Constraining white-dwarf kicks in globular clusters: III. Cluster Heating

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ABSTRACT
Recent observations of white dwarfs in globular clusters indicate that these stars may get a velocity kick during their time as giants. This velocity kick could originate naturally if the mass loss while on the asymptotic giant branch is slightly asymmetric. The kicks may be large enough to dramatically change the radial distribution of young white dwarfs, giving them larger energies than other stars in the cluster. As these energetic white dwarfs travel through the cluster they can impart their excess energy on the other stars in the cluster. This new heat source for globular clusters is expected to be largest during the clusters’ youth.

Key words: white dwarfs — stars: AGB and post-AGB — globular clusters: general — stars: mass loss — stars: winds, outflows

1 INTRODUCTION

Spruit (1998) proposed that white dwarfs can acquire their observed rotation rates from mild kicks generated by asymmetric and off-centered winds toward the end of their time on the asymptotic giant branch (AGB) (Vassiliadis & Wood 1993). Fellhauer et al. (2003) invoked these mild kicks to explain a putative dearth of white dwarfs in open clusters (e.g. Weidemann 1977; Kalirai et al. 2001). Davis et al. (2008) observed a possible signature of white-dwarf kicks in NGC 6397, and Calamida et al. (2007) found similar but weaker hints in Omega Centauri. Davis et al. (2008) found that young white dwarfs are less centrally concentrated than either their progenitors near the top of the main sequence or older white dwarfs whose velocity distribution has had a chance to relax.

Early in the life of a cluster mass loss due to stellar evolution competes with the loss of stars due to evaporation from the cluster (Spitzer 1987). Without a kick young white dwarfs would have a velocity distribution nearly equal to that of their more massive progenitors on the main sequence. In this case the kinetic energy of these white dwarfs is much less than equipartition; therefore, as their velocity distribution relaxes they cool the rest of the cluster. If on the other hand white dwarfs receive a substantial kick at birth as observations indicate (Davis et al. 2008), young white dwarfs may heat the rest of the stars in the cluster. This letter will examine how white dwarf kicks affect the energy balance within a globular cluster.

2 CALCULATIONS

Clusters of stars can typically be modelled with a lowered isothermal profile (or King model) (Michie 1963; King 1966; Binney & Tremaine 1987).

\[
f = \frac{dN}{d^3xdp} = \begin{cases} \rho_i(2\pi\sigma_i^2)^{-3/2}(\epsilon/\sigma_i^2 - 1) & \text{if } \epsilon > 0 \\ 0 & \text{if } \epsilon \leq 0 \end{cases}
\]

where \( \epsilon = \Psi - \frac{1}{2}v^2 \) and \( \Psi \) is the gravitational potential. Because the distribution function depends only on constants of the motion (the energy), it is constant in time as well.

With time the kinetic energy within the cluster approaches equipartition between the various stars such that \( m_i\sigma_i^2 = m_j\sigma_j^2 \) (Spitzer 1987). The progenitors of young white dwarfs will be the most massive main-sequence stars in a cluster at the time, so they will typically have \( \sigma_{TO} < \sigma_{\text{cluster}} \), where \( \sigma_{\text{cluster}} \) is the mean velocity dispersion of the cluster. As these stars evolve they lose mass. During a globular cluster’s youth, this stellar mass loss dominates the mass loss from...
the cluster; later the relaxation of the stellar velocity distribution to a Maxwellian and the subsequent evaporation of stars from the cluster dominates.

2.1 Kicks

At middle age the mass of white dwarfs that remain in the cluster may exceed a third of the total mass of the cluster; consequently, if white dwarfs receive a kick comparable to the velocity dispersion of the cluster [Davis et al. 2008; Heyl 2007a, 2008], the total kinetic energy of the kicks may approach 10-20% of the binding energy of the cluster as shown in Fig. 1.

Specifically, Heyl (2008) found that an initial distribution of white-dwarf progenitors with $\sigma_{\text{TO}} = 0.5\sigma$ and a typical kick velocity of $v = 1.84\sigma_{\text{TO}}$ could explain the observations (Davis et al. 2008). Essentially, young white dwarfs receive a kick of the same order as the velocity dispersion of the cluster. Furthermore, unlike neutron stars whose kicks nearly always cause them to leave the cluster, most of the young white dwarfs remain in the cluster to heat it up (only about two percent escape within a crossing time).

These results provide an estimate of the total power in white-dwarf kicks,

$$\frac{c_{\text{kick}}\tau}{M^{\sigma^2}} \approx \frac{\zeta}{2} \left[ \frac{\ln N}{\ln \tau} \right]^{-1} \left\{ \frac{0.38M_{\odot}}{m_{\text{TO}}} + 0.15m_{\text{TO}} \right\} 0.38M_{\odot} + 0.15m_{\text{TO}}$$

where $dN/dm$ is the number of stars per unit mass in the cluster (the mass function), $M$ is the total mass of stars in the cluster, $\bar{m}$ is the mean mass of stars in the cluster, $\tau(m)$ is the duration of the main sequence for a star in the cluster, $\tau = \tau(m_{\text{TO}})$ (the age of the cluster), and $\zeta = (v_{\text{kick}}/\sigma)^2 \approx 0.85$. Iben & Renzini (1984) give the initial-final mass relation in the numerator of the rightmost expression.

Richer et al. (2007) estimate the current mass function for a region near the half-light radius of NGC 6397 to be

$$\frac{dN}{dm} = A m^{-\alpha}, \frac{d\ln N}{dm} = 1 - \alpha$$

where the slope of the mass function today is given by $\alpha = 0.13$ and $m_{\text{TO}} \approx 0.8 M_{\odot}$ ($\tau_0 \approx 12$ Gyr is the current age of the cluster) and $\frac{d\ln \tau}{d\ln m} \approx -3.75$ (Straniero & Chieffi 1991) for a cluster of the age and metallicity of NGC 6397.

Integrating Eq. (3) over the masses of the stars in the cluster gives the mean mass of a star in the cluster (assuming $\alpha < 1$ and $m_{\text{TO}} \gg m_{\text{min}}$, the minimum mass of a star),

$$\bar{m} = \frac{1 - \alpha}{2 - \alpha} m_{\text{TO}} \approx 0.37 M_{\odot}$$

so

$$\frac{c_{\text{kick}}\tau}{M^{\sigma^2}} \approx \frac{\zeta}{2} \left[ \frac{\ln N}{\ln \tau} \right]^{-1} \left\{ \frac{0.38M_{\odot}}{m_{\text{TO}}} + 0.15 \right\} \approx 0.13$$

for the current observations of NGC 6397.

2.2 Binaries

In a binary a fraction of the energy of the kick is used to change the orbital parameters [Heyl 2007b]. If the masses of the primary and secondary are similar due to dynamical biasing (e.g. McDonald & Clark 1993), the total kick to the binary is about 70-80% of the kick imparted to a single star, so given that the fraction of binaries is small in the cluster as a whole and the correction to the kick for binaries is also small, the energetics of changing the orbits of binaries will be ignored.

On the other hand, the binaries provide an important energy source for the cluster (in fact the only energy source if one excludes the kicks). The interaction of a binary with a single star can result in an exchange or the dissolution of the binary, but generally it results in an increase in the kinetic energy of final single star (like a kick) at the expense of the increased binding energy of the binary. The velocity increment of the primary and secondary are similar due to dynamical binary (Heyl 2007b). If the masses of the primary and secondary are similar due to dynamical biasing (e.g. McDonald & Clark 1993), the total kick to the binary is about 70-80% of the kick imparted to a single star, so given that the fraction of binaries is small in the cluster as a whole and the correction to the kick for binaries is also small, the energetics of changing the orbits of binaries will be ignored.

$$\epsilon_{\text{binary}} = \frac{0.92}{\ln \lambda} \frac{m_{\text{TO}}^2}{2}$$

per relaxation time.
The result in general is turnoff. In this regime, the derivation of Eq. (5) is not valid.

\[ \alpha > \text{low mass stars are lost from the cluster; therefore, it is natural} \]

function becomes more and more top heavy with time as the function of the cluster in the past are needed. First, the mass course proportional to the number density of the binaries and (Davis et al. 2008). The power produced by the binaries is of suitable for a typical region of the cluster outside the core (Davis et al. 2008). The power produced by the binaries is of course proportional to the number density of the binaries and inversely proportional to the velocity dispersion that sets the cross-section per binary.

Comparing Eq. (5) to (6) shows that the power sources are similar for the region of NGC 6397 observed by Richer et al. (2007).

### 2.3 Evolution

To look at the relative importance of binaries and kicks early in the life of the cluster, some assumptions about the mass function of the cluster in the past are needed. First, the mass function becomes more and more top heavy with time as the low mass stars are lost from the cluster; therefore, it is natural to assume that \( \alpha > 1 \) in the past and possibly \( \alpha > 2 \) near the turnoff. In this regime, the derivation of Eq. (5) is not valid. The result in general is

\[ \frac{\partial \text{binary}}{\partial M \sigma^2} \approx 0.22 \left( \frac{\bar{m}}{0.37 M_\odot} \right)^2 \left( \frac{n_b}{1 \text{pc}^{-3}} \right)^{1/2} \left( \frac{1 \text{ kms}^{-1}}{\sigma} \right)^3 \frac{\tau}{12 \text{ Gyr}} \]

where the binary fraction is taken to be around a few percent suitable for a typical region of the cluster outside the core (Davis et al. 2008). The power produced by the binaries is of course proportional to the number density of the binaries and inversely proportional to the velocity dispersion that sets the cross-section per binary.

### 3 CONCLUSIONS

Over the life of a globular cluster such as NGC 6397, white-dwarf kicks may provide a significant energy source. In a region outside the core today, kicks provide about one-half of energy input from binaries. Early in the life of the globular cluster when stars of several solar masses are leaving the main sequence, the white-dwarf kicks may actually dominate over binaries as an energy source; consequently, young globular clusters such as those in starburst galaxies may actually differ structurally from their older peers. Drukier et al. (1992) found that an energy source beyond binaries was required to avoid core collapse in M71; perhaps white dwarf kicks could explain this discrepancy. Regardless, these calculations indicate that further study of the effects of white-dwarf kicks on the dynamics of globular clusters is warranted.

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