


**Today in Astronomy 142:
associations of galaxies**

- ❑ Groups, clusters and superclusters
- ❑ Galaxy cluster dynamics
- ❑ Dark matter in clusters of galaxies
- ❑ Interacting galaxies
 - Starbursts
 - Origin of active galaxy nuclei?

Markarian's Chain, at the core of the Virgo Cluster (Palomar-Quest team, Caltech).



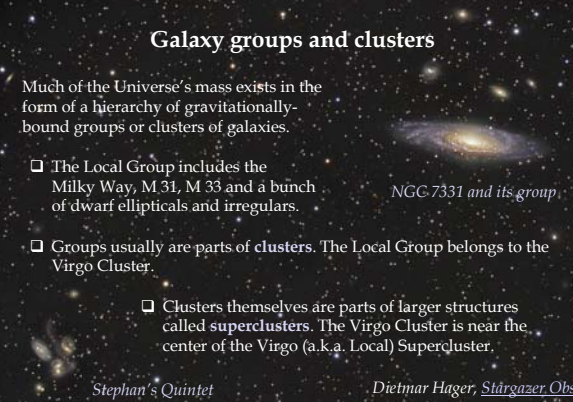
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Galaxy groups and clusters

Much of the Universe's mass exists in the form of a hierarchy of gravitationally-bound groups or clusters of galaxies.

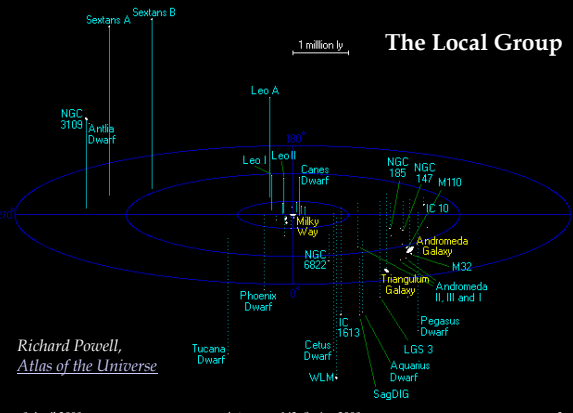
- ❑ The Local Group includes the Milky Way, M 31, M 33 and a bunch of dwarf ellipticals and irregulars. *NGC 7331 and its group*
- ❑ Groups usually are parts of clusters. The Local Group belongs to the Virgo Cluster.
- ❑ Clusters themselves are parts of larger structures called superclusters. The Virgo Cluster is near the center of the Virgo (a.k.a. Local) Supercluster.

Stephan's Quintet *Dietmar Hager, Stargazer Obs.*



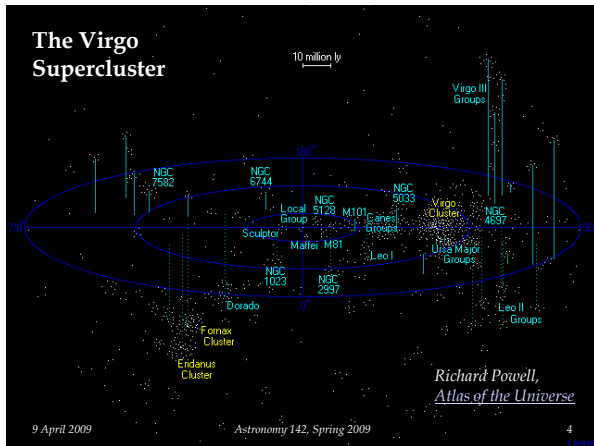
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The Local Group



Richard Powell, Atlas of the Universe

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Typical galaxy clusters

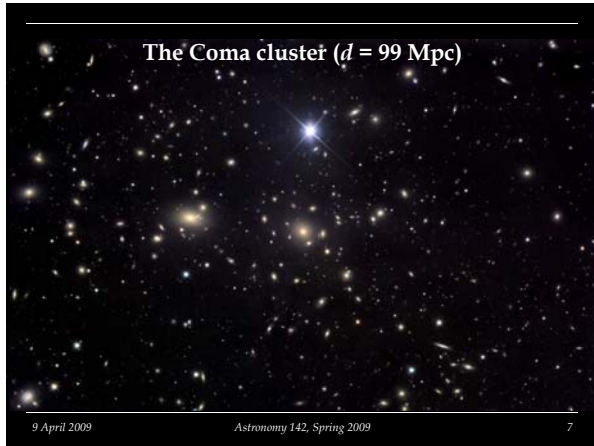
Galaxy clusters usually contain between several hundred and several thousand galaxies, spread over tens of Mpc but with cores 1-3 Mpc in radius.

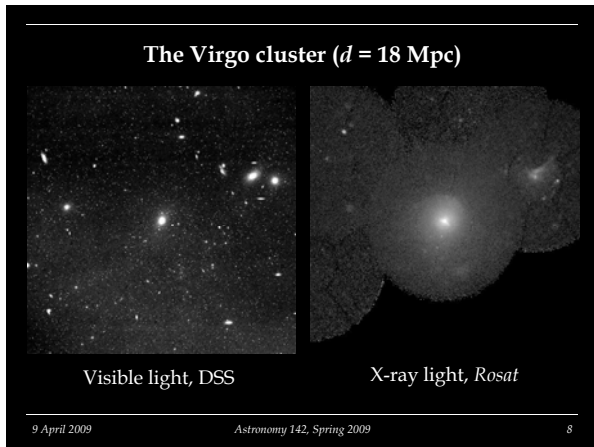
- ❑ Clusters come in a variety of “richness” (degree of central concentration). Rich clusters are dominated at their centers by one or more **cd galaxies**, and include mostly elliptical galaxies.
- ❑ “Poor” clusters are often dominated by spirals.
- ❑ Spiral galaxies within rich clusters tend to have less diffuse interstellar matter than field galaxies; S0 galaxies are much more abundant in clusters than the field. Both of these features probably due to galaxy collisions.
- ❑ The stripped-off interstellar matter is visible at X-ray energies as a hot intracluster medium (ICM)

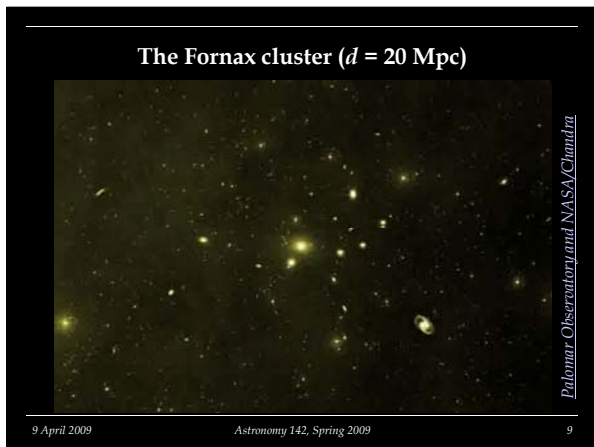
The Coma cluster ($d = 99$ Mpc)

Visible light, DSS
(galaxies)

X-ray light, XMM-Newton
(hot intracluster gas)







cD galaxies

They are giant ellipticals, with a few other differences from normal besides total mass:

- ❑ More extended, relative to their core radii and the normal elliptical-galaxy luminosity profile.
- ❑ Often exhibit multiple nuclei, either because they are assimilating other cluster members (“galactic cannibalism”), or because these nuclei are cluster galaxies on linear (highly eccentric) orbits.
- ❑ Often surrounded with shells of infalling intergalactic gas, that compress and cool as they fall (“cooling flows”).
- ❑ Often associated with bright, **strong gravitational lensing** of more distant galaxies, clusters or quasars.

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Abell 2218 and gravitational lensing




Photo by *Andy Fruchter et al.*, with HST/WFPC2

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Masses of galaxy clusters

One can try to measure the masses of clusters by adding up the masses of the contents.

- ❑ Count the galaxies and add up their masses, including their dark-matter haloes.
- ❑ Measure the X-ray spectrum and image.
 - The X-ray emission is due to radiation by electrons scattering from nuclei, a process called **thermal bremsstrahlung**.
 - The X-ray brightness at any energy is proportional to the square of electron density; the X-ray “color” gives the temperature.
 - Usually the X-ray distribution appears spherically **symmetrical and fairly smooth**.

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Masses of galaxy clusters (continued)

Results for typical rich clusters like Coma and Virgo:

- Galaxies and X-rays distributed similarly, with a core radius around 1 Mpc; looks like **hydrostatic equilibrium**.
 - The radial dependence of number per unit projected area is just like the radial dependence of surface brightness in globular clusters:

$$\mathcal{N}(r) = \mathcal{N}(0) \exp\left[-(r/r_0)^{-1/4}\right]$$

}
Core radius
- Galaxies, including their dark haloes, typically amount to $1-3 \times 10^{13} M_{\odot}$.
- X-ray-emitting gas has density around $n_e \sim 10^{-4} \text{ cm}^{-3}$, temperature around $T \sim 10^8 \text{ K}$, and mass around $1-3 \times 10^{14} M_{\odot}$, ten times as much as the galaxies.

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Masses of galaxy clusters (continued)

This leaves two odd dynamical features of galaxy clusters:

- The relaxation times for galaxy clusters,

$$t_c \cong \left(\frac{2r_0}{v}\right) \frac{N}{24 \ln(N/2)}$$

tend to be larger than the age of the Universe (1.4×10^{10} years); need to be much smaller in order to treat the galaxies in a cluster as a gas.

 - e.g. for Coma ($N = 10^4$, $r_0 = 3 \text{ Mpc}$, $v = 1700 \text{ km sec}^{-1}$), $t_c = 1.7 \times 10^{11}$ years.
 - Yet $\mathcal{N}(r)$ looks just like that for thermalized galaxy bulges and star clusters, and the distribution of their random velocities looks like Maxwell-Boltzmann.

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Masses of galaxy clusters (continued)

- The thermal velocity for intracluster gas,

$$v_{th} = \sqrt{3kT/m_H},$$

is typically about the same as the escape speed from the observed mass, $v_{esc} = \sqrt{2GM/r_0}$.

Thus, all of the hot gas originally in the typical galaxy cluster should have escaped by now.

 - AST 111 veterans know how to calculate the **Jeans escape time scale**:

$$\tau_{Jeans} = \frac{\sqrt{\pi}}{8} \left(\frac{2kT}{m_H}\right)^{3/2} \frac{r_0^3}{(GM)^2} e^{GMm_H/kTr_0} \approx 10^9 \text{ years}$$

for typical galaxy clusters.

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Masses of galaxy clusters (continued)

If the equilibrium-like appearance of the distribution of galaxies in clusters is taken to indicate equilibrium despite the inferred relaxation time, we can apply the virial theorem to estimate masses. As in Homework #7,

$$M = \frac{2r_0 \overline{v^2}}{G} = \frac{6r_0 \overline{v_r^2}}{G}$$

← Random component of radial velocity, relative to average of cluster.

- Typically this gives a result ten times higher than the mass of the visible galaxies and X-ray gas.
- Example: Coma, which has $M_{X\text{-ray}} = 3 \times 10^{14} M_\odot$ and the properties listed on page 14:

$$M = \frac{2r_0 \overline{v^2}}{G} = 4 \times 10^{15} M_\odot.$$

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Dark matter III


The discrepancy between visible-galaxy mass and virial mass was first noted Fritz Zwicky for the Coma cluster in 1933. He suggested an invisible form of matter to make up the difference; this was the original suggestion of the existence of dark matter.

So: what if galaxy clusters are 90% dark matter?

- Then the clusters *could* be in equilibrium. The dark-matter “nucleus” of each cluster could have thermalized early in the life of the Universe, and the visible galaxies formed after their dark haloes were already in equilibrium.
- This is enough mass to keep the X-ray gas from getting away: with the mass above, the Jeans escape time for the hot ICM in Coma is 2×10^{15} years, much longer than the age of the Universe.

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Dark matter III (continued)



Dark matter seen more directly: the Bullet Cluster, 1E0657-558, consists of two merging galaxy clusters. In the interaction, the hot gas from the clusters, visible in X rays (red) has suffered inelastic collisions and is now separate from the dark matter (blue), as detected *via* weak gravitational lensing.

Clowe et al. 2006

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Interacting galaxies

Galaxies have extents (tens of kpc) that are a significant fraction of the typical separation of galaxies in groups or clusters (hundreds of kpc), so collisions between them during the life of the universe aren't all that rare.

The stellar disks can be relatively unaffected by these encounters, because the stars themselves do not collide.

Interstellar gas clouds are big, though, and they do suffer inelastic collisions and tidal "stripping" that can result in transfer of ISM from one galaxy to the other.

- ❑ Transfer with large angular momentum: settles into disk and/or polar rings.
- ❑ Transfer with small angular momentum: falls into galactic nucleus, leads to **starbursts**.

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Interacting galaxies (continued)

Polar-ring galaxies were discussed before, on [26 March](#).

Starburst: a brief but dramatic increase in the rate of production of stars (100-1000 times faster than is normal in the disks of spiral galaxies), visible in the large number of OB stars and supernovae.

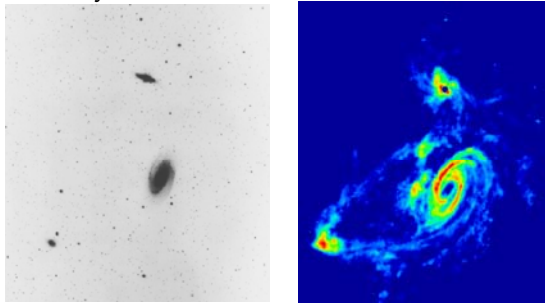
- ❑ Archetype: the M 81 group, 3.25 Mpc away, with M 82 undergoing a substantial starburst using material transferred from M 81.
- ❑ Very close encounters can result in mergers of galaxies. If such galaxies are gas-rich, then collisions among their interstellar clouds can result in compression or loss of angular momentum (subsequently falling into one of the galaxy nuclei), again resulting in a starburst.

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Galaxy mass transfer: M82, M81 and NGC 3077




Visible light (left, Palomar) and H I 21 cm (right, VLA); [Yun, Ho and Lo 1994](#)

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M82 (NGC 3034), archetype starburst galaxy




B, V, R and H α composite photograph by S. Kohle and T. Kredner, with the Calar Alto 1.2 m telescope.

The star formation rate in the nucleus of M82 is a factor of 10-100 larger than in a spiral disk, owing to infall of ISM "stolen" from M81.

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Galaxy merger: NGC 4038/4039



Left: wide angle view, showing tidal tails. Right: zoom in on galaxy nuclei and interaction region (NASA/STScI).

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Galaxy interactions and active galaxies

There is a continuum among the properties of starburst and interacting galaxies, and the properties of **ultraluminous infrared galaxies** like Arp 220.

- ❑ The luminosity function (number density per unit luminosity as a function of luminosity) of infrared ultraluminous galaxies is about the same as that of quasars, at high luminosity.
- ❑ This suggests that **active-galaxy accretion disks form in galaxy interactions.**
- ❑ It may suggest that the formation of the central black holes themselves is related to galaxy interaction and starbursts. At the moment, though, we can only speculate about black-hole formation details.

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