Whittle : EXTRAGALACTIC ASTRONOMY

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12. GALAXY INTERACTIONS & MERGERS

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(1) Introduction

(a) Importance of Interactions

Our view of the importance of galaxy-galaxy interactions has changed dramatically in the last 50 years.

- when galaxies were first discovered, they were termed "**island universes**"
  they were thought of as isolated, fixed and essentially unchanging
- Hubble's classification scheme considered only normal undisturbed galaxies
  only later were Irregular (type II) and peculiar classes added

Recognition of the importance of interactions gradually grew :

- Catalogs & surveys noted "peculiar" &/or closely paired galaxies showing distortions and tails
- Since interactions are short lived ($\approx 10^8$yr), their apparent rarity is misleading
  integrated over a Hubble time, many galaxies are expected to have experienced interactions
- star formation was apparent in some systems
  → deeper changes are occurring besides mere morphological disturbance
- The difference in cluster and field Hubble type mix clearly indicates that environment can affect morphology

Taken together, Galaxy-Galaxy interactions are **important in understanding many aspects galaxy evolution :**

→ Morphological and dynamical structures
→ Star formation and starburst histories, with associated chemical enrichment history
→ AGN creation and fuelling
→ Elliptical galaxy formation

→ Formation of **all** galaxies in the Heirarchical merging scenario.

(b) Different Physical Regimes

To help clarify this topic, keep in mind several different regimes :

- Strength of interaction :
  - **Weak** and/or distant encounters :
    flyby with associated **tides**
    satellite orbit decay due to **dynamical friction**
    tidal **evaporation** of orbiting satellite
    tidal or gravitational **shocks**
  - **Strong** and/or close encounters :
    can lead to **mergers**
    more **global** gravitational effects become important
- Relative size of merging galaxies :
  major mergers : roughly equal sized galaxies
  minor (eg satellite) mergers : one galaxy is significantly smaller than the other
- Hubble type of interacting/merging galaxies :
  disks : dynamically cold (tend to generate narrow tidal tails)
  spheroids : dynamically hot (tend to generate wider tidal fans)
- Different galaxy constituents :
  these can respond quite differently during a merger and can play quite different roles
  stars : a collisionless system
  gas : dissipational; star formation; feedback
  dark matter : extended collisionless reservoire for absorbing Energy and AM
- Relics :
  Visible effects can survive long after the main merger (or interaction) has ended, particularly at large radii where relaxation times are very long :
  Polar rings
  Shells
  HI at large radii, possibly raining back down on the remnant
  Kinematically distinct cores
  Elliptical galaxies (may be merger relics !)

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(2) Catalogs

(References below are taken from Keel's web notes)

(a) Interactions

Recognising interactions/peculiarities is relatively easy
There are a number of catalogs, all derived from inspecting the PSS (or equivalents) :

- Vorontsov-Velyaminov 1959, *Atlas and Catalog of Interacting Galaxies*, Shternberg Inst., Moscow; continued in 1972 A&ASuppl 28, 1.
- Arp 1966, *Atlas of Peculiar Galaxies*, Caltech; also appeared as ApJSuppl 14,1.
- Arp and Madore 1987, *A Catalogue of Southern Peculiar Galaxies and Associations*, Cambridge U.
- Johansson & Bergvall 1990 A&A Suppl 86, 167 (followup in A&A Suppl 113, 499, 1995) selected pairs from the southern polar cap;
- Reduzzi and Rampazzo 1995 (ApL 30, 1) southern equivalent to northern Karachentsev pairs.

(b) Pairs

- Recognising bound pairs is more difficult (distortion is **not** a criterion)
  Projection effects are always a concern
  Selection criteria usually include size and separation ratios for paired and nearest third neighbor
  Sometimes, background corrections are included and/or redshift information.
  Note : catalogs over-emphasise equal luminosity pairs (fainter companions suffer projection confusion)
- **Isolated** pairs are particularly useful :
  they are dynamically clean
  they can be used (statistically) to measure galaxy M/L ratios beyond rotation curve radii.

- Catalogs of galaxy pairs include :
    - Holmberg 1937 (Ann. Lunds Astron. Obs. 6) - visual search
    - Karachentsev 1972 (Soobsch. Spets. Astrof. Obs.7, 3) - complete search of PSS (redshifts now complete)
    - Turner 1976 (ApJ 208, 20) - from catalog data only, problems at faint levels
    - Peterson 1979 (ApJ Suppl 40, 527) - similar but improved sample.
    - Zhenlong et al. 1989 (Publ. Beijing Astron. Obs. 12, 8) - from SERC survey in southern galactic cap.

- about 10% of luminous galaxies are in 2-body systems
  more for E/SO ($\approx$ 11%), less for later spirals ($\approx$ 6%)
  → continuation of morphology (local) density relation
- This fraction is too high to arise from chance encounters of unrelated galaxies
  → pairs are usually **bound**
- I0 and Irr II galaxies are **always** paired → transient response to tidal interaction
- Relatively high pair/interaction frequency + short expected interaction timescales
  → many large galaxies have experienced major mergers
  → all galaxies have experienced minor mergers

Once again → mergers/interactions may be important in the history of **all** galaxies.

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(3) Analytic Tools

We first consider four regimes which are analytically tractable as well as dynamically important.
They also develop our ability to interpret numerical simulations of more complex regimes.

(a) A small system moving through a larger one (dynamical friction)
(b) Tidally driven evaporation : the Jacobi (Roche) Limit
(c) "Slow" encounters, where $V_{internal} >> \Delta V_{encounter}$ (adiabatic approximation)
(d) "Fast" encounters, where $V_{internal} << \Delta V_{encounter}$ (impulse approximation; tidal shocking)

Unfortunately, major mergers do not conform to any of these regimes;
they cannot be treated analytically and require numerical simulation (see § 4 & 5)

(a) Dynamical Friction

- Consider a mass M moving at speed V through a population of stars with uniform space density n.
  The stars have mass m (<<M) velocity distribution f(v) (expressed as # per v)
- Gravitational focussing creates a wake behind the moving mass which pulls back on it
  This retarding force is called **dynamical friction**

(i) Simplified Derivation of the Retarding Force

- Consider a **single** star passing with impact parameter b
  it experiences a force towards M of $F_{\perp} \approx GMm/b^2$ for a time $\Delta t \approx 2b / V$
- after passing by, the impulse has imparted a perpendicular velocity :

$\Delta v_\perp \approx \Delta t\, F_\perp/m = 2GM / bV$

- The (small) angle of deflection is therefore tan $\theta \approx \theta \approx \Delta v_\perp / V = 2GM / bV^2$
(this approximates the hyperbolic Kepler/Coulomb solution)
- The encounter has symmetry about the vector of closest approach
ie the line ½θ backwards from the original perpendicular impact parameter vector
Newton's 3rd law demands that the impulse felt by m is equal and opposite to the impulse felt by M :
$m\Delta v = M\Delta V$
- We are interested in the component of the force **parallel** (and backwards) to the motion of M
(the perpendicular component will average to zero when summing over all stars)
So, we have for a single star's retarding force :
$\Delta F_{drag} = -m\Delta v_{||} = -m\, 2GM/bV \tan ½\theta = -2G^2M^2m / b^2V^3$
- Integrating over all impact parameters ($2\pi b\, db$) and over the encounter rate nV, we get :

$$\boxed{F_{\rm drag} = -\frac{4\pi G^2M^2nm\ln\Lambda}{V^2} = -\frac{4\pi G^2M^2\rho\ln\Lambda}{V^2}} \quad (15.1)$$

Here, $\Lambda = b_{max} / b_{min} = b_{max}V^2 / GM$ is the usual Coulomb logarithm
where b_{min} is defined when $\Delta v \approx V$ and b_{max} is the effective size of the region
Note also that nm is simply the total density : ρ

- Approximately, we have for $\ln \Lambda$:
Open clusters (≈6); Globular Clusters (≈11); L* E galaxy (≈22); Galaxy clusters (≈7)

- Allowing for an (isotropic) field star velocity distribution, f(v), we get the **Chandrasekhar (1943) dynamical friction formula** :

$$\boxed{F_{\rm drag} = -\frac{4\pi G^2M^2m\ln\Lambda}{V^2}\int_0^V 4\pi v^2 f(v)dv} \quad (15.2)$$

Note the approximations used in this derivation :

M >> m the object significantly outweighs the field stars
$M << M_{system}$ the responding field distribution is ≈ symmetric about the object
the field stars have an isotropic velocity field
we have ignored the self gravity of the wake

Despite these approximations, the equation works well in a wide range of situations.

(ii) Special Cases

- if M moves **slowly** compared to the stars : V << v :
we replace f(v) with f(0) to get :
$F_{drag} = -(16/3)\pi^2G^2M^2m \ln \Lambda\, f(0)\, V$

→ only stationary stars contribute to the wake, the rest quickly leave the area
→ Since $F_{drag} \propto V$, this resembles Stokes's law for motion through a viscous fluid.

- if M moves **fast** compared to the stars : V >> v :
the integral converges, and we recover the simple equation 13.1
$F_{drag} = -(4\pi G^2M^2\rho \ln \Lambda) / V^2$

→ **all** stars contribute to the wake
→ since with $F_{drag} \propto V^{-2}$, the drag **decreases** for faster moving masses

- for a **Maxwellian** f(v), with dispersion σ, we obtain :

$$\boxed{F_{\rm drag} = -\frac{4\pi G^2 M^2 nm \ln\Lambda}{V^2}\left[\mathrm{erf}\,(X) - \frac{2X}{\sqrt{\pi}}\exp\left(-X^2\right)\right]} \qquad (15.3)$$

where $X = V / \sigma\sqrt{2}$
Note that the star masses enter as nm, ie the total mass density ρ
the drag is therefore independent of m, and the equation works for a spectrum of masses
→ $F_{drag} \propto M^2$: gravitationally focussed mass $\propto$ M so force $\propto M^2$
→ $F_{drag} \propto V^{-2}$: fast objects **don't** experience much drag.

(iii) Applications of the Dynamical Friction Formula

- **Satellite in Circular Orbit**
For an isothermal galaxy with flat rotation curve V_c = const, we have :
$\rho(r) = V_c^2 / 4\pi G\, r^2$; dispersion $\sigma = V_c/\sqrt{2}$ (ie X = 1); giving $F_{drag} = -0.43 \ln\Lambda\, GM^2/ r^2$
As the satellite spirals inwards, its angular momentum is always : $L = MV_c r$
so, the rate of change of L is given by the torque :
$dL/dt = F_{drag} r = -0.43 \ln\Lambda\, GM^2/ r$
and we get
$MV_c r\, dr/dt = -0.43 \ln\Lambda\, GM^2$
Solving this ODE from initial radius r_i (at t=0) down to r=0 at t_{infall}, we get
$\tfrac{1}{2} r_i^2 = 0.43 \ln\Lambda\, GM / V_c\, t_{infall}$
Using as fiducials, numbers appropriate for a Globular cluster orbiting the MW :
$M = 10^6 M_\odot$; V_c = 250 km/s; $b_{max} = r_i$ = 2 kpc; (so $\ln\Lambda \approx 10$)
This gives :
$t_{infall} \approx 2.6\times10^{11}$ yr $(\ln\Lambda)^{-1}\, r_{2kpc}^2\, V_{250}\, M_6^{-1}$

so although most GCs at large radii have not significantly changed their orbits,
GCs with initial radii $r \lesssim$ 1.5 kpc may have already settled to the MW center.

- **Massive Galaxy Encounter**
Although this case is not strictly legitimate ($M \approx M_{system}$) it is nevertheless instructive :
for $M \approx 10^{10}\, M_\odot$; $r_i \approx$ 20 kpc; $V \approx V_c$
we get :
$r_{infall} \approx 2\times10^8$ yr $\approx$ 1 orbital period

Clearly, massive galaxies entering eachother's halos experience strong dynamical friction.

- **Large and Small Magellanic Clouds**
For the LMC, we have $M \approx 2\times10^{10}\, M_\odot$ and $r \approx$ 60 kpc (so $\ln\Lambda \approx 3$) giving
$t_{infall} \approx 3\times10^9$ yr, suggesting the LMC should have **already** spiralled inwards

<u>However</u> : This assumes a circular orbit.
A more thorough analysis (Murai & Fujimoto '80) requires :

(a) that the LMC & SMC have **remained bound to eachother** in the past
(b) their orbital plane includes the HI Magellanic stream ?

They find

- the LMC+SMC orbit is elongated with pericenter/apocenter ratio $\approx$ 0.5
- they are currently near pericenter
- their orbit has decayed by ×2 in radius over the past 10^{10}yr
- the Magellanic stream came from the SMC following a close encounter with the LMC 2×10^{8} yr ago
- the LMC and SMC will tidally separate when they come within 30 kpc of the galaxy
- they will finally settle to the galactic center in further 10^{10} years.

(b) Tidally Driven Evaporation : Trunction and Disruption

- The outer luminosity profiles of globular clusters are **often sharply truncated**
  Naively, this is puzzling since stellar systems don't naturally have "edges"
- The reason : outer stars become more bound to the galaxy than to the GC potential
  This is an example of **Tidal Stripping** or **Tidal Truncation**
  (Similar effects are seen in some cluster galaxies)

(i) Tidal (Jacobi/Roche) Limit

- How far must a star "wander" from its satellite before it is lost to the galaxy ?
  If you answer : "where the r^{-2} force of the satellite and galaxy are balanced" you would be **wrong**
  You forgot to include the fact that the satellite is **also orbiting the galaxy**
  The satellite and galaxy are "fixed" only in a **rotating frame**, in which **pseudo-forces** are also important.

- In this rotating frame, the star's energy $E = ½\mathbf{V}^2 + \phi(\mathbf{r})$ **is not conserved**
  (recall, space probes can use planets to gain energy in a "gravitational slingshot")
  Instead, the **Jacobi Integral** $E_J = ½\mathbf{V}^2 + \phi_{\rm eff}(\mathbf{r})$ **<u>is</u> conserved**;
  where we have again introduced the **effective potential** in a rotating frame :

  $$\phi_{\rm eff}(\mathbf{r}) = \phi(\mathbf{r}) - ½\,|\,\boldsymbol{\Omega}\times\mathbf{r}\,|^2$$

  where Ω refers to the satellite's orbit and **r** has origin at the Center of Gravity ($\approx$ galaxy center)
  The **derivative** of $\phi_{\rm eff}(\mathbf{r})$ yields the **coriolis** and **centrifugal** forces (plus gravity, of course)
  Here (& viewgraph) is a contour plot of $\phi_{\rm eff}(\mathbf{r})$ for two point masses

- Note the 5 **Lagrange points** : maxima in $\phi_{\rm eff}$ where stars are **stationary** (in the rotating frame)
  L1 is the deepest; L1, L2, L3 are **unstable**; L4, L5 are **stable** (recall, Trojan asteroids)
  (although L4, L5 are maxima, coriolis force keeps objects in a slow "epicyclic orbit" around them)

- Consider the simplest case :
  two point masses : a small satellite in circular orbit about a massive galaxy (ie m<<M)
  evaluate $\phi_{\rm eff}$ along a line connecting m and M (separation R), with origin at m :

  $$\phi_{\rm eff}(x) = -GM/(R-x) - Gm/x - ½\,\Omega^2(x-R)^2$$

  Now find the turning points :
  substitute for $\Omega^2 = GM/R^3$; differentiate w.r.t. x; set to zero and solve for $x = r_J$:

$r_J = R(m / 3M)^{1/3}$ is the **Jacobi Limit** (also called the tidal or Roche radius)

- If we re-calculate for the case of a galaxy with isothermal (flat V_{rot}) galaxy halo, we get :
  $r_J = R(m / 2M)^{1/3}$

  In general, a useful approximation is that r_J marks the point at which :

  the orbital period of the satellite about the galaxy is similar to
  the orbital period of a star about the satellite (in the absence of the galaxy).

- In practice, measured tidal radii agree **only roughly** with our simple expression for r_J.
  The derivation should be considered as indicative rather than predictive.

(ii) Satellite Evaporation and Possible Destruction

- The value of ϕ_{eff} at r_J divides stars into those which can escape from those which cannot
  Consider a satellite star with E_J moving away from the satellite : V is decreasing
  as the star approaches the contour $\phi_{eff} = E_J$, V approaches zero and the star turns around
  Clearly, if $E_J > \phi_{eff}(r_J)$ then the star **crosses the critical contour**
  If this happens to be near L1 (or L2), the star proceeds "down hill" **and is lost from the satellite**
  Thus, over time we expect to lose all stars with $E_J > \phi_{eff}(r_J)$

- The satellite **evaporates**, in the sense that it is losing stars with the highest energy
  Unlike the slow evaporation of an isolated cluster, when stars scatter into orbits with $V > V_{esc}$ (see 8.12.d.iii)
  tidal evaporation is **independent of scattering within the cluster** :
  → even **bound stars** (ie $E < 0$ for an isolated satellite) can have $E_J > \phi_{eff}(r_J)$ and can be lost

- For a satellite which is **approaching** a galaxy, r_J and $\phi_{eff}(r_J)$ continually decrease :
  → the cluster may lose an ever increasing number of stars.
  Recall from Topic 8.10.h.ii that **most** stars are marginally bound (ie N(E) peaks near $E \approx 0$) :
  → a small decrease in $\phi_{eff}(r_J)$ can result in the loss of many stars.

- Finally, the loss rate depends on the star finding its way through the L1 (or L2) gateway
  it may undergo many orbits with apocenter missing L1
  If the Satellite passes pericenter before the star finds L1 it may never, in fact, be lost

(c) Adiabatic Approximation (Slow Encounter)

- During a tidal encounter, the orbits of many stars are significantly affected.
  However, some orbits are **not** greatly affected : those for which $t_{orbit} << t_{encounter}$
  As the tidal field slowly changes, the orbit responds slowly and **reversibly**
  → cf the response of the moon's orbit during the year as the Earth's distance to the sun changes
  This type of response is called **adiabatic**

- If the encounter is a "flyby", the tidal field first grows, then decays
  → the rapid orbits slowly modify, but then **return to their original form**
  Thus, stars on rapid orbits near galaxy centers are **not greatly affected** by tidal encounters
  (unless, of course, the encounter proceeds to become a merger)

(d) Impulse Approximation (Fast Encounter : Tidal Shocks)

- The opposite extreme occurs when $t_{orbit} >> t_{encounter}$

This occurs when $V_{internal} << \Delta V_{encounter}$
In this case **stars don't move much during the encounter**
→ no change in PE : $\Delta PE \approx 0$
However, they do feel **an impulse**, (ie a force acting over a short time)
→ changes in both global and internal velocities : $\Delta \mathbf{V}_{CM}$ and $\Delta \mathbf{V}_{internal}$ (B&T p434-435)
→ so internal KE **does change** : $\Delta KE \approx ½ \Sigma m \Delta V_{int}^2$ (note : always +ve)
→ The effect of the tidal shock is to **heat** the stars
We say the system has experienced a **tidal shock**

- How does the system respond (relax) **after** experiencing the tidal shock ?

  Loosely speaking :
  the increased KE causes the system to **expand** and **cool**
  (recall, self gravitating star systems have -ve specific heat : Topic 8.12.d.i)

  More formally :
  using subscripts o="original", i="initially after encounter", and f="finally after relaxation"
  Virial theorem applies to the original and final relaxed systems : $E_o = -KE_o$ and $E_f = -KE_f$ (see 8.6)
  immediately following the encounter we have : $KE_i = KE_o + \Delta KE$ and $E_i = E_o + \Delta KE = -KE_o + \Delta KE$
  following relaxation, we have : $E_f = E_i \rightarrow -KE_f = -KE_o + \Delta KE$ giving $KE_f = KE_o - \Delta KE$
  → from original to final, the system has indeed **cooled**, by an amount ΔKE
  → since the shock **heats** the original system by ΔKE, then
  during relaxation (i to f) the system cools by $-2\Delta KE$ (ie $KE_f = KE_i - 2\Delta KE$)
  of course, the system has also **expanded**, increasing the final PE by ΔKE

- Since the stars receive energy, some may become **unbound** ($E > 0$)
  → these are lost from the system : they **evaporate**
  If there are **repeated** tidal shocks, a cluster may be disrupted and **disintegrate**

- Finally, if the encounter is distant, the "tidal approximation" applies : (B&T p 437-438)
  eg, a spherical system (mass M, rms size r) is passed by a mass m at distance b with speed V
  → the change in its energy is $\Delta E \approx (4 G^2 M^2 m r^2) / (3 b^3 V^4)$
  → it is left elongated, long axis pointing to the point of closest approach (cf lunar tides)

- Examples :
  - Open clusters are shocked by the passage of Dense Molecular Clouds (DMCs)
    → there are very few old open clusters
    → most have evaporated from repeated shocks on a timescale $\approx 5\times10^8$ yr.

  - Globular Clusters are shocked when they pass through the MW disk
    → can lead to evaporative disruption (depends on where in the disk)
    eg for GC with $\sigma = 5$ km/s, r = 10pc, $V_\perp = 170$ km/s crossing at at ≈ 3.5 kpc,
    → disruption timescale is $\approx 6\times10^9$ yr

  - Tidal shocking of galaxies in clusters is termed : **galaxy harassment**
    → disks are **heated** → they get thicker and Toomre's Q parameter increases (see 8.5.a)
    → spiral arm formation is therefore suppressed
    → appear to have **earlier** Hubble types (eg Sb → Sa)

  - Ring galaxies are formed from tidal shocks
    Perturber passes rapidly through & close to center of a disk galaxy ($V >> V_c$)
    → shock induces $\Delta V_r \approx \pi V_c (V_c / V)$ radially inwards for **all stars**
    → this sets up **synchronised** epicyclic motion
    (recall, velocity perturbations to orbiting stars yield epicyclic motion; see 8.2)

the response is an **expanding circular density wave** → a ring !
these density waves can, of course, trigger star formation

Although quite rare, there are many nice examples (viewgraph),
the most famous is the "cartwheel" : pic1, pic2 and simulation.

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(4) Numerical Simulations : Methods

- In many situations, analytic approaches fail
  Simulations have therefore played a **crucial role** in understanding interactions and mergers.

- Early work was **analog !** → clusters of light bulbs, each with R^{-2} flux law (Holmberg 1943)
  '70 - '85 : stellar systems only; limited N
  '85 - '95 : add gas and dark matter; explore parameter space
  '95 - '05 : focus on physics of gas and star formation
  (note : B&T published '87, so omits much recent work)

- In broad outline :
  Constituents : Stars; Gas; Dark Matter
  Processes : Gravity; Hydrodynamics; Star Formation; Feedback (SNe, winds, etc)

- Gravity :
  Mass points represent : stellar disk; stellar bulge; gas disk; DM halo
  each point is accelerated by "all" others (optimization demands shortcuts, see 8.8.c)
  use Newton's law with a softening parameter (which also limits spatial resolution)
  Tree-codes are popular for galaxy interactions :
    Lagrangian (follows **particles**) which suits a sparse system better than a grid.
    efficient : O(N log N) calculations per timestep
    $N \approx 10^{5-6}$ maximum currently possible → each "particle" has mass $\simeq 10^{4-5}$ $M_\odot$
    → **not** individual stars → "star aggregates"
    resolution is $\approx$few $\times 10^2$ pc → still cannot do nuclei or small scale star formation well.

- Hydrodynamics :
  Smooth Particle Hydro (SPH) often used
  Gas "particles" carry information on thermodynamic and hydrodynamic quantities
  interpolate ("smoothing") between adjacent particles gives quasi-continuous description
  follow hydrodynamic conservation laws
  add artificial viscosity to achieve shocks
  including a cooling function is critical → allows gas to be **dissipational**

- Star Formation :
  Physics uncertain (currently weak point)
  adopt a Schmidt Law : $\mathrm{SFR} \propto \rho_{gas}^{\alpha}$ with $\alpha \approx 1.5$

- Feedback :
  Winds and Supernovae → heat the gas and give it KE
  difficult physics → currently under investigation

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(5) Numerical Simulations : Results

Simulations have been applied in a range of circumstances

(a) Flyby and Tidal Tails

- Earliest (and easiest) to be simulated (eg Toomre & Toomre '72)
  long thin features have **tidal origin** from **cold disks**
  (not jets; explosions; shocks; as had been suggested previously)
  classic example : the antennae (NGC 4038/39) (viewgraph)
  (Note : in Toomre's simulation only the two galaxy centers had mass → all stars are massless)

- Mechanism :
  tidal field together with rotation leads to a **shearing off** of stars
  on the far side, this becomes a **tidal tail**
  on the near side, this becomes a **tidal bridge**

- Spin - Orbit Coupling/Resonance :
  Whether the galaxy spins in the **same or opposite** sense as the flyby makes a **big difference**
  → **prograde** (same AM direction) : **strong** tidal tails
  → **retrograde** (opposite AM direction) : **muted** tidal tails
  This movie by Chris Mihos shows two galaxies passing by eachother :
    top to bottom is the **prograde** galaxy → strong extended tidal arm
    bottom to top is the **retrograde** galaxy → mild tidal distortion
    (see also viewgraph : Figs 7.13/14 in B&T)
  The reason : for prograde(retrograde) encounter :
    the stars on the side closest to the passing galaxy move in the **same(opposite)** direction
    The relative velocity is **small(large)** so that tidal perturbations act for a **long(short)** time
    The response **can(cannot)** build up and is therefore **strong(weak)**

- Because tides act along a line, a strong m=2 perturbation is set up in the perturbed galaxy
  If the galaxy is bulge dominated, the response is to form **strong spiral arms** (Barnes simulation)
  If the galaxy is disk dominated the response is to form a **strong bar**
  Either way, the **gas** response is to shock, form stars, lose AM, and move towards the center.
  Consequently, flybys are often associated with enhanced disk and nuclear star formation.

(b) Major Mergers

- Here are two movies :
  Merging Pair : simulation by Mihos & Hernquist (ApJ 464 641 '96). Stars=yellow, gas=blue.
  Merging Group : simulation by Josh Barnes

  From these and many other simulations, a number of general results have emerged :

(i) Global Behaviour

- Mergers are **surprisingly rapid** : 1 - few orbital times.
  Galaxy components settle on $\simeq$ dynamical timescale $\simeq 1 / \sqrt{(G \langle\rho\rangle)}$
  as $\langle\rho\rangle$ increases, settling speeds up : (viewgraph)
  → first couple of passes take a while
  → third & fourth are much quicker
  → final merging happens rapidly
  Large scale inhomogeneities cause globally acting torques
  Angular momentum transfer is much faster than the idealized dynamical friction formula

- Galaxy encounters are **very sticky**
  Even **hyperbolic** encounters can result in capture and merger (viewgraph : B&T Fig 7.9)
  This is mainly because the AM and Energy of the **orbit** is transferred to **internal motions**
  (particularly the halo -- see next)

- Dark Matter halos play a **crucial role** in the merger
  Here's why :
    - it is the Dark Matter halo which absorbs most of the orbital AM and energy
      this occurs via :
      → strong dynamical friction
      → global torques acting across the complex mass distribution.
      (note that tidal tails only exert a modest torque on the galaxies)
    - at a simpler level, even if stellar systems "miss" eachother, the DM halos will "collide"
      → ie the halos significantly increase the cross-section for interactions/mergers

  In summary :
  Without DM halos, galaxies would only **slowly** spiral inwards and mergers would be **rare**

- As with flybys, the spin-orbit alignment can affect the merger timescale
  prograde encounters lead to quicker merging than retrograde encounters

(ii) Behaviour of Collisionless (Stellar) Components

- Disks are fragile, they are **destroyed** during the merger
  Bulges merge at the center
  Violent relaxation occurs, but is **incomplete**
  → significant **phase space structure** remains
  → even though the **actual space density** is smooth (viewgraph)

- The final density distribution is **close to an $R^{1/4}$ law**
  this is due to :
  → $R^{1/4}$ law components present in the progenitors,
  → the dynamical effects of the merger.
  The classic demonstration of this was for NGC 7252 (Schweizer 1982, figure, viewgraph)

- For a "head on" collision (ie b ≈ 0) the final product tends to be **prolate or triaxial** with little rotation
  For an oblique collision (b significant) the end product tends to be **axisymmetric** with some rotation.

(iii) Behaviour of Dissipational (Gas) Component

- Gas follows much of the general behaviour described in (i) above
  However, it behaves quite differently from the collisionless component described in (ii) above
  This is ultimately because of its **dissipational nature**
  This difference would not be as dramatic if it were not for an interesting lever arm effect :

- Unlike the stars, much of the gas **goes to the center** quite quickly
  Simulation by Mihos, showing stars and SFR (which ≈ traces gas)
  Clearly, the gas is losing its angular momentum, but how does this happen ?
    The response of both the stars and gas to the first passage is to form a **strong bar**
    However, the gas is shocked on the leading edge of the bar
    This leads to an **angular offset** of the gas and star bars
    The gravitational pull on the gas by the stars **drains angular momentum from the gas**
    The gas now falls towards the center (images from B & H '96 : stars & gas; just gas; nucleus)

  This process is **remarkably efficient** : ≈ 99% of the gas AM can be lost (image & viewgraph).

  Simulations show that the AM loss is almost entirely due to gravitational torques
  (as opposed to hydrodynamic torques)

    ≈ 30% to the neighbor during the first encounter
    ≈ 70% to the host disk and bar
    ≈ none to the host halo

- The inflow of gas also depends critically on its **radiative cooling**
  Simulations without cooling have little gas going to the center (viewgraph)
  the reason is that dissipational settling necessarily releases energy (virial theorem !).

without cooling the gas either escapes as a hot wind or is supported by thermal pressure.
At least **some** of the huge FIR luminosity in merging starbursts is allowing the collapse to continue

- The efficiency/speed of inflow depends on at least a couple of factors :
  Inflow efficiency is **lower** for **retrograde** encounters than prograde encounters (see above)
  Hosts with more **stable** disks **slow** the gas inflow :
  → large bulges suppress disk instabilities and hence slow AM loss and gas inflow
  this plot (from Mihos) compares simulations with/without a bulge
  the nuclear star formation is delayed when a bulge is present
  → lowered disk surface density similarly reduces disk instabilities and therefore gas inflow rate

- Gas dissipation creates much denser galaxy cores than would be possible with stellar mergers alone.
  These dense cores can affect the nuclear regions much like massive black holes (see 9.5.b)
  → box orbits are scattered by the central concentration, destroying any triaxiality
  → the nuclear regions are significantly rounder
  → the orbit distribution is quite different, with fewer box orbits and more z-tube orbits (viewgraph)

(iv) Fueling Starbursts and AGN

- As gas goes to the center, we expect high nuclear star formation rates → Starburst
  The simulations confirm this, showing large spikes in the SFR
  This is a major success : showing how starbursts/LIGs/ULIGS can arise from mergers
  Future modelling will try to get the physics more accurate :
  → aiming to reproduce aspects such as superwinds, chemical enrichment, and ISM energetics.

- What can the simulations tell us about fueling AGNs ?
  Unfortunately, not very much.
  Since the resolution is only $\approx$ 100 pc, processes in the very nucleus are not modelled.
  While is seems plausible that some gas reaches a central black hole, there is a gigantic AM barrier :
    need to take 200 km/s gas at 1 kpc down to 10^4 km/s at 10^{-4} pc (BH accretion disk)
    This requires a loss in AM by a factor $\approx 10^5$
    The merger might get a factor 10^2 but that leaves another factor of 1000 !
  While a number of mechanisms have been discussed, none are proven
  Perhaps a small amount can get to the very center while the majority stays at a few × 10^2 pc ?

(c) Minor Mergers and Satellite Accretion

- We expect **frequent encounters** with smaller companions
  eg MW has $\approx$ 14 satellites :
  → LMC/SMC at $\approx$ 50 kpc → tidal stream (image)
  → Saggitarius Dwarf passing MW disk on far side; it spans $\approx 30^\circ$ → disruption (image)

- Clearly, unlike the major mergers, a minor merger is less disruptive
  → dynamical friction operates more slowly, over several ($\approx$ 10) orbits
  → accretion occurs more slowly, possibly along with tidal stripping
  diffuse (eg dSph) satellites may dissolve before they fully merge
  compact (eg dE or cE) satellites may survive to reach the center

- material stripped from a satellite generates a **tidal stream**, ahead and behind in its orbit (viewgraph)
  Past tidal stripping may have been important in the origin of the (stellar) halo : $\approx 10^9 L_{\odot B}$
  eg Searle & Zinn ('78) suggested the halo formed from the accretion of a few × 10^2 satellites
  Currently, considerable effort to identify tidal streams associated with MW satellites (cf Majewski)

- If the satellite survives to the inner galaxy → affects the **disk**
  Image from Mihos simulation showing small satellite spiraling into center of disk
  Edge on view also interesting : (viewgraph)
  Some general results from these and other simulations of satellite accretion :

  - heats and thickens the disk
  - ultimately, enters the disk plane → disk **warps** to conserve AM (eg NGC 3628)
  - induces spirals and bar → gas inflow
    → SFR increases; AGN turns on
    → gas cleared from disk
  - stars scattered by bar → pseudo bulge.

Conclusion : even minor mergers may drive significant evolution in disk galaxies.

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(6) Merger Relics

Although ongoing mergers are quite rare (they are short lived), **former** mergers (relics) should be common
There are a number of possible examples, though we start with a rather special one.

(a) Elliptical Galaxy Formation

- The possibility of mergers becoming ellipticals was suggested in '77 by Toomre
  Here was his reasoning :
  - violent relaxation scrambles disks to yield a smooth and dynamically hot system (= elliptical ?)
  - Statistically : we see $\approx$ 10 local mergers, which each last $\approx 8\times10^8$ yr
    allowing for cosmic expansion, we expect an encounter rate $\propto t^{5/3}$
    → expect $\approx$ 750 ellipticals locally, which is about correct
  - if merger endpoints are **not** ellipticals, then what **are** they ??

- A bit later, Schweizer ('82) studied the merger NGC 7252 (viewgraphs)
  - it has an approximate $R^{1/4}$ brightness profile spanning 7 magnitudes
  - The central light profile keeps rising with PL index ≈ -1.3
  - it has a high central surface brightness and luminosity density
  - its core properties fit the 2-parameter correlations for Spheroids

  these are all properties associated with Ellipticals (not all were measured in '82)

- The suggest that Ellipticals were merger remnants has an interesting history
  The idea met with considerable (unreasonable ?) resistance
  Here are some of the objections, with their (current) responses :
  1. Elliptical phase space density is **higher** than spirals,
     but violent relaxation **preserves** phase space density.
     Answer : gas dissipation and star formation can increase the phase space density
  2. Ellipticals have many more globular clusters (per unit luminosity) than spirals
     Answer : globular clusters are formed during mergers
  3. Ellipticals are found in clusters, where ΔV is too large for mergers
     Answer : Clusters form heirarchically; Ellipticals form earlier in smaller groups
  4. How can merging spirals preserve/create the metallicity - luminosity/radius correlations ?
     Answer : star formation during the merger liberates metals

- The question of whether **all** Ellipticals formed by spiral mergers is still open
  However, in the heirarchical picture **all** galaxies formed by merger, the question now becomes :
  → **what** merged to form Ellipticals ?
  high-z observations show **cluster** Ellipticals formed **even earlier**
  maybe even **before** massive spiral disks
  This introduces the possibility that Cluster and Field ellipticals have different origins
  One possibility :
  - Cluster Ellipticals form from the rapid assembly of many smaller progenitors
  - `Field' Ellipticals form from the merger of spirals

This must remain speculative, not least because cluster and field ellipticals are observationally almost indistinguishable

(b) Counter-Rotating Disks

- Recall that in mergers, the gas can experience 99% loss of AM
  In such a chaotic process, the final AM of the most nuclear gas may be quite unrelated to the initial AM.
  A nice example of this arose in one of the simulations of B & H '96 (figure & viewgraph)
  Their merger remnant contained a **counter-rotating** nuclear gas disk
- If star formation ensues, a counter-rotating **stellar disk** will result
  Of course, counter-rotation is only the most dramatic endpoint,
  in general one may form a "Kinematically Distinct Core" (KDC)
  Such systems are seen in a significant fraction ($\approx$ 25%) of ellipticals (see 5.6.d)
- KDCs can also form in **minor mergers** when a gas rich spiral falls into a pre-existing elliptical.

(c) Polar Ring Galaxies

- Polar ring galaxies are quite **rare** and are thought to arise from **accretion**
  they usually comprise an S0 galaxy with approximately $\perp^r$ ring of material (gas &/or stars)
  Archetype is NGC 4650A, though there are other nice examples (viewgraph)
  (note : these are not to be confused with **ring galaxies** which have rings **in** galaxies)
- Usually, an accreted companion ends up in the primary's **disk**
  Occasionally, however, gas enters an approximately **polar** orbit
  although most inclined orbits are unstable, those close to a $\perp^r$ plane can be stable
- Star formation in the ring can then lead to a stellar component
  Age estimates of a few Gyr confirm that polar rings are quite stable.
- If accretion angles are random, then only $\approx$few % will find stable polar orbits
  → **much larger** fraction of S0s experience accretion (at the other angles)

(d) Shell Galaxies

- '70s - '80s Malin developed photographic image enhancement techniques, (cf AAO image collection)
  Using these techniques, he discovered low surface brightness **shells** around E galaxy M89 (1977)
  Subsequently, $\approx$ 50% `field' Es and $\approx$ 30% field S0s found to have faint shell/arc-like features.
  Examples : NGC 3923 as well as some Arp galaxies.
- Shells/arcs typically comprise $\approx$ 5 - 25 % of the total light
  they are slightly bluer than the host Δ(B - V) $\approx$ -0.15, so similar to disk star colors
  Arc/shell boundaries can be remarkably sharply defined
  Often, the arc radii on opposite sides **alternate**
- Originally thought to result from a minor merger : a small spiral falls into a pre-existing elliptical
  Now realise that major (spiral spiral) mergers are also important
  Requires accretion of a **dynamically cold** stellar system
  stars move out to a radius depending on their energy
  The sharp edge is formed as stars reach apocenter and turn around (a slow process)
  coming up to replace them are stars with slightly higher energy, which get a bit higher
  the shell slowly moves out as stars of different energy populate it
  Simulations do a nice job reproducing these shells :
  eg Toomre's early work; Quinn 1984 ApJ; with associated Velocity-Radius diagram at time 18.
- The shells might be useful in other contexts :

Number of shells increases with the age of the system → estimate age since merger
shell spacing related to the form of the DM halo potential → use to probe halo potentials
presence and number of shells contributes to a "merger parameter" :
→ Σ used in studies of mergers and their products

(e) Tidal Origin of Dwarf Galaxies

- Zwicky (1956) first suggested that material in tidal tails might self-gravitate to form dwarf galaxies
- Example : dwarf star/gas system near tip of south tail in Antennae (viewgraph)

  $M_V \approx -14.4$, $R_{25} \approx 10$ kpc; $M_{HI} \approx 4\times10^8 M_\odot$ → similar to normal dwarf
- The dwarfs then go into orbit as satellite companions.
  Simulations certainly find self-gravitating knots in tidal arms (eg B & H '96 figure & viewgraph)
  So on theoretical grounds it seems plausible
- Currently unclear what fraction of dwarfs might have been formed this way.

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