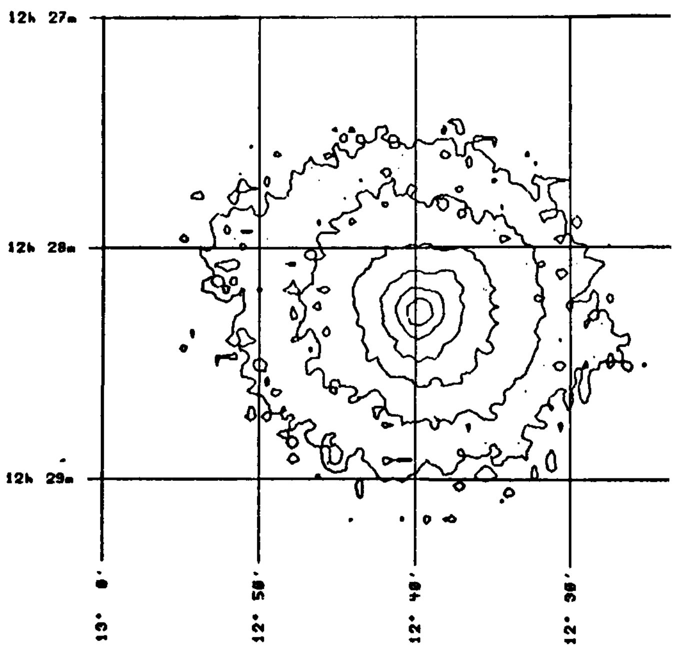

Figure 1. Contour plot of Central Region of M87.

https://doi.org/10.1017/S1539299600004603 Published online by Cambridge University Press

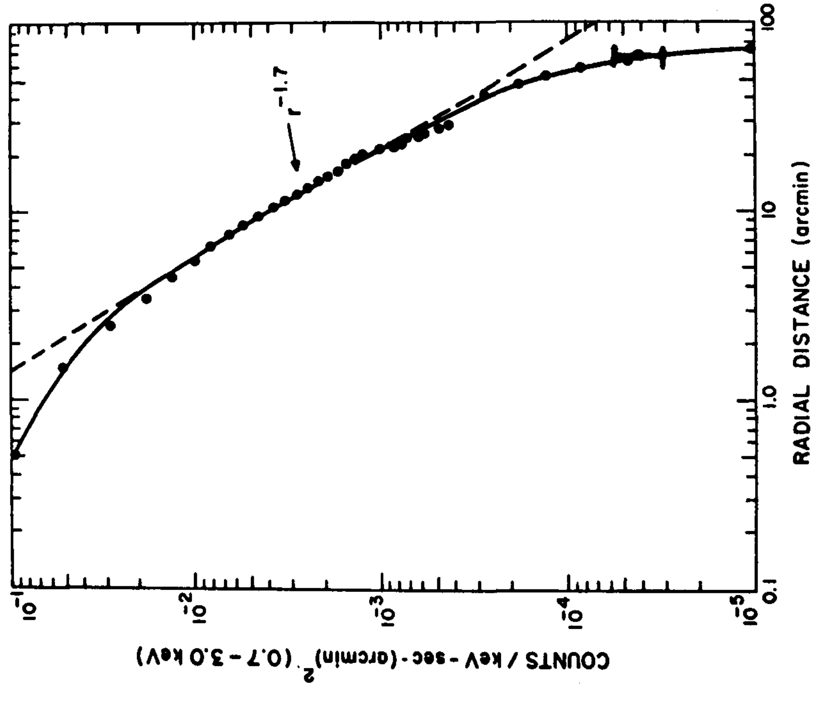

Figure 2.
0.7 – 3.0 keV Surface Brightness Profile of M87.

https://doi.org/10.1017/S1539299600004603 Published online by Cambridge University Press

0.7-3.0 keV surface brightness falls to a level approximately equal to that of the Virgo cluster in the same energy band at a radius between 50 and 60 arcminutes. At 70 arcminutes, M87's surface brightness is only about 10% of the cluster's.

By convolving model spectra (calculated using the recently revised plasma emission code of Raymond and Smith) with the detector response and comparing them to the data, we find no evidence for a temperature or abundance gradient in the gas in the region 5' - 15'. Here, the temperature is 2.6 ± 0.6 keV assuming an iron abundance of 4.0×10^{-5} relative to hydrogen. At radii less than 5', the gas temperature appears to fall below this value. Between 15' and 30', the temperature lower limit is ~ 2.5 keV. Due to the lack of more precise spectral data, we have assumed in what follows that the gas temperature is constant at 2.6 keV.

In considering models for the gas distribution around M87, hydrostatic equilibrium in the gravitational potential of the galaxy is not only the simplest assumption, but the X-ray data provide some fairly compelling reasons for considering it the most plausible one. Certainly the bulk of the gas surrounding M87 is not contained by the pressure of the external cluster medium because this matter is not sufficiently dense. If the 2 keV gas surrounding M87 is not in hydrostatic equilibrium at all, it would expand ~ 100 kpc in 10^8 years, leading to the implausible possibilities that either we see M87 in a transitory phase or that the gas is resupplied at a rate approaching $10^4\ M_\odot$/yr. Finally, the limits on the temperature gradient are incompatible with an alternative hypothesis of freely infalling gas.

Mathews (1978) has shown that if the gas around M87 is isothermal and in hydrostatic equilibrium, M87 must have a massive extended dark halo in order to gravitationally contain the gas. The gas is not massive enough by an order of magnitude to be selfgravitating, and the visible galaxy is much too compact for it to be the source of the gravitational potential. He derived a halo mass $\gtrsim 10^{14}$ solar masses based on model fitting to earlier, less precise X-ray measurements. Because we now know the surface brightness profile is well approximated by a power law, we may simply estimate the mass of M87's halo as follows. Combining the equation of hydrostatic equilibrium and the ideal gas law:

$$\frac{dP_{gas}}{dr} = \frac{-GM(r)\rho_{gas}}{r^2} \quad \text{and} \quad P_{gas} = \frac{\rho_{gas} kT_{gas}}{\mu M_H}$$

we obtain for an isothermal gas:

$$M(r) = \frac{kT_{gas}}{\mu M_H G} \cdot \left(\frac{-d\ \ln\rho_{gas}}{d\ \ln r}\right) \cdot r$$

Since the surface brightness follows a 1.7 power law, the unprojected gas density will have a $r^{-1.35}$ dependence. Thus:

https://doi.org/10.1017/S1539299600004603 Published online by Cambridge University Press

$$M(r) = 1.3 \times 10^{13} M_{\odot} \left(\frac{r}{100 \text{ kpc}}\right)$$

for 40' or $\sim$ 210 kpc, M $\sim 2.7 \times 10^{13} M_{\odot}$.

The figure of $2.7 \times 10^{13} M_{\odot}$ should be viewed as a lower limit to the mass of M87. Pressure exerted by the external cluster medium will become significant beyond 200 kpc, so the X-ray measurements at larger radii will no longer accurately reflect the halo mass distribution. The halo could cut off steeply beyond 200 kpc, but conversely, it could continue indefinitely and not perturb the X-ray measurements. However, to attain a total mass of $10^{14} M_{\odot}$, M87's halo would have to have a radius of 0.8 Mpc or $\sim 2.3^{\circ}$ at the distance of M87.

There have been previous indications of extended, dark halos from optical work, including sensitive photometry and studies of pairs of galaxies, but the X-ray data provide a direct means of measuring the halo mass distribution.

REFERENCES

Davison, P.J.N.: 1978, M.N.R.A.S. 183, 39P.

Fabricant, D., Topka, K., Harnden, F.R. Jr., Gorenstein, P.: 1978, Ap. J. (Letters) 226, L107.

Gorenstein, P., Fabricant, D., Topka, K., Tucker, W., and Harnden, F.R. Jr.: 1977, Ap. J. (Letters) 216, L95.

Lawrence, A.: 1979, M.N.R.A.S. 185, 423.

Mathews, W.G.: 1978, Ap. J. 219, 413.

Raymond, J.C. and Smith, B.W.: 1977, Ap. J. (Suppl.) 35, 419.