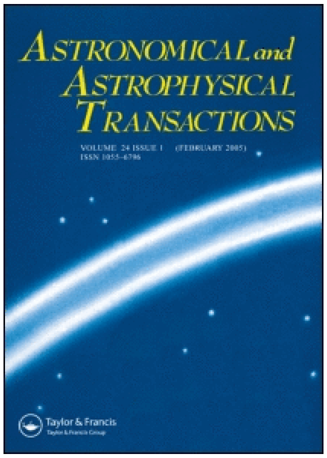

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# TIDAL SHOCKING AND DESTRUCTION OF GLOBULAR CLUSTERS

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Dynamical evolution of globular clusters is strongly influenced and often driven by tidal interactions with the Galaxy. Passing through the Galactic disk or near the bulge, globular clusters experience fast gravitational perturbations, the compressive tidal shocks. A succession of tidal shocks leads to kinematic heating of the clusters and their ultimate destruction. I present the latest Fokker–Planck models including the first and second order tidal diffusion coefficients. In the limit of strong shocks, the typical value of the core collapse time $t_{cc}$ decreases from 10 to 3 half-mass relaxation times, while the destruction time is just 2, $t_{cc}$. The effects of tidal shocks are rapidly self-limiting: as clusters lose mass and become more compact, the importance of the shocks diminishes. This implies that tidal shocks were more important in the past.

KEY WORDS Globular clusters, galaxy evolution

## 1 THEORY OF TIDAL SHOCKS

The dynamical evolution of globular clusters caused by weak stellar encounters is described by the Fokker–Planck equation (Spitzer, 1987). Tidal shocks can be included in the Fokker–Planck models by defining the tidal diffusion coefficients $\langle \mathcal{D}_t(\Delta E)\rangle_V$ and $\langle \mathcal{D}_t(\Delta E^2)\rangle_V$:

$$\frac{\partial N(E)}{\partial t} = -\frac{\partial}{\partial E}(N(E)\langle \mathcal{D}_t(\Delta E)\rangle_V) + \frac{1}{2}\frac{\partial^2}{\partial E^2}(N(E)\langle \mathcal{D}_t(\Delta E^2)\rangle_V),$$

which are the phase-averaged first and second order energy changes of stars with the initial energy per unit mass $E$ (Gnedin, Lee and Ostriker, 1999). In the case of disk shocking (Ostriker, Spitzer and Chevalier, 1972; Gnedin and Ostriker, 1997),

$$\frac{\langle \Delta E\rangle_E}{\Delta t} = \frac{2g_m^2 r^2}{3V_z^2 P_z} A_1,$$
$$\frac{\langle \Delta E^2\rangle_E}{\Delta t} = \frac{4g_m^2 v^2 r^2 (1+\chi_{r,v})}{9V_z^2 P_z} A_2,$$

where $g_m$ is the maximum vertical gravitational acceleration produced by the galactic disk, $V_z$ is the vertical component of the cluster velocity with respect to the disk, $P_z$ is the vertical period, and $r$ and $v$ are the rms position and velocity of stars of energy $E$. Here $\chi_{r,v}$ is the position-velocity correlation factor, which takes values from $-0.25$ to $-0.57$ (Gnedin and Ostriker, 1999). The adiabatic corrections, $A_1$ and $A_2$, account for conservation of the adiabatic invariants of stars for which the orbital period in the cluster $(2\pi/\omega(E))$ is short compared to the effective duration of the shock, $\tau \equiv H/V_z$, where $H$ is the characteristic scale-height of the disk. The results of numerical integrations can be fitted as

$$A_n = (1 + \omega^2\tau^2)^{-\gamma_n}, \tag{1}$$

where $\gamma_1 = 1.5 - 2.5$ and $\gamma_2 = 1.5 - 3$, depending on the duration of the shock (Gnedin and Ostriker, 1999). Traditional adiabatic corrections (Spitzer, 1987) have used the exponential cutoff at large $\omega\tau$.

The first order energy change, $\langle \Delta E \rangle$, causes the reduction in the binding energy of the system and leads to evaporation of the marginally bound stars. The second order change, $\langle \Delta E^2 \rangle$, causes a much larger energy dispersion which allows additional stars to leave the cluster. The two effects cooperate and lead to faster dissolution of the cluster. The efficiency of tidal shocks is characterized by the parameter

$$\beta \equiv \frac{t_{\rm rh}}{t_{\rm sh}} = \frac{t_{\rm rh} \langle \mathcal{D}_t(\Delta E) \rangle_V}{E}.$$

The theory of bulge shocking is discussed in Gnedin, Hernquist and Ostriker (1999). For an alternative linear theory calculation see Weinberg (1994) and Murali and Weinberg (1997a, b, c).

## 2 MODELS OF NGC 6254

The efficiency of tidal shocks depends sensitively on the globular cluster orbit. With the new data on proper motions from *Hipparcos* we can now reconstruct full three-dimensional velocities for some of the Galactic globular clusters (Odenkirchen *et al.*, 1997) and to build realistic models of their evolution. As an example, we consider the cluster NGC 6254 which orbits the Galaxy in $1.4 \times 10^8$ yr and has a small eccentricity, $e = 0.21$. The observed structure of NGC 6254 is well characterized by a King model with the concentration $c = 1.4$ and total mass $2.3 \times 10^5 M_\odot$. For simplicity we consider the single-mass models with $m_* = 0.7 M_\odot$.

Figure 1 shows that the mass loss from the cluster is increased as we include the first and second order tidal diffusion coefficients. Without tidal shocks, internal two-body relaxation leads to the destruction of the cluster in about 32 half-mass relaxation times, $t_{\rm rh,0}$. The $\langle \Delta E \rangle$ term alone changes $t_d$ to $26\, t_{\rm rh,0}$ and the shock-induced relaxation $\langle \Delta E^2 \rangle$ brings it to $24 t_{\rm rh,0}$. The second order term is not as strong as the first order term in this model because of the limiting adiabatic corrections (Eq. 1). For comparison, we also show the mass loss that would have been due

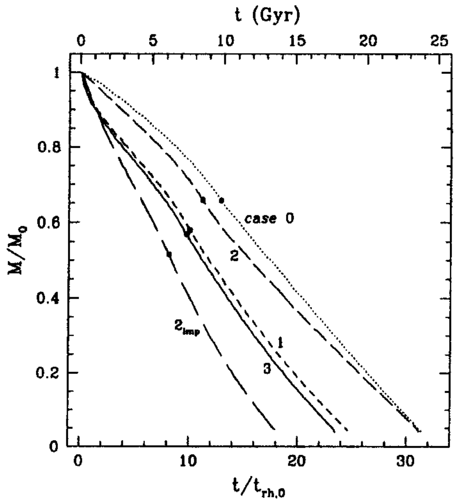

**Figure 1** The mass loss for the single-mass models of globular cluster NGC 6254. Time is expressed in units of the initial half-mass relaxation time, as well as in billions of years. Dots are for the model with two-body relaxation only (*case 0*), dashes are for the model that includes the effects of the energy shift due to tidal shocks (*case 1*), long dashes are for the model that includes the second order energy dispersion (without the heating term; *case 2*), and the solid line is for the final model including proper treatment of all of the shock effects (*case 3*). For illustration, thin dashes show the effect of the second order term (marked '$2_{\rm imp}$') if it had not had adiabatic corrections. Filled circles indicate the time of maximum core collapse.

to the shock-induced relaxation if there were no adiabatic corrections (the impulse approximation). The latter effect would reduce the destruction time by a half.

Tidal shocking generally speeds up core collapse. When the evolution is expressed in units of the core-collapse time, $t_{cc}$, it depends essentially on the internal concentration $c$ and the external tidal shock strength $\beta$. For the low values of $\beta$, the evolution is due to two-body relaxation and is independent of $\beta$. Figure 2 illustrates that as the cluster collapses, the half-mass density $\rho_h$ rises but less than by a factor of 2. After core collapse, the cluster re-expands and the mean density falls back. The evolution with strong tidal shocks ($\beta > 0.1$) is dramatically different. Tidal heating changes the structure of the clusters, removing low-energy stars from the outer parts and adding energy dispersion in the core. This quickly increases the mean density and accelerates core collapse. Subsequent evolution proceeds with a noticeable mass loss at each shocking event, leaving the characteristic ripples in the density plot.

The right panel of Figure 2 shows that tidal shocking is rapidly self-limiting. As the clusters start to collapse, the relaxation time becomes shorter and the tidal shock time becomes longer as the mean density $\rho_h$ rises. Clusters with large values of $\beta$ quickly lose mass and evolve to $\beta < 0.1$. Just a few shocks can lower the value of $\beta$ by several orders of magnitude. Every subsequent shock causes the see-saw variations of the tidal shock parameter, with an increasing amplitude towards the

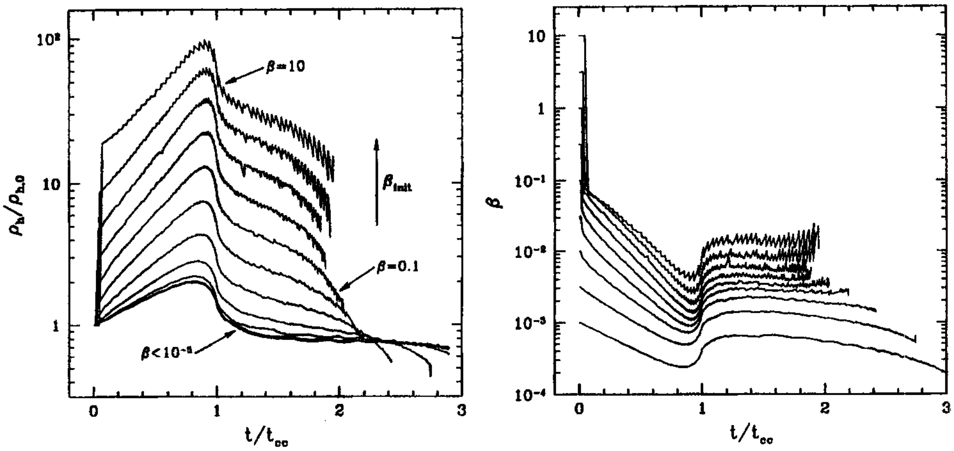

**Figure 2** *Left panel:* The mean density, $\rho_h$, as a function of time normalized to the core collapse time. All models have the same initial concentration $c = 1.4$ but different shock parameters varying from $\beta = 10^{-5}$ to $\beta = 10$. Models with $\beta < 10^{-3}$ show essentially identical evolution. At the time of core collapse, the mean density is higher for the higher values of $\beta$. *Right panel:* The evolution of the shock parameter for the same models.

late stage of the evolution when fewer stars are left.

This implies tidal shocks were much more important in the early evolution of the Galaxy. A large fraction of the initial population of globular clusters might have already been destroyed (Gnedin and Ostriker, 1997; Murali and Weinberg, 1997c).

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