Constraining white dwarf kicks in globular clusters – IV. Retarding core collapse

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ABSTRACT

Observations of white dwarfs in the globular clusters NGC 6397 and Omega Centauri indicate that these stars may get a velocity kick during their time as giants. If the mass loss while on the asymptotic giant branch is slightly asymmetric, the resulting white dwarf could be born with such a velocity kick. These energetic white dwarfs will impart their excess energy on other stars as they travel through the cluster. A Monte Carlo simulation of the white dwarfs kicks combined with estimate of the phase-space diffusion of the white dwarfs reveals that as the white dwarfs equilibrate, they lose most of their energy in the central region of the cluster. They could possibly augment the effect of binaries, delaying core collapse or increasing the size of globular cluster cores.

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

1 INTRODUCTION

Several phenomena give circumstantial evidence that white dwarfs may receive a velocity boost (or kick) at birth. The observed rotation rates of white dwarfs could result from mild kicks (≈5 km s⁻¹) generated by asymmetric and off-centred winds towards the end of their time on the asymptotic giant branch (Spruit 1998). It is unclear at present how white dwarfs could actually obtain such a kick; however, given the evidence it is natural to explore the consequences of white dwarf kicks. Mild kicks may explain the possible lack of white dwarfs in open clusters (Weidemann 1977; Kalirai et al. 2001; Fellhauer et al. 2003). Most directly, Davis et al. (2008) observed that the young white dwarfs in NGC 6397 had a more expansive radial distribution than either their progenitors or the older white dwarfs. Calamida et al. (2008) found similar but weaker hints in Omega Centauri.

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 may indicate (Davis et al. 2008), young white dwarfs may heat the rest of the stars in the cluster. Neutron stars that form in the cluster may get a very large velocity kick as well; however, two factors make their contribution less important. The first is that neutron stars are relatively rare, and the second is that neutron stars travel so quickly that most escape the cluster before imparting much energy to the rest of the stars (Pfahl, Rappaport & Podsiadlowski 2002). In contrast with the neutron star result, Heyl (2007) found that most of the kicked white dwarfs remain in the cluster. Heyl (2008b) found that the energy input from the white dwarf kicks around the half-light radius is about half that from binaries at the present day and dominated in the first half of the life of the cluster. This Letter examines where in the cluster white dwarfs dump their excess energy from the kicks.

2 CALCULATIONS

A globular cluster is often modelled with a lowered isothermal profile (or the King model) (Michie 1963; King 1966; Binney & Tremaine 1987),

$$f = \frac{dN}{d^3x} = \begin{cases} \rho_1(2\pi\sigma^2)^{-3/2}(e^{\epsilon/\sigma^2} - 1) & \text{if } \epsilon > 0 \\ 0 & \text{if } \epsilon \leq 0 \end{cases}$$

(1)

where $\epsilon = \Psi - \frac{1}{2}v^2$ and $\Psi$ is the gravitational potential, $\sigma$ is the velocity dispersion of the cluster stars and $\rho_1$ is a characteristic number density. The distribution function depends only on the energy, $-\epsilon$, a constant of the motion; therefore, it is constant in time as well.

As the stars interact with each other, their kinetic energy approaches equipartition such that $m_i\sigma^2 = m_j\sigma^2$ for masses $m_i$ not equal to $m_j$ (Spitzer 1987). The most massive main-sequence stars in the cluster are the progenitors of the white dwarfs so they will typically have $\sigma_{\text{TO}} < \sigma_{\text{cluster}}$, where $\sigma_{\text{cluster}}$ is the mean velocity dispersion of the cluster. To model the cluster, the turn-off stars and the white dwarf kicks, we use the best-fitting model from Heyl (2008a). Specifically, we take $\sigma_{\text{cluster}} = 1$ for the cluster stars, $\sigma_{\text{TO}} = 0.5$ for

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the turn-off stars, the central potential to \( \Psi(0) = 6 \) and the mass of the white dwarfs to be 1.5 times the mass of the typical cluster member. We model the kick as a Gaussian in velocity with a dispersion of \( \sigma_k = 0.92 \). This means that the kick is similar to the velocity dispersion of the cluster. Although this is reasonable for clusters such as NGC 6397 with \( \sigma_{\text{cluster}} \approx 5 \text{ km s}^{-1} \), it is more difficult to achieve for clusters such as 47 Tuc and Omega Centauri with \( \sigma_{\text{cluster}} > 20 \text{ km s}^{-1} \).

2.1 Relaxation from a kick

The rate that a particular star gains energy as it passes through the cluster is given by (Binney & Tremaine 1987)

\[
D(\Delta E) = 16 \pi^2 G^2 m a^2 \ln \Lambda 
\times \left[ \int_0^\infty v_a f_a(v_a) \, dv_a - \frac{m}{m_a} \int_0^\infty v_f f_f(v_f) \, dv_f \right],
\]

(2)

where \( m \) and \( v \) are the mass and velocity of the star, \( m_a \) and \( v_a \) are the mass and velocity of the other cluster members, \( \ln \Lambda \) is the Coulomb logarithm and \( f_f(v_f) \) is the phase-space density. The first term is the energy that a particular star gains from encounters with faster moving stars. For a King model, it is

\[
\int_0^\infty v_a f_a(v_a) \, dv_a = \rho_1 (2\pi \sigma^2)^{-3/2} \left[ \sigma^2 \left( \frac{\epsilon}{\sigma^2} - 1 \right) - \epsilon \right],
\]

(3)

where \( \epsilon = \Psi - \frac{1}{2} v^2 \) for the particular star, \( \sigma \) is the dispersion for the cluster as a whole. The second term is the energy that the star loses from encounters with slower moving stars,

\[
\frac{m}{m_a} \int_0^\infty v f_f(v_f) \, dv_f = \rho_1 \frac{m}{m_a} (2\pi \sigma^2)^{-3/2} 
\times \left[ \sqrt{\frac{\pi}{2}} \rho_3 \epsilon^{1/2} \mathrm{erf} \left( \frac{v}{\sqrt{2}\sigma} \right) - \left( \frac{v}{\sqrt{2}\sigma} \right)^2 \right].
\]

(4)

Because we know the position and velocity of each of the white dwarfs in the simulation, it is straightforward to calculate the energy loss and gain from these equations.

3 RESULTS

To explore the distribution of the energy from the kicks to the rest of the cluster members, we created a Monte Carlo realization of 100 000 newly born white dwarfs both with and without kicks (see Heyl 2007 for further details). For each realization, the white dwarfs are sorted by radius and the total energy deposited into the cluster stars is summed by radius resulting in the cumulative distribution of power depicted in Fig. 1. The upper curve traces the result for white dwarfs with kicks. The white dwarfs are travelling too fast for their mass so they deposit the excess energy into the cluster. The lower curve shows the result for white dwarfs without a kick – here, the white dwarfs are born with the velocity dispersion of their progenitors who are significantly more massive than themselves; therefore, the white dwarfs sap energy from the cluster stars as they heat up. The exact locations of the two curves depend on the assumed value of the ratio between the white dwarf mass and that of the cluster stars (the figure gives the result for 1.5; as the ratio increases both curves move up).

The distance between the cumulative energy deposition rates is the net effect of the white dwarf kicks. This net effect is rather robust because regardless of the assumed ratio between the white dwarf masses and the rest of the stars, white dwarfs are typically created near the centre of the cluster because their progenitors are massive. Furthermore, even with a kick, the white dwarfs will return to the radius of their birth until their orbits relax. At small radius, the speed of the white dwarf is largest and so is the density of the rest of the stars; therefore, at small radii the white dwarfs lose most of their excess energy. Fig. 2 demonstrates this fact. For the assumed
model, about 90 per cent of the energy of the white dwarf kicks is deposited within the core radius, and the white dwarfs actually remove energy from the outer regions of the cluster.

During the collapse of a globular cluster core, two-body interactions result in the transfer of energy from the dense central region of the cluster to the outer regions; the core shrinks and the envelope of the cluster expands. The white dwarfs deposit their energy in precisely the opposite way, supplying energy to the core at the expense of the outer regions; therefore, white dwarf kicks may retard core collapse or increase the size of cluster cores.

4 CONCLUSIONS

After a globular cluster forms, the negative heat capacity of the cluster’s self-gravity inexorably draws the cluster towards core collapse, unless another energy source is present. The central region or core will collapse to very large densities within a few relaxation times while the outer regions expand, and stars evaporate from the system. The standard energy source that is invoked to retard the collapse is binaries (e.g. Goodman & Hut 1989). After the core has already reached high densities, binaries necessarily form through tidal and three-body interactions preventing the core from forming a singularity (e.g. Hurley, Aarseth & Shara 2007).

\(N\)-body models with a primordial binary fraction of a few per cent can avoid the complete collapse of the core but the core does contract dramatically over the age of the cluster. If all old globular clusters had compact cores, this scenario would not pose a problem; however, several old, presumably relaxed clusters have large cores without an obvious energy source to explain the observed state (De Marchi, Paresce & Pulone 2007). Several possibilities have been invoked to explain this: a very high initial binary fraction approaching unity [however, Heggie, Trenti & Hut (2006) found that the effect of binaries saturates at about 10 per cent], an intermediate-mass black hole (e.g. Trenti et al. 2007) or a black hole binary (Mackey et al. 2008) at the centre of the cluster. As for the white dwarf kicks, the evidence for these possibilities is circumstantial.

There are several lines of evidence that white dwarfs get a mild velocity kick at birth. Furthermore, the total power deposited into the cluster by the white dwarf kicks may be comparable or larger than binaries (Heyl 2008b: although these calculations should be generalized to the core for completeness) and the energy is deposited in such a way that it directly opposes core collapse, so these kicks may provide an explanation for the fraction of globular cluster that have large cores today. We do however see a variety of core sizes including collapsed cores, so the combination of white dwarf kicks and binaries may not always be effective or perhaps the clusters are at various stages of their evolution. Explaining these differences in the white dwarf kick model is difficult as one would expect that all globular clusters should exhibit the effects of the kicks. On the other hand, the black hole models can easily explain these differences; some clusters could have a large black hole at their centres and others lack one.

The Monte Carlo model present here is illustrative, but rather rudimentary. Two obvious avenues for further study are the inclusion of white dwarf kicks in \(N\)-body models (e.g. Hurley et al. 2007) and Monte Carlo simulations (e.g. Heggie & Giersz 2008) – either of these avenues would allow us to include both binaries and white dwarf kicks together consistently to get a more robust estimate of their relative importance. Furthermore, one could use a more realistic multimass King model for the background stars in the cluster to perform an analysis similar to that presented here. One would expect that results could differ quantitatively but the qualitative results the white dwarfs kicks dump energy in the central regions of the cluster and that this energy may be comparable or larger than that from binaries are robust.

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REFERENCES

Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Calamida A. et al., 2008, Mem. Soc. Astron. Italiana, 79, 347
Davis D. S., Richer H. B., King I. R., Anderson J., Coffey J., Fahlman G. G., Hurley J., Kalirai J. S., 2008, MNRAS, 383, L20
De Marchi G., Paresce F., Pulone L., 2007, ApJ, 656, L65
Fellhauer M., Lin D. N. C., Bolte M., Aarseth S. J., Williams K. A., 2003, ApJ, 595, L53
Goodman J., Hut P., 1989, Nat, 339, 40
Heggie D. C., Giersz M., 2008, MNRAS, 389, 1858
Heggie D. C., Trenti M., Hut P., 2006, MNRAS, 368, 677
Heyl J. S., 2007, MNRAS, 381, L70
Heyl J. S., 2008a, MNRAS, 385, 231
Heyl J. S., 2008b, MNRAS, 390, 622
Hurley J. R., Aarseth S. J., Shara M. M., 2007, ApJ, 665, 707
Kalirai J. S., Ventura P., Richer H. B., Fahlman G. G., Durrell P. R., D’Antona F., Marconi G., 2001, AJ, 122, 3239
King I. R., 1966, AJ, 71, 64
Mackey A. D., Wilkinson M. I., Davies M. B., Gilmore G. F., 2008, MNRAS, 386, 65
Michie R. W., 1963, MNRAS, 125, 127
Pfahl E., Rappaport S., Podsiadlowski P., 2002, ApJ, 573, 283
Spitzer L., 1987, Dynamical Evolution of Globular Clusters. Princeton Series in Astrophysics, Princeton, NJ
Spruit H. C., 1998, A&A, 333, 603
Trenti M., Ardi E., Mineshige S., Hut P., 2007, MNRAS, 374, 857
Weidemann V., 1977, A&A, 59, 411

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