Virgo Cluster
Bruno Binggeli, John Huchra

From
Encyclopedia of Astronomy & Astrophysics
P. Murdin

© IOP Publishing Ltd 2006

ISBN: 0333750888
Virgo Cluster

The Virgo cluster is the nearest and best-studied rich cluster of galaxies, lying at a distance of about 55 million light-years in the constellation of Virgo. Figure 1 is a map of the distribution of nearby galaxies (as determined by their redshifts) in a 1500 square degree region of the constellation of Virgo. The Virgo cluster is the strong, somewhat irregular, concentration of galaxies at the center. In three-dimensional (3D) space, the Virgo cluster constitutes the nucleus of the Local Supercluster (LSC) of galaxies, in whose outskirts our Milky Way Galaxy is situated.

As early as 1784, Charles Messier noted an unusual group of nebulae in Virgo. Fifteen out of the 109 famous Messier objects are, in fact, member galaxies of the Virgo cluster. However, only in the 1920s, following Edwin Hubble’s proof of the extragalactic nature of those nebulae, was Messier’s group understood as a self-gravitating system of hundreds of galaxies, and the first systematic investigations of the Virgo cluster, as it was henceforth called, were carried out by Harlow Shapley and others.

Virgo was the first galaxy cluster to be studied dynamically by Smith and Zwicky in the 1930s. Their work showed that the dynamical mass of Virgo, estimated by using the virial theorem

$$2T + U = 0$$

where $T$ and $U$ are the time-averaged kinetic energy and potential energy of the relaxed system, was much larger than the mass inferred by integrating the light of all the galaxies in the cluster and multiplying by a mass-to-light ratio ($M/L$) like the average of stars in the solar neighborhood. This was the first clear detection of dark matter, or more properly, non-luminous mass. The distribution of galaxies in the direction of Virgo in redshift space is shown in figure 2, and figure 3 displays the histogram of galaxy velocities inside a circle of 6° radius centered on the core of the cluster at 12°28′ and 10°28′.

The Virgo cluster lies at the center of the LSC, first dynamically studied by G de Vaucouleurs and collaborators in the 1950s. The Milky Way appears to be falling into the Virgo cluster, relative to the general expansion of the universe, with a velocity of about 250 km s$^{-1}$. That is to say, we are still moving away from the cluster core with an apparent velocity, $cz$, of about 1100 km s$^{-1}$, but that velocity is 250 km s$^{-1}$ less than it would have been if the cluster had no mass. Curiously, the $M/L$ for the whole LSC derived from this Virgo infall is similar to that derived via the virial theorem for the dynamically relaxed cluster core; both $M/L$ values, when applied to the mean luminosity density of the universe derived from redshift surveys, imply a mean matter density of the universe that is only 1/4 to 1/3 of the critical density.

The kinematics of the cluster is quite complex as can be seen in figures 1 and 4. There are two main concentrations of galaxies; the largest and densest is centered on the well-known galaxy M87 (NGC4486) which is both a strong radio source (Virgo A) and a strong x-ray source. This subcluster, at 12°30′ +8 +12°3, is also a strong x-ray source produced by a reservoir of extremely hot intracluster gas. This intracluster medium is at a temperature of about 10$^7$ K, emits thermal bremsstrahlung radiation and is a major contributor to the total mass of the system. The southern large subcluster is centered on M49 (NGC 4472) at 12°29′ +8 +8°0′, the most luminous galaxy in the cluster, but is significantly less massive than the M87 subcluster. The total mass of the Virgo core region is about 10$^{15}$ $M_\odot$, that of the M87 subclump ∼3 × 10$^{14}$ $M_\odot$, and the M49 subclump is ∼1 × 10$^{14}$ $M_\odot$, assuming a distance to the cluster core of 16 Mpc. The cluster distance of (the Virgo cluster proper, so to speak)—and M87 itself, the giant, active galaxy with its famous jet, can truly be regarded as the heart of the Virgo cluster. The smaller subclusters seem to be in a state of merging with the M87 subcluster. In this sense, the Virgo cluster (like many, if not most, clusters of galaxies) is still in the making.

The Virgo cluster has always been, and still is, one of the most important stepping stones for the cosmological distance scale. Much of the current debate on the value of the Hubble constant boils down to a debate on the mean distance of the Virgo cluster (see below).

A new and very exciting era of Virgo cluster research has recently been opened by the first detection of intracluster planetary nebulae (PNe) and single red giant stars, i.e. stellar objects that are not bound to a single galaxy but to the cluster as a whole. This adds a whole new population to the cluster, which in the future will be used to explore the 3D structure and dynamical history of the Virgo cluster.

Global structure

The primary optical database for the galaxy content of the Virgo cluster is the Las Campanas photographic survey, carried out in the 1980s by Allan Sandage and collaborators, and encapsulated in the Virgo Cluster Catalog (VCC). Figure 4 is a map of the ca 1300 galaxies in the Virgo cluster.
Figure 1. The distribution of nearby galaxies (apparent recession velocities less than 3000 km s\(^{-1}\)) in the direction of Virgo. Each circle represents a galaxy; the size of the circle represents its apparent brightness. Galaxies with apparent velocities less than 500 km s\(^{-1}\) are shown in red, those above 2100 km s\(^{-1}\) in green, and those between 500 and 1300 km s\(^{-1}\) and between 1300 and 2100 km s\(^{-1}\) in blue and magenta, respectively. This figure is reproduced as Color Plate 63.

the sky area covered by the Las Campanas survey that were judged to be members of the Virgo cluster. The membership criteria were based on (1) the morphological appearance of the galaxies, e.g. dwarf ellipticals have a characteristically low surface brightness, and/or (2) the measured radial velocities, which for members have to be smaller than ca 2700 km s\(^{-1}\) (helio-centric). Velocities are at present available only for the brightest 400 members (but this number, too, will steadily grow in the future).

The magnitude limit of completeness of the Las Campanas survey is around apparent blue magnitude \(B = 18\) or, if we assume a mean distance of 16 Mpc, absolute magnitude \(M_B = -13.0\). However, fainter members (up to \(B = 20\)) were included as well. For comparison, the brightest cluster members, M49 and M87, have \(B \approx 9.0\) and \(B \approx 9.5\), respectively. Thus the known cluster population spans a range of \(\approx 10000\) in luminosity.

From the distribution of symbol sizes in figure 4 one can obtain a feeling of the exponentially growing luminosity function of galaxies. Of the 1300 known members, 850 alone are of the dwarf elliptical (dE) type. The basic characteristic of dEs is a relation between luminosity and surface brightness: fainter dwarfs have also lower surface brightness. As the detection limit for extended objects such as galaxies is set by the surface brightness rather than total magnitude, it is clear that many hundreds, if not thousands more, of extremely faint and diffuse dE members of the Virgo cluster have yet to be discovered by future deep surveys. These will be the analogs of the dwarf spheroidal companions of our Galaxy, which are as faint as \(M_B = -8\) (corresponding to \(B \approx 23\) at Virgo distance).

Among the remaining 450 member galaxies, there are roughly 80 elliptical (E) and S0 galaxies, 130 spirals, 90 irregulars and 90 dwarf galaxies of intermediate type.
Figure 2. The distribution of galaxies in redshift space in the direction of the Virgo cluster. We are at the apex of the wedge. The main body of the cluster is the picturesquely named ‘Finger of God’ at the center of the wedge. This is not a real feature. Its extension along the line of sight in this plot is a measure of the internal velocity dispersion (and thus the mass) of the galaxy cluster so that a galaxy with a given radial velocity is placed in front of or behind its true position. The large and diffuse structure seen to the right ($10.5^h - 11^h$ and 1100 km s$^{-1}$) of Virgo is the Leo group.

Figure 3. Histogram of apparent velocities for galaxies within a 6° radius of the center of the Virgo cluster. The breadth of the distribution from 0 to 300 km s$^{-1}$ accounts for the ‘Finger of God’ structure in figure 2.

(Irr–dE). The distribution of these morphological types within the cluster varies considerably—in accord with Dressler’s galaxy morphology-density relation: Es and S0s are strongly confined to the regions of highest galaxy density, defining the ‘skeleton’ of the cluster (dwarf Es only to a slightly lesser degree), while spirals and irregulars...
velocity of the Virgo cluster, Note that this is not the cosmic (Hubble flow) recession spirals observed to be H I deficient have apparently their lack of dynamical relaxation (virialization). Those falling, into the cluster from the surroundings, explaining Irrs may have fallen only recently, or are still in the stage of galaxies around the cluster core. Most Virgo spirals and are probably caused by infalling and expanding shells of distribution for (S+Irr) are very weakly clustered, lying preferentially in the cluster outskirts.

This morphological segregation is also reflected in the velocity distributions. An analysis of the radial velocity data so far available gives a velocity dispersion (1σ) of ≈600 km s⁻¹ for early-type galaxies (E, S0, dE), but one of ≈750 km s⁻¹ for late types (S+Irr), i.e. late types are more dispersed in space and velocity. Moreover, the velocity distribution for (S+Irr) is distinctly non-Gaussian with a low-velocity and a high-velocity wing. These wings are probably caused by infalling and expanding shells of galaxies around the cluster core. Most Virgo spirals and Irrs may have fallen only recently, or are still in the stage of falling, into the cluster from the surroundings, explaining their lack of dynamical relaxation (virialization). Those spirals observed to be H I deficient have apparently already fallen through the cluster core.

The all-cluster mean heliocentric velocity is ≃1050 km s⁻¹ (there is no difference with respect to type). Note that this is not the cosmic (Hubble flow) recession velocity of the Virgo cluster, (v)helio, which can be derived by (1) correcting for the solar motion with respect to the centroid of the Local Group by subtracting ≈100 km s⁻¹ and (2) correcting for the Virgocentric infall (deceleration) of the Local Group by adding ≈250 km s⁻¹. This finally gives (v)helio ≃ 1200 km s⁻¹.

Subcluster dynamics
The primary structural characteristic of the Virgo cluster (cf figure 4) is certainly its high degree of irregularity and subclustering. Several subclumps (gravitationally bound subclusters) of galaxies suggest themselves: a main northern subclump around M87, M86 and M84, a southern clump around M49 and possible subgroups around M60 and M100. The global structure of Virgo seems defined by two main axes: one N–S, i.e. M100–M86/M87–M49, and one E–NW, i.e. M60–M87–M86/M84. Remarkably, the former axis is nearly perfectly aligned with the position angle of the outer isophotes of M87, while the latter is perfectly aligned with the jet axis of M87. This shows once more that M87 is the heart of the Virgo cluster.

The reality of the main N–S double structure cannot be doubted, because the northern and southern subclumps are sufficiently well separated. Both have a very similar mean radial velocity, which would suggest that they are at the same distance, i.e. lying in the plane of the sky (however, see below). The southern M49 clump is rather spiral rich and has a surprisingly small velocity dispersion of σ ≈ 500 km s⁻¹.

The core region with M87, M86 and M84 is much harder to disentangle. The key observation here is that the velocity distribution of galaxies in this northern clump (especially for dEs) is strongly skewed towards low velocities. In the low-velocity tail we find the most blueshifted galaxies known in the sky (the record holder, VCC846, has v = −730 km s⁻¹). These objects tend to be clustered around M86, which itself has a negative velocity (v = −227 km s⁻¹). On the other hand, the velocity distribution is peaked around v = 1300 km s⁻¹—nearly coinciding with the velocity of M87 (v = 1258 km s⁻¹).

A clear asymmetry in the velocity distribution of a cluster of galaxies is almost certainly an indication of ongoing subcluster merging. In the Virgo cluster we seem to witness the merging between a subclump around M87 and another clump around M86 (or rather, the infall of the M86 subclump into the more massive M87 subcluster, see below). Both giant galaxies must be the centers of huge swarms of dwarf galaxies. M86 is apparently falling into, or through, the M87 subclump from the back, hence with a high relative (negative) velocity, dragging along its dwarf companions. (The giant galaxy M84, very close to M86 in the sky, but with v = 1000 km s⁻¹, has to be a member of the M87 subcluster.)

This whole picture is fully confirmed by an analysis of the x-ray structure of the Virgo cluster. Figure 5 shows, as a gray-scale image, the distribution of the x-ray intensity in the Virgo cluster as measured by the X-RAY satellite. The x-rays originate from the hot intracluster gas via thermal bremsstrahlung. The gas feels the same gravitational potential of the cluster as the galaxies. The global appearances of the cluster in the x-rays and in the optical (figure 5 versus figure 4) are therefore very similar. However, the main subclusters around M87, M86 and M49...
the Virgo cluster distance are now within the reach of the HUBBLE SPACE TELESCOPE (HST). This achievement was so long awaited that the first Cepheid-based distance determination of a Virgo cluster spiral in 1994 (M100 at 17 Mpc) had an enormous impact. The caveat with this was, and is, that spirals tend to avoid the cluster core and may be in the field far off the cluster (cf also above). It has been conjectured that M100, as well as other spirals located by Cepheids with HST later on, might lie at the near side of the cluster.

On the other hand, from work based on the TULLY-FISHER (TF) RELATION, which allows the distance to an individual spiral galaxy to be given with an accuracy of ≈0.4 mag, there is consistent evidence that Virgo late types are distributed in a prolute cloud, or filament, stretching—nearly along our line of sight—from the cluster backwards to the so-called ‘W cloud’ at twice Virgo’s distance. Probably this is part of a very long filament that is running way back to the ‘Great Wall’ at the distance of the Coma cluster. On the near side of Virgo it might even be connected with the ‘Coma–Sculptor cloud’ that is running through us, i.e. includes the Local Group.

There is a hint, again from TF distances, that the southern M49 subcluster is lying significantly in the back of the M87 subcluster. If so, the M49 subcluster must be infalling from the back with a velocity of several 100 km s⁻¹, as the mean observed velocities of the two subclusters are very similar. The merging of subclusters along the large-scale filament in which they are embedded is plausible.

To determine the distance of the core of the Virgo cluster one should avoid late-type galaxies. The safest would be to use only elliptical and dwarf elliptical members. Unfortunately, the primary distance indicators here, RR LYRAE STARS, are much too faint at the distance of Virgo even for HST. The secondary distance indicators which can be applied to Virgo ellipticals give controversial results: globular clusters, D_n–σ and novae tend to give large distances (D ≈ 20 Mpc), SBFs and PNe lead to a small D ≈ 16 Mpc. Great efforts are spent in the application of the SBF method because its claimed distance uncertainty for an individual galaxy is almost as small as with Cepheids (≤0.2 mag) and hence would allow us to resolve the cluster depth (the front-to-back depth is about 2 Mpc, or 0.2 mag, if the cluster is spherical). Individual Virgo E distances, with a surprisingly large scatter, have indeed been reported, but there is still some concern whether all variations of the stellar content of ellipticals, on which the method critically depends, are sufficiently well understood. For instance, the SBF distance of M49 is much smaller than the (probably more reliable) TF distance of the whole M49 subcluster, which means that either M49 is lying in the foreground, being projected on top of the background ‘M49’ subcluster by chance, or the SBF method is wrong.

Some hope for the future is resting with dwarf ellipticals, of which there is an almost inexhaustible reservoir in the cluster. A first, very promising
application of the tip-of-the-red-giant-branch (TRGB) distance indicator to a particular dE based on HST observations has given $D \approx 16$ Mpc. A recent claim that dEs are distributed in a prolate structure pointing towards us, based on the shape of the luminosity profile of these galaxies, will soon be tested by an extension of the SBF method to dEs.

A new tool to determine the mean distance and depth of the Virgo cluster core may be provided by the recently discovered population of free-floating giant stars and PNe. Such a population has long been suspected in clusters of galaxies, as stars will be ripped from galaxies by tidal encounters in the cluster core, a process called ‘galaxy harassment’. The data available so far suggest that approximately 10% of the stellar mass of the Virgo cluster is in intergalactic stars. There are ongoing programs with large telescopes to measure the radial velocities and metallicities of a large number of intracluster PNe. These data will provide crucial constraints on the dynamical state and history of the Virgo cluster.

Bibliography

Binggeli B 1999 The Virgo cluster—home of M87 The Radiogalaxy M87 ed H-J Röser and K Meisenheimer (Berlin: Springer) p 9


Bruno Binggeli and John Huchra