Shell Galaxies and Dynamical Friction

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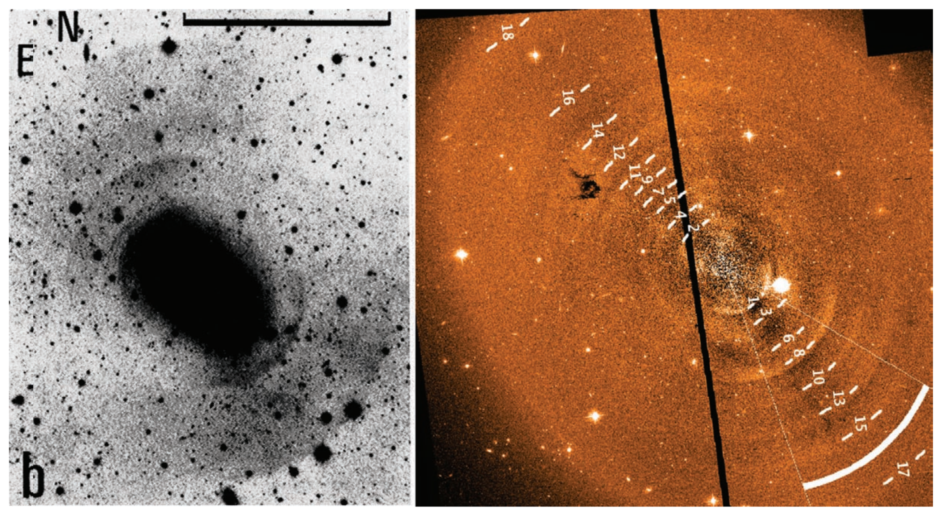
Shell galaxies – What are they?

Shell galaxies are galaxies containing ring-like fine structures. These structures are made of stars and form open, (almost) concentric arcs which do not cross each other. Shells are relatively common in elliptical or S0 galaxies. At least 10 % of all these galaxies in the local universe possess shells but they occur markedly most often in regions of low galaxy density (perhaps up to half of E and S0 galaxies in these environments are shell galaxies), Malin & Carter (1983), Schweizer, (1983), Schweizer & Ford (1985). The number of shells in a galaxy ranges from 1 to more than 30 and they occur from ~1 kpc to about 100 kpc from the nucleus of the host galaxy. Shells contain at most a few percent of the overall galaxy brightness and their contrast is low (0.1–0.2 mag).

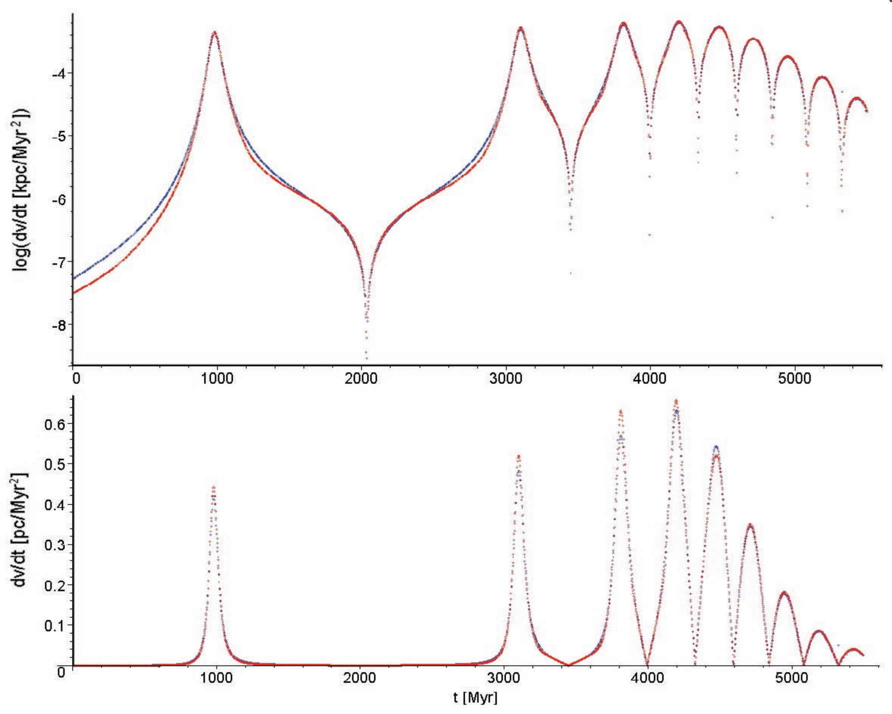


NGC 3923, one of the most prominent examples of a shell galaxy with dozens of individual shells, ranging from the outer parts of the galaxy down to its center. Left: Malin & Carter (1983), scale bar is 5′ (~35 kpc), Right: Inner region of the same galaxy, Sikkema et al. (2007). The field of view is approximately 3′ (~20 kpc).

The origin of shells

The model of a radial merger of two galaxies (Quinn 1984, Dupraz & Combes 1986, Hernquist & Quinn 1988) seems to be the most successful in reproducing the observed regurlar shell systems. When a small galaxy enters the scope of influence of a big elliptical galaxy on a radial or close-to-radial trajectory, it disintegrates and its stars begin to oscillate in the potential of the big galaxy, which itself remains almost unaffected. At their turning points, the stars have the lowest speed and thus tend to spend most of the time there – they pile up and produce arc-like structures in the luminosity profile of the host galaxy.

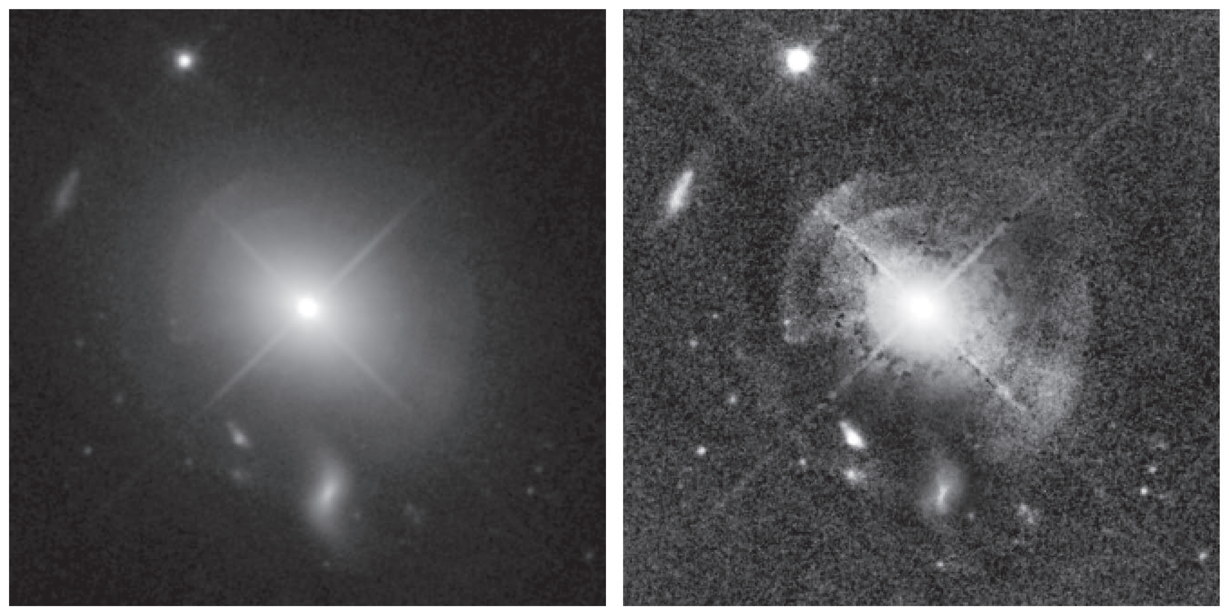
Two well-known active galaxies, NGC 5128 (Centaurus A, left, credit: ESO) and NGC 1316 (Fornax A, right, credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)) which also possess shells.



An example of a comparison between the friction from the numerical integration (blue) and the Chandrasekhar formula (red), where the latter is evaluated with either b_{max}=10 kpc or ln(Λ) =2, whichever choice gives the larger value of ln(Λ) (which is the combination with the least deviation from the numerical case in this particular encounter). Maxima appear when the small galaxy goes through the centre of the big galaxy.

Our simulations

Our goal is to present an improved treatment of the dynamical friction on the evolution of shells (its effects on shells were first pointed out by Dupraz & Combes, 1987). We start from the Quinn's model of shells origin – a radial merger of two galaxies with significantly different masses. In our simulations, two 3D analytical potentials (which represent spherical galaxies) fall towards each other. As many as 2 millions test particles are initially distributed to represent the secondary galaxy and they form the shells during the radial merger. The potential of the bigger galaxy remains unaffected, but the other one gradually vanishes, following the gradual decay of the small galaxy. The dynamical friction is added to the equation of motion of the small galaxy.



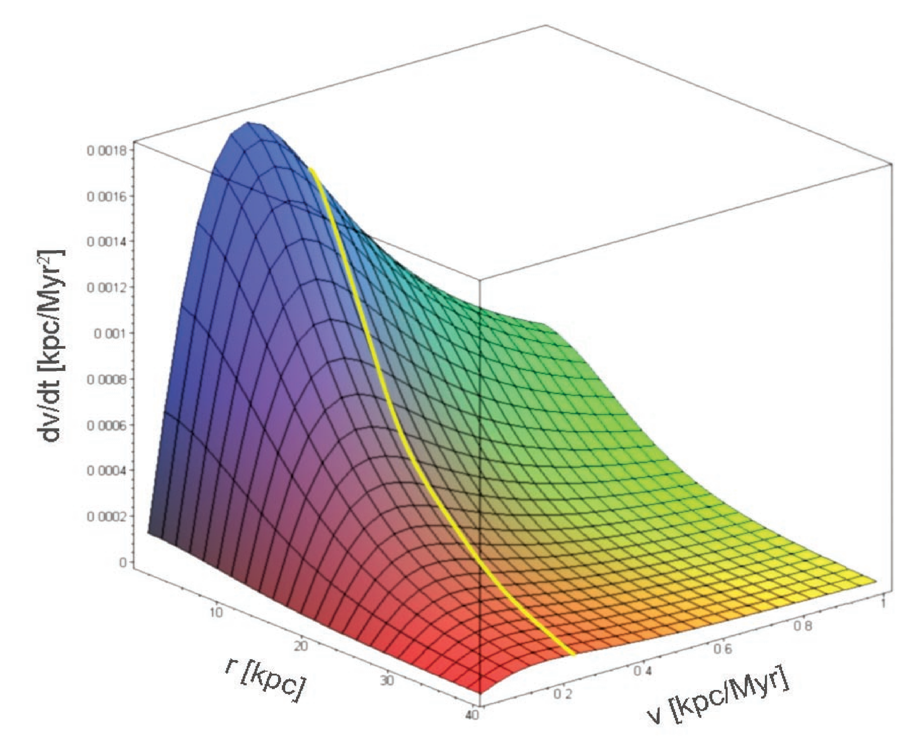
Deep HST/ACS images of the host galaxy of the quasar MC2 1635+119 (Canalizo et al. 2007, Bennert et al. 2008). The left panel shows the original image, the right panel the residual after the subtraction of the fitted primary light profile of the primary galaxy.

Observational motivation

We have recently (Canalizo et al. 2007, Bennert et al. 2008) presented observations of shells in the host galaxy of the quasar MC2 1635+119. Using simple N-body simulations, we attempted to put constraints on the age of the merger that presumably triggered the formation of the shell system. Here, we extend our previous modeling to take into account the effects of the dynamical friction.

Improving the Chandrasekhar formula

The relative simplicity of the Chandrasekhar formula is allowed, among others, by the assumption of homogeneity of the stellar distribution, which is nevertheless a false one in many cases (including the one we deal with). Instead, we used the radial symmetry of our big galaxy to simplify the integrals so they can be reasonably solved numerically. This calculation is still too slow to be repeated in every step of the simulation – but it can be used to fix the ad-hoc parameters of the Chandrasekhar formula. We found that the best agreement between the numerically computed values and the Chandrasekhar formula is reached when the Coulomb logarithm is calculated from a fixed cut-off (b_{max}) and the relative velocity of galaxies, but it is not allowed to become lower than a chosen critical value. This algorithm is easily introduced into our simulations using test particles. The magnitude of the Coulomb logarithm and the critical value slowly vary with collision parameters, but they can be always easily recalculated, when necessary.



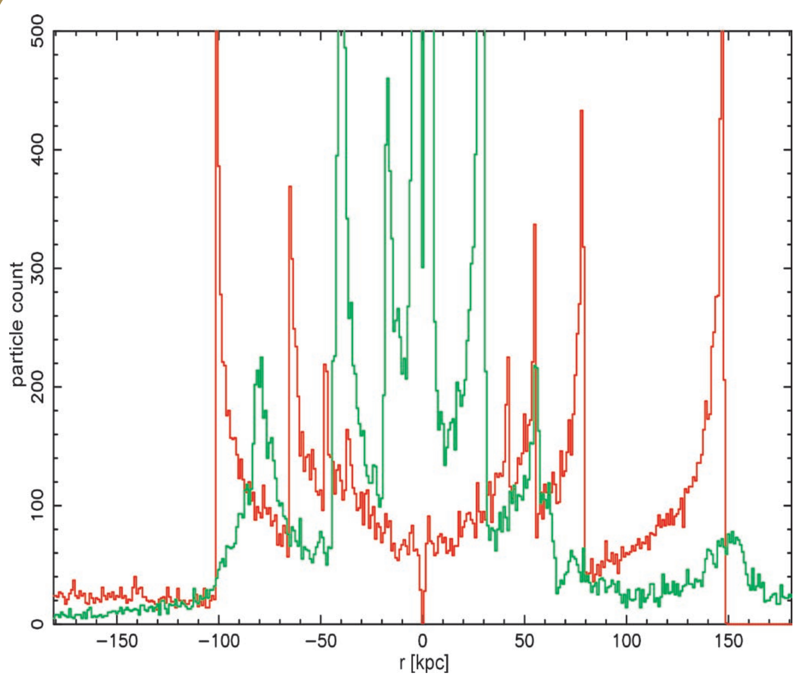
A 3D plot which shows the dynamical friction (from the numerical integration) as a function of the velocity of the small galaxy and its distance from the centre of the big galaxy (which are the only two parameters of the integration in the radial case). The yellow line corresponds to an example of an actual simulated merger.

Dynamical friction

A braking force of gravitational origin acts on every massive body which flies through a field of other gravitating bodies. It results from the natural transfer of energy from more energetic bodies to the less energetic ones. In our case, a small galaxy is being slowed down by the stars and dark matter of the bigger one. An easy way to compute this effect analytically is the Chandrasekhar formula:

$$\frac{\mathrm{d}\mathbf{v}_{M\|}}{\mathrm{d}t} = -16\pi^2 \ln(\Lambda) G^2 m(M+m) \frac{\int_0^{v_M} f(v_m) v_m \mathrm{d}v_m}{v_M^3} \mathbf{v}_M \qquad \Lambda = \frac{b_{max} V_0^2}{G(M+m)}$$

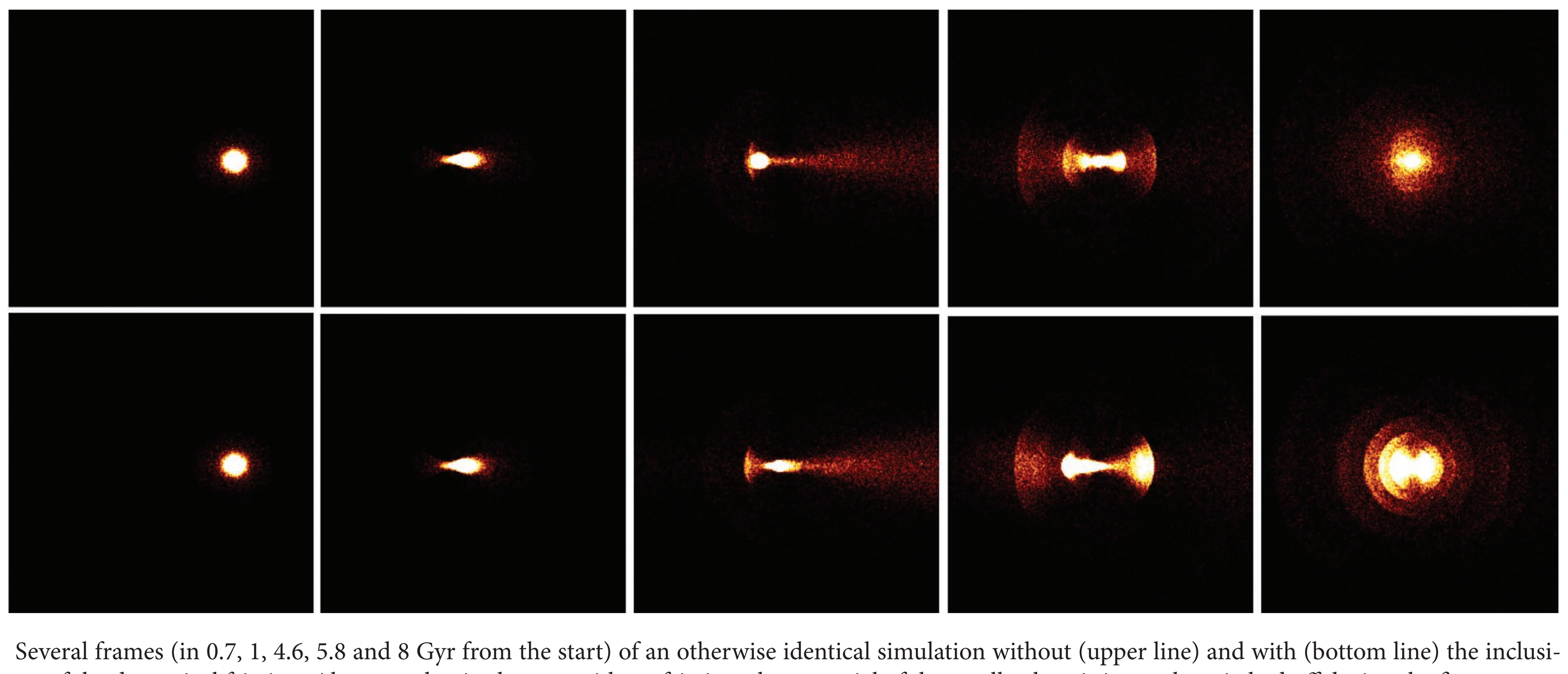
It assigns a change to the parallel (to the direction of motion) component of the velocity v_M of the braked body (the small galaxy in our case) with mass M in a finite homogenous field of stars. Each star has the mass m and velocity v_m. The function $f(v_m)$ is the velocity distribution of stars, often taken to be Maxwellian. The term „ln(Λ)“ is called the Coulomb logarithm and depends on the 'typical speed of a star' relatively to the braked body V_0. Both V_0 and b_{max} (which cuts off an otherwise divergent integral) have to be chosen "by hand", which makes the Coulomb logarithm an uncertain quantity.



Radial histogram of stars of the small galaxy, centered on the big galaxy from the simulations with (green) and without (red) the dynamical friction. The shells are prominent as peaks of stellar density. While the position of the outermost shell remains almost unaffected by the friction, the intensity of the shell is clearly very weakened.

Effects on the simulation

The introduction of the dynamical friction and the gradual decay (none of which were present in the Quinn's model) to our simulations dramatically changes the appearance of shell structures. While the position of the outermost shell is not much affected by the dynamical friction, its brightness is rapidly lowered due to the many particles staying trapped in the weakened but remaining potential of the small galaxy. The following shells are shifted and other generations of shells are added during next passages of the small galaxy through the center of the big one. The concept of easily inferring the age of the collision which created the shell system seems to be ruined by these effects, but we can hope to get some information by detailed analysis of the simulations.



Several frames (in 0.7, 1, 4.6, 5.8 and 8 Gyr from the start) of an otherwise identical simulation without (upper line) and with (bottom line) the inclusion of the dynamical friction. Also note that in the case without friction, the potential of the small galaxy is instantly switched off during the first passage through the center of the primary galaxy, whereas in the case with the friction, the gradual disruption is applied. Only stars of the small galaxy are shown corresponding to the subtraction of the profile of the primary galaxy. Each frame shows a box of 300×300 kpc around the centre of the primary galaxy.

References: Bennert et al., 2008, ApJ, 677, 846; Canalizo et al., 2007, ApJ, 669, 801; Dupraz, C. and F. Combes, 1986, A&A, 166, 53; Dupraz, C. and F. Combes, 1987, A&A, 185, L1; Hernquist, L. and P. J. Quinn, 1988, ApJ, 331, 682; Malin, D. F. and D. Carter, 1983, ApJ, 274, 534; Quinn, P.J., 1984, ApJ, 279, 596; Sikkema et al., 2007, A&A, 467, 1011; Schweizer F., 1983, IAU Symp. no. 100. Reidel, Dordrecht, p. 319; Schweizer, F. and W. K. Ford, Jr., 1985, Lecture Notes in Physics, Vol. 232, p. 145

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Background image: The giant elliptical galaxy NGC 1132 which may as well contain shell-like structures. Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration