THE PRINCIPAL AXIS OF THE VIRGO CLUSTER

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ABSTRACT

Using accurate distances to individual Virgo Cluster galaxies obtained by the method of surface brightness fluctuations, we show that Virgo’s brightest elliptical galaxies have a remarkably collinear arrangement in three dimensions. This axis, which is inclined by ~10°–15° from the line of sight, can be traced to even larger scales where it appears to join a filamentary bridge of galaxies connecting Virgo to the rich cluster Abell 1367. The orientations of individual Virgo elliptical galaxies also show some tendency to be aligned with the cluster axis, as does the jet of the supergiant elliptical galaxy M87. These results suggest that the formation of the Virgo Cluster, and its brightest member galaxies, have been driven by infall of material along the Virgo-A1367 filament.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: formation — large-scale structure of universe

1.INTRODUCTION

The Virgo Cluster, at a distance of approximately 15 h⁻¹ Mpc, is the nearest richly populated cluster of galaxies and, consequently, one of the best studied. A number of authors have pointed out that Virgo’s brightest elliptical galaxies have a remarkably linear arrangement along a projected position angle of roughly 110° (measured north through east). Arp (1968), for example, noted that “all the E galaxies in the northerm half of the Virgo Cluster fall on a line going through M87.” Similarly, Binggeli, Tammann, & Sandage (1987) suggested that “the line connecting M87 and M84 appears as a fundamental axis of the cluster.” This can be seen in Figure 1, which plots the distribution of probable member galaxies in the northerm portion of the Virgo Cluster, as seen on the plane of the sky. The distribution of Virgo dwarf elliptical galaxies also appears somewhat elongated in this direction (Binggeli 1999), as does the distribution of hot X-ray-emitting intracluster gas (Böhringer et al. 1994; Schindler, Binggeli, & Böhringer 1999). However, without accurate distances to individual galaxies, it is impossible to say for certain whether Virgo’s apparent principal axis is a genuine three-dimensional structure or merely an illusory chance alignment of galaxies. Furthermore, three-dimensional information would allow one to measure the true shape and spatial orientation of this axis.

Here we present evidence that Virgo’s bright elliptical galaxies trace a highly elongated, three-dimensional structure that is actually a small segment of a much larger filament passing through the heart of the Virgo Cluster.

2.RESOLVING THE VIRGO CLUSTER IN THREE DIMENSIONS

A variety of methods exist for measuring galaxy distances (see Jacoby et al. 1992 for a review). One of the most powerful is the technique of surface brightness fluctuations (SBFs), whereby distances to galaxies are estimated from the ratio of the second and first moments of their stellar luminosity functions (Tonry & Schneider 1988; see Blakeslee, Ajhar, & Tonry 1999 for a recent review). This method works best for early-type galaxies, although it has also been applied to the bulges of some spiral galaxies. Ferrarese et al. (2000) have concluded that SBF is the most accurate early-type galaxy distance indicator reaching cosmologically interesting distances.

Tonry et al. (2000) have recently published SBF distances for 300 nearby galaxies that were observed as part of their I-band SBF survey. Based on distances for 31 probable Virgo Cluster members, they derived a mean cluster distance modulus of 31.15 ± 0.03, corresponding to a distance of 17 ± 0.3 Mpc. Uncertainties in individual Virgo galaxy distances are ~1.5–2 Mpc, which suggests that it should be possible to resolve the Virgo Cluster along the line of sight, at least partially. Indeed, Tonry, Ajhar, & Luppino (1990) attempted to do this a decade ago, but they lacked a suitable calibration. They assumed that the I-band SBF magnitude was insensitive to stellar population variations among elliptical galaxies, as implied by the best population models at the time. As a result, they essentially found that bluer Virgo elliptical galaxies were systematically in front of redder ones. Following a decade of work, the stellar population dependence of SBF has been empirically well characterized and calibrated out (Tonry et al. 1997; Ferrarese et al. 2000), so that there is no longer any correlation of the distances with stellar population parameters. Moreover, the empirical calibration now has strong support from theoretical modeling (Worthey 1994; Liu, Charlot, & Graham 2000; Blakeslee, Vazdekis, & Ajhar 2000).

Table 1 lists data for all elliptical galaxies in the northern portion of the Virgo Cluster with SBF distances from the Tonry et al. (2000) survey. The first column gives the galaxy name, the second lists the SBF distance of each galaxy from Tonry et al. (2000), and the third gives the orientation of the galaxy major axis, taken from the Lyon-Meudon Extragalactic Database (LEDA). The positions and distance moduli of these galaxies are also indicated in Figure 2.

Table 1 and Figure 2 suggest some tendency for those galaxies located in the western region of the cluster to be more distant than those on the eastern side. This trend can be seen more clearly in Figure 3, which shows a clear correlation between galaxy right ascension and distance, with a systematic...
trend of increasing galaxy distance as one moves in the westerly direction. Pearson (parametric) and Spearman (nonparametric) rank correlation tests both confirm that this trend is statistically significant at the 97% and 99% confidence levels, respectively (the correlation becomes even stronger if NGC 4168 is also included). We note that Neilson & Tsvetanov (2000) have recently measured independent SBF distances with the Hubble Space Telescope for 15 Virgo galaxies, including 10 elliptical galaxies along this central ridge line, and have observed the same trend in their data.

To measure the three-dimensional shape and orientation of this axis, we computed the moments of inertia of the system of galaxies in Table 1 after converting their right ascensions, declinations, and distances to supergalactic Cartesian coordinates. Diagonalization of the inertia tensor yields the three eigenvalues corresponding to the principal moments of inertia, and the associated eigenvectors provide information on the orientation of the principal axis.

We find that the Virgo elliptical galaxies have a remarkably collinear arrangement in three dimensions, with an rms scatter of only ~400 kpc about the principal inertial axis along its ~8 Mpc length between NGC 4387 and NGC 4660. This axis is inclined at an angle of approximately ~75°–80° with respect to the plane of the sky, i.e., close to the line of sight. Presumably, with smaller distance uncertainties, Virgo’s principal axis would be found to be even narrower.

### 3. GALAXY ORIENTATIONS IN VIRGO

Additional evidence of the special nature of the axis defined by Virgo’s brightest elliptical galaxies comes from the orientations of the galaxies themselves. As Table 1 shows, the majority have projected major-axis position angles between 100° and 140°, quite similar to the 110° projected orientation of the cluster principal axis. A Kolmogorov-Smirnov (K-S) test indicates a probability of only ~7% that the galaxy position angles in Table 1 are randomly oriented between 0° and 180°.

![Figure 1](image1.png)

**Fig. 1.**—Map of the distribution of likely member galaxies in the Virgo Cluster, taken from the catalog of Binggeli et al. (1985). Galaxy positions are measured relative to NGC 4886 (M87). The area of each symbol is proportional to galaxy luminosity. The dashed lines indicate regions not included in the Binggeli et al. survey. As discussed in the text, the brightest galaxies in the northern part of the cluster form a chain oriented along a projected position angle of ~110°.

![Figure 2](image2.png)

**Fig. 2.**—Plot of those elliptical galaxies in the northern half of the Virgo Cluster for which SBF distances are available from the survey of Tonry et al. (2000). We have also included NGC 4168, which, although not a Virgo member, lies in the field of view and also has a measured SBF distance.

![Figure 3](image3.png)

**Fig. 3.**—Right ascension vs. SBF distance modulus for the Virgo elliptical galaxies in Table 1. NGC 4168 is also indicated.

| Galaxy        | $m - M_{3100}$ | Position Angle (deg) |
|---------------|----------------|----------------------|
| NGC 4374 (M84) | 31.32 ± 0.11   | 135                  |
| NGC 4387       | 31.65 ± 0.73   | 140                  |
| NGC 4406 (M86) | 31.17 ± 0.14   | 130                  |
| NGC 4458       | 31.18 ± 0.12   | 46                   |
| NGC 4473       | 30.98 ± 0.13   | 100                  |
| NGC 4478       | 31.29 ± 0.28   | 140                  |
| NGC 4486 (M87) | 31.03 ± 0.16   | 160                  |
| NGC 4487       | 31.19 ± 0.17   | 70                   |
| NGC 4552 (M89) | 30.93 ± 0.14   | 125°                 |
| NGC 4564       | 30.88 ± 0.17   | 47                   |
| NGC 4621 (M59) | 31.31 ± 0.20   | 165                  |
| NGC 4649 (M60) | 31.13 ± 0.15   | 105                  |
| NGC 4660       | 30.54 ± 0.19   | 100                  |
| NGC 4733       | 30.87 ± 0.20   | 115                  |

* With the exception of NGC 4552, all major-axis position angles are taken from LEDA. No position angle was listed for NGC 4552 in LEDA, and so we adopted a value of 125° from the study by Carollo et al. 1997 (see also King 1978).
While one must be cautious not to overinterpret the statistical significance of results based on a small sample like this, it is nevertheless suggestive that the orientations of Virgo’s large elliptical galaxies may be somehow related to the direction of the cluster principal axis. A similar alignment effect is seen for the brightest elliptical galaxies in the Coma Cluster (West 1998) as well as other clusters (Binggeli 1982; Porter, Schneider, & Hoessel 1991; West 1994 and references therein).

To test whether fainter Virgo elliptical galaxies might also have preferred orientations with respect to the cluster major axis, we used the Virgo Photometry Catalogue (VPC) of Young & Currie (1998), which provides data, including orientations, for 1180 galaxies in the core region of the cluster. Because the VPC includes both Virgo members and unrelated galaxies along the line of sight, we cross-correlated it with the list of probable Virgo members from Binggeli, Sandage, & Tammann (1985) to produce a sample of 108 Virgo elliptical galaxies with measured major-axis position angles. Application of the K-S test to this sample shows no statistically significant tendency for the fainter elliptical galaxies to have preferred orientations. However, when the roundest galaxies—whose position angles are most uncertain—are eliminated by restricting the sample to only those with ellipticities greater than 0.2, then the K-S test indicates that this subset of 69 galaxies has only a \(4\%\) probability of being consistent with a randomly orientated population, with a median galaxy position angle of \(107^\circ\).

4. A LINK BETWEEN VIRGO AND THE A1367-COMA SUPERCLUSTER?

One of the most striking features of the large-scale distribution of galaxies is its filamentary appearance, with long, quasi-linear arrangements of galaxies that extend tens or perhaps even hundreds of megaparsecs in length. Given the linear arrangement of galaxies along Virgo’s principal axis, it is natural to ask whether this might be related to filamentary features on larger scales.

As viewed on the plane of the sky, Virgo’s principal axis points in the direction of Abell 1367, a rich cluster located some \(75 h^{-1}\) Mpc away along a projected position angle of \(125^\circ\). A1367 itself forms part of a well-known supercluster with the Coma Cluster (Gregory & Thompson 1978; de Lapparent, Geller, & Huchra 1986). This raises the intriguing possibility that the Virgo, A1367, and Coma clusters may all be members of a common filamentary network, an idea suggested two decades ago by Zeldovich, Einasto, & Shandarin (1982).

Figure 4 plots the distribution of nearby poor galaxy clusters from the catalog of White et al. (1999). A narrow bridge of material is clearly seen connecting Virgo and A1367. Furthermore, the chain of giant elliptical galaxies that defines Virgo’s principal axis appears to be a segment of this filament. Hence, the Virgo Cluster points toward A1367, not only in two dimensions, but in three. Additional indirect evidence of a Virgo-A1367 connection comes from X-ray observations that show a plume of hot gas being stripped from this galaxy along a projected position angle of \(140^\circ\) (Jones & Forman 1999) and thus in the general direction of the Virgo Cluster.

Of course, the Virgo Cluster is often considered part of the larger supercluster which includes Hydra-Centaurus and Pavo-Indus (e.g., Tully 1986). Lynden-Bell et al. (1988) viewed this extended, planar supercluster complex as centered on the “Great Attractor,” with Virgo near the outskirts. Thus, we can now trace an apparent link between two of the most massive structures in the local universe: from the “Great Wall” encompassing the Coma Cluster to the Great Attractor, through A1367 and the Virgo Cluster.

5. CONCLUSION

We have shown that the brightest elliptical galaxies in the Virgo Cluster have a remarkably collinear arrangement in three dimensions. This axis appears to be part of a larger filament connecting the Virgo Cluster to Abell 1367. Virgo’s elliptical galaxies also exhibit a tendency for their major axes to share this same orientation.

Cosmological N-body simulations show that clusters of galaxies often form at the intersection of filaments, with material flowing into the cluster along one or more axes (van Haarlem & van de Weygaert 1993; Bond, Kofman, & Pogosyan 1996). Built by a series of subcluster mergers that occur along preferred directions, clusters naturally develop major-axis orientations that reflect the orientation of the dominant filament feeding them (West, Jones, & Forman 1995). Furthermore, if large elliptical galaxies are products of galaxy mergers, then the highly anisotropic nature of the merger process will tend to produce elliptical galaxies whose major-axis orientations are also aligned with the surrounding filamentary structure (West 1994; Dubinski 1998).

The results presented here are consistent with a picture in which the formation of the Virgo Cluster and its elliptical galaxy population has been driven by anisotropic inflow of material along the Virgo-A1367 filament. Although Virgo may be fed by more than one filament (Tully 1982), the one joining the cluster to A1367 appears to dominate. Additional evidence in support of this interpretation comes from X-ray observations of M86, which show a plume of hot gas being stripped from this galaxy along a projected position angle of \(110^\circ\) (Forman et al. 1979), presumably as a result of ram pressure as
the galaxy travels along the cluster principal axis at over 1200 km\,s$^{-1}$.

Finally, it is intriguing that M87’s famous jet also emanates along the same direction as the Virgo Cluster major axis. This is true not only in two dimensions, where both are oriented along projected position angles of $\sim$110–120°, but also in three dimensions. Detailed models of the jet’s observed properties indicate that it is most likely oriented within $\sim$20° of the line of sight (Heinz & Begelman 1997; Biretta, Sparks, & Macchetto 1999), very close to the 10°–15° line-of-sight inclination angle of the cluster principal axis found in § 2. While this might be purely coincidental, alternatively, it might be an indication that Virgo’s principal axis has influenced not only the orientations of its member elliptical galaxies, but perhaps even the massive black hole at the center of M87 that is believed to power its nuclear activity (West 1994).

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