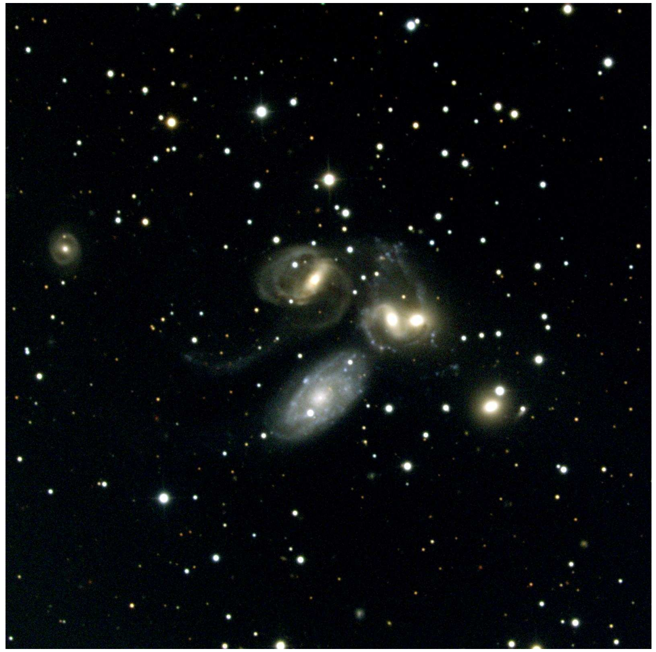
Galaxy Groups and Clusters



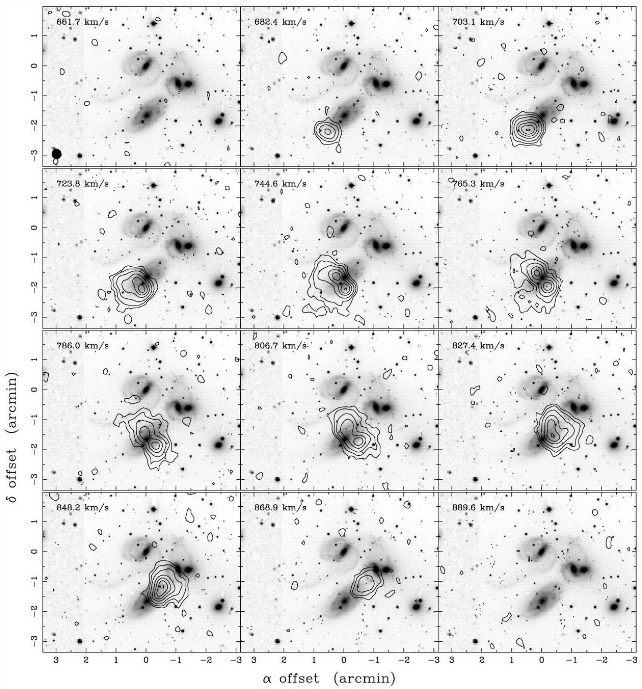
Stephan's quintet: compact group of galaxies; Credit: ESO

Observations

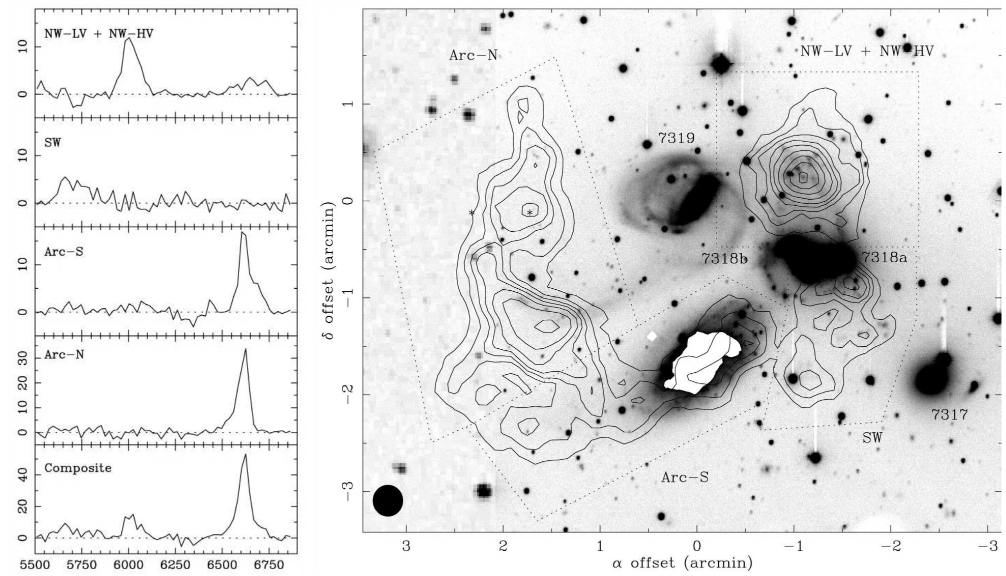
$\sim$ 50 % of all galaxies are found in *groups and clusters*!

Rule of thumb characteristics of groups and clusters:

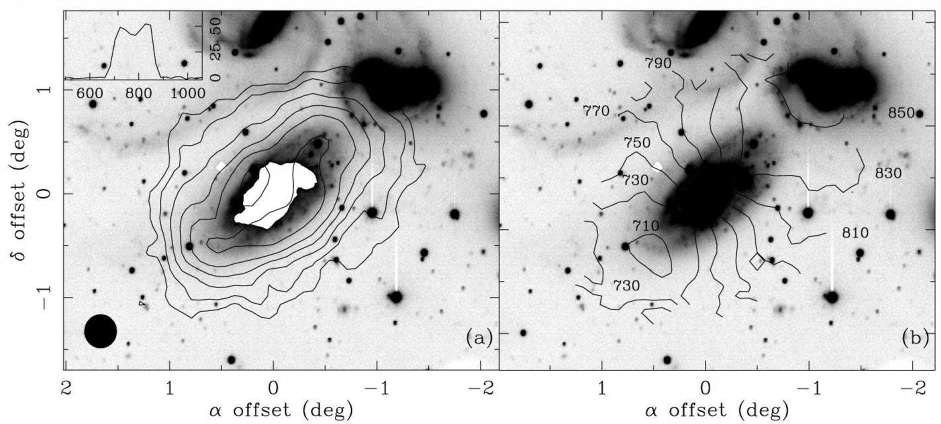
- Ensemble of galaxies packed into $\lesssim 1\,\mathrm{Mpc}$
- Gravitationally bound
- $M \gtrsim 10^{13} M_\odot$ (groups); up to $M \sim 10^{15} M_\odot$ for largest clusters
- *Galaxy Groups:* $\lesssim$ 50 members, $M \lesssim 10^{14} M_\odot$, mostly spirals and irreg. galaxies, about 50 % of all groups contain hot gas ($T > 10^6\,\mathrm{K}$) that shines at X-rays
- *Galaxy Cluster:* $\gtrsim$ 50 members, $M \gtrsim 10^{14} M_\odot$, mostly ellipticals and S0 galaxies, most mass in a hot intracluster gas (X-ray emission)
- Cosmologically *young* structures (see structure formation)



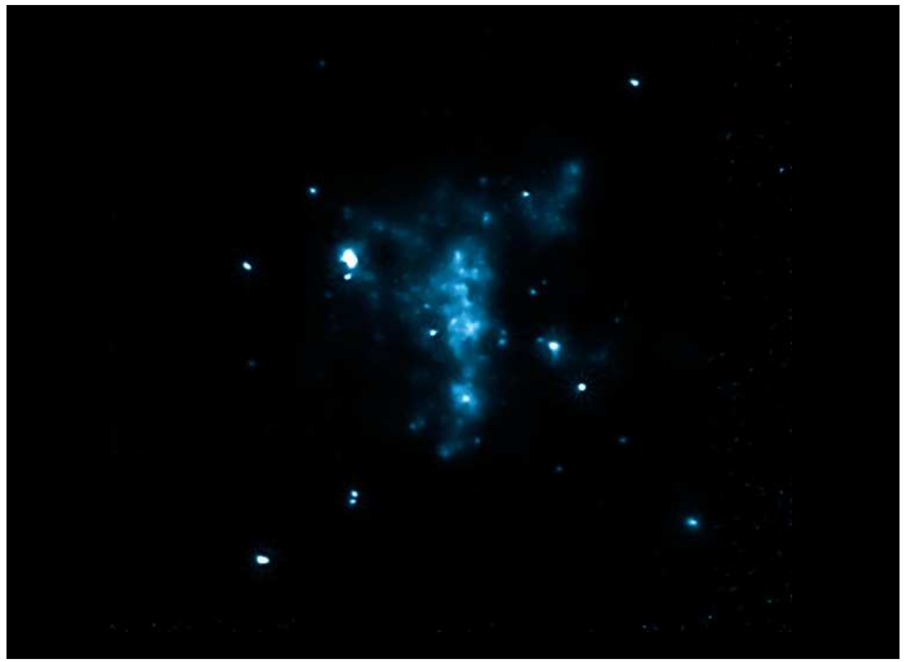
H I emission of Stephan's quintet around 780 km s^{-1} radial velocity (Williams et al., 2002)



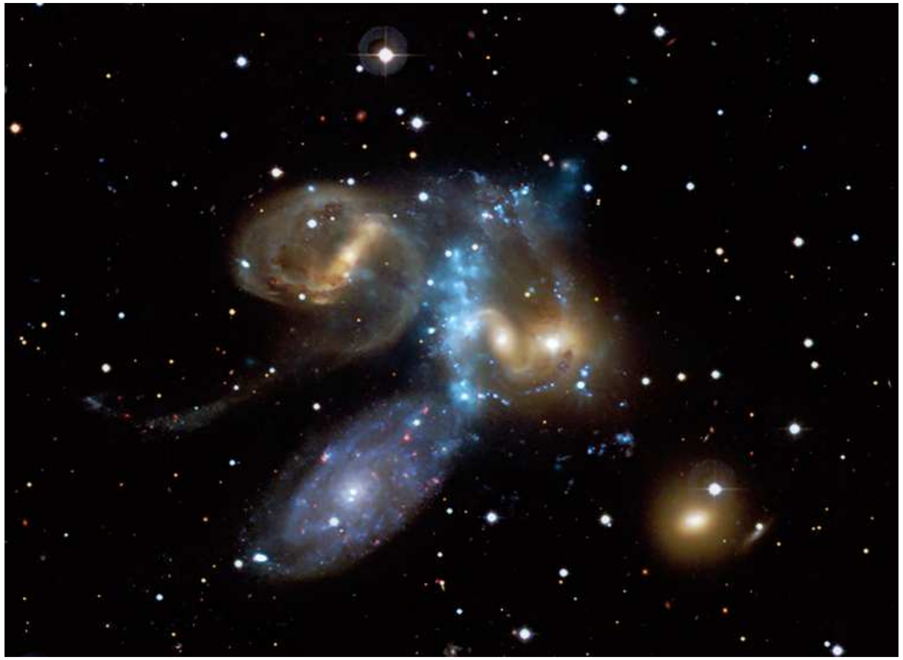
H I distribution of Stephan's quintet between 5597 km s^{-1} and 6918 km s^{-1} radial velocity (Williams et al., 2002). Neutral hydrogen is distributed between the group galaxies.



H I distribution of NGC 7320 and Spider diagram (Williams et al., 2002)

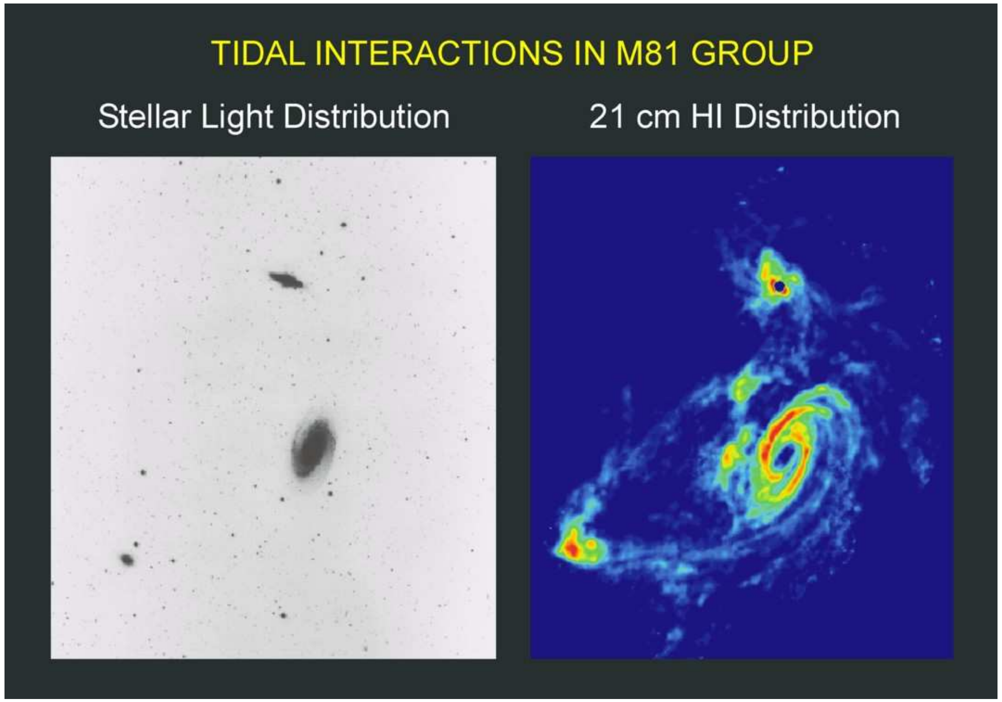


Chandra X-ray image of Stephan's quintet (NASA/CXC/CfA/E.O'Sullivan)

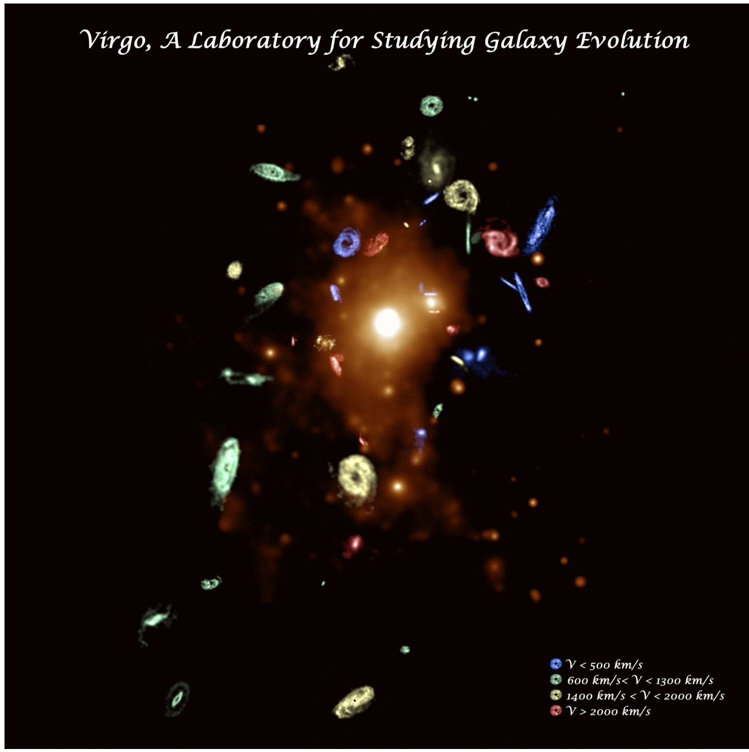


X-ray (NASA/CXC/CfA/E.O'Sullivan); Optical (Canada-France-Hawaii-Telescope/Coelum)

Coma cluster: prototype for rich clusters; courtesy Jim Misti



Optical DSS image (left), HI VLA image (right); Credit: NRAO/AUI



HI images (VLA) of 47 spiral galaxies in Virgo, overlaid on X-ray image (*ROSAT*). Galaxy sizes upscaled by a factor of 10.

Most central cluster galaxies have been stripped of their cool HI gas. Interaction with the hot intracluster gas.

Image courtesy of NRAO/AUI and Chung et al., Columbia University

Classification of Groups and Clusters

First catalog of galaxy clusters: Abell (1958)

- Palomar Observatory Sky Survey (POSS): visual identification; northern sky
- Criteria: $>$ 50 galaxies in brightness range $m_3 < m < m_3 + 2\,\mathrm{mag}$ within 1.5 Mpc of cluster center (m_3: magnitude of 3rd brightest galaxy)
- Distance estimate based on brightness of 10th-brightest member; $z \lesssim 0.2$
- $\sim$ 4000 Clusters (including southern extension of catalogue, “Abell-Clusters”, e.g., A1656=Coma)

Any catalog based on galaxy counts and 2D-density determination, will be incomplete and will contain both foreground and background objects.

Richness classes 1–5: number of galaxies $>$ 50, $>$ 80, $>$ 130, $>$ 200, $>$ 300.

Classification of Groups and Clusters

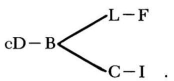
Pub. Astron. Soc. Pacific, Volume 83, June 1971

“TUNING FORK” CLASSIFICATION OF RICH CLUSTERS OF GALAXIES

HERBERT J. ROOD AND GUMMULURU N. SASTRY
Van Vleck Observatory, Wesleyan University, Middletown, Connecticut

Received 28 December 1970

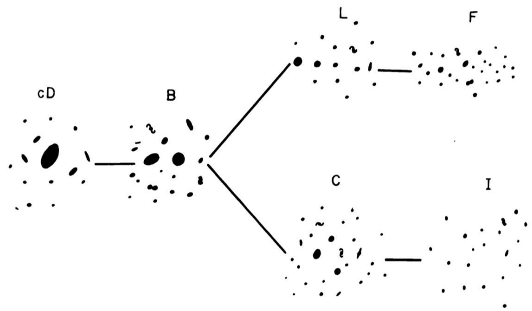
A classification scheme of rich clusters of galaxies based on the distribution of the ten brightest member galaxies is described. The cluster types, which fall naturally into an ordered sequence with criteria varying systematically from one end to the other, can be represented by a “tuning fork” diagram:



Preliminary types are listed for the 111 Abell clusters with distance classes less than four.

Key words: clusters of galaxies — galaxies

Classification of Groups and Clusters



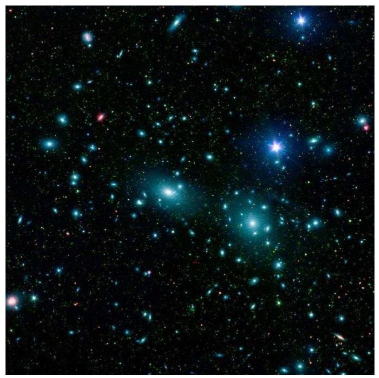
Rood & Sastry (1971)

- *cD*: dominated by a central cD galaxy
- *B*: central pair of bright galaxies
  - *L*: linear configuration of the dominant galaxies
  - *F*: flattened configuration of brightest galaxies
  - *C*: multiple galaxies in one core region
  - *I*: irregular configuration

Classification of Groups and Clusters

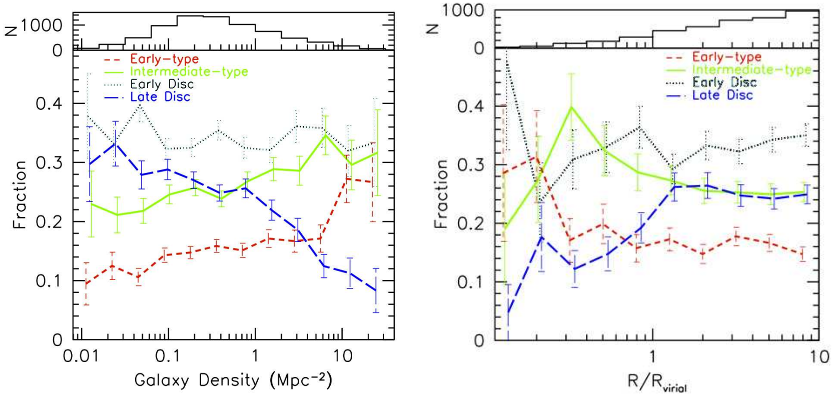
Simplified classification:

- Regular clusters: compact configuration, mainly elliptical and S0, large richness
- Irregular clusters: open configuration, more spirals, low richness



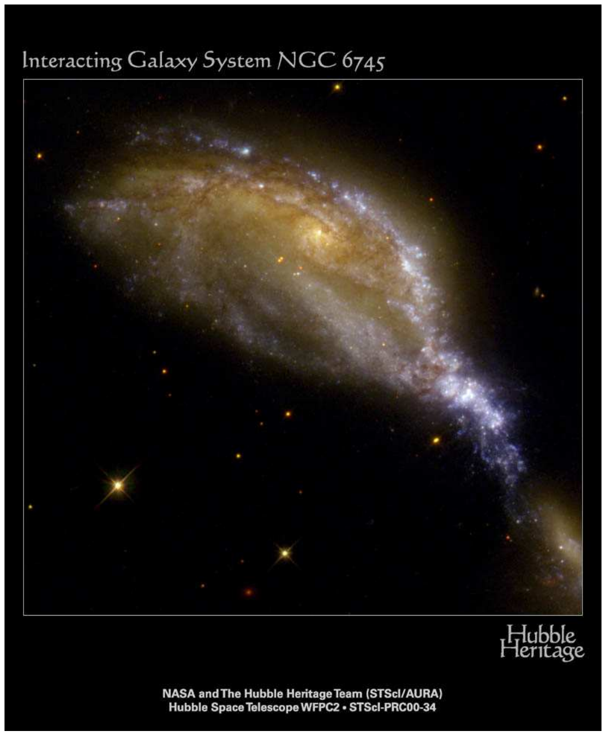
Coma cluster (left): NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.; Hercules cluster (right): Tony Hallas

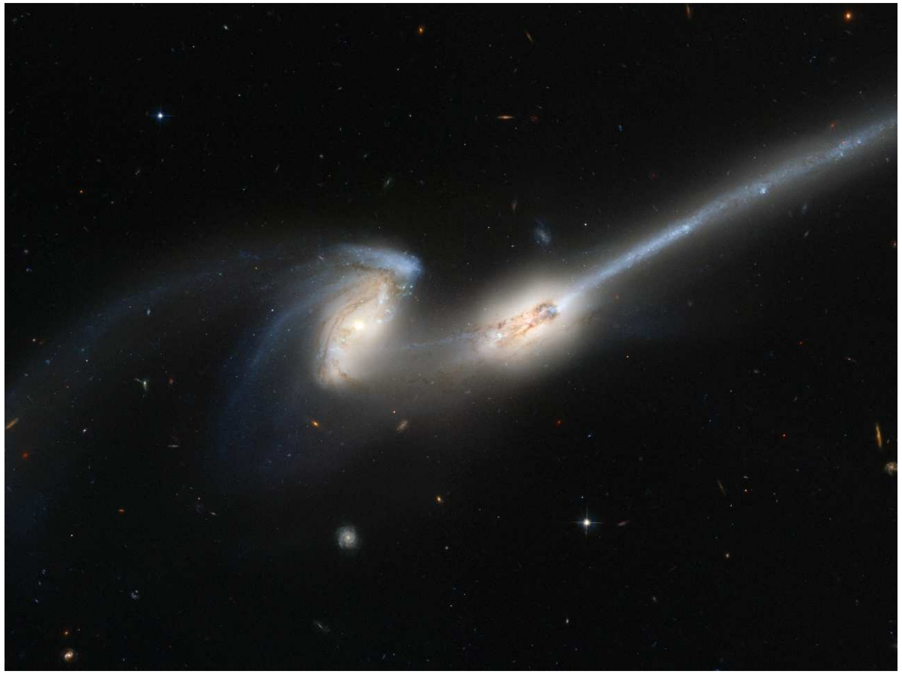
Classification of Groups and Clusters



Goto et al. (2003, , based on SDSS data)

Local galaxy density determines morphological galaxy mixture!



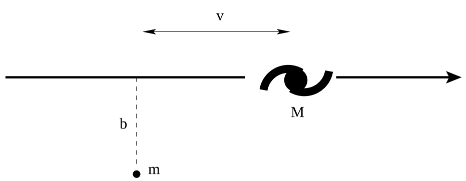


The Mice (NGC 4676); Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA

Dynamical Friction, III

What happens when two galaxies in a group or cluster pass close to one another?

Part of their energy of motion is transferred to motion of individual stars. The interacting galaxies are slowed down and may eventually merge.



m: star in a galaxy 1
$\mathcal{M}$: galaxy 2 passing by galaxy 1 at minimal distance b from the star in galaxy 1 at speed v

after Sparke & Gallagher

Perpendicular force:

$$\mathbf{F}_\perp = \frac{Gm\mathcal{M}b}{(b^2+v^2t^2)^{3/2}} = \mathcal{M}\frac{\mathrm{d}v_\perp}{\mathrm{d}t} \quad . \tag{7.1}$$

Integrating over time gives:

$$\Delta v_\perp = \mathcal{M}^{-1}\int \mathbf{F}_\perp(t)\mathrm{d}t \quad , \tag{7.2}$$

Dynamical Friction, IV

$$\Delta v_\perp = \int \frac{Gmb}{(b^2+v^2t^2)^{3/2}}\mathrm{d}t = \frac{2Gm}{bv} \quad . \tag{7.3}$$

The faster the galaxies move, the smaller the velocity change.

This calculation assumes that the galaxies are much smaller than b and that we have a rapid flyby, i.e., $\mathcal{M}$ and m do not move during the encounter.

The star m gains an equal and opposite momentum, so the total energy transferred into perpendicular motion is:

$$\Delta E_{\mathrm{kin},\perp} = \frac{\mathcal{M}}{2}\left(\frac{2Gm}{bv}\right)^2 + \frac{m}{2}\left(\frac{2G\mathcal{M}}{bv}\right)^2 = \frac{2G^2m\mathcal{M}(\mathcal{M}+m)}{b^2v^2} \quad . \tag{7.4}$$

The object of the smaller mass (here: the star) acquires most of the energy. The object with the higher mass (the galaxy) is slowed down in $v_\parallel$.

Dynamical Friction, V

Long before and long after the encounter, the potential energy is small and the energy equation can be expressed solely with the various terms of the kinetic energies:

$$\frac{\mathcal{M}}{2}v^2 = \Delta E_{\mathrm{kin},\perp} + \frac{\mathcal{M}}{2}(v+\Delta v_\parallel)^2 + \frac{m}{2}\left(\frac{\mathcal{M}}{m}\Delta v_\parallel\right)^2 \quad . \tag{7.5}$$

If $\Delta v_\parallel \ll v$, the quadratic terms can be dropped:

$$\Delta v_\parallel \approx -\frac{\Delta E_{\mathrm{kin},\perp}}{\mathcal{M}v} = -\frac{2G^2m(\mathcal{M}+m)}{b^2v^3} \quad . \tag{7.6}$$

Finally, integrate over all stars in galaxy 2 (n stars of mass m):

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\int nv\frac{2G^2m(\mathcal{M}+m)}{b^2v^3}2\pi b\mathrm{d}b = -\frac{4\pi G^2(\mathcal{M}+m)}{v^2}nm\ln\Lambda \quad , \tag{7.7}$$

with $\Lambda = b_{\mathrm{max}}/b_{\mathrm{min}}$.

Deceleration of galaxy 2 by the stars of galaxy 1: **dynamical friction**.

Dynamical Friction, VI

Eq.7.7 shows that the slower $\mathcal{M}$ moves, the larger is its deceleration and that more massive systems are slowed down more quickly than small systems.

Once v falls below the velocity dispersion of stars, $\mathrm{d}v/\mathrm{d}t \propto -v$ (Stokes' law).

$\Rightarrow$ the LMC is likely to merge with the Milky Way in a few gigayears, while most globular clusters are in no danger.

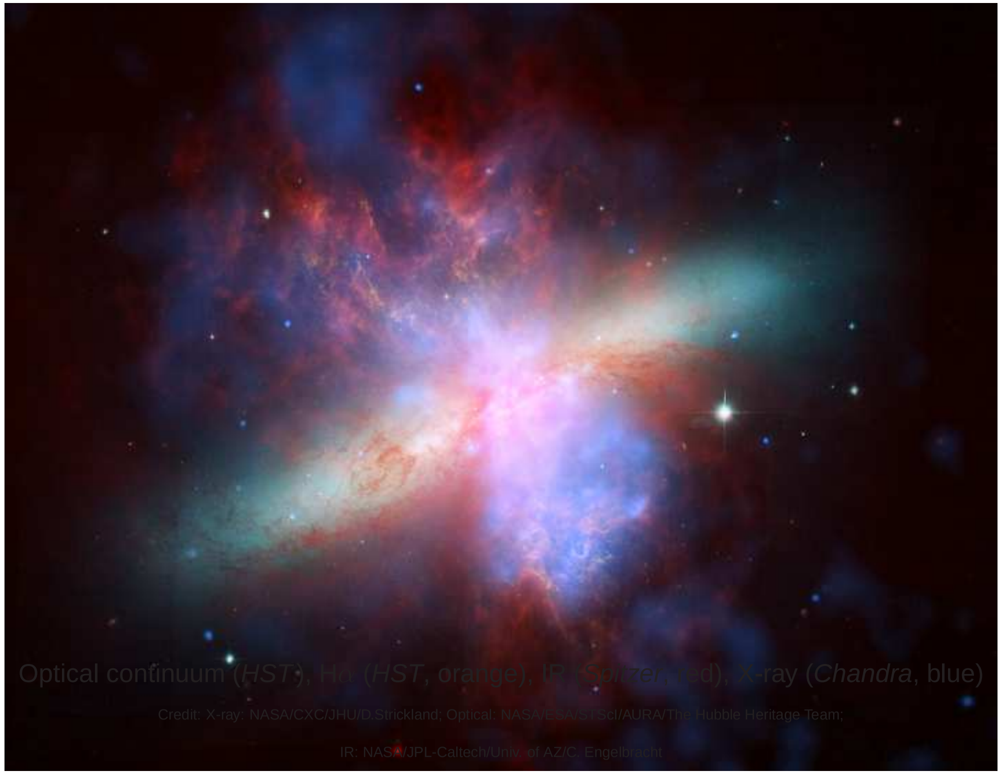
- Galaxy encounters transfer bulk kinetic energy into internal kinetic energy $\Rightarrow$ the system is less strongly bound and expands. Stars can escape from their galaxy and in disk systems, the stellar disks are thickened.
- High velocities in clusters prevent the galaxies from merging. Almost all mergers are observed in groups.
- As we saw before, close encounters can trigger bar formation and force gas towards the galaxy center to fuel an active nucleus. Both NGC 7319 in Stephan's Quintet and M 81 are Seyfert galaxies.

Dynamical Friction, VII

Movie time: `http://www.nicolascretton.ch/Astronomy/Galaxies/Galaxy_mergers/Mice_long.mpg`

M81 and M82; Image: Johannes Schedler (Panther Observatory)

M82 starburst and wind; Image: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

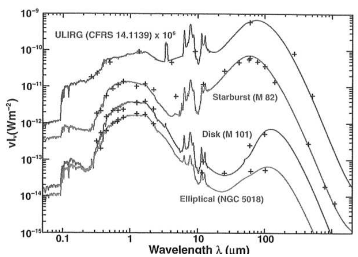


Optical continuum (*HST*), Hα (*HST*, orange), IR (*Spitzer*, red), X-ray (*Chandra*, blue)

Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

Starbursts, IV

Starbursts: Stars form so rapidly as to exhaust the gas supply within a few hundred million years.

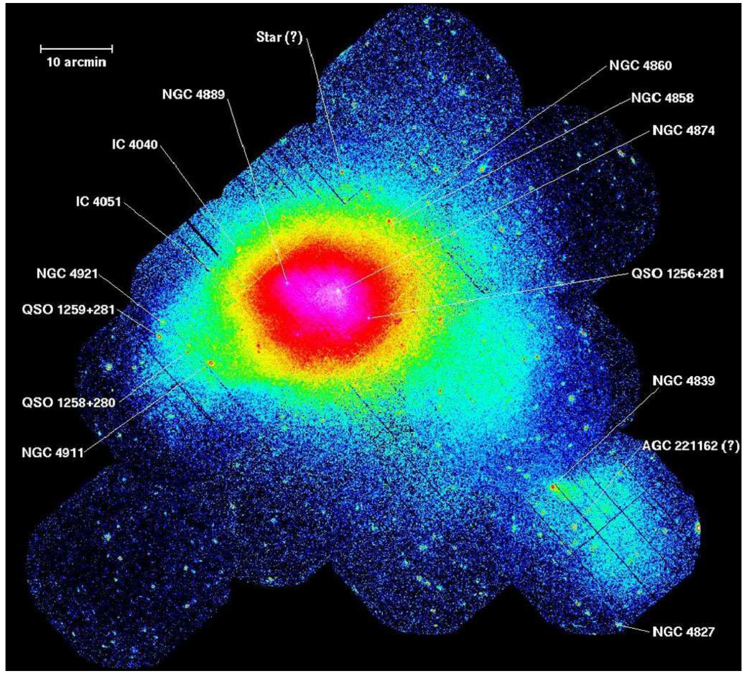


Sparke & Gallagher Fig 7.7

- Primary (blue) light of newborn stars largely absorbed by dust
- Re-emitted in the IR
- Even more extreme: *Ultraluminous infrared galaxies (ULIRGs)*
- In almost all cases triggered by interactions of gas-rich galaxies
- Star formation rate: $\frac{\mathrm{SFR}}{M_\odot/yr} \approx \frac{L_{\mathrm{FIR}}}{6\times10^9 L_\odot}$
  $\Rightarrow$ up to $1000 M_\odot/yr$

Observations, I

- 1965: M87 is first extragalactic source detected in X-rays
- 1969: Perseus clusters detected
- 1973–1975: *UHURU* detects emission from many clusters
- 1979: *HEAO-1*: Spectra: optically thin radiation
- 1984: Einstein: imaging and high resolution spectra
- 1990: *ROSAT*: Emission from essentially *all* clusters
- 1990: *ASCA*: high resolution spectra
- 2000: *XMM-Newton*/Chandra: high resolution spectra, imaging,. . .



XMM-Newton mosaic of the Coma cluster

Observations, II

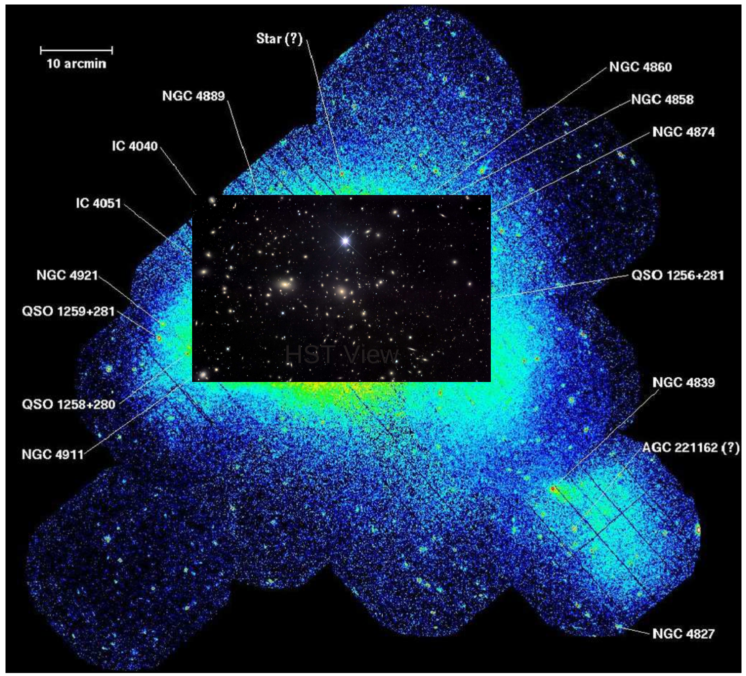
X-ray astronomy has shown that galaxy clusters are the brightest X-ray sources in the sky (next to AGN). In contrast to AGN, the emission is resolved by modern X-ray telescopes and may be difficult to detect in small field-of-view observations.

In the richest systems, there is 10 times more mass in hot gas than is in stars!

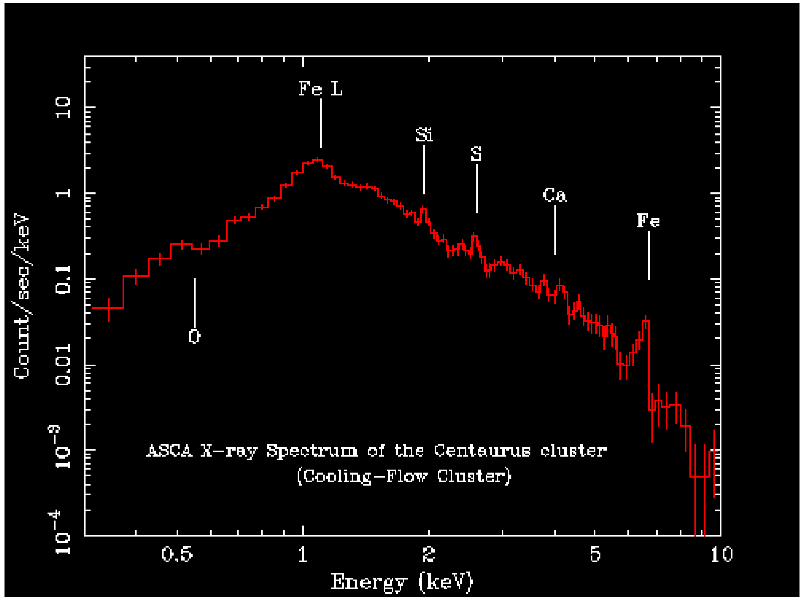
The hot gas fills the whole cluster and can be traced to larger radii than the stellar light.

Possible ways to add energy to the intracluster gas:

- Starbursts (see, e.g., *Chandra* image of M 82.)
- AGN and jets



XMM-Newton mosaic of the Coma cluster



First seen with Einstein: Cluster gas emits Kα lines from highly ionized Mg, Si, S, Fe, etc. No primordial gas!

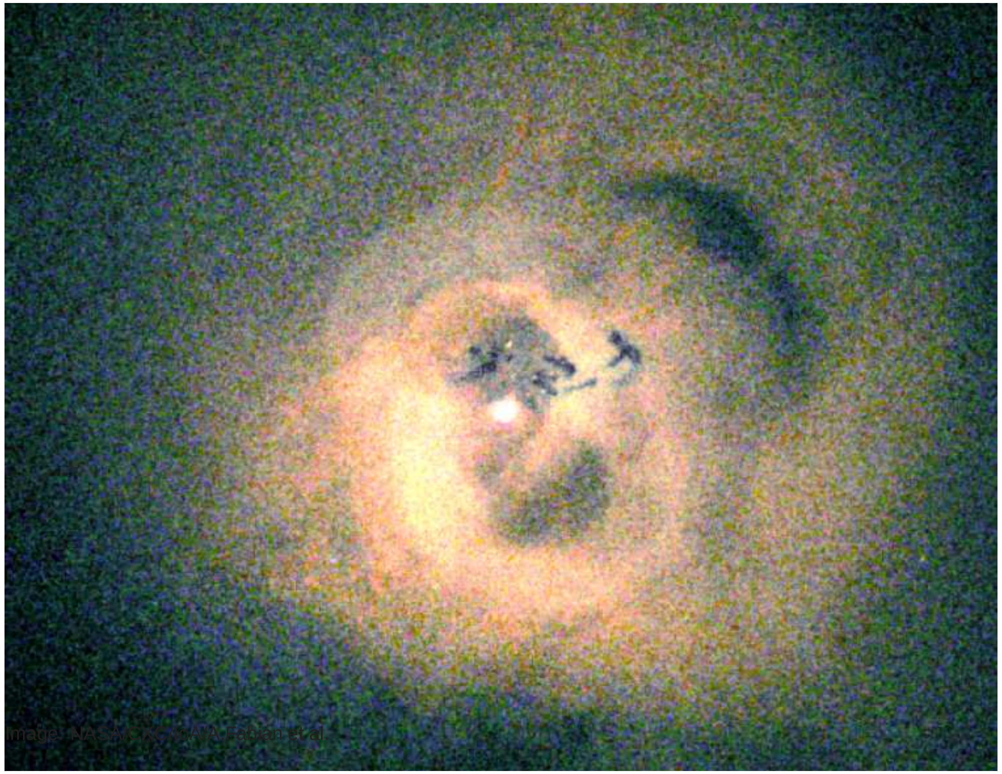
Cooling Flows

X-ray emission is a very efficient way of cooling the intracluster gas (radiate away its energy). This effect should be strongest at the cluster centers. Pressure of the outer (hotter) regions should drive material inward ⇒ Cooling Flow.

Cool gas should trigger massive star formation.

There is little evidence for cool X-ray emitting gas nor for massive star-bursts in cluster centers ⇒ Cooling Flow Problem ⇒ Gas must be re-heated.

The currently favored model for the heating involves AGN feedback (Example: Perseus cluster).



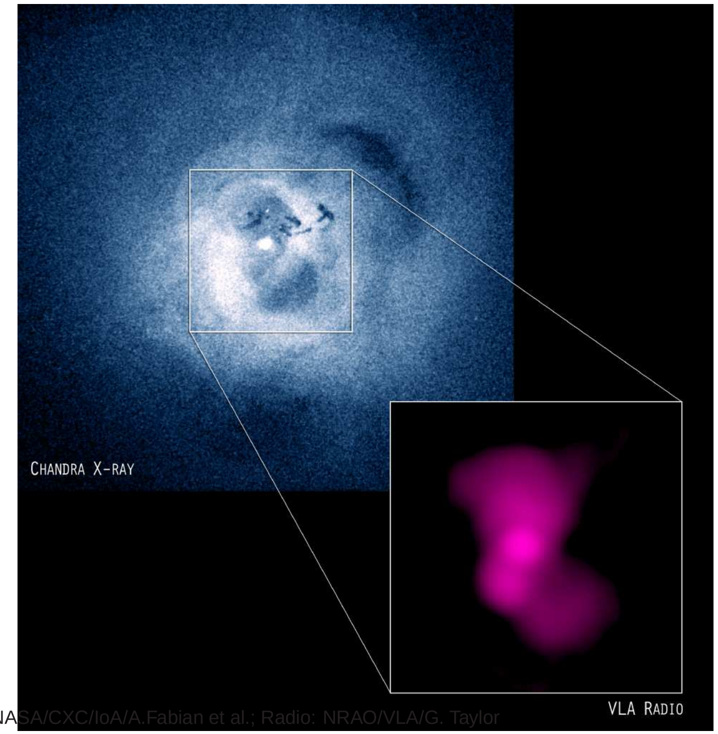


Image: X-ray: NASA/CXC/IoA/A.Fabian et al.; Radio: NRAO/VLA/G. Taylor

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