Galactic Interactions & Elliptical galaxies

Dynamical friction & Galaxy merging
Cluster transformation
Structure & Dynamics
Formation of Elliptical Galaxies

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Tidal trails

Antennae Galaxies (NGC 4038 & NGC 4039)

Dynamical friction

When an object of mass M_S moves through a large collisionless system whose constituent particles (field particles) have mass $m \ll M_S$, it experiences a drag force — dynamical friction.

Dynamical friction transfers the orbital energy of the satellite galaxy (and dark matter subhalos) to the dark matter particles that make up the host halo, causing the satellite (subhalo) to drift to the center of the potential well, where it can ultimately merge with the central galaxy (galactic cannibalism).

Intuitive picture 1: Equipartition

Two-body encounters move systems towards equipartition

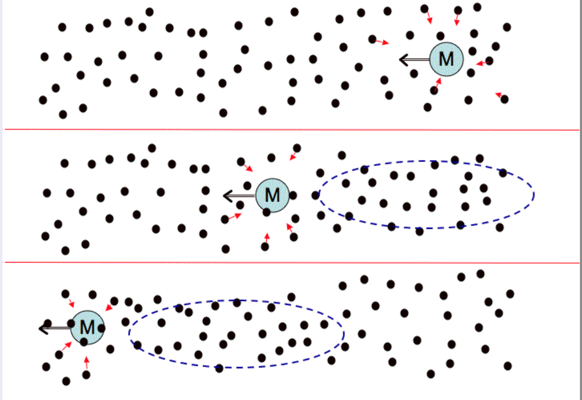
$$m_1 \langle v_1^2 \rangle = m_2 \langle v_2^2 \rangle = m_3 \langle v_3^2 \rangle$$

Initially, $v_S^2 \sim \langle v_{\mathrm{field}}^2 \rangle$ and $M_S \gg m$, so the subject mass will (on average) lose energy to the field particles, slowing down. Dynamical friction is a manifestation of mass segregation.

Dynamical friction

Intuitive picture 2: Gravitational wake

The moving subject mass perturbs the distribution of field particles, creating a trailing density enhancement (“wake”). The gravitational force of this wake on M_S slows it down.



Orbital decay from dynamical friction

Consider the subject mass on a circular orbit in a spherical, singular isothermal host halo with the density distribution

$$\rho(r) = \frac{V_c^2}{4\pi G r^2}$$

(Remember: V_c is independent of radius.) Under the assumption that the velocity distribution of field particles is a Maxwell-Boltzmann distribution with velocity dispersion $\sigma = \frac{V_c}{\sqrt{2}}$, the dynamical friction force is

$$F_{df} = -0.428 \frac{G M_S^2}{r^2} \ln \Lambda \hat{v}_S$$

where $\ln \Lambda$ is the Coulomb logarithm, which can be approximated as $\ln \Lambda \approx \left(\frac{b_{\max}}{b_{90}}\right)$. $b_{\max} \sim R$ is the maximum impact parameter, approximately equal to the size of the system in which the mass is orbiting, and $b_{90} \sim \frac{G M_S}{\sqrt{\langle v_m^2 \rangle}}$ is the impact parameter for which a field particle is deflected by 90°.

Orbital decay from dynamical friction

Being on a circular orbit, the rate at which the subject mass loses its orbital angular momentum $L_S = r v_S$ is therefore

$$\frac{dL_S}{dt} = r\frac{dv_S}{dt} = r\frac{F_{df}}{M_S} = -0.428\frac{GM_S}{r}\ln\Lambda$$

Since V_c is independent of r, the subject mass continues to orbit with a speed $v_S = V_c$ as it spirals inwards, so that the orbital radius changes as

$$v_S\frac{dr}{dt} = -0.428\frac{GM_S}{r}\ln\Lambda \quad \rightarrow \quad r\frac{dr}{dt} = -0.428\frac{GM_S}{V_c}\ln\Lambda$$

With this, we can calculate how long it takes for the orbit to decay from some initial radius r_i to $r = 0$. The dynamical friction time is

$$t_{df} = \frac{1.17}{\ln\Lambda}\frac{r_i^2 V_c}{GM_S} = \frac{1.17}{\ln\Lambda}\left(\frac{r_i}{r_h}\right)^2\left(\frac{M_h}{M_s}\right)\frac{r_h}{V_c}$$

with $V_c = \sqrt{GM_h/r_h}$. Only systems with $M_s/M_h > 0.03$ experience significant mass segregation.

Orbital decay from dynamical friction

When orbits are eccentric, dynamical friction may cause the orbit's eccentricity to evolve as a function of time. As shown by van den Bosch et al. (1999),

$$\frac{de}{dt} = \frac{\eta}{v}\frac{de}{d\eta}\left[1 - \left(\frac{v}{V_c}\right)^2\right]\frac{dv}{dt}$$

where

$$e = \frac{b}{a} \text{ is the eccentricity}$$

$$\eta = \frac{L}{L_c(E)} \text{ is the circularity, where}$$

L is the orbital angular momentum

$L_c(E)$ is the orbital angular momentum of a circular orbit with the same energy

Orbital decay from dynamical friction

Since $\frac{de}{d\eta} < 0$ and dynamical friction causes $\frac{dv}{dt} < 0$,

$$\frac{de}{dt} < 0 \text{ for } v > V_c \rightarrow \text{orbit circularizes near pericenter}$$
$$\frac{de}{dt} > 0 \text{ for } v < V_c \rightarrow \text{orbit becomes more eccentric near apocenter}$$

Numerical simulations show that these two effects cancel, so $\frac{de}{dt} \sim 0$ over an entire orbit. Therefore, dynamic friction does not circularize orbits.

Simulations also show that $t_{df} \propto \eta^{0.53}$: more eccentric orbits decay faster.

Impact of mass loss with dynamical friction

Unless the system mass is compact, the tidal forces of the host system will cause mass loss, decreasing M_S with time.

Accounting for mass loss results in an increase of the average dynamical friction time by a factor of $\sim$2.8.

Simulations show that the dependence of the dynamical friction time on the orbital circularity becomes

$$t_{df} \propto \eta^{0.3-0.4}$$

when mass loss is taken into account. This effect is weaker than ignoring mass loss, reflecting the fact that tidal stripping is more effective in orbits with small pericenters.

Dynamical friction assumptions

This expression for the dynamical friction force is based on the following three assumptions:

- The subject mass and field particles are point masses.
- The self-gravity of the field particles can be ignored.
- The distribution of field particles is infinite, homogeneous, and isotropic.

The last of these is the reason why the Coulomb logarithm has to be introduced; the maximum impact parameter is needed to prevent the divergence of the field particles.

This dynamical friction is considered as the sum of uncorrelated two-body interactions between a field particle and the subject mass. However, this ignores the collective effects due to self-gravity of the field particles.

Criterion for galaxies to merge

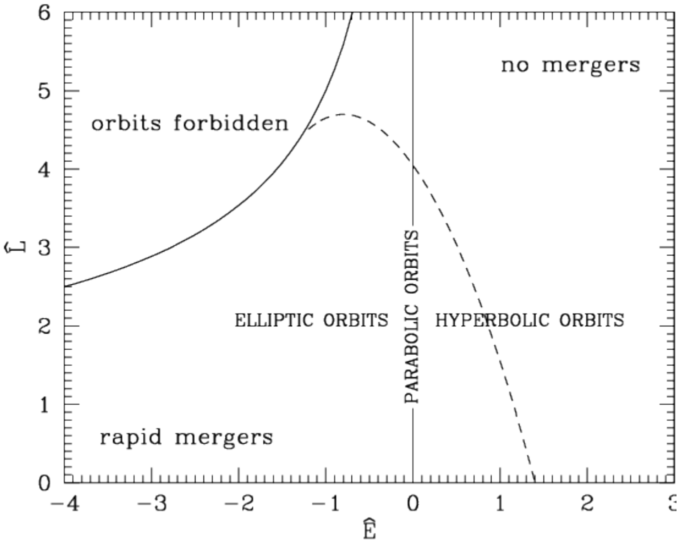
In the simple case, we have two identical galaxies which are non-rotating and spherical. If each galaxy has a mass M and an average radius r_{med}, then their internal mean-square velocity is

$$\langle v^2 \rangle = \frac{aGM}{r_{\text{med}}}$$

The results of the encounter can then be completely defined by the orbital energy per unit mass, E_{orb} and the orbital angular momentum per unit mass, L, via

$$\hat{E} \equiv \frac{2E_{\text{orb}}}{\langle v^2 \rangle} \qquad \hat{L} \equiv \frac{L}{\sqrt{\langle v^2 \rangle r_{\text{med}}}}$$

Galaxy merge criterion



Merger demographics

NGC 7252 *(ESO, HST/NASA/ESA)*

Merger demographics

The resulting structure of the merger remnant mainly depends on four properties:

- Progenitor mass ratio, $q \equiv \frac{M_1}{M_2}$, where $M_1 \geq M_2$
- Progenitor morphologies
- Progenitor gas mass fraction
- Orbital properties

Mergers can produce starbursts, AGN

Centaurus A (*ESO/WFI, MPIfR/ESO/APEX/A. Weiss et al., NASA/CXC/CfA/R. Kraft et al.*) & M82 (NASA/ESA/Hubble Heritage Team)