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The Life and Death of Globular Clusters

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Abstract. Globular clusters are embedded in galactic potential. Various processes such as dynamical friction, steady tidal field, and shocks by disk and bulge contribute to the dissolution of globular clusters. Most of them are closely coupled with internal dynamical processes. The tidal shock is very effective during the initial phase of the cluster evolution while steady tidal field becomes more important in the later phase. Recent studies revealed that the rotation of the cluster could significantly accelerate the evolution and evaporation. We emphasize that the lifetime of the clusters could be much shorter than the previous estimates of $\sim 20t_{rh}$ for more realistic models.

1. Introduction

Stars can easily be ejected from cluster potential by acquiring even a small amount of energy. Ambartsumian (1938) and Spitzer (1940) realized that the evaporation of stars from clusters is an important process that affects the internal dynamics. Even isolated clusters would lose mass since the two-body relaxation tends to produce the Maxwellian velocity distribution which inevitably contains stars that exceed the escape velocity. The evaporation is closely related to the dynamical evolution and we expect that the lifetime of the clusters is some multiple of relaxation time.

There are about 150 observed globular clusters in our Galaxy. Substantial fraction of these clusters have relaxation time scale much shorter than the Hubble time. This means that the current population of globular clusters could have been seriously affected by the disruption processes. Although it is rather difficult to trace the evolution backward, understanding of the evaporation process should provide us with the valuable information on the general evolution of star clusters.

Star clusters, being much more massive than the field stars, experience dynamical friction through the interaction with stars. This leads to the spiral-in of clusters' orbits to the central parts of the Galaxy, where the clusters are immediately destroyed by the strong tidal field. The dynamical friction time scale for a cluster with mass M in a singular isothermal sphere with rotation speed v_c is (Binney & Tremaine 1987, p428)

$$t_{fric} = 2.6 \times 10^{10} \left(\frac{r_i}{2\mathrm{kpc}}\right)^2 \left(\frac{v_c}{250\mathrm{km\ s}^{-1}}\right) \left(\frac{10^6 \mathrm{M}_\odot}{M}\right) \ \mathrm{yr}, \qquad (1)$$

where r_i is the initial orbital radius and M is the cluster's mass. The dynamical friction preferentially destroys massive clusters with small galactocentric radius ($r_i < 1$ kpc). Thus this process acts only for very limited ranges of clusters, and would not be an important factor in controlling the general evolution of globular cluster population.

Supernova explosions in the early phase of cluster evolution could be destructive: if the mass loss is taking place rather rapidly (compared to the internal dynamical time scales), the 50% of total mass loss is required to destroy the cluster instantaneously. This condition is not easily satisfied unless the cluster contains a large fraction of high mass stars. The tidally limited clusters could be completely destroyed even with much smaller amount of mass loss by stellar evolution, but the stellar evolution does not seem to be an important mechanism for disruption of early population of clusters if the lower limit of stellar mass is close to 0.1 $M_\odot$ (Chernoff 1993). Thus we concentrate on the evaporation of clusters by two-body relaxation and tidal shock in this paper.

2. The Galactic Clusters Today

The lifetime of the clusters depends on whether the initial size was much smaller than the tidal limits: the clusters with initial radii much smaller than r_t, where r_t is the tidal radius for a given tidal field, have much longer time to disruption than the tidally limited ones. Thus it is important to know the relationship between r_t and cluster sizes.

The determination of limiting radius of star clusters is rather difficult because the stellar density drops to very low level near the boundary. Nevertheless, the limiting radii have been determined for most of the Galactic globular clusters. Lee (1990) has analyzed the data compiled by Webbink (1985), and found that the distribution of the sizes are consistent with the simple model that assumes limiting sizes as the tidal radii at perigalactic passage, and isotropic distribution of cluster orbits. Therefore the current Galactic globular clusters seem to be tidally limited.

The cluster expands up to the tidal limit through the dynamical evolution if the initial size was smaller than r_t. The time scale to reach tidal limit should also be some multiple of the cluster's relaxation time which should have been very short for clusters with size much smaller than r_t. This means that the clusters would become quickly tidally limited even if they started with very compact configuration. It is highly likely that the clusters have been tidally limited from very early phase of the life.

The most important parameter to determine the lifetime of the cluster is the relaxation time. Based on the compilation of cluster data by Djorgovski (1993), we have plotted the accumulated fraction of clusters whose half-mass relaxation time scale is less than t_{rh} as a function of t_{rh} in Fig. 1. Depending on the life-time in units of t_{rh}, we can estimate what fraction of clusters will be destroyed in specified period of time using this figure.

3. Evaporation Rate and Life Expectancy of Clusters

It is convenient to define the dimensionless evaporation rate as

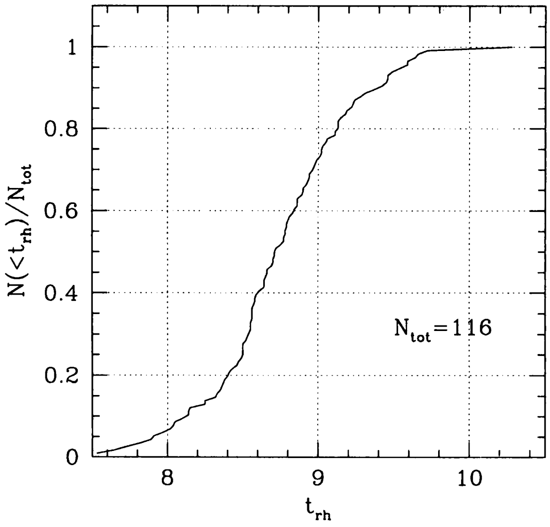

Figure 1. The distribution of t_{rh} for the current globular cluster populations, based on data compiled by Djorgovski (1991).

$$\xi_e \equiv -t_{rh} \frac{1}{M} \frac{dM}{dt}, \tag{2}$$

where t_{rh} is the half-mass relaxation time. For clusters in tidal field, the mass decreases nearly linearly in time and the above equation leads to

$$t_{ev} - t = \frac{t_{rh}}{\xi_e}, \tag{3}$$

where t_{ev} is the time for evaporation of the cluster. Thus the time to disruption (life-expectancy) is t_{rh}/ξ_e.

The evaporation rate can be computed by assuming that the equilibrium velocity distribution is established during t_{rh}. For an isolated cluster, one obtains that $\langle v_e^2 \rangle = -4\frac{W}{M} = 4v_{rms}^2$, where W is the potential energy of the cluster, and v_{rms} is the density weighted velocity dispersion. This corresponds to $\xi_e = 0.0074$ for Maxwellian velocity distribution and the cluster will be evaporated in about 140 t_{rh} (Ambartsumian 1938; Spitzer 1940). If the cluster is tidally limited, the escape speed becomes smaller because the escape energy (per unit mass) should be reduced by $2GM/r_t$, where r_t is the tidal radius. The escape velocity for a tidally limited cluster becomes (e.g., Spitzer 1987, §3.2)

$$\left\langle v_e^2 \right\rangle^{1/2} = 4v_{rms}^2 \left(1 - \frac{5r_h}{4r_t}\right). \tag{4}$$

Once the escape speed is determined by eq. (4)ξ_e can be computed by

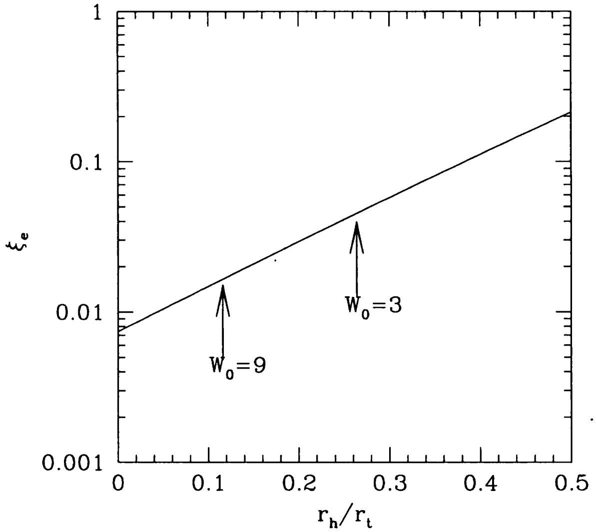

Figure 2. The evaporation rate as a function of r_h/r_t using the Ambartsumian-Spitzer argument for Maxwellian velocity distribution [eq. (5)]. The observed globular clusters can be fitted by the King models with $W_0 = 3 \sim 9$, and the locations of corresponding r_h/r_t are marked with arrows. Within this range of r_h/r_t, ξ_e lies between 0.015 and 0.04. However, note that the dynamical modeling gives systematically higher values of ξ_e than the Ambartsumian-Spitzer formula implies.

$$\xi_e = \frac{\int_{v_e}^{\infty} f(v) d^3v}{\int_0^{\infty} f(v) d^3v}, \tag{5}$$

where $f(v)$ is the velocity distribution function. In Fig. 2we have shown the behavior of ξ_e as a function of r_h/r_t, by assuming that the stellar velocity distribution is Maxwellian. Also shown in this figure as arrows are the locations of King models with $W_0 = 3$ and $W_0 = 9$, which is the typical range of King parameter for observed globular clusters. Within this range of W_0, ξ_e varies from 0.015 to 0.04. The life-expectancy decreases rather dramatically from isolated clusters ($\xi_e = 0.0074$) to tidally limited clusters.

3.1. Tidally Limited Clusters

The evaporation rate of actual clusters is usually somewhat larger than the simple estimate given by the eq. (3). The first accurate determination was done by Henón (1960): based on the self-similar model with infinitely small core radius heated by unspecified energy source, he obtained $\xi_e = 0.045$ (or equivalently, life-expectancy of 22.5 t_{rh}). Lee & Ostriker (1987) subsequently obtained similar value for ξ_e by integrating the Fokker-Planck equation. From Fig. 1 we expect that about 40 % of current globular clusters will evaporate

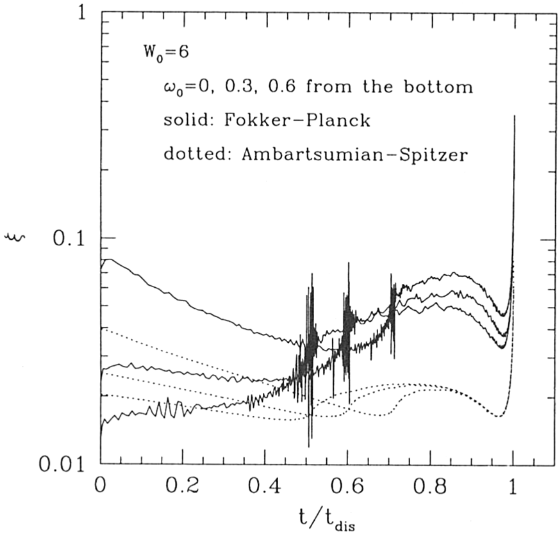

Figure 3. The life-expectancy in units of t_{rh} for multi-mass models with $\mu \equiv m_{max}/m_{min}=7$. Different lines indicate different slopes for the mass function, which is assumed to be power-law: $N(m)dm = Cm^{-(1+x)}$, $m_{min} < m < m_{max}$. Note that the life-expectancy becomes as small as $6t_{rh}$ which is nearly a factor of 4 shorter than the single component case (data from Lee & Goodman 1995).

during next Hubble time if we assume that the life-expectancy is 22.5 t_{rh}. These models assumed single mass component.

If the cluster has the mass function, the low mass components tend to have higher velocities than average. The evaporation rate correspondingly becomes larger for multi-mass clusters than single component clusters. Lee & Goodman (1995) found that the evaporation rate depends on the shape of mass function including the ratio between low and high ends of the mass function. In Fig. 4 we have shown the life-expectancy of the multi-mass models with different mass functions. The life-expectancy becomes as short as $6t_{rh}$, implying that about 80 % of globular cluster population will be completely evaporated in the next Hubble time. This means that there should have been a significant loss of globular clusters during the lifetime of the Galaxy.

3.2. Tidal Shocks

The tidal field varies with time if the cluster is moving on a non-circular orbit or the Galactic potential is not spherically symmetric. If the time scale for the variation of tidal field is much shorter than the orbital time scale, the stars will

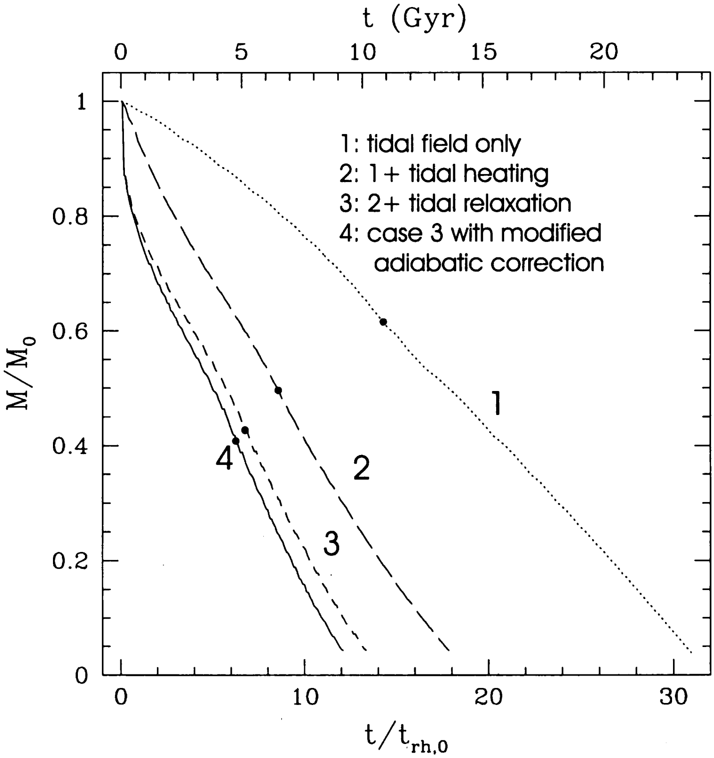

Figure 4. An example of the evolution of mass of a single-component cluster under various assumptions: (1) steady tidal field only, (2) tidal field and shock heating, (3) tidal field, shock heating and shock relaxation, and (4) same as (3) except for the modified adiabatic correction by Weinberg (1994).

be accelerated significantly by the time varying tidal force. For example, stars will experience the vertical acceleration when a cluster passes through the thin disk. Similar effect appears when a cluster approach the Galactic bulge on a very elongated orbit.

Kundić & Ostriker (1996) found that the tidal shock not only increases the stellar kinetic energy but also increases the dispersion of stellar energies. This called 'tidal relaxation' because it is similar to what the two-body relaxation does to the cluster. The shock heating enhances the evaporation rate (which in turn accelerates the evolution), and the shock relaxation accelerates the dynamical evolution (which in turn accelerates the evaporation). Weinberg (1994) revised the adiabatic correction term for stars with orbital period shorter than the shock time scale. Compared to formulation by Spitzer (1987 §5.2), the new study has revealed deeper penetration of shock effect to central parts of the cluster.

Gnedin, Lee, & Ostriker (2000) has carried out extensive Fokker-Planck calculations by taking into account the shock heating, relaxation as well as revised adiabatic correction. The cluster's lifetime is further reduced by the presence of shock, over the simple estimates based on steady tidal field approximation (see Fig. 5). The shock is most important in the early phase of the evolution. If the shock acts efficiently, it truncates the outer parts rather quickly and the relative importance diminishes with time.

4. Effects of Rotation

Most of the dynamical modelings are done for the non-rotating clusters. The rotation has been detected only for a very small number of globular clusters (M13, M15, ω Cen, 47 Tuc, and NGC 6397, e.g., Gebhardt et al. 1995), but small deviation of cluster shapes from circular symmetry may indicate the presence of rotation in many other clusters.

The initial clusters are likely to have significant amount of rotation. Unless the initial rotation does not exceed the instability limit of $-T_{rot}/W = 0.14$ (Ostriker & Peebles 1973), the clusters will follow similar evolutionary path to the non-rotating ones. The dynamical evolution of rotating clusters has been studied only recently by Einsel & Spurzem (1999). Although only very simplified models have been studied until now, the results have interesting implications on the cluster evolution. Similar to the gravothermal instability due to negative specific heat, the rotating clusters have gravo-gyro instability due to negative specific angular momentum. The stellar system rotates faster by transporting angular momentum outward. Since the total angular momentum must be conserved, the cluster core has to collapse. Thus rotating clusters undergo core-collapse in shorter time scale than non-rotating clusters.

The overall evolution of the cluster is further accelerated because the stellar evaporation is also enhanced. The stars with high angular momentum diffuse outward faster than low angular momentum components, and they contribute to the evaporation process significantly. The enhanced mass loss truncates the outer parts of the cluster at a faster rate, and the relaxation time scale becomes smaller, making the life-expectancy of the cluster shorter.

Kim et al. (2001) extended the dynamical modeling of rotating clusters using Fokker-Planck equation to post-collapse phase to follow the evolution until complete disruption. Non-rotating cluster with initially King model with $W_0 = 6$ disrupts completely at 23 $t_{rh,i}$ where $t_{rh,i}$ is the initial half-mass relaxation time, but similar model with $T_{rot}/W = -0.10$ is found to be disrupted completely in about 10 $t_{rh,i}$. Therefore, a moderate amount of initial rotation plays important role in accelerating the evolution including the disruption. The importance of the rotation is illustrated in Fig. 5, which shows the behavior of ξ_e as a function of time for a non-rotating cluster and cluster that initially rotates with $-T_{rot}/W = 0.10$. The rotating models have larger value of ξ_e.

The rotation energy decays rather rapidly. For example, only about 10 % of the initial rotational energy is left at the time of core collapse for the rotating model mentioned above. However, the evaporation rate is still larger than that of non-rotating model by almost a factor of ~ 2 during the late phase of evolution. This may be due to the angular momentum redistribution. The location of the peak angular momentum moves outward where the mass ejection becomes important. Even though the present day clusters may have very small amount of rotation, the dynamical effect may could be still significant.

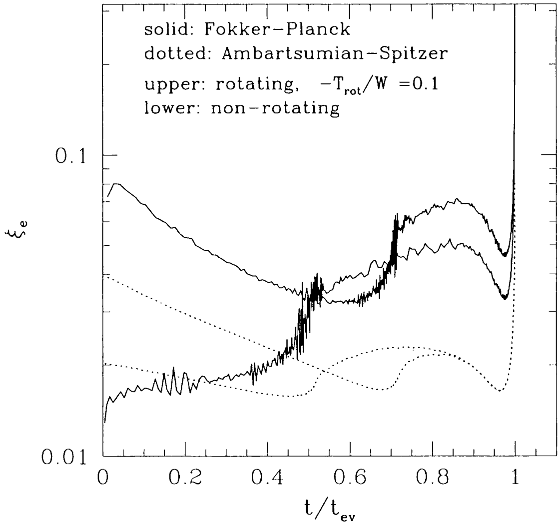

Figure 5. Evaporation rates for rotating and non-rotating models. Also shown as dotted lines are the evaporation rates computed by eq. (5) using the r_h/r_t of the model clusters.

As we have mentioned in §3, the mass spectrum alone accelerates the evolution significantly. The rotating models have been explored for mostly single component models. Dynamical modeling for clusters with mass spectrum is very valuable. Lee (2001) has reported the acceleration of core-collapse of two-component models with rotation over the corresponding model without rotation. Thus the rotating models with mass spectrum is likely to evaporate much faster than non-rotating models.

5. Implications

We have seen that the life-expectancy in units of half-mass relaxation can be much shorter than the earlier estimates based on simple models. The presence of the mass function could cause acceleration of about a factor of 3. The tidal shocks and rotation could further reduce the lifetime of the clusters. The life-expectancy could be as small as only a few t_{rh}, implying that most of Galactic globular clusters will be destroyed in next Hubble time. Such a short lifetime also means that the current population of globular clusters could have been seriously affected by the evaporation and evolution processes.

Fig. 1 shows that there are very small number of clusters with $t_{rh} < 10^8$ years. This can be easily understood because most of 'small' clusters must have been destroyed already. The remaining clusters with relatively short t_{rh} are probably those in process of disruption. The large clusters with long t_{rh} should have been less affected by the evaporation, and they may possess the memory of the initial conditions. Since the less massive clusters tend to have shorter relaxation time scales, the evaporation should have acted to destroy the low mass clusters preferentially. More detailed treatments of the evolution of cluster systems and the cluster luminosity functions can be found in these proceedings by M. Fall for our Galaxy and E. Vesperini for Elliptical galaxies.

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Discussion

C. Grillmair: You say tidal shocking doesn't happen in elliptical galaxies, but aren't bulges identical to ellipticals - both structurally and dynamically?

H. M. Lee: At least there is no disk shock in elliptical galaxies. Bulge shock should depend on the shape of the gravitational potential toward the center of galaxies.