Galactic Encounters: The Dynamics of Mergers and Satellite Accretion

Sarah Buehler

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1 Motivation

The interaction and merging of galaxies and pre-galactic fragments play a crucial role in the formation and evolution process of galaxies. In both, theory and observation, strong evidence has been found, that galaxies are built up hierarchically by the merging of smaller, sub-galactic building blocks. Galaxies in the process of merging or galaxies that show the signature of former mergers are commonly observed. In general we distinguish between major and minor mergers.
Major mergers happen due to encounters of large disk galaxies of comparable mass. They stimulate star formation, disrupt galaxies and can lead to the formation of tidal tails (see Fig. (1)). Giant elliptical galaxies are believed to be the end product of a fairly disruptive version of a major merger.
Minor mergers take place when a small dwarf companion that is orbiting a larger galaxy gets captured and accreted. The accretion of small companion galaxies by larger disk galaxies is believed to contribute to the built up of the stellar halo. In Fig. (1) a map of star counts of the Andromeda galaxy (M31) is shown (taken from Ferguson *et.al* (2002)). Close to the southern minor axis a giant stellar stream can be seen. This stream stems from a small satellite companion that is in the process of being accreted by Andromeda. As we will see later on, minor mergers do not only lead to subpopulations within a galaxy, but can also change the structure of a galaxy. Some frequently observed features in galaxies can only be explained by previous accretion processes. Dynamical stirring of the disk by a captured satellite can lead to heating and thickening of the disk. Depending on the direction of the

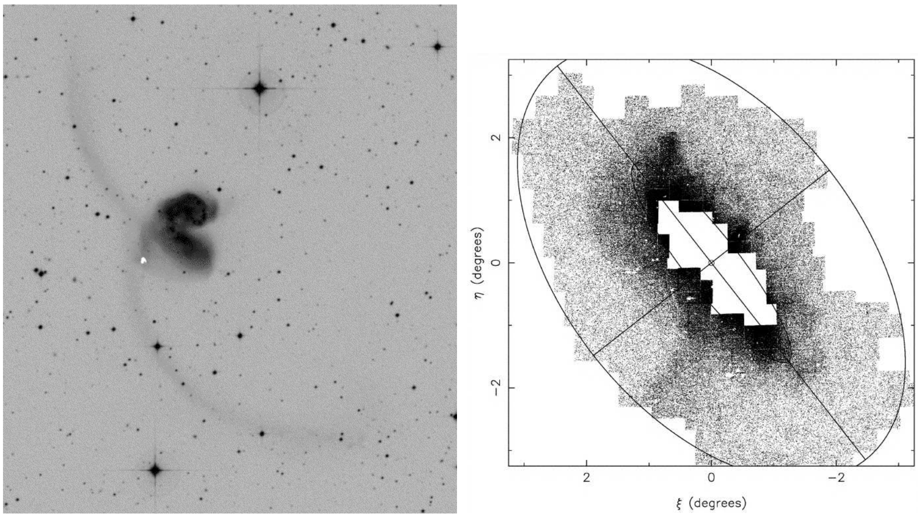

Figure 1: *Left: NGC 4039 is an example for a major merger between two disk galaxies. Tidal arms form as the merging disk galaxies are disrupted. Right: Surface density map of red RGB stars in M31 taken from Ferguson et.al (2002). Substructure from recent satellite accretion can be seen at large radii. Note in particular the giant stellar stream close to the southern minor axis that stems from a satellite that is in the process of being accreted by the Andromeda galaxy at the very moment.*

infall with respect to the rotational direction of the host galaxy, an infalling satellite can also induce a central bar in the larger galaxy.
Besides using observations, mergers are best investigated theoretically via computer models (N-body models) of the gravitational forces on individual particles as the galaxies approach each other. But some simple analytic approximations give a good general idea of the process. In the following section the underlying dynamical processes shall be discussed and illustrated by results from N-body simulations.

2 Dynamical Friction

Not all galactic encounters lead to mergers. Some do and some don't, depending on the mass and velocity of the two galaxies involved, which will be shown in more detail in this section. But encounters, no matter if they lead to mergers or not, change the dynamical state of stars in the encoun-

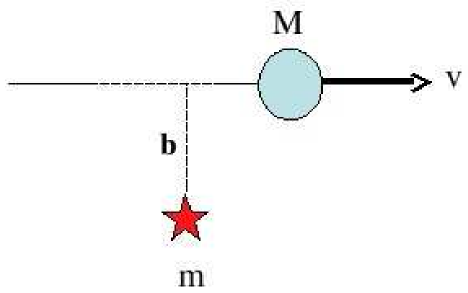

Figure 2: *A galaxy with mass M is passing a stationary star with mass m that is located in a second galaxy. v is the velocity of the passing galaxy and b the distance to the star from its path, e.g. the distance of closest approach.*

tering galaxies. Orbital energy of two interacting galaxies is converted into internal energy within the galaxies and this can lead to merging. When two galaxies merge, direct hits of stars are very unlikely. This shouldn't be surprising, considering how small the fraction of the area filled by stars in a galaxy is. For the solar neighbourhood we typically have 20 stars/pc^3 and the radius of each star is about $0.2R_{\rm sun}$ on average. So the fractional area covered by stars is 10^{-14}! But even though there are almost no direct hits during the encounter, the dynamical state of the stars changes. The reason for that is dynamical friction. A mass M doesn't move unimpeded through the background 'sea' of material: as M moves forward, the other objects are gravitationally pulled towards its path with the closest one feeling the largest force. This produces a region of enhanced density along the path with a high-density 'wake' trailing M. Note that we neglect the gravitational potential generated by this sea of stars so that the motion of each star is solely determined by the gravitational force from M ('Jeans swindle'). The dynamical friction can then be calculated as a net gravitational force on M that opposes its motion. Kinetic energy is transfered from M to the surrounding material as M's speed is reduced. Physical quantities envolved in this must be the mass M, its velocity v_M and the mass density of the surrounding objects ρ. In the following a simplified derivation of the deceleration effect is shown (see also Sparke & Gallagher (2000)). Imagine a galaxy of mass M_g moves with a velocity v past a stationary star of mass m in a second galaxy at distance b from its path. The situation in illustrated in Fig. 2. If we measure the time from the moment of closest approach t_0 at impact parameter b, we know that the distance between star and galaxy at time t is: $\sqrt{(b^2 + v^2t^2)}$. Then we get for the component of the force perpendicular to the motion:

$$F_\perp = \frac{Gm_\star M_g b}{(v^2t^2 + b^2)} = M\frac{\mathrm{d}v_\perp}{\mathrm{d}t} \tag{1}$$

$$\tag{2}$$

From that we can get the velocity of the galaxy perpendicular to the motion of the star at time t after the closest approach:

$$\Delta v_{\perp g} = \frac{1}{M_g}\int_{-\infty}^{\infty} F_\perp dt = \frac{2Gm_\star}{bv} \tag{3}$$

$$\tag{4}$$

Because of conservation of momentum we get for the velocity of the star:

$$\Delta v_{\perp\star} = \frac{2GM_g}{bv} \tag{5}$$

$$\tag{6}$$

So the total gain in kinetic energy is:

$$\Delta K_\perp = K_{\perp g} + K_{\perp\star} = 0.5M_g\Delta v_{\perp g}^2 + 0.5m_\star\Delta v_{\perp\star}^2 = \frac{2G^2m_\star M_g(m_\star + M_g)}{b^2v^2} \tag{7}$$

with the gain in kinetic energy being much bigger for the star than for the galaxy. This energy gain comes from the forward motion of the galaxy, that therefore must slow down by an amount Δv. If we match the loss in kinetic energy of the galaxy in forward direction with the gain of kinetic energy in perpendicular direction we get:

$$\Delta K_\perp = \Delta K_{loss,\star} + \Delta K_{loss,g} \tag{8}$$

$$\Leftrightarrow \Delta K_\perp = \frac{M_gv^2}{2} - \frac{M_g(v^2 - \Delta v^2)}{2} - \frac{m_\star}{2}(\frac{M_g}{m_\star}\Delta v)^2 \tag{9}$$

(the reduced velocity of the star stems from conservation of momentum). Under the assumption that $\Delta v \ll v$ and $m_\star \ll M_g$ we get for the change in velocity:

$$\Delta v \simeq \frac{\Delta K_\perp}{M_gv} = \frac{2G^2m_\star M_g}{b^2v^3} \tag{10}$$

We will get the overall rate of change of the forward velocity of the galaxy if we integrate over stars at all possible impact parameters:

$$\frac{dv}{dt} = -\int_{b_{min}}^{b_{max}} \frac{2G^2 m_\star M_g}{b^2 v^3} \times nv2\pi b\,\mathrm{d}b = \frac{4\pi G^2 m_\star M_g n}{v^2} ln(b_{max}/b_{min}) \quad (11)$$

with n = number density of stars, $vdt \times 2\pi b\,\mathrm{d}b$= volume of the cylindrical shell at impact parameter b swept out in time dt. Roughly the rate of change in velocity simplifies to:

$$\frac{dv}{dt} \simeq -\frac{4\pi G^2 M_g \rho_\star}{v^2},\ \rho_\star = nm_\star \quad (12)$$

This is a simplified version of the so called Chandrasekhar formula.
For a uniform density in the field of matter, with matter particles significantly lighter than the major particle under consideration, and with a Maxwellian distribution for the velocity of the matter particle, the dynamical friction force is as follows:

$$f_{dyn} = M\frac{dv_M}{dt} = -\frac{4\pi ln(b_{max}/b_{min}) G^2 M^2 \rho}{v_M^3} v_M \quad (13)$$

Eq. (12) shows, that the slower the galaxy M_g moves, the larger its deceleration is. Merging can only happen if the deceleration is large enough, which requires a small relative velocity and a high mass density of stars. The one galaxy will then fall in towards the other after a number of closer and closer passages. The larger galaxy will hereby be slowed more, this means that larger neighbours will be swallowed first. This phenomenon is also called 'galactic cannibalism'. For the Milky Way for example this means that the Large Magellanic Cloud is likely to merge with our Galaxy within a few gigayears but the Globular Clusters, that are about 10^5 times lighter can stay in orbit.
Eq. (13) tells us, that, the slower the galaxy's speed is, the stronger the dynamical force, the more intense the interaction. But this is only true if the velocity of the galaxy is not far below the velocity dispersion of the stars it is passing through. In that case the Navier Stoke's equation applies and dv/dt proportional to v.
The timescale for merging can be easily derived by using the simplified Chandrasekhar formula (Eq. 12) above:

$$t_{merge} \sim \frac{v}{dv/dt} \sim \frac{v^3}{4\pi G^2 M_g \rho_\star} \quad (14)$$

This doesn't tell us the detailed outcome of the process, but we can get a rough estimate for the timescale within which mergers happen. We would find that timescales for mergers typically happen within some 10^9 years.
Even if the initial speed of an infalling galaxy is high enough that merging can't happen, this still can affect both galaxies extremely. Dynamical friction increases the energy in random stellar motions and hence the galaxy's internal energy. We can see that by using the Virial Theorem: say the internal kinetic energy before the encounter is κ_0. Then the potential energy is $p_0 = -2\kappa_0$ and the total internal energy of the system before merging is

$$\epsilon_0 = \kappa_0 + p_0 = -\kappa_0 \tag{15}$$

A long time after the encounter when the system is virialised and in equilibrium again the total internal energy is accordingly:

$$\epsilon_1 = -\kappa_1 \tag{16}$$

The encounter will change the internal energy by $\Delta\kappa$. It increases the kinetic energy of the stars. Therefore the internal energy changes as follows:

$$\epsilon_1 = \epsilon_0 + \Delta\kappa \tag{17}$$

But long after the encounter, when the system is in equilibrium again, the internal kinetic energy is less than before:

$$\kappa_1 = -(\epsilon_0 + \Delta\kappa) = \kappa_0 - \Delta\kappa \tag{18}$$

During the virialisation process the kinetic energy changes from $\kappa_0 + \Delta\kappa$ to $\kappa_0 - \Delta\kappa$ by $2\Delta\kappa$. The virialisation after the encounter changes the internal energy of the system much more than the encounter itself did. The kinetic energy has in the end decreased as a result of encounter plus virialisation but the systems' energy as a whole of course is more positive. It is less strongly bound and therefore expands. Typically some stars escape while the others remain loosely attached as a bloated outer envelope.
Our derivation above is only a rough description of the true picture. Imagine for example two systems that are on bound orbits around each other. The various encounters of the stars that then happen during the merger are not independent of each other because Galaxy M will encounter the same stars several times and resonance effects can take place. N-body simulations will give us a more detailed picture as we will see in the next chapter.

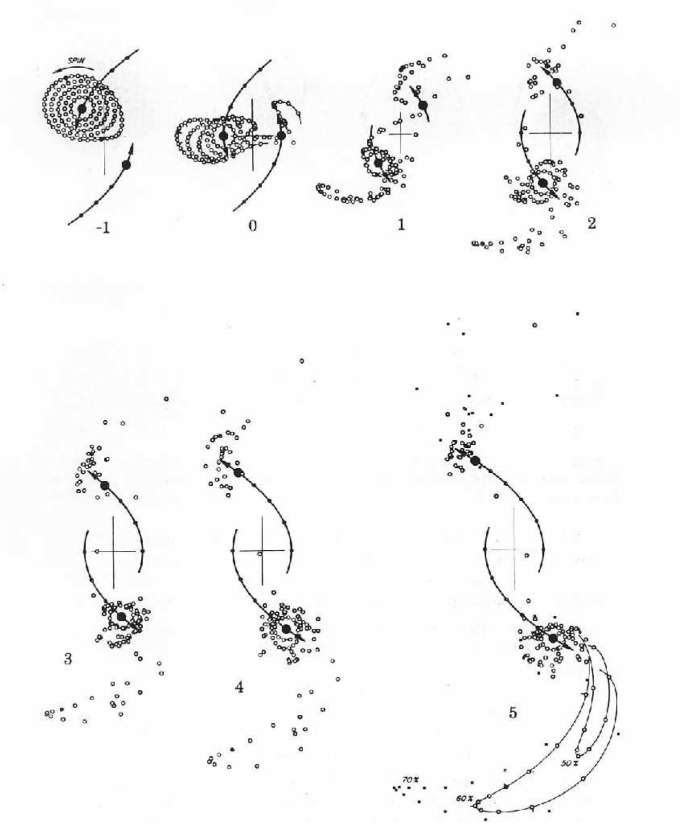

Figure 3: *Prograde encounter (Toomre and Toomre (1972)). The infalling galaxy is represented by a point mass M, the second galaxy by a central point mass surrounded by rings of massless test particles. In a prograde encounter these rings get disrupted due to resonance effects.*

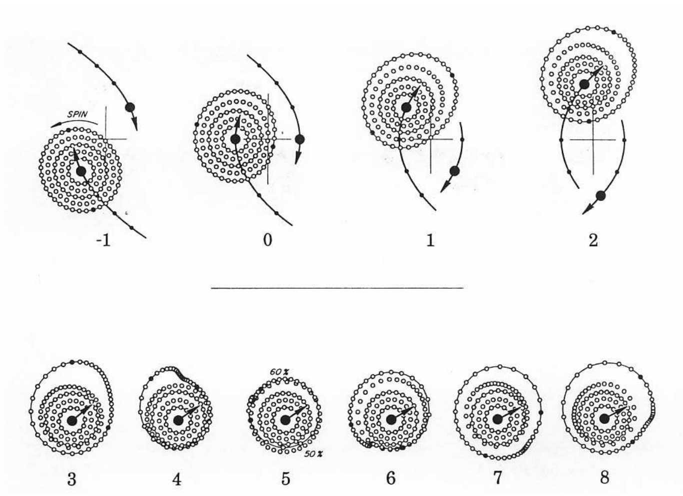

Figure 4: *Retrograde encounter (Toomre and Toomre (1972)). The rings get only mildly distorted here.*

3 Prograde and Retrograde Encounters

In the early seventies, Toomre & Toomre (1972) heavily influenced the field by reproducing many of the features from interacting galaxies with very simple simulations. As computing power was more limited than today they used only a few hundred particles, no gas and no dark matter but still, their simulations revealed some fundamental mechanisms about galaxy mergers. The infalling galaxy is represented by a point mass M and the second galaxy by a central point mass M surrounded by rings of massless test particles. Fig. (3) and (4) show the simulations for prograde and retrograde encounters. In a prograde encounter the spin of the galaxy and the direction of infall of the intruder are the same (orbital and spin angular momenta are parallel). In the retrograde case the direction of infall is anti-parallel to the spin of the galaxy. The simulations by Toomre & Toomre (1972) show that prograde encounters merge more rapidly than retrograde encounters. We see in Fig. (3) that for the prograde case the rings of massless test particles are disrupted by the time of closest approach. They form thin tidal tails and are then broken up. In case of the retrograde encounter the rings are just modestly distorted.
The reason for why the prograde encounters are much more violent, is resonance - resonance of the orbital frequency in the disk with the orbital frequency of the two encountering galaxies.

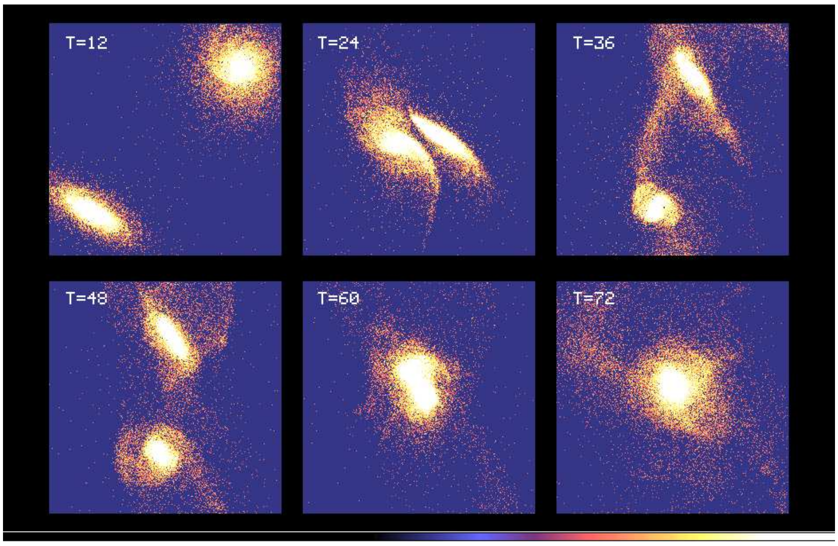

Figure 5: *Simulation by Walker, Mihos & Hernquist (1996) of a major merger of disk galaxies including bulges. The two galaxies are initially in a parabolic orbit and the encounter is exactly prograde. The timescale for the merger is 1.5 billion years, the frames are stepped in 30 million year intervals.*

The orbital frequency of the test particle is:

$$\omega_{ring}^2 = \frac{GM}{r^3} \tag{19}$$

The angular velocity of the line connecting the center of the two galaxies at a minimum distance D_{min} is:

$$w_{orb}^2 = (1+e)(2GM/D_{min}^3) \tag{20}$$

In the case of resonance:

$$\frac{GM}{r^3} = (1+e)\frac{2GM}{D_{min}^3} \tag{21}$$

Resonance occurs at $r \sim 0.5D_{min}$. A particle on the near side of the disk will experience the pull of the intruder continuously during prograde resonance while in the retrograde case the pull is changing sign and the disturbance is much less considerable.
Since Toomre and Toomre's pioneering work, simulations of major mergers

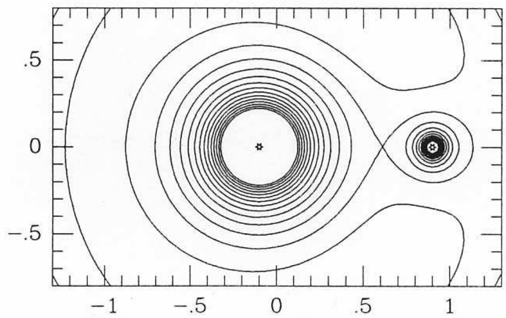

Figure 7-8. Contours of equal effective potential $\Phi_{\rm eff}$ defined by equation (7-81) for two point masses, m and $M = 9m$, in circular orbit about one another. The particles are unit distance apart. The center of mass is at the origin, and the central Lagrange point is located near (0.6,0).

Figure 6: *Contours of equal effective potential $\Phi_{\rm eff}$ for two point masses taken from Binney & Tremaine (1987). Note the saddle point between the two masses where $\delta\Phi_{\rm eff}/\delta x = 0$.*

have revealed more and more interesting results. Fig. (5) shows a simulation done by Walker, Mihos & Hernquist (1996). During this prograde merger the structure of both galaxies gets disrupted over a time of 1.5 Gyrs. It is a known fact today that major mergers can result in an elliptical galaxy although it is not clear yet, how big the fraction of ellipticals made that way is.

4 Tidal Radii and Satellite Accretion

However, most galaxy collisions do not involve two big galaxies. They involve a larger galaxy swallowing a smaller companion. Cosmological considerations suggest, that most galaxies have experienced such a minor merger in their lifetime.
Accretion also plays an import role during the build-up of the stellar halo. It is not clear yet, how much of the stellar halo comes from discretely accreted objects, but simulations suggest that at least 10% of the stars in the stellar halo stem from satellite accretion. This section will illustrate under which conditions a satellite galaxy gets torn apart by the gravitational field of the large galaxy it is orbiting, followed by a short discussion on the implications

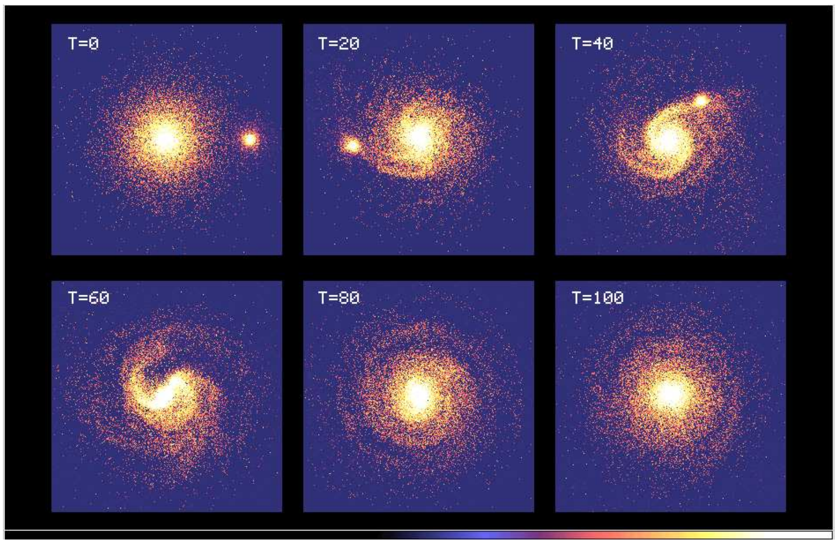

Figure 7: *Simulation of a satellite accretion by Walker, Mihos & Hernquist (1996). The timescale for the capture is 1.5 billion years, frames are stepped in 30 million years intervals. The satellite has a mass of 10% of the disk mass and falls in on a nearly prograde orbit with an initial inclination of 30 degrees to the plane.*

that arise for the host galaxy. Therefore it is necessary to derive an equation for the tidal radius. For a detailed derivation please see Sparke & Gallagher (2000) or Binney & Tremaine (1987). Here, a rough discussion of the problem shall suffice. Consider a satellite of mass m in a circular orbit around a host of mass M at a distance D. We know the angular velocity around the common center of mass:

$$\Omega^2 = \frac{G(m+M)}{D^3} \tag{22}$$

We define a frame of reference rotating uniformly about this center of mass. Then we can define an effective potential Φ_{eff} for the stars' motion. In this rotating frame we have the Jacobi integral:

$$E_J = 0.5v^2 + \Phi_{\text{eff}}(\mathbf{r}) \tag{23}$$

In Fig. (6) you can see how the contours of Φ_{eff} have a saddle point between the two masses where $\delta\Phi_{\text{eff}}/\delta x = 0$. If we assume that the mass of the satellite is much smaller than the mass of the galaxy than we get as a measure of the

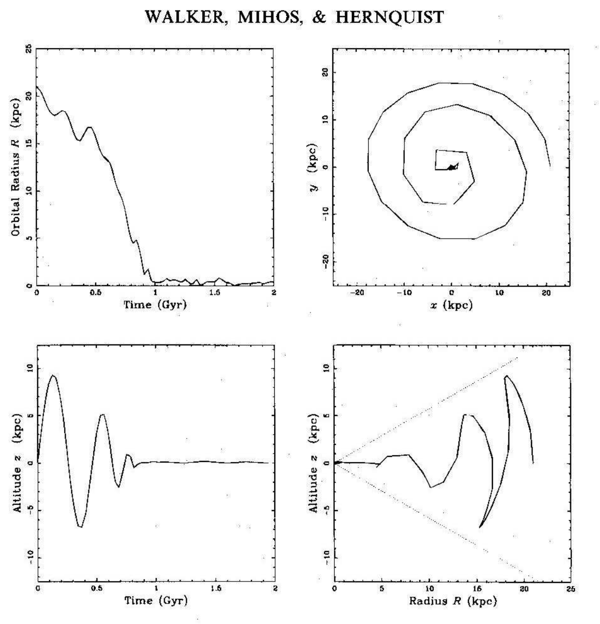

Figure 8: *Decay of a prograde satellite orbit. The merger is all over after 1Gyr (upper and lower left panel). The satellite settles into a low-inclination orbit at large radii already (lower right panel). It completes less than two orbits before it arrives at the center (upper right panel).*

tidal radius of the satellite:

$$r_J = (\frac{m}{3M + m})^{1/3} D \tag{24}$$

This radius is also known as the Roche limit and might be familiar from stellar physics: in a close binary material can only flow from the secondary star onto the primary if the secondary fills out its Roche lobe. We have the same principle here. Stars that are not further away from the satellite center than r_J will remain bound to it. Stars that lie beyond this radius will be removed from the satellite by the tidal forces.
The densities at which tidal removal of matter will happen can be derived as follows: If we take the stellar density of the infalling satellite within the tidal radius

$$\rho(r_J) = \frac{m}{\frac{4}{3}\pi r_J^3} \tag{25}$$

and compare it to the density of the galaxy within a distance D from its center

$$\rho(D) = \frac{M}{\frac{4}{3}\pi D^3} \tag{26}$$

then we can easily see by plugging in the formula for the tidal radius r_J into eq. (25), that

$$\rho(r_J) \sim \rho(D) \tag{27}$$

In other words: we would expect an infalling satellite to remain intact in to a distance D from the larger galaxy such that the density of the galaxy at that distance equals the mean density of the satellite.
Fig. (7) shows a simulation by Walker, Mihos & Hernquist (1996) that illustrates the capture of a dwarf satellite by a disk galaxy with a bulge. In this simulation, the satellite falls in on a nearly prograde orbit with an inclination of 30 degrees to the plane. The timescale for the simulation is 1.5 billion years and the frames are stepped in 30 million years intervals. It is obvious that the coupling of orbital and rotational motion of this prograde encounter induces a central bar. Along its orbit the satellite is pulling constantly at the same position before it gets disrupted.
Fig. 8 additionally illustrates the timescale of the decay from a face-on as well as an edge-on view. As the satellite orbit decays, its inclination to the plane becomes less due to the effects of dynamical friction. The orbital energy and orbital angular momentum go primarily into the stars of the disk. The disk heats up due to the dynamical stirring but this effect is limited as the satellite gets stripped at some point. Finally after about 2 orbits the satellites sinks into the plane and arrives at the center.

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