ORBITAL ECCENTRICITY OF BINARY RADIO PULSARS IN GLOBULAR CLUSTERS AND THE INTERACTION BETWEEN STARS

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ABSTRACT

We analyze the observed distribution of the orbital eccentricity and period of binary radio pulsars in globular clusters using computational tools to simulate binary–single-star interactions. Globular clusters have different groups of pulsars arising from separate interaction scenarios. Intermediate eccentricities of cluster pulsars can mostly be accounted for by fly-bys although locally lower stellar densities at pulsar positions may alter the situation. Very high eccentricities are likely to be the result of exchanges and/or mergers of single stars with the binary companion of the pulsar.

Key words: globular clusters: general – pulsars: general

1. INTRODUCTION

Sustained high-sensitivity searches of globular clusters (GCs) for radio pulsars with improved pulsar-search algorithms have yielded 140 pulsars so far in 26 GCs1 (Camilo & Rasio 2005 and references therein). Radio pulsars can be timed more easily and accurately by ground-based telescopes over well-separated epochs, as the underlying neutron stars (NSs) are less prone to noise from episodically varying accretion torques (as for X-ray pulsars). These lead to easier measurement of orbital parameters. Binary systems can provide an important source of energy for GCs, since the binding energies of a few, very close binaries can approach that of a moderately massive host GC (Hut et al. 2003) and therefore can have dynamical effects on the cluster’s evolution. On the other hand, the observable parameters of the neutron stars and their binary companions in the clusters, such as spin, orbital period and eccentricity, projected radial position in the cluster, companion mass, and their distributions provide a valuable test bed to examine the theoretical scenarios of formation and evolution of recycled pulsars. These parameters can provide a tracer of the past history of dynamical interactions of the binary NSs in individual GCs. We discuss below the distribution of orbital eccentricities and periods of GC pulsars in light of interaction of stars with binaries already formed or in the process of formation inside GCs, due to the high stellar density in their cores. The observed distributions are examined with analytical results and our numerical experiments of scattering of stars simulated by direct N-body integration tools.

2. OBSERVED DATA

Although there are a number of low-mass X-ray binaries (LMXBs) in the GCs, their orbital period and eccentricity information is poorly known compared to that for radio pulsars; moreover the initial eccentricity of formation is quickly quenched due to tidal coupling with the Roche lobe-filling companion. Hence we concentrate entirely on binary radio pulsars whose companions are usually smaller than their Roche lobes, and less well coupled tidally. Of the 140 radio pulsars in the GCs, 74 are binaries (a large fraction of which are millisecond pulsars), 59 are isolated and seven others have no published timing/orbital solutions. Orbital parameters are not well determined for one binary (PSR J2140–2310B in M30), only the lower limit of $P_{\text{orb}}$ and $e$ are known as $P_{\text{orb}} > 0.8$ days and $e > 0.52$, and thus it is excluded from the present study. In Figure 1, we plot $e$ versus $P_{\text{orb}}$ for 73 binaries in GCs with known orbital solutions. Logarithmic scales in both eccentricity and orbital periods are chosen, as the enormous range of both variables and the regions occupied by observed pulsars are less obvious in linear scales. Observed binary radio pulsars in GCs can be categorized into three groups: (I) 21 pulsars with large eccentricity ($1 > e \geq 0.01$); (II) 20 pulsars with moderate eccentricity ($0.01 > e \geq 2 \times 10^{-6}$); (III) 32 pulsars with small eccentricity ($e \sim 0$). Using the “R” statistical package2 $k$-means test, we show that these groups are distinct at a statistically significant level.3

In the database, several pulsars’ orbital eccentricities have been listed as zero, but we assign them an arbitrarily small value of $e = 3 \times 10^{-7}$. Note that the smallest eccentricity measurable is determined by how well the orbit of the binary is sampled and the overall timing accuracy achieved for radio pulse arrivals (Phinney 1992). The timing accuracy translates into an upper limit on the smallness of the eccentricity. This is displayed as the brown solid line in the lower left corner of Figure 1 following the functional relation: $e_{\text{min}} = (\delta t)/(a \sin i/c) = 4\pi^2 c \delta t / [\sin i (G (m_p + m_c)^{1/2})^{3/2} P_{\text{orb}}^{2/5}]$. Here $i$ is the inclination angle of the binary, $m_p$ is the pulsar mass, $m_c$ is the companion mass, and $\delta t$ is the timing accuracy. We take $m_p = 1.4 M_\odot$, $m_c = 0.35 M_\odot$, $i = 60^\circ$, $\delta t = 1 \mu$sec for the “limit of timing sensitivity” line.

Observational selection effects may be influencing the distribution of GC pulsars seen in Figure 1 (Camilo & Rasio 2005), the most important selection effect operates toward the left of the diagram: it is more difficult to detect pulsars with larger DM and/or shorter spin periods, especially millisecond pulsars in short orbital periods and highly eccentric binaries. Another important selection effect is due to distance, since only the brightest pulsars can be observed at large distance.

1 Information on these pulsars are found on P. Freire’s webpage updated August 2008, http://www.naic.edu/~pfreire/GCpsr.html, compiled from radio timing observations by many groups.

2 www.R-project.org.

3 Here we assign random eccentricities of the group III pulsars in such a way that they remain below the “limit of timing sensitivity” line. We obtained three clusters of sizes 18 (medium eccentricity), 34 (low eccentricity), 21 (high eccentricity) with the sum of squares from points to the assigned cluster centers of 10.2, 13.2, and 19.9 respectively whereas the squares of inter-cluster distances are: $d^2_{18} = 7.6$, $d^2_{34} = 30.5$, $d^2_{21} = 10.8$. 

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values of their host GCs. A pulsar is located on the upper left half of the corresponding
figure. Peters & Mathews (1963). Pulsars with projected positions inside the cluster core are marked with +, those outside the cluster core with × and the pulsars with unknown positions with ◻ (see Footnote 1 and S. Ransom’s webpage at www.cv.nrao.edu/~sransom/). The color scheme for $t_{gr}$ and $t_{fly}$ contours are shown on the right. The solid red curve for $t_{fly} = 10^{10}$ yr for $v_{10}/n_4 = 0.0024$ (Ter 5) is outside the range plotted. Individual pulsars are marked with the same colors as $v_{10}/n_4$ values of their host GCs. A pulsar is located on the upper left half of the corresponding $t_{fly}$ line (e.g., the pulsar shown by a black diamond in the middle of the figure) is most likely a primordial binary unless it is in the range of eccentricities typical for exchanges and merger. Six high-eccentricity ($e > 0.1$) binaries in Ter 5 are marked with their names. Different groups of GCs according to the increasing values of $v_{10}/n_4$ are: (1) Ter 5 (red); (2) NGC 6440, M30, NGC 1851, M62, M15 (green); (3) NGC 6441, NGC 6544, 47Tuc (blue); (4) M28, NGC 6342, NGC 6752, NGC 6760, NGC 6539, NGC6397 (magenta); (5) M4, M5, M3, M22 (cyan); (6) M71, M13, NGC 6749, M53 (black).

3. TWO- AND THREE-BODY STELLAR INTERACTIONS IN GLOBULAR CLUSTERS

The presence of a large number of LMXBs in GCs compared to the galactic field had led to the suggestion (Fabian et al. 1975) that a binary is formed by tidal capture of a noncompact star by a neutron star in the dense stellar environment of the GC cores. If stable transfer of mass and angular momentum ensued from the companion star, this could lead to recycled pulsars in binaries or as single millisecond pulsars e.g., Alpar et al. (1982). However tidal capture of a neutron star by a low-mass main-sequence star can lead to large energies being deposited in tides. The resultant structural readjustments of the star in response to the dissipation of the modes could be very significant in stars with either convective or radiative damping zones (Ray et al. 1987; McMillan et al. 1987) and the companion star can undergo size “inflation” due to its high tidal luminosity which may be much larger than that induced by nuclear reactions in the core. The efficiency of viscous dissipation and orbit evolution is crucial to the subsequent evolution of the system as viscosity regulates the growth of oscillations and also the extent to which the extended star is bloated and shed. A significant fraction of the encounters lead to binaries that either become unbound as a result of de-excitation or heating from other stars in the vicinity or they are scattered into orbits with large pericenters (compared to the size of the noncompact star) due to angular momentum transfer from other stars (Kochanek 1992). For a recent summary of the formation channels of retained neutron star binaries in GCs obtained via population synthesis, see Ivanova et al. (2008).

If the local binary fraction is substantial, the binary–single-star interaction can exceed the encounter rate between single stars by a large factor (Sigurdsson & Phinney 1993). The existence of a significant population of primordial binaries in GCs (Yan & Mateo 1994; Pryor et al. 1989) indicate that three-body processes have to be accounted for in any dynamical study of binaries involving compact stars. For a literature summary of the constraints on the binary fraction in GCs see Davis et al. (2008).

An encounter between a field star and a binary may lead to a change of state of the latter, e.g., (1) the original binary may undergo a change of eccentricity and orbital period but otherwise remain intact—a “fly-by” interaction; (2) a member of the binary may be exchanged with the incoming field star, forming a new binary—an “exchange” process; (3) two of the stars may collide and merge into a single object, and may or may not remain bound to the third star—a “merger” process; or (4) all three stars become unbound—an “ionization” process.

4. FLY-BY, EXCHANGE- AND MERGER-COLLISION INDUCED ECCENTRICITY

The formation scenario of millisecond pulsars in primordial binaries suggests that their eccentricity should be very small, $\sim 10^{-5}$ (Phinney 1992). But inside GCs, they may acquire eccentricity through interactions with single stars. Rasio & Heggie (1995); Heggie & Rasio (1996) studied the change of orbital eccentricity ($\delta e$) of an initially circular binary following a distant encounter with a third star in a parabolic orbit. They used...
the secular perturbation theory, i.e., averaging over the orbit of the binary for sufficiently large values of the pericenter distance \( r_p \), where the encounter is quasi-adiabatic and used
nonsecular perturbation theory for smaller values of \( r_p \) where the encounter is nonadiabatic. In the first case \( \delta e \) varies as a power law with \( r_p/a \) and in the second case \( \delta e \) varies exponentially with \( r_p/a \) (\( a \) is the semimajor axis of the binary). The power law dominates for \( e \lesssim 0.01 \) and the exponential dominates for \( e \gtrsim 0.01 \). They estimated the cross sections \((\sigma)\) for eccentricity changes and calculated timescales for eccentricity changes as \( t = 1/(\sigma v) \) where \( n \) is the number density of the stars and \( v \) is the velocity of the incoming star. The expressions of the timescales for fly-by are (see Rasio & Heggie 1995):

\[
\begin{align*}
\tau_{\text{fly}} &= 4 \times 10^{11} n_4^{-1} v_{10} P_{\text{orb}}^{-2/3} e^{2/3} \quad \text{for} \quad e \lesssim 0.01 \\
\tau_{\text{fly}} &= 2 \times 10^{11} n_4^{-1} v_{10} P_{\text{orb}}^{-2/3} \left[ -\ln(e/4) \right]^{-2/3} \quad \text{for} \quad e \gtrsim 0.01
\end{align*}
\]

where \( n_4 \) is the number density \((v)\) of single stars in units of \(10^4\) pc\(^{-3}\) and \( v_{10} \) is the velocity dispersion \((v)\) in units of \(10\) km s\(^{-1}\) in GCs; \( P_{\text{orb}} \) is the orbital period in days giving \( \tau_{\text{fly}} \) in years.

The eccentricities of the binary pulsars in GCs are likely to be due to binary single star interactions when the interaction timescale is less than the binary age. We take the maximum age of the binaries in a GC to be the GC ages which are timescale is less than the binary age. We take the maximum age of the initial binary along the top \( x \)-axis and \( P_{\text{orb,fin}} \) along the bottom x-axis. \( P_{\text{orb,fin}} \) is obtained from \( P_{\text{orb,ini}} \) putting \( \Delta = 0 \) in the relation

\[
\delta m = [m_a m_b m_1 (1 - \Delta)]
\]

where \( m_1 \) and \( m_2 \) are masses of the members of the initial binary, \( m_3 \) is the mass of the incoming star, \( m_a \) and \( m_b \) are masses of the members of the final binary, \( \Delta \) is the fractional change of binary binding energy. For exchange, \( m_a = m_1, m_b = m_3; \) for merger, \( m_a = m_1, m_b = m_2 + m_3. \)

It is clear from the scatter plots (Figure 2) that the final binaries will most probably have \( e > 0.1 \) if they undergo either exchange or merger events. Six high-eccentricity \((e > 0.1)\) binaries in Ter 5 are also shown (black in color, symbols same as used in Figure 1) in this plot. All of them may result from exchange interactions with either a normal-mass companion \((\sim 0.40 M_\odot)\) or with a low-mass companion \((\sim 0.16 M_\odot)\). PSR U, X, and Z may even come from exchange with ultra-low-mass companion \((\sim 0.024 M_\odot)\). Note that all the exchange conclusions here are only guidelines, since they are based on stars of a single mass \((0.33 M_\odot)\) exchanging into the systems, and some of the minimum inferred companion masses are quite different from \(0.33 M_\odot\). Mergers with \(0.40 M_\odot\) (initial) companions and incoming \(0.33 M_\odot\) stars are problematic because of the high final companion masses. \( Q \) is the only system for which this might be possible, and that would require a fairly small orbital inclination angle. Similar problems apply to initial companion masses of \(0.16 M_\odot\) for all except \( Q \) and \( U \). Finally, while the mass restriction is not really a problem for any of the lower-mass systems in the ultra-low-mass case, the small orbital periods imply that too long a time would have to pass before a suitable encounter took place.

In Figure 1, there is a cluster of three pulsars with \(0.1 < e < 0.1\) and \( 60 < P_{\text{orb}} < 256 \) d—NGC1851A, M3(D), and Ter 5(E), all with companions of mass in the range \( m_e = 0.21 - 0.35 M_\odot \) assuming \( i = 60^\circ \) (except NGC 1851A which has a \( 1.12 M_\odot \) companion). These are possibly white dwarf (WD) cores of red giant companions that overflowed from the Roche lobe (Webbink et al. 1983). Such binaries would normally have the “relic” eccentricities \( \sim 10^{-4} \) (Phinney 1992). The above binary pulsars with their present mildly high eccentricities, have undergone fly-by encounters with field stars, rather than exchange reactions, which would produce very high eccentricities \( e > 0.1 \). Ter 5 E lies outside the core but even then, the density may have been high enough to allow a strong fly-by interaction. It could also have been ejected out of the high-density core after a strong interaction. In addition, the pulsar B1620–26 (in M4) occupies approximately the same region of the phase space. However, this system is most likely a triplet system with a planet sized third body and their interactions lead to the characteristics of the inner orbit (Thorsett et al. 1999, Ford et al. 2000, Sigurdsson et al. 2003 and references there in). Another set of 3 ms pulsars have \(0.01 < e < 0.1\), \( 2 < P_{\text{orb}} < 10\) d—Ter 5 (W), 47 Tuc (H) and NGC6440 (F). These clusters have low values of \( v_{10}/n_4 \), and so fly-by encounters in these clusters would be efficient and could generate these eccentricities in GCs, even if their progenitor binaries had short orbital periods and had sub-giant companions of the NSs. Alternately, these binaries could also have been formed by fly-by interactions from a presently less abundant longer period \( 2 < P_{\text{orb}} < 10 \) d cluster of “intermediate eccentricity” binaries to the right of the pulsars seen in the middle of Figure 1.

The “intermediate eccentricity” binaries (group II : \(0.01 > e > 2 \times 10^{-5})\), could have been generated by fly-by encounters with low- (or “zero”) eccentricity progenitor pulsars below the

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4 www.ids.ias.edu/~starlab/.
Figure 2. Timescales (denoted by “+”) and final eccentricity distributions (scatter plot of points) with initial and final orbital periods ($\Delta = 0$) for exchange (purple points on the left panel) and merger (green points on the right panel) interactions with different stellar parameters. Each set of panels had 5000 trial densities for each orbital period for the mass combination shown (typically 15,570 total scatterings led to 10,960 fly-bys, 3722 exchanges, 982 two-mergers and six three-mergers for each $P_{\text{orb, in}}$ in set 2). We plot $P_{\text{orb, in}}$ along the top x-axis and $P_{\text{orb, fin}}$ along the bottom x-axis. The left y-axis gives the final eccentricities while the right y-axis gives the timescales of interactions. Vertical orange lines give boundaries of orbital periods where interaction timescales $< 10^{10}$ yr. Six high-eccentricity ($e > 0.1$) binaries in Ter 5 are also shown (colored black, symbols same as used in Figure 1 regarding their positions) in each case.

line of “timing sensitivity limit” (group III pulsars). Some of the shorter $P_{\text{orb}}$ binaries would again be circularized by gravitational radiation (see $t_{\text{gr}}$ contours in Figure 1 calculated using the formalism of Peters & Mathews 1963). The progenitor group III pulsars, themselves occur in regions of favorable fly-by encounters inducing higher eccentricities. These nearly circular binaries have their $P_{\text{orb}}$ in the range of 0.06–4 days among which the tighter binaries cannot be progenitors of exchanges/mergers whenever interaction timescales are greater than $10^{10}$ yr (see Figure 2). The minimum $P_{\text{orb, in}}$ above which they can undergo exchange/merger interactions decreases as $m_2$ decreases. About the origin of the group III pulsars themselves, we
note that Camilo & Rasio (2005) discuss the dynamical formation of ultracompact binaries involving intermediate mass main sequence stars in the early life of the GC. These companions must have been massive enough (beyond the present-day cluster turn-off mass of $0.8 \, M_\odot$) so that the initial mass transfer became dynamically unstable, leading to tight NS–WD binaries through common envelope evolution. Alternately, present-day red giant and NS collisions lead to a prompt disruption of the red giant envelope and the system ends up as eccentric NS–WD binary (Rasio & Shapiro 1991). NS–WD binaries can be circularized to group III by gravitational wave radiation if $P_{\text{orb}} < 0.2$ days (see Figure 1 here and also discussions by Camilo & Rasio 2005).

In conclusion, we find that the presently observed orbital eccentricity and period data of GC binary pulsars are largely consistent with numerical scattering experiments on stellar interaction scenarios of fly-bys, exchanges, and mergers with typical field stars characterized by the central regions of the GCs. The efficiency of fly-by interaction is subject to the local stellar density at the location of the initially circular binaries. Exchange and merger interactions induce the highest range of eccentricities ($1 \gtrsim e \gtrsim 0.1$) and may be operative in different GCs.

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