EVIDENCE IN VIRGO FOR THE UNIVERSAL DARK MATTER HALO

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ABSTRACT

A model is constructed for the mass and dynamics of M87 and the Virgo Cluster. Existing surface photometry of the galaxy, mass estimates from X-ray observations of the hot intracluster gas, and the velocity dispersions of early-type Virgo galaxies are all used to constrain the run of dark matter density over \(0 \leq r \leq 2\) Mpc in the cluster. The “universal” halo advocated by Navarro, Frenk, & White, \(\rho_{\text{dm}} \propto (r/r_c)^{-1}(1 + r/r_c)^{-2}\), provides an excellent description of the combined data, as does a Hernquist profile with \(\rho_{\text{dm}} \propto (r/r_c)^{-2}(1 + r/r_c)^{-3}\). These models are favored over isothermal spheres, and their central structure is preferred to density cusps either much stronger or much weaker than \(r^{-1}\). The galaxies and gas in the cluster trace its total mass distribution \(\rho_{\text{gal}} \propto \rho_{\text{dm}}\), the galaxies’ velocity ellipsoid is close to isotropic, and the gas temperature follows the virial temperature profile of the dark halo. The virial radius and mass and the intracluster gas fraction of Virgo are evaluated.

Subject headings: dark matter — galaxies: clusters: general — galaxies: clusters: individual (Virgo) — galaxies: individual (M87) — intergalactic medium

1. INTRODUCTION

Some recent simulations of structure formation in CDM universes have suggested that dark matter halos generally form with a “universal” density profile, in which \(\rho_{\text{dm}} \propto (r/r_c)^{-1}(1 + r/r_c)^{-2}\) (Navarro, Frenk, & White 1997, hereafter NFW). However, this claim has been questioned by other numerical work (e.g., Anninos & Norman 1996; Kravtsov et al. 1998); in particular, Moore et al. (1998) find instead that \(\rho_{\text{dm}} \propto r^{-1.4}\) as \(r \rightarrow 0\) in a set of highly resolved N-body halos. The little observational evidence that has been brought to bear on this issue is also ambiguous; e.g., the basic form of the NFW halo appears to apply in Canadian Network for Observational Cosmology (CNOCS) clusters of galaxies (Carlberg et al. 1997), but not in the dwarf galaxy DDO 154 (Burkert & Silk 1997). This Letter tests the viability of the proposed universal halo, among other models for the dark matter distribution, in the nearby Virgo Cluster \((D = 15\) Mpc; Pierce et al. 1994).

The X-ray emission from Virgo, which is centered on the cD galaxy M87, has been used many times to constrain mass models for the cluster core (Nulsen & Böhringer 1995, and references therein). Here, an attempt is made to supplement this standard analysis with larger scale constraints on \(\rho_{\text{dm}}(r)\) from the spatial distribution and dynamics of the galaxies in Virgo. To do so, the infalling late-type galaxies that are responsible for much of the cluster’s irregular optical structure are excluded from analysis. Instead, reference will be made only to the early Hubble types in Virgo, which are spatially concentrated (about a point \(-1^\circ\) northwest of M87) with a roughly Gaussian velocity distribution (centered near the velocity of M87), thus suggesting the existence of a relatively smooth and relaxed underlying mass distribution (see Binggeli, Tamman, & Sandage 1987). In what follows, this is essentially adopted as a postulate. It is further assumed that Virgo is spherically symmetric and centered on M87. This is a reasonable first-order characterization of the X-ray structure around the galaxy, and it will serve as a coarse, average approximation to the overall cluster structure. As part of this, the apparent offset between M87 and the centroid of the early-type galaxy isophotes is taken not to reflect a large perturbation in the fundamental mass distribution, and it is ignored. While imperfect, these simplifications ultimately admit a model for Virgo that is of interest both for its basic structure—the central scaling \(\rho_{\text{dm}} \propto r^{-1}\) of NFW is indicated, and it is favored clearly over the steeper cusps of either Moore et al. (1998) or a singular isothermal sphere—and for the relations it suggests between the galaxies, gas, and dark matter in this cluster.

2. DATA AND HALO MODELS

A significant contribution to the total mass on the smallest spatial scales in Virgo comes from the stars in M87 itself. With the stellar mass-to-light ratio of this galaxy (as measured in its core by van der Marel 1991) taken to be independent of radius, the mass density profile \(\rho_{\text{M87}}(r)\) follows from the B-band surface photometry of de Vaucouleurs & Nieto (1978), which extends to \(R = 100\) kpc. (Here and throughout, three-dimensional radii are denoted by \(r\), and projected radii are denoted by \(R\).) Specifically, fitting \(\rho_{\text{gal}}\) with density models from the family discussed by Dehnen (1993) and Tremaine et al. (1994) yields the profile defined in Table 1 (for \(D = 15\) Mpc, and with \(A_g = 0.09\) mag of extinction [Burstein & Heiles 1984 taken into account). Note that this model closely approximates a standard \(R^{1/4}\) law in projection (see Dehnen 1993).

Moving outward, density and temperature profiles for the hot gas within \(10 \leq r \leq 200\) kpc of M87 have been obtained from ROSAT Position-Sensitive Proportional Counter observations by Nulsen & Böhringer (1995, hereafter NB95). Their analysis assumes homogeneity, or a single-phase medium, which could be a potential source of error if a cooling flow has produced a multiphase gas in Virgo; however, this possibility appears to be of concern only at radii near the low end of the range in the ROSAT data (viz., \(r \leq 15\) kpc; Canizares et al. 1982; Tsi 1994). Thus, use is made here of the model-independent gravitational mass profile \(M_{\text{gas}}(r)\), which NB95 derive by applying the standard assumption of hydrostatic equilibrium to their \(\rho_{\text{gas}}(r)\) and \(T(r)\) measurements.

Still further out, the (azimuthally averaged) surface density of dwarf elliptical galaxies in Virgo is given by Binggeli et al.
TABLE 1

| Component | Parameters |
|-----------|------------|
| Stars (M87) | \( \rho_{\text{gal}} = [(3 \gamma /4) (T_b L_b \pi a^2) (ra) / (1 + ra)^{\gamma - 1}] \) |
| \( \gamma = 1.33, \ a = 5.1 \pm 0.6 \) kpc |
| \( L_b = (5.55 \pm 0.80) \times 10^9 L_{\odot} \) |
| \( T_b = 14.6 \pm 0.2 \ M_{\odot} \ L_{\odot} \) |
| Dark Matter (NFW Model) | \( \rho_{\text{gal}} = K (r/ra)^{-3} \) |
| \( M_{\text{gal}} = 4 \pi K r^2 \ln (1 + r/a) / (1 + r/a) \) |
| \( K = (3.2_{-0.7}^{+1.1}) \times 10^9 \ M_{\odot} \ pc^{-1} \) |
| \( D = \pi a^2 K T_b L_b = (1.65_{-0.16}^{+0.23}) \times 10^{-4} \) |
| \( r_c = 560_{-70}^{+30} \) kpc, \( \eta = r_c/a = 110_{-6}^{+10} \) |
| Dark Matter (Hernquist Model) | \( \rho_{\text{gal}} = K (r/ra)^{-4} \) |
| \( M_{\text{gal}} = 2 \pi K r^2 [r/(r + r)] \) |
| \( K = (1.6 \pm 0.7) \times 10^9 \ M_{\odot} \ pc^{-1} \) |
| \( D = \pi a^2 K T_b L_b = (8.1 \pm 3.6) \times 10^{-5} \) |
| \( r_c = 1.07_{-0.06}^{+0.10} \) Mpc, \( \eta = r_c/a = 210_{-8}^{+6} \) |

where \( \beta_{\text{gal}} \equiv 1 - \sigma^2 / a^2 \) is the usual measure of orbital anisotropy. The dispersion along any single line of sight then follows from the projection

\[
N_{\text{gal}} \sigma_p^2(R) = 2 \int_{0}^{R} n_{\text{gal}} \sigma_p^2(r) \left( 1 - \beta_{\text{gal}} \right) \frac{R^2}{r^2} \frac{r dr}{\sqrt{r^2 - R^2}},
\]

with \( N_{\text{gal}}(R) = 2 \int_{0}^{R} n_{\text{gal}} r^2 (r^2 - R^2)^{-1/2} r dr \). Finally,

\[
\sigma_{\text{ap}}^2(R) = \left[ \int_{0}^{R} N_{\text{gal}} \sigma_p^2(x) x dx \right] \left[ \int_{0}^{R} N_{\text{gal}}(x) x dx \right]^{-1},
\]

is compared with the observed aperture velocity dispersion profile at \( R \geq 200 \) kpc. If this comparison is unsatisfactory but the basic assumption of dynamical equilibrium is retained, then the underlying form of \( \rho_{\text{gal}}(r) \) may be rejected. A potential complication is that the orbital anisotropy of the galaxies is not known a priori, and a given \( f(r/a) \) can safely be discarded only if it cannot reproduce the empirical \( \sigma_{\text{ap}}(R) \) for any assumed \( \beta_{\text{gal}}(r) \). Fortunately, the Virgo data prove to be quite consistent with a simple \( \beta_{\text{gal}} \equiv 0, \) i.e., isotropic orbits.

3. RESULTS

The field of possible halo profiles can be narrowed somewhat by first requiring consistency with a small subset of the data: from NB95 and Girardi et al. (1996),

\[
M_{\text{gal}}(r \leq 30 \text{ kpc}) = (1.6_{-0.11}^{+0.13}) \times 10^{12} M_{\odot},
\]

\[
M_{\text{gal}}(r \leq 150 \text{ kpc}) = (1.9 \pm 0.8) \times 10^{13} M_{\odot},
\]

\[
\sigma_{\text{ap}}(R \leq 2 \text{ Mpc}) = 640_{-45}^{+85} \text{ km s}^{-1},
\]

where all uncertainties are \( \approx 2 \sigma \) limits. Figure 1 illustrates tests of four different form functions against these three constraints only: in Figure 1a, \( f(r/a) = [1 + (r/a)^{2}]^{-3} \) (an isothermal sphere with a core; cf. NB95); in Figure 1b, \( f(r/a) = (r/a)^{-5/2} (1 + r/a)^{-2} \); in Figure 1c, \( f(r/a) = (r/a)^{-1} (1 + r/a)^{-2} \) (the model of NFW); and in Figure 1d, \( f(r/a) = (r/a)^{-1} (1 + r/a)^{-1.5} \) (as in the N-body simulations of Moore et al. 1998). The different line types in each panel contain combinations of \( D \) and \( \eta \) that are consistent (for \( \beta_{\text{gal}} \equiv 0 \)) with the 2\( \sigma \) limits on the individual data points in equation (5); the various dots identify models that yield the best estimates for both members of different data pairs. A minimally self-consistent...
sistent model for $\rho_{dm}$ must draw its normalization and scale length from the intersection of the three bands in the appropriate panel of Figure 1, and ideally the three dots should coincide at a unique ($\eta, D$).

Figure 1d shows that a central cusp as steep as $r^{-1.5}$ (Moore et al. 1998) cannot easily account for the observed $M_\text{tot}$ inside both 30 and 150 kpc; the implied $M_\text{dm} \propto r^{-1.5}$ at small $r$ is shallower than what is inferred from the observed excess of $M_\text{tot}(r)$ over the stellar $M_\text{dst}(r)$. This is even more of a problem for the singular isothermal sphere ($\rho_\text{dm} \propto r^{-2}$ and $M_\text{dm} \propto r$), which is altogether inconsistent with the X-ray masses (see also NB95). On the other hand, the mass constraints at $r \approx 200$ kpc are satisfied by any of the halos with central $\rho_\text{dm} \propto r^{-1}$ or shallower; but the weak cusps in panels Figures 1a and 1b give the best agreement for scale radii $r_s$ that are so small [to limit a steeply rising $M_\text{dm}(r)$] as to imply total halo masses that are too low to support the velocity dispersion of the Virgo galaxies on large spatial scales.2 Thus, the “universal” halo of NFW, with its central $\rho_\text{dm} \propto r^{-1}$ and with $\beta_{gal} \equiv 0$, emerges as the best candidate for a self-consistent description of the Virgo Cluster (Fig. 1c).

This simple analysis is limited in two respects. (1) At very small $r \approx 10$–15 kpc, where $M_\text{gal}(r) \gg M_\text{dm}(r)$, the halo could depart from $\rho_\text{dm} \propto r^{-1}$ and not conflict with any observations, and (2) little can be said about the behavior of $\rho_\text{dm}$ in the limit $r \to \infty$; for example, the same procedure that leads to Figure 1 shows that the profile of Hernquist (1990), $\rho_\text{dm} \propto \frac{1}{(1 + r/r_s)^{3}}$ (as suggested by the early simulations of Dubinski & Carlberg 1991), is just as acceptable as the NFW $\rho_\text{dm} \propto \frac{1}{(1 + r/r_s)^{2}}$ in Virgo. The best fits of these two models have different parameters (given in Table 1), but show no real physical differences on $\approx 2$ Mpc scales.

Figure 2 compares the full sets of data discussed in § 2 with models using the best-fit NFW and Hernquist halos. The top panel shows the best X-ray estimate and 95% confidence limits for $M_\text{tot}(r)$ (dashed line and bold curves), along with results from optical spectroscopy of the stars in M87 (Sargent et al. 1978; filled triangles) and from radial velocities of its globular clusters (Cohen & Ryzhov 1997; open triangles). These latter sets of data independently corroborate the models. (The globular cluster dynamics specifically will be discussed in a future paper.) The middle panel of Figure 2 then compares the surface density profile of early-type galaxies with that of each fit to the dark matter halo. This shows—the analysis did not assume—that $\rho_{gal} \propto \rho_\text{dm}$ in Virgo. This fact is used to compute aperture dispersion profiles that, for $\beta_{gal} \equiv 0$, show excellent agreement with the data in Figure 2 (bottom). It also allows the uncertainties on $\eta$ in Table 1 to be estimated by fitting the projection of $\rho_\text{dm}(r)$ to $N_\text{gal}(R)$; the limits on $D$ then follow from plots like Figure 1c.

In either of these models, the virial radius of the dark matter halo—roughly, that within which its mean density is 200 times the critical density for closure—is $r_{200} = 1.55 \pm 0.06$ Mpc (for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$), corresponding to a mass of $M_\text{tot}(r_{200}) = (4.2 \pm 0.5) \times 10^{14} M_\odot$. This emphasizes that the dark matter (and the gas) around M87 is associated—by construction—with the whole of Virgo; and this weakens previous arguments (Binggeli et al. 1987) that suggested that the cluster could not be relaxed.

Finally, Figure 3 shows that the hot gas within 200 kpc of M87 directly traces the distribution of dark matter (and gal-

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2 This conclusion is insensitive to the assumed form of $\rho_{gal}$ as $r \to \infty$. Also, while some shallow-cusp models with radial anisotropy ($0 < \beta_{gal} \leq 1$) can reproduce the observed $\sigma_{gal}$ at $R = 2$ Mpc, they are inconsistent with the full profile at smaller radii.
of Figure 3 also shows a close agreement between the observed gas temperatures and the virial temperature $kT(r) = 0.6m_p\sigma^2(r)$ of the dark matter halo. Thus, simple virialization of gas that traces the dark matter in an $r^{-1}$ halo suffices to explain the density and temperature structure of the intracluster medium at the center of Virgo. This suggests—if an NFW-type halo truly is universal, and if the proportionality $\rho_{gas} \propto \rho_{dm}$ is typical—that central density cusps and temperature drops in the gas of X-ray clusters may not, by themselves, prove the existence of cooling flows. That said, however, radiative cooling times are unequivocally short in the core of Virgo ($t_{cool} \approx 10^{10}$ yr for $r \approx 70$ kpc); and it remains to be seen whether a single-phase gas virialized in an NFW halo can account for the observed low-energy X-ray line fluxes from Virgo, or if these still require mass drop out and the development of a multiphase medium at small radii in a cooling flow (cf. Tsai 1994).

Of course, Virgo by itself cannot establish the “universality” of a central $\rho_{dm} \propto r^{-1}$ structure, even among only cluster-sized halos. It is worth noting, then, that clusters at $z \approx 0.3$ in the CNOC survey are also well fit by an NFW model for the dark matter (Carlberg et al. 1997). Moreover, the NFW concentration of Virgo, $c_{vir} = r_{vir}/r_{1/2} = 2.8 \pm 0.7$, is consistent with that of the CNOC clusters. This $c$ seems low, however, by comparison with Λ-CDM simulations of halo evolution (NFW; Thomas et al. 1998). The physical origin of this discrepancy—and, for that matter, of the $r^{-1}$ cusp itself—is unclear.

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