“Activity” in galaxies

- Tides, collisions, mergers
  - Distorted appears due to gravitational forces
- Starburst
  - Star formation rate much higher than "normal" (i.e. the average in Milky Way today)
- “Active Galactic Nucleus” (AGN; Seyfert galaxies; Quasar/QSO)
  - Presence of extremely bright, star-like nucleus which shows evidence (fast moving gas clouds; high energy photons) of SMBH

Sometimes more than one of these applies in the same system => cause and effect
Broad Emission line region photoionized by continuum emission; size is ~few light-days to months; densities $> 10^9$ /cm$^3$; stratified (higher-ionization lines from smaller radii)

Narrow Emission line region also photoionized; size is ~10 to 1000 pc; densities $\sim 10^3 - 10^6$ /cm$^3$; complex morphology

Obscuring Torus of dust is believed to form around perimeter of accretion disk
Spectral distinctions

Diagram from Bill Keel, U Alabama
AGN diagnostics


- See Osterbrock's book
- Red circles: AGN
- Blue triangles: Star forming galaxies
AGN/Star formation diagnostics


- Blue triangles: Unambiguous star forming galaxies, 4-line method
- Red circles: Four-line AGN
- Green squares: Two-line AGN

- Stars refer to AGN's identified by other studies.
Spectral diagnostics

• For nearby, resolved objects, HST can provide color-magnitude diagrams, but for more distant objects, we must deduce the star formation history from spectra (if we’re lucky…)

• Does the spectrum show the characteristics of a static, evolved, old stellar population?
  • Age of the stellar population?
  • e.g. Hydrogen Balmer absorption: A-stars but no emission lines means no O,B stars

• Does the spectrum contain emission lines as expected for HII regions?
  • Current massive star formation

• Does the spectrum show absorption lines that are much broader than normal => SMBH
Interactions in distant clusters
Galaxies and their environments

Gravitational Lens
Galaxy Cluster 0024+1654
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA

Stephan's Quintet
Morphological Alteration Mechanisms

I. Environment-independent
   a. Galactic winds
   b. Star formation without replenishment

II. Environment dependent
   a. Galaxy-galaxy interactions
      i. Direct collisions
      ii. Tidal encounters
      iii. Mergers
   b. Galaxy-intracluster medium interactions
      i. Ram pressure stripping
      ii. Thermal evaporation
      iii. Turbulent viscous stripping
   c. Galaxy-cluster interactions
      i. Harrassment
During tidal interactions and mergers, gas tends to be driven towards the centers of galaxies through gravitational torques on it by tidally induced stellar bars ⇒ dissipation and shocks

- Starbursts
- Globular cluster formation
- Feeding of AGN
Slow Moving Encounters
Toomre & Toomre 1972

- The galaxy's mass is concentrated at a point
- The outer disk particles are arranged in 5 rings
- They do not interact with each other (no self-gravity)
- All passages involve two galaxies that have a close, slow moving parabolic approach
- Each time unit is 100 million years
Toomre\textsuperscript{2} results

- Galaxy encounters are not accidental; most pairs are bound already
- Direct encounters cause more damage than retrograde ones
- Tails (nice) are easier to make than bridges (messy)
- Viewing geometry is critically important
Retrograde passages

Toomre & Toomre found that retrograde passage (ones in the opposite direction to a galaxy’s spin) have little tidal effect. See Picture below.

From now, we will only discuss direct passages, which are far more disruptive.

Fig 1. Flat retrograde (i=180°) parabolic passage of a companion of equal mass.
• Direct passages are more effective
• More damage from equal mass companion
Fig. 13.—Results of four differently inclined passages of fixed argument $\omega = +60^\circ$. The top row depicts the $\beta = 0^\circ$ face-on appearances of these four severely perturbed disks at $t = 3.143$, whereas the bottom row shows how each object would look if viewed at tilt $\beta = 60^\circ$ from the same longitude $\lambda = 45^\circ$. 
• Unlike bridges, tails involve some particles escaping towards infinity.
• To form major tails, the galaxies should be similar in mass.
• Like bridges, tail making is less effective at higher inclination planes. Again, the difference between $0^\circ$ and $30^\circ$ is small.
• However, in higher inclinations, the tail is raised from the orbit plane. This allows the tails to be crossed, as in NGC 4038/9.
Driven Systems

Passage of nearby galaxies causes a perturbation that produces a spiral arm. Confirmed using N-body numerical simulations... more on this......
Encounter geometry

- Disks shown in their original position.
- Each disk inclined 60° with respect to orbital plane
The Antennae in HI

http://www.cv.nrao.edu/~jhibbard
b) M51 and NGC 5195

Unlike the above, the most famous "bridge" linking two galaxies now seems definitely a fraud. Certainly both M51 (= NGC 5194) and its companion NGC 5195 show major signs of tidal damage. But as we are about to demonstrate, that damage only completes the proof that NGC 5195 lies at present well behind M51.

To begin, we would like it clearly understood here that our immediate concern is not with the magnificent spiral structure seen in M51 within, say, 20 of its center. Rather, in our view much of the explicit tidal damage to M51 itself only commences

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**Fig. 20**—Auxiliary studies of M51. (a) The top row offers five face-on ($\beta = 0^\circ$) views of the evolving shapes of three test-particle rings of initial radii 0.2, 0.4, and 0.6 $R_{\text{vir}}$, after being perturbed by an inclined $i = -70^\circ$, $\omega = 15^\circ$, elliptic $e = 0.8$ passage of a companion of one-third mass. Also shown, at times $t = 2.0$ and 2.8, are the corresponding shapes from instances where the mass ratio of the satellite to the primary was assumed one-half and one-fifth; in those cases, the original radius of the outermost ring was altered to 0.55 and 0.65 $R_{\text{vir}}$ respectively. (b) Slightly tilted ($\lambda = \phi = -30^\circ$) and 3 enlarged view of the above $t = 2.4$ configuration. It excludes the 0.2 and 0.7 $R_{\text{vir}}$ particles, but it includes two additional rings from 0.15 and 0.85 $R_{\text{vir}}$. The left-hand picture has been decomposed on the right into its four constituent rings; the italicized numbers there are the Doppler velocities of various particles, relative to the primary, obtained after scaling the similar speed of the satellite to $+110$ km s$^{-1}$.
Fig. 21.—Model of the recent encounter between M51 and NGC 5195. Shown here at $t = 2.4$ are three mutually orthogonal views of the consequences of a highly elliptic $e = 0.8$ passage of a supposedly disklike "5195." This satellite was chosen to be one-third as massive, and of exactly 0.7 times the linear dimensions, of the "5194" primary—which itself contains particles from initial radii $0.2(0.05)0.4(0.03)0.633 R_{	ext{sun}}$. The orbit plane differs by an angle $i_b = -70^\circ$ from the initial spin plane of the larger disk and by $i_b = -60^\circ$ from that of the smaller; however, the arguments $\omega_4 = \omega_5 = -15^\circ$ of the pericenters were here kept identical, to make the above nodal axes $x_4$ and $x_5$ exactly antiparallel. The three views show the combined system as it would appear not only (b) to us ($\lambda_4 = 65^\circ$, $\phi_5 = -20^\circ$), but also edge-on to our sky from (a) the "north" ($-25^\circ$, $90^\circ$) and (c) the "west" ($65^\circ$, $70^\circ$) directions.
M51

Figure 1. M51: The Whirlpool Galaxy.
H\textsc{i}: VLA C+D-array, 34" resolution, contours=4 \times 10^{19} \text{ cm}^{-2} \times 2^\circ.
Optical: DSS, FOV=26' \times 29'.
"The Mice"
Mice encounter simulation
Mice encounter simulation
Fig. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius $0.7R_{\text{min}}$ experienced an $e = 0.6$ elliptic encounter, having begun flat and circular at the time $t = -16.4$ of the last apocenter. As viewed from either disk, the adopted node-to-peri angles $\omega_A = \omega_B = -90^\circ$ were identical, but the inclinations differed considerably: $i_A = 15^\circ$, $i_B = 60^\circ$. The resulting composite object at $t = 6.086$ (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from $\lambda_A = 180^\circ$, $\beta_A = 85^\circ$ or $\lambda_B = 0^\circ$, $\beta_B = 160^\circ$—in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.
“The Mice”
Chris Mihos' Cartwheel movie
Cartwheel
How likely are encounters?

- Slow encounters are unlikely in dense clusters
- Simulated passages are unlikely to be hyperbolic
- Tails and bridges are the least observed in dense clusters
- Close encounters unlikely in loose groups
- Therefore, most tidal effects must have been created by galaxies gravitationally bound
The Magellanic Clouds

- The Magellanic Clouds are contained within a common HI envelope.
- The Magellanic Stream traces their interaction with the MW.
cD N4881 in Coma

cD = “cluster diffuse”

Much brighter than next brightest galaxy

NGC 4881
Coma Cluster
HST · WFPC2

Surface brightness

Log radius

excess

PF95-07 · ST ScI OPO · January 1995 · W. Baum (U.WA), NASA

1/27/95 zgl
cD surface brightness profile

- cD galaxy in the cluster A496
- Note the excess light at $R^{1/4} > 2$

$$SB(r) = SB(r_{\text{eff}}) \exp \left(-7.67[(r/ r_{\text{eff}})^{1/4} - 1]\right)$$

where $r_{\text{eff}}$ is the effective radius

Morretti et al.
Luminosity function

• The L.F. gives the number of galaxies per unit volume per luminosity (or magnitude) interval.

• Schechter (1980) expressed the LF as an analytic function with both a power law and an exponential:

\[ \phi(L) dL = \phi^*(\frac{L}{L^*})^\alpha e^{(-\frac{L}{L^*})} \frac{dL}{L^*} \]

\[ \phi(M) dM = \frac{2}{5} \phi^* (\ln 10) \left[ 10^{\frac{3}{5}(M^*-M)} \right]^{\alpha+1} e^{[-10^{\frac{3}{5}(M^*-M)}]} dM \]

\( \alpha \) = faint end slope
\( \varphi(L) \)
\( L^* \) = luminosity at “knee” of L.F.

cD’s too bright!
cD galaxies

- In the cores of regular rich clusters (or at a density enhancement)
  - *Local* conditions are important
- Offset (too bright) from the luminosity function of normal galaxies
- Extensive (~1Mpc) stellar envelopes of low surface brightness
- Many have multiple nuclei

*Sarazin (1988)*

![cD galaxy in Abell 3827](image)
How do cD’s form?

- **Galactic Cannibalism** (Ostriker & Hausman, 1977)
  - *Dynamical friction* brings massive galaxies to the center of clusters
  - *Merger* of these massive galaxies in the cluster cores
  - Giant galaxy then swallows other galaxies going through the core

![Centaurus A](image-url)
Dynamical friction

- Suppose an object of mass $M$ is moving within a sea of other objects of mass $m$, with $m < M$.
- As $M$ moves forward, the other objects are pulled towards it, with the closest ones feeling the strongest force.
- This produces a region of enhanced density along the path of $M$, including a wake trailing it.
- **Dynamical friction** = net gravitational force on $M$ due to others that opposes its motion.
- Kinetic energy is transferred from $M$ to surroundings, thus reducing its speed.
Cartoon of dynamical friction

Mass $M$ sees stars approach at velocity $-V$
Stars are deflected a bit by $M$
Slight excess of mass behind mass $M$
Galaxy harassment

Multiple rapid encounters in a cluster may also seriously impact galaxy evolution.

Animation courtesy of G. Lake
Harassment

• Supporting evidence:
  - **Intra cluster diffuse light (ICL)**
    • Intergalactic stars, ~10-40% of the cluster stellar population (Feldmeier et al., 2003)
  - **Tidal debris**
    • e.g. Plumes and arc-like structures
    • The amount of tidal debris and ICL depends on local density, which supports the merger scenario (Combes, 2004)
  - **Rings of star formation that are more common than two-armed spirals** (Oemler et al., 1997)
    • Due to bars triggered during tidal interactions?

Calcaneo-Roldan et al. (2000)
Ram pressure sweeping

- Spirals in Virgo are HI deficient.
- Hydrodynamical simulations show effectiveness of ram pressure stripping
- Stripping occurs if 
  \[ \rho_{ICM} V^2 > 2\pi G \Sigma_{gas} \Sigma_{stars} \]

\[ \downarrow \]
- Ram pressure exerted by stationary gas on moving galaxy
- V is velocity of galaxy with respect to cluster

\[ \text{\textbullet\textbullet\textbullet} \]
- Gravitational “restoring” force of stars and gas in galaxy
- \( \Sigma \) is surface density

Vollmer et al. 2001
Ram Pressure Stripping

- Ram Pressure Stripping can remove the gas supply of galaxies that pass through clusters
  - Interaction between ISM and ICM
  - Could explain metal content of the ICM
  - Episodes of starburst?

Simulation by B. Vollmer
Formation of a cluster like Virgo

$z=49.000$

Ben Moore’s web site
The Virgo Cluster

- Virgo Cluster Catalog (BST85)
- ~2000 objects
- Based on morphological appearance
- Largely confirmed by redshift measurements

Binggeli, Sandage & Tammann 1985, AJ 90, 1681
Structure in the Virgo Cluster

- Extended X-ray emission implies hot ICM
- Redshift distribution implies substructure including main cluster around M87, secondary one around M49, plus infalling spiral groups
Morphological segregation

- Ellipticals prefer highest density regions.
- Spirals are found preferentially in the field.

What about dwarfs?

Dressler 1980

**Fig. 4.**—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-3}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.
Morphological subclustering in Virgo

Binggeli, Popescu & Tammann, AApS 1993, 98, 275


**HI Deficiency:**

HI properties of 324 isolated galaxies: Haynes & Giovanelli, 1984

\[
\text{Def}_{HI} = \log \left( \frac{M(\text{HI}:D)_{\text{pred}}}{M(\text{HI}:D)_{\text{obs}}} \right)
\]

(positive for systems more deficient than isolated galaxies of same type)
HI deficiency in Virgo

Galaxies embedded in the hot X-ray gas are deficient in their HI relative to isolated galaxies of the same size and morphology.