Shell Galaxies and Dynamical Friction

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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 all big 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).

The origin of shells

The model of radial merger of two galaxies (Quinn 1984, Dupraz & Combes 1986, Hernquist & Quinn 1988) seems to be the most successful in reproducing the observed regular 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 arcs: like structures in the luminosity profile of the host 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 to 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.

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 integral 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 ($v_{esc}$) 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 parameter and the critical velocity slowly vary with collision parameters, but they can be always easily recalculated, when necessary.

Dynamical friction

A braking force of gravitational origin acts on every massive body which lies 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 in the Chandrasekhar formula)

$$\frac{dv}{dt} = -16\pi \ln(2) g^2 \left( m + \sum m_i \right) \frac{v_{esc}^2 - v^2}{v_{esc}^2} \Delta_{\text{CORE}}$$

It assigns a change to the parallel (to the direction of motion) component of the velocity $v_{par}$ of the braked body (the small galaxy in our case) with mass $m$ in a finite homogeneous field of stars. Each star has the mass $m$ and velocity $v_{par}$. The function $\Delta_{\text{CORE}}$ represents the velocity distribution of stars, often taken to be Maxwellian. The term $\ln(2)$ is the Coulomb logarithm and depends on the "typical speed of a star" relatively to the braked body $v_{par}$. Both $v_{par}$ and $\Delta_{\text{CORE}}$ (which diverges integral) have to be chosen "by hand", which makes the Coulomb logarithm an uncertain quantity.

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 starting 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.

References:

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Background image: Shell galaxy M 81 (NGC 3125) which marks the position of the main spiral galaxy of the M 81 group. (W. F. Manipour, Carnegie Observatories).