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A NOVEL MECHANISM FOR CREATING DOUBLE PULSARS

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ABSTRACT

Simulations of encounters between pairs of hard binaries, each containing a neutron star and a main-sequence star, reveal a new formation mechanism for double pulsars in dense cores of globular clusters. In many cases, the two normal stars are disrupted to form a common envelope around the pair of neutron stars, *both* of which will be spun up to become millisecond pulsars. We predict that a new class of pulsars, double millisecond pulsars, will be discovered in the cores of dense globular clusters. The genesis proceeds through a short-lived double-core common envelope phase, with the envelope ejected in a fast wind. It is possible that the progenitor may also undergo a double X-ray binary phase. Any *circular*, short-period *double* pulsar found in the galaxy would necessarily come from disrupted disk clusters, unlike Hulse-Taylor class pulsars or low-mass X-ray binaries which may be ejected from clusters or formed in the galaxy.

Subject headings: globular clusters: general — pulsars: general

1. INTRODUCTION

Of the "exotic" stellar remnants seen in globular clusters (GCs), the hard binary millisecond pulsars (MSPs), as exemplified by PSR 2127+11C (Anderson et al. 1990) in M15, are of particular interest. In these systems the observed pulsar is a short-period, low magnetic field, recycled MSP, and its companion most likely a "vanilla" long-period, high field pulsar which has spun down past the "death line" and is no longer observable as a radio source. The presence of PSR 2127+11C and a number of other binary MSPs in GCs coupled with the anomalous distribution of the MSPs among clusters of different density (Fruchter & Goss 1990; Johnston, Kulkarni, & Goss 1991), strongly supports the theory that primordial binaries are critical in GC evolution (Goodman & Hut 1989). Through mass segregation, binaries concentrate in the cores of clusters, where exchanges and binary-binary interactions harden, eject, and destroy the binaries (Sigurdsson 1991; Hut et al. 1992a; Leonard 1989). As the cluster evolves toward core collapse, a large fraction of the primordial main-sequence binaries undergo exchanges with field neutron stars and many of the binaries interacting in the core may contain a neutron star. It is thought that the MSPs currently observed in GCs (Phinney & Kulkarni 1992) were mostly formed as a consequence of binary interactions, with both binary–single star and binary-binary interactions contributing to the process. In the core, three-body exchange reactions preferably leave neutron stars (and heavy white dwarfs) as binary members. The binary encounter rate is dominated by the field neutron stars in high concentration GCs, in part due to their high concentration, and in part because of stronger gravitational focusing of the more massive neutron stars. Binary-binary interactions also produce binaries with neutron star members, with the lighter binary often destroyed by the encounter (Hut, McMillan, & Romani 1992b). Both types of encounters tend to systematically "harden" the surviving binaries, and as the cluster evolves toward core collapse, the core will contain many very "hard" (semimajor axis $a \ll 1.0$ AU) binaries containing neutron stars.

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PSR 2127+11C is thought to consist of a pair of neutron stars, with the observed pulsar having been spun up in the core of the cluster. The system likely formed when a "field" neutron star exchanged into the binary in place of the former companion, the resulting binary being ejected from the core onto its current orbit in the outer part of the cluster in the process (Phinney & Sigurdsson 1991; Prince et al. 1991). The companion is most probably a "dead" neutron star, with a probability of less than 10^{-2} that the neutron star exchanged is also a "recyclar." As all conjectured scenarios for MSP formation involve an accretion phase, a cluster MSP cannot form in a double neutron star binary, and any exchange leading to a short-period double neutron star binary will necessarily eject the resulting, highly eccentric, binary from the cluster core, possibly even the cluster.

In the case of Galactic binary pulsars, such as the Hulse-Taylor pulsar, there is a small possibility that the companion is still active, that the beam of radio pulses does not intersect Earth and is thus not observable; but as the lifetime of the recycled pulsar is two orders of magnitude greater than that of a typical vanilla pulsar, it is improbable that we observe the system during this phase. Hulse-Taylor class pulsars in the galaxy may be formed either in situ in high-mass X-ray binaries or by ejection from globular clusters (Burrows & Woosley 1986; Verbunt 1990; Phinney & Sigurdsson 1991).

2. BINARY SIMULATIONS

To investigate the dynamics of binary-binary interactions, 12,000 interactions were simulated in the point mass approximation, with a small number of tidal encounters further simulated using TREESPH (Hernquist & Katz 1989). The method used is described in Goodman & Hernquist (1991). The initial conditions for the point-mass simulations were drawn randomly from a uniform distribution in phase space, following the method of Hut & Bahcall (1983) (see also Hut 1992), for mass ratios of 2:1 (corresponding to a neutron star with a turn-off mass main-sequence star companion), and equal semimajor axis, *a*. Both orbital eccentricities were set to zero, previous simulations having indicated that the final states are not sensitive to initial eccentricity. The simulations are scale free, with an implicit scale set when the ratio of stellar radii to binary semimajor axis is chosen. The integration was followed until at least one of the stars escaped to infinity, so rates for four-body events are complete. A limited attempt was made to follow three-body resonant states that sometimes develop when one star is ejected, the integration being allowed to proceed for up to 10^6 time steps; consequently the collision rates may be underestimated. The maximum separation of the binary centers of mass at closest separation was approximately $4a$, and a comparison between runs at different maximum impact parameters showed that the "beamwidth" used was sufficient to give complete collision rates. During the integration, the distance of closest approach between pairs of stars was monitored, and compared to the stellar radii, assuming some physical separation (either 0.1 AU or 0.03 AU, characteristic of evolved primordial binaries in dense cluster cores [Sigurdsson 1991; Phinney & Sigurdsson 1991]). If any pair of stars approached each other closer than the sum of their respective stellar radii, a collision was deemed to have occurred; the stars were assumed to merge in a perfectly inelastic collision, conserving momentum in the center-of-mass frame. The remnant was assigned a stellar radius equal to the sum of the stellar radii of the merging stars, and a mass equal to the sum of the two stellar masses, and the integration of the remaining bodies was continued. As expected, a number of stellar mergers were observed, including both main-sequence–main-sequence mergers, thought to produce "blue stragglers" (Sandage 1953; Leonard 1989), and main-sequence–neutron star mergers, thought to lead to accretion onto and spin-up of the neutron star. Rather surprisingly, a significant fraction of the encounters led to triple or quadruple mergers. For $a = 0.1$ AU, 0.06% of the encounters led to a four-way merger, out of a 4% total collision rate; for $a = 0.03$ AU, the total collision rate was 10%, while the four-way merger rate was 0.7%. Thus the relative rate for a quadruple collision is 1.5% and 7% for $a = 0.1$ and 0.03 AU, respectively. This compares with a relative rate of about 12% for blue straggler formation via this channel (the total blue straggler formation rate is dominated by binary interactions where neither of the binary members is a neutron star). If the MSP formation rate is dominated by binary encounters, the formation rate of quadruple mergers involving two neutron stars is then of order 1%–3% of the total MSP formation rate is the densest clusters (which contain most of the MSPs), with most of the uncertainty in the relative formation rate due to the unknown relative contribution of binary–single star and binary-binary encounters to the MSP formation rate. Triple mergers involving two neutron stars and a main-sequence star, which may also generate this class of MSPs, are neglected to provide a conservative estimate of the total fraction of double pulsars formed.

3. RESULTS

The initial conditions for the SPH calculation were set by integrating the corresponding point mass trajectory until the closest pair of stars was separated by six stellar radii, at which point the positions and velocities of the point masses were passed to TREESPH as the center-of-mass coordinates of the respective stars. The majority of collisions turned out to be glancing collisions, as expected from the relative cross sections for glancing versus head-on collisions, although one predicted near head-on collision in the point mass approximation turned out to be a glancing collision when tidal effects were included in the SPH calculation. However, all systems involving glancing collisions remained bound after the collision, and the encounters proceeded to the subsequent predicted multiple collision, with a surprisingly small deviation from the projected point mass trajectories, validating the completely inelastic collision approximation. We present one encounter selected for integration through to the final merger using TREESPH. The run consisted of binaries containing a neutron star (mass $M_{NS} = 1.4\ M_\odot$) and a main-sequence star (mass, $M_* = 0.7\ M_\odot$, radius $R_* = 0.7\ R_\odot$), each of semimajor axis 0.03 AU and zero eccentricity. The relative speed at infinity was approximately 0.15 times the critical velocity, at which the total energy of the system is zero in the center-of-mass frame. In no way was this run "special," and so it should well represent the general dynamical features of multiple mergers. Figure 1 shows the details of the encounter.

As the merger proceeds to the final collision, the neutron stars form a distinct double core inside a common envelope. Each neutron star gathered a few hundredths of a solar mass accretion disk about itself, fairly distinct from the rest of the gas, one disk significantly more massive than the other. Surrounding these is a turbulent transition region a few stellar radii in diameter, outside of which there is an extended ($\sim 50\ R_\odot$) envelope showing strong bulk radial motion. At the surface of the envelope, gas is escaping to infinity at approximately 100 km s^{-1}, as can be seen from Figure 2. The consequent strong wind is powerful enough to eject of order 10 $M_\odot$ of intracluster gas from the cluster, thus providing a mechanism for removing dust and gas from the cluster. The resulting nebula would be observable for order 10^4 yr, appearing similar to a planetary nebula. Asymmetry of the mass loss is only of the order of a percent, so the merged remnant is nearly stationary in the center-of-mass frame and will consequently not be ejected from the cluster core. Any subsequent encounter close enough that the recoil would eject the system from the core would result in an eccentric binary with lifetime due to decay through gravitational radiation too short to be plausibly observable. The semimajor axis of the neutron star binary cannot be calculated directly, as pressure support mediated by the tightly bound disks leads to sub-Keplerian orbital velocities of the neutron star–disk system. Considered as a dynamically decoupled system, at a semimajor axis, $a_f \approx 2R_*$ the neutron star pair will have released enough binding energy to eject the entire envelope surrounding it. The binding energy of each star is fGM_*^2/R_*, where $f \sim \frac{1}{2}$ depends on the stellar structure ($f = 0.43$ for $\gamma = 5/3$ polytropes). Neglecting the initial binary binding energy and assuming the gravitational binding energy of the final neutron star binary is efficiently deposited in the envelope, $a_f \geq (M_{NS}/M_*)^2 R_*/4f$. Currently in globular clusters, $M_* \leq M_{NS}/2$, implying $a_f \geq 2R_*$. If significant energy is released by burning of stellar material during the collision or evolution of the merged remnant, a will be somewhat larger. As expected, the neutron star separation is $\gtrsim 4R_*$ at late stages of the simulation with the inferred orbital eccentricity of the neutron stars decreasing rapidly. It should be noted that accretion onto the neutron star surface is not permitted in the model, nor is it expected to be significant on the time scales involved.

As this system evolves, the effective semimajor axis of the neutron star cores should slowly shrink due to drag in the envelope, with the common envelope evolution phase lasting for a time scale $\tau = \min\{\tau_{drag}, \tau_{accn}\}$. Here, $\tau_{drag} = E_c/L$ is the time scale due to orbital drag by the surrounding gas, where E_c is the binding energy of the core and $L = \pi a_a^2 \rho v^3$ is the envelope drag (Taam & Bodenheimer 1991). In this latter

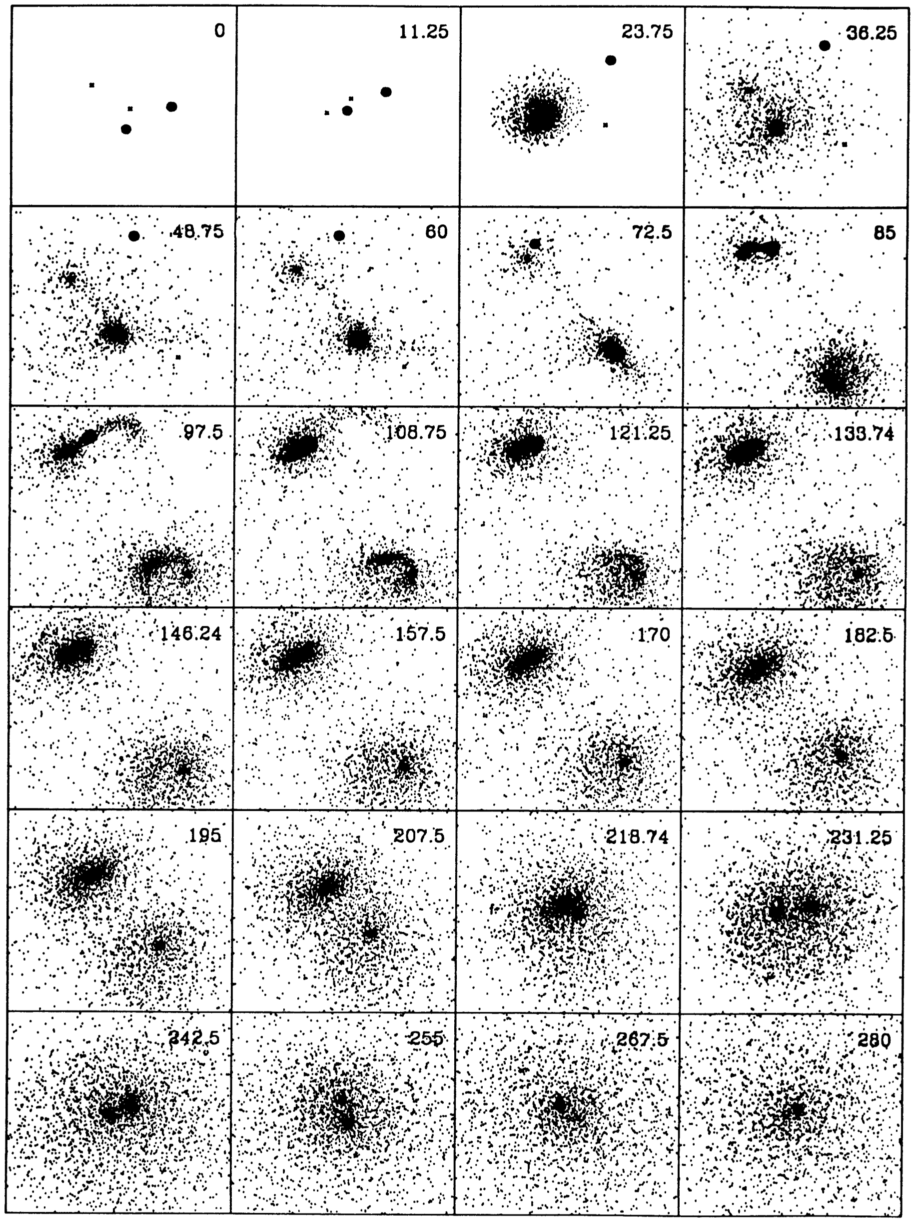

FIG. 1.—Collisional merger of two neutron stars and two main-sequence stars. Each frame is $40R_*$ across, and the time is shown in dimensionless units, such that the initial binary had orbital period 10.4 = 54.5 hr. At about $t = 20$ one of the neutron stars (shown as a small cross) undergoes a glancing collision with one of the main-sequence stars. A small amount of matter is captured into a disk about the neutron star and the main-sequence star "puffs" out. The partially disrupted main-sequence star then undergoes a second collision with the second neutron star, while the first neutron star and attending disk collide almost simultaneously with the other, hitherto unperturbed, main-sequence star at about $t = 75$. The neutron stars sink rapidly into the cores of the now severely disrupted main-sequence stars, which start evolving extended envelopes. The two merged objects are nearly stationary with respect to each other. The merged remnants then fall to the final four-way merger, extending their envelope as they merge, the envelopes joining at $t = 210$. The neutron star cores orbit each other in the core, the gravitational binding energy released further extending the envelope and powering a fast wind from the surface of the envelope. The envelope, while uniform in structure, is not well mixed.

expression, ρ is the local gas density, v is the speed at which the neutron stars move through the gas, and a_a is the effective accretion radius at which gas is accreted onto the system. $\tau_{\rm accn} = E_e/\epsilon L_{\rm Edd}$ is the time scale for envelope ejection due to accretion onto the neutron stars, $E_e \approx GM_*^2/10R_*$ being the binding energy of the envelope to the core, ϵ is the accretion efficiency onto the neutron stars, and $L_{\rm Edd} \approx 2 \times 10^{38}$ ergs s^{-1} is the Eddington luminosity. τ is highly uncertain, owing to the uncertainty in a_a, but it likely less than 1000 yr. Estimates of the orbital parameters of the neutron star binary from the simulation suggest a period of approximately 6 hr and a small eccentricity as the most likely final state, with each neutron star retaining a small, $r < R_\odot$, accretion disk containing a few hundredths of a solar mass. As the neutron stars continue accreting from the inner disks, the binary may enter a double X-ray phase. This phase is estimated to last order $M_{\rm disk}/\dot{M}_{\rm Edd} \approx 10^6$ yr. Angular momentum transport in the disk thus reduces to the disk angular momentum transferring to the neutron stars rather than being lost from the system, further widening and circularizing the orbit of the neutron stars. As

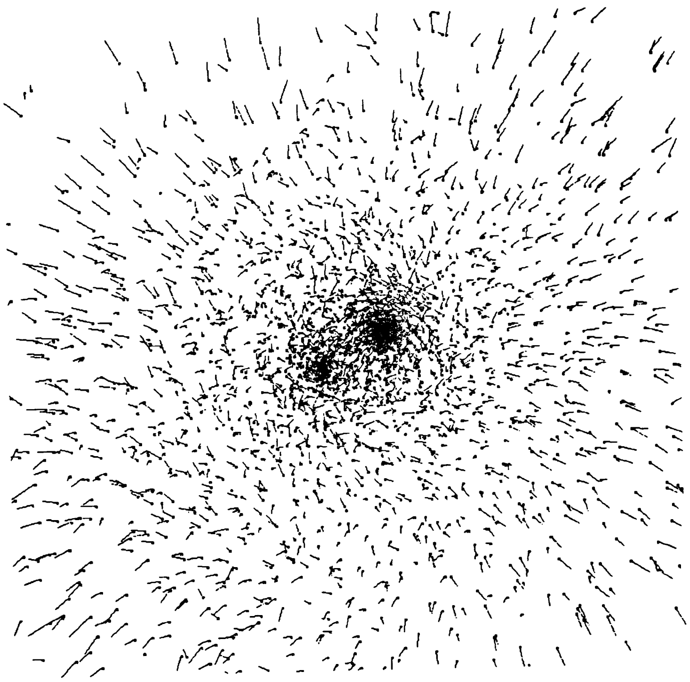

FIG. 2.—Velocity structure of the merged remnant at $t = 225$, after the final four-way merger. The accretion disk about each neutron star are clearly distinct; the separation of the two neutron stars is a little over $4R_*$. Surrounding them is a turbulent boundary region extending to about $8R_*$, beyond which is the envelope, extending to almost $200R_*$ at this time, showing coherent radial outflow. The arrows are proportional to local velocity, with the longest arrows at the outskirt of the envelope representing speeds of about 150 km s^{-1}.

the final mass is accreted and blown away, a tight, low-eccentricity MSP binary should remain, characterized by the presence of a pair of pulsars of comparable period, $P \approx 6(0.01 M_{\odot}/M_{\rm disk})^{3/4}$ ms (Phinney & Kulkarni 1992), and with parallel spin axis. The lifetime of the binary to orbital decay through gravitational radiation of the unperturbed system is expected to be of the order of the spin-down time or greater, 10^8–10^9 yr, even for periods as low as 5 hr, as the final eccentricity is expected to be small.

We note that our simulation applies equally well to binaries containing white dwarfs; however, the resulting system is likely to spiral in to contact on a short time scale, owing to the smaller separation of the common envelope cores expected energetically, and the larger effective accretion radius, a_a, and smaller accretion luminosity permitting the envelope drag to act more effectively. As a consequence, the white dwarf pair would be expected to merge, leading to detonation and a Type I supernova, or accretion induced collapse (AIC) (Grindlay & Bailyn 1988) leaving a solitary MSP.

With over 20 MSPs discovered in GCs, it is possible that a double MSP will be observed in the core of a dense cluster in the next few years. Selection effects against detecting short-period binary MSPs (Johnston et al. 1991) are likely to be less effective for this class of objects, due to the low expected orbital eccentricity. Unlike the PSR 2127+11C class of binary pulsars, the double MSPs should be observed in cores of clusters or, conceivably, in the galaxy after disruption of its parent cluster. Observation of such a system in the galaxy would provide a strong indication of GC disruption.

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