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Coma, with Virgo, is one of the best-studied GALAXY CLUSTERS. The cluster is located at right ascension $12^h59^m48.7^s$, declination $+27°58'50''$ (J2000) and lies almost at the north Galactic pole, $(l, b) = (58°, +88°)$. In the major catalog of galaxy clusters by Abell, its designation is Abell 1656 (see ABELL CLUSTERS). The mean redshift of the cluster is approximately 6900 km s^{-1}, which puts it at a distance of $69h^{-1}$ Mpc (where $H_0 = 100h$ km s^{-1} Mpc^{-1}). Coma is one of the richest nearby clusters, having 650 confirmed member galaxies and, including dwarfs, probably as many as 2000 galaxies in total. It has two central, dominant galaxies and therefore is classified as a binary cluster.

Coma has long been taken as the archetypal rich cluster. It appears regular and roughly spherical, with a strong central concentration. The spherical symmetry and general regularity meant that it was considered to be a good (if rare) example of a cluster that had achieved dynamical equilibrium and was therefore amenable to straightforward theoretical analysis. Work over the last two decades, however, has gradually revealed that Coma is far from relaxed, with many substructures. The complexity of the dynamical system reveals clues to the process of cluster formation.

The total mass of Coma has been estimated from observations of its gravitational effects on the galaxies and hot x-ray gas in the cluster. Assuming that the cluster is in dynamical equilibrium, the total mass is found to be much greater than the observed mass in the galaxies and x-ray gas. This result, first obtained by ZWICKY in 1933, remains one of the strongest pieces of evidence that the universe is predominantly composed of some form of unseen DARK MATTER.

History

William Herschel was the first to note the concentration of nebulae in the constellation COMA BERENICES in 1785 (see figure 1). The first catalog of 108 nebulae in Coma was given by Wolf in 1902 and expanded by Curtis to over 300 objects in 1918. The recession velocities for a few members of the cluster were measured by Hubble and Humason in 1931.

The place of the Coma cluster as a touchstone of extragalactic astronomy and cosmology was established when Zwicky derived an estimate for the mass of the cluster in 1933 and found it to be at least $2 \times 10^{14}h^{-1}M_\odot$, which was much greater than could be accounted for by the visible matter. This was the first evidence suggesting that some form of dark matter existed in the universe.

Cluster galaxies

Richness

Coma has 276 member galaxies brighter than $B = 18$ within $0.75h^{-1}$ Mpc (0.67°) of the cluster center and approximately 900 members brighter than $B = 20$ out to $1.5h^{-1}$ Mpc (1.33°). The distance modulus for Coma is $34.2-5\log h$, so that $B = 20$ corresponds to $M_B = -14.2$; about half the members of the Local Group of galaxies are dwarf galaxies with absolute magnitudes fainter than this, so the total number of galaxies in Coma is about 2000.

Luminosity function

The number of galaxies as a function of luminosity has been determined in Coma at optical, infrared, ultraviolet and radio wavelengths. The optical and near-infrared luminosity function (LF) is not very well fitted by the standard Schechter functional form and appears to have three main regimes: the number of galaxies per unity luminosity increases rapidly between the brightest cluster member at $B = 12.6$ and $B \approx 16$ ($L \approx 3 \times 10^9 h^{-1} L_\odot$), and then levels off to $B \approx 18$ ($L \approx 0.5 \times 10^9 h^{-1} L_\odot$), before increasing as a power law, $N(L) \propto L^\alpha$, for the dwarf galaxies at fainter magnitudes. The LF varies with position in the cluster. In the central regions the LF in fact has a peak at around $B \approx 16.5$ and a dip at $B \approx 17.5$ before rising steeply. This may be due to mass (luminosity) segregation as the cluster approaches equipartition of energy in the center, or due to increased merging in the cluster core or due to different evolutionary histories for the central galaxies. The steepness of the power law for dwarf galaxies also depends on position in the cluster, going from $\alpha \approx -1.3$ in the core to $\alpha \approx -1.8$ on the periphery.

Morphologies

As in most clusters, the galaxies in the core of Coma are mostly ellipticals and lenticulars, while the outskirts have a higher proportion of spirals. For the brightest 200 galaxies in the cluster, the mix is approximately E:S0:Sp = 30%:55%:15%. The variation in the morphological mix is reflected in the colors of the galaxies, with red galaxies dominating in the center and blue galaxies on the periphery. There is an excess of early-type galaxies in the region between the NGC4839 subcluster and the main cluster that show evidence of recent star formation, which may have been triggered by interaction with the tidal field of the cluster or the intracluster medium (ICM) as these objects fell into Coma. More generally, the E and S0 galaxies in the cluster are strongly concentrated along a northeast–southwest axis while the spirals show a more diffuse and isotropic distribution.

Dominant galaxies

There are three dominant (D or cD) galaxies in the Coma cluster. Two of these (NGC4874 and NGC4889) lie in the cluster core and cause it to be classified as a binary cluster (Bautz–Morgan class II). NGC4874 ($B = 12.8$) is a cD galaxy with an extended halo and an absolute luminosity of $5.8 \times 10^{10}h^{-1}L_\odot$ that is located close to the peak of the distributions of galaxies and x-ray gas. NGC4889, 0.12° east of NGC4874, is even brighter ($B = 12.6$, $6.9 \times 10^{10}h^{-1}L_\odot$), although it lacks an extended halo. Both NGC4874 and NGC4889 are estimated to have masses (within $80h^{-1}$ kpc) of $1.4 \times 10^{13}h^{-1}M_\odot$. NGC4874 is a strong radio source but NGC4889 is not. The third dominant

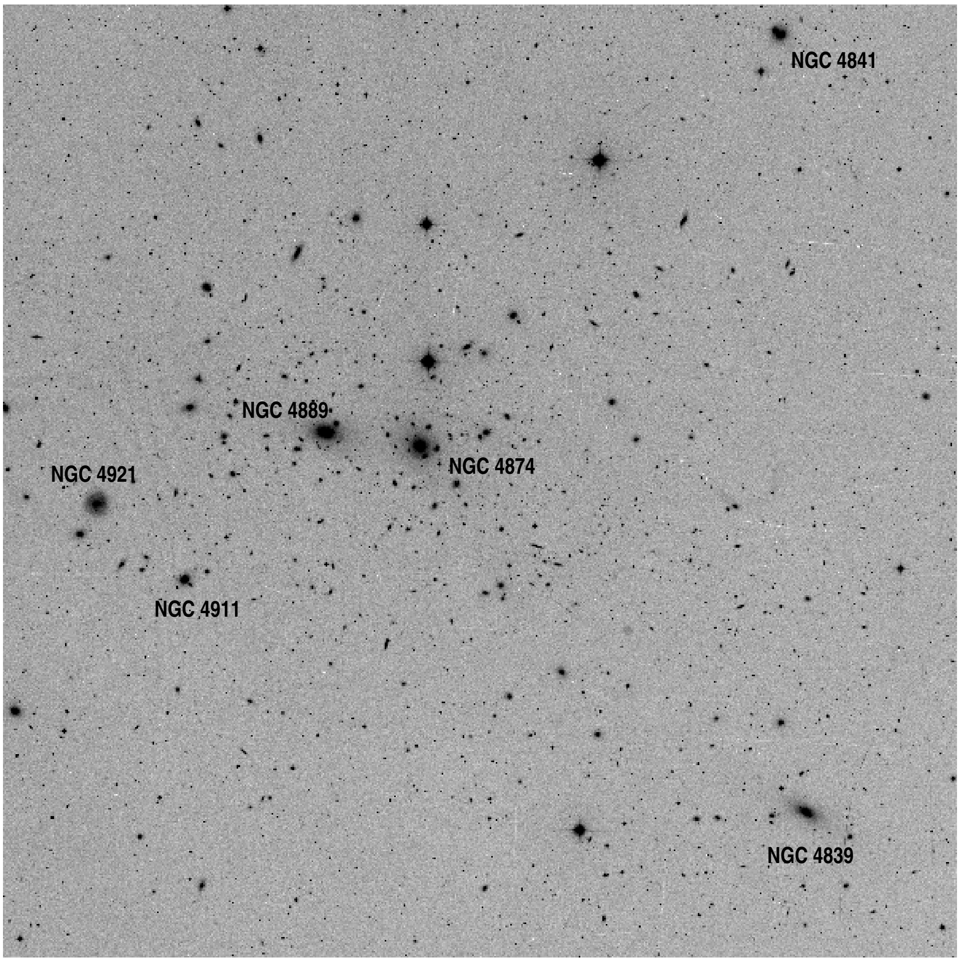

Figure 1. The visual appearance of the central region of the Coma cluster. This image, from the Palomar Observatory Sky Survey, is centered at $12^{h}59^{m}15^{s}$ + 27°55′00″ (J2000) and covers 1.2° × 1.2°; north is at the top, east is at the left. It shows the core of the cluster around NGC4874 and NGC4889 and the southwestern group around NGC4839. (Credit: National Geographic Society, California Institute of Technology, Space Telescope Science Institute.)

galaxy is NGC4839 ($B = 13.5$), which lies well outside the cluster core, 0.67° away to the southwest of NGC4874. It is another cD galaxy, with luminosity $3.0 \times 10^{10} h^{-1} L_{\odot}$. It is also a head–tail radio source, with the tail pointing away from the cluster center. Each of the three dominant galaxies is the leading member of a subcluster within Coma (see below).

Dynamics

REDSHIFTS have been measured for 650 cluster members. The line-of-sight velocity distribution within the cluster can be resolved into two Maxwellian (Gaussian) distributions. One of these is the main body of the cluster, with a mean velocity of 6900 km s^{-1} and a one-dimensional velocity dispersion of 1100 km s^{-1}. The second is the group of galaxies around NGC4839, with a mean velocity of 7300 km s^{-1} and a dispersion of 300 km s^{-1}. The E and S0 galaxies which dominate the main cluster have a Maxwellian velocity distribution, indicating that they are approximately in dynamical equilibrium. However, the spiral galaxies in the cluster have a broader and flatter velocity distribution, which suggests that they are freely falling onto the cluster.

Intracluster medium

Coma has long been known to be a strong source of x-ray emission. The total x-ray luminosity of the cluster is approximately $2.5 \times 10^{44} h^{-2}$ erg s^{-1}. The x-ray emission comes from the ICM, a hot (8 keV $\approx 9 \times 10^{7}$ K) plasma with a mass at least as large as the mass in galaxies. Figure 2 shows the deepest x-ray image of the whole Coma cluster, taken with the ROSAT satellite. The cluster appears fairly regular apart from the obvious second peak in the x-ray emission centered on NGC4839, which has a luminosity of $10^{43} h^{-2}$ erg s^{-1}, typical of a bright group of galaxies. The temperature of this subcluster is higher than expected given its luminosity, suggesting that it has been shock-heated by its interaction with the cluster.

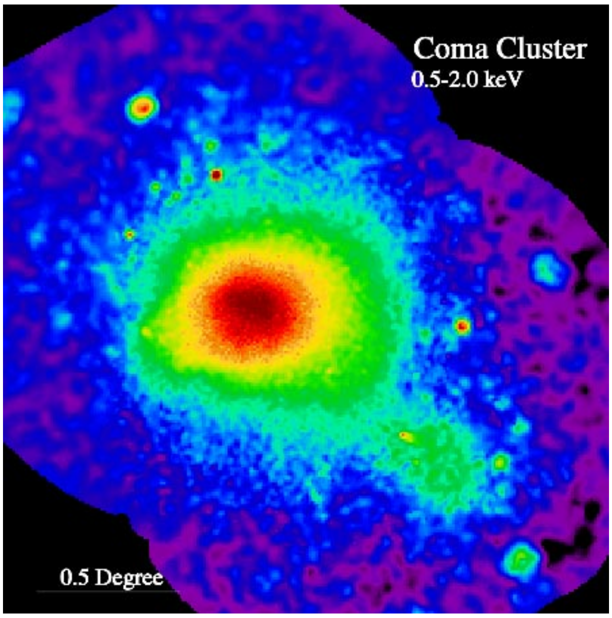

Figure 2. An x-ray image of the Coma cluster obtained with the ROSAT satellite, showing both the main cluster and the NGC4839 group to the south-west. (Credit: S L Snowden, High Energy Astrophysics Science Archive Research Center, NASA.)

Detailed analysis of the x-ray gas distribution shows that there is a double core in the cluster, with peaks associated with NGC4874 and NGC4889, surrounded by a more symmetrical diffuse component. The luminosity and temperature of the gas in these peaks are more consistent with a rich group or poor cluster than with individual galaxies. Unlike many other clusters, Coma does not possess a central cooling flow. This presumably is due to the disruption of the central regions associated with the interaction between the NGC4874 and NGC4889 subclusters. As well as the double core, there is also a distinct 'tail' of x-ray emission running outwards from the cluster center, passing through NGC4911 and ending near NGC4921. This feature has a luminosity of $10^{42}h^{-2}$ erg s^{-1} and an estimated gas mass of a few times $10^{11}h^{-1}M_{\odot}$. It may be associated either with another subcluster around NGC4911 or with the passage of the NGC4874 group through the cluster.

The temperature of the cluster generally decreases out from the center but also shows hot and cool regions. Initial maps of the x-ray gas temperature show evidence for variations associated with the substructures in the cluster. Mapping the temperature of the cluster with future x-ray satellites such as AXAF will greatly improve our understanding of the conditions in the ICM and the dynamics of the cluster. Images of the cluster in the extreme ultraviolet obtained with the EUVE satellite indicate that there is also a substantial amount of sub-10^6 K gas in Coma.

Coma is one of only 10 clusters possessing a diffuse radio halo (the 'Coma C' source); none of these clusters has a COOLING FLOW. This halo is probably produced by the *in situ* acceleration of relativistic electrons by a large-scale magnetic field. The conditions required to create a persistent cluster-wide radio halo have probably been produced by the on-going merger between the NGC4874 and NGC4889 subclusters, although the mechanism by which the kinetic energy of the merger is converted into radio emission remains unclear.

Structure

Detailed analysis of the distribution and dynamics of the galaxies and x-ray gas shows that there are at least four subclusters in Coma. The NGC4874 and NGC4889 subclusters are in the final stages of a merger at the core of the cluster, while the NGC4839 subcluster is either entering Coma for the first time from the direction of the nearby cluster Abell 1367 or is returning from that direction having already made its first passage through the cluster core. The fact that NGC4839 has a radio 'tail' pointing away from the main cluster indicates that the subcluster is inward bound and moving through a fairly dense ICM. Another subcluster has been identified around NGC4911, and there is some evidence for other, lower-level, structures.

There is a significant relation between structures on scales ranging from $10h^{-1}$ kpc up to $100h^{-1}$ Mpc. The major axes of the dominant galaxies and the distribution of E and S0 cluster galaxies and the x-ray gas are all approximately aligned with the filamentary structure (the 'GREAT WALL') running through Coma southwest to Abell 1367 at $cz = 6500$ km s^{-1} and northeast to Abell 2197/2199 at $cz = 9100$ km s^{-1}. The inference is that the cluster has been built up predominantly of material, both subclusters and individual galaxies, which have fallen in along this filament.

Mass and matter content

Ignoring the substructure and treating Coma as a spherical system with both the galaxies and x-ray gas in hydrostatic equilibrium, the total mass of the cluster is estimated to be $(3.1 \pm 0.5) \times 10^{14}h^{-1}M_{\odot}$ inside $1h^{-1}$ Mpc and $(6.5 \pm 2.5) \times 10^{14}h^{-1}M_{\odot}$ inside $3h^{-1}$ Mpc. Even within the limited context of these assumptions this is a wide range. For determinations of cluster mass using galaxy dynamics, this is partly due to the unknown anisotropy in the galaxy orbits (whether, at a given radius, the galaxies are predominantly on isotropic, radial or circular orbits); for determinations based on x-ray observations, the uncertainty lies in the unknown temperature distribution. As well, there is the unknown distribution of the dark matter which dominates the total mass of the cluster.

All current observations are consistent with a model in which 'light traces mass' (i.e. the dark matter has the same distribution as the visible matter), the galaxies are on isotropic orbits and the cluster has a uniform temperature. However, they are also consistent with models which depart significantly from this simplest case. The best-fitting models suggest that the ICM and galaxies have somewhat more extended distributions than the dark matter. The core assumption of all these models, namely that Coma is in hydrostatic equilibrium, is clearly violated at some level. The extent to which the observed substructure invalidates the conclusions of the equilibrium models is not yet clear, although early indications are that the mass estimates are reasonably accurate.

Zwicky's 1933 estimate of the V-band mass-to-light ratio (M/L) in the Coma cluster was about $100hM_\odot/L_\odot$; today's mass estimates correspond to values in the range 300–400$hM_\odot/L_\odot$. This exceeds M/L for individual galaxies by a factor of 10 or more, implying that there is of order 10 times as much mass in dark matter as there is in galaxies. However, the cluster M/L falls well short of the M/L of a critical-density ($\Omega = 1$) universe, for which $M/L \approx 1600hM_\odot/L_\odot$. The ratio of the luminous baryonic mass (i.e. the mass in galaxies and x-ray gas) to the total cluster mass is about 0.15 inside $1h^{-1}$ Mpc and 0.2–0.4 inside $3h^{-1}$ Mpc. This is considerably higher than the baryon fraction $\Omega_B h^2 = 0.012 \pm 0.002$ that is predicted by big bang nucleosynthesis for an $\Omega = 1$ universe (even for $h = 0.5$). Taken at face value, the mass-to-light ratio and baryon fraction of Coma both suggest a low-Ω universe.

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Comprehensive and up-to-date reviews on all aspects of the Coma cluster, with references to the literature, can be found in

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