1991-05

1991ApJ...374L..41P

THE ASTROPHYSICAL JOURNAL, 374:L41–L44, 1991 June 20
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TIMING OBSERVATIONS OF THE 8 HOUR BINARY PULSAR 2127+11C IN THE GLOBULAR CLUSTER M15

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Received 1991 January 24; accepted 1991 March 29

ABSTRACT

We present new results on the position and characteristics of the 8 hr binary pulsar 2127+11C in the post–core-collapse (PCC) globular cluster M15. Our results indicate that PSR 2127+11C has been ejected from the cluster core via a close encounter with another binary system or isolated star. In particular, the position derived from a phase-connected timing solution places the PSR 2127+11C system 2.7 pc (projected) from the core, well outside the compact region containing the other four detected pulsars and the X-ray binary system X2127+11/AC 211. While PSR 2127+11C is likely still bound to the cluster, it is nonetheless probable that other compact binary pulsars have been totally ejected, thereby contributing to the population of field binary pulsars. Timing results from PSR 2127+11C also show a relativistic advance of periastron of $4\overset{\circ}{.}46$ yr^{-1}, indicating that the total mass of the system is 2.71 $M_\odot$.

Subject headings: pulsars — clusters: globular — stars: binaries

1. INTRODUCTION

Binary star systems are expected to play a central role in the evolution of globular clusters during core collapse. In the dense environment of cluster cores, binaries are hardened through collisions with other stars, releasing binding energy which eventually halts the collapse of the core (Elson, Hut, & Inagaki 1987). When a binary becomes sufficiently hard, further collisions are expected to eject it from the core. We have determined that the 8 hr binary pulsar 2127+11C in the globular cluster M15 is such a hard binary system ejected from the core by a close encounter with another binary system or a single star.

PSR 2127 + 11C was discovered in observations of the globular cluster M15 (NGC 7078) taken with the 305 m Arecibo[1] radio telescope (Anderson et al. 1990). The pulsar was first discovered at an acceleration of -9.5 m s^{-2}, indicating that it was a member of a short-period binary system. Subsequent observations showed the pulsar to be in a highly eccentric 8.05 hr orbit. In the first phase of analysis, as reported in Anderson et al. (1990), the five Keplerian parameters of the orbit were obtained by measurement of the apparent pulse period and pulse arrival times in 17 observations taken during 1989 May. Because of the restricted time span of the observations, neither an accurate position nor relativistic orbital parameters were derived from the data.

Following these initial observations, additional observations were made at the Arecibo telescope to further refine the orbital and timing parameters of the pulsar. In this second phase of the analysis, which is reported here, we have analyzed data taken over a 372 day period to obtain a phase-connected timing solution for PSR 2127+11C which provides an accurate timing position, a measure of the precession of the periastron, and more accurate determinations of the five nonrelativistic orbital parameters. These yield significant new information concerning the origin and probable history of PSR 2127+11C, which relates directly to the role of binary systems in the evolution of globular clusters. We discuss results of the timing analysis in § 2 and implications in § 3 of this *Letter*. Interpretations of the observational results presented in this *Letter* are also discussed by Phinney (1991), Phinney & Kulkarni (1991), and Phinney & Sigurdsson (1991).

2. ANALYSIS AND RESULTS

A total of 51 separate observations were made of M15, spanning the 372 day period from 1989 April 16 to 1990 April 22. The observations were taken with a central frequency of 430 MHz and a 10 MHz receiver bandwidth. The signal was sampled at an effective rate of 1.974 kHz using the Arecibo correlation spectrometer with 128 lags and 3 level quantization. The resulting autocorrelation data were recorded on magnetic tape along with accurate time reference information.

The data from the digital correlation spectrometer were first folded at the apparent pulse period obtained from an ephemeris based on the values of the initial Keplerian orbital parameters. The pulse time of arrival (TOA) was then computed by cross-correlating the pulse profile derived from the folding process against a high signal-to-noise ratio reference profile. Each TOA was based on 689 s of data and was measured to a typical accuracy of 70 μs. The best-fit orbital and pulsar parameters (Table 1) were derived using TEMPO, a standard least-squares minimization program for pulsar timing analysis. Because of the faintness of the pulsar signal and the large orbital accelerations, it was necessary to iterate the TOA measurement process several times, at each step using the improved orbital parameters computed from the previous iteration. This gradually removed artificial pulse broadening due to errors in the pulsar ephemeris, especially near periastron. The final parameters presented in Table 1 are based on 290

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[1] Arecibo Observatory is part of the National Astronomy and Ionosphere Center, operated by Cornell University under contract with the National Science Foundation.

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TABLE 1

PULSAR AND ORBITAL PARAMETERS

Parameters	Symbol	Value[a]
Pulsar:		
Pulsar period	P	30.5292951285(9) ms
Pulsar period derivative	$\dot{P}$	$4.99(5) \times 10^{-18}$ s s^{-1}
Dispersion measure	DM	67.12(4) pc cm^{-3}
Right ascension	α	$21^{\rm h}27^{\rm m}36^{\rm s}.188(4)$ (B1950.0)
	$\alpha - \alpha_{\rm core}$	$+41''.65(5)$[b]
Declination	δ	$11°57'26''.29(7)$ (B1950.0)
	$\delta - \delta_{\rm core}$	$+37''.49(7)$[b]
Orbital:		
Orbital period	$P_{\rm b}$	28,968.3693(5) s
Projected semimajor axis	$a_1 \sin i$	2.520(3) lt-s
Eccentricity	e	0.68141(2)
Longitude of periastron	ω_0	$316°.40(7)$
Apsidal motion	$\dot{\omega}$	$4°.457(12)$ yr^{-1}
Epoch of periastron	T_0	JD 2,447,632.4672065(20)
Derived:		
Mass function	f	0.15285(55) $M_\odot$
Total mass	$M = m_1 + m_2$	2.706(11) $M_\odot$
Characteristic age	τ_c	0.96×10^8 yr
Magnetic field	B	12×10^9 G
Predicted orbital decay time	$\tau_{\rm gr}$	2×10^8 yr

[a] Numbers in parentheses represent a 3 σ error in the last digit(s).

[b] Position relative to cluster center: ($\alpha_{\rm core} = 21^{\rm h}27^{\rm m}33^{\rm s}.35$, $\delta_{\rm core} = 11°56'48''.8$).

TOAs measured over the 372 day period with the corresponding residuals shown in Figure 1.

Table 1 gives the position of PSR 2127+11C relative to the cluster center obtained from the timing analysis. Figure 2 is a map of M15 showing the position of PSR 2127+11C, along with the timing positions of the four other known radio pulsars in M15 and the optical position of the X-ray binary system X2127 + 11/AC 211. Pulsars 2127+11D and 2127+11E are new detections, not described previously in the published literature. Both have relatively short spin periods, 4.80 and 4.65 ms, respectively. Further details will be published in a later paper. As indicated by Figure 2 and Table 1, PSR 2127+11C has an offset from the center of the cluster of 56″, unexpectedly large compared with the much smaller offsets of the other five

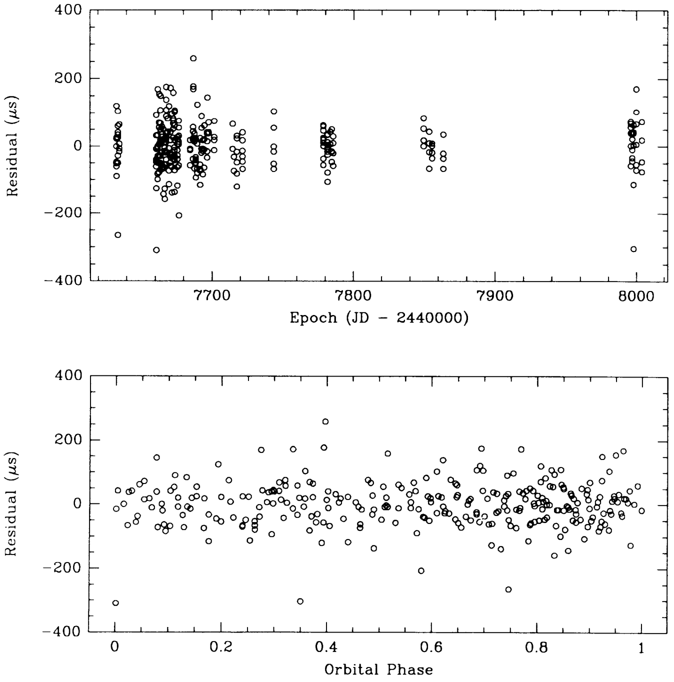

FIG. 1.—Timing residuals for the timing solution given in Table 1 as a function of both Julian Date and orbital phase.

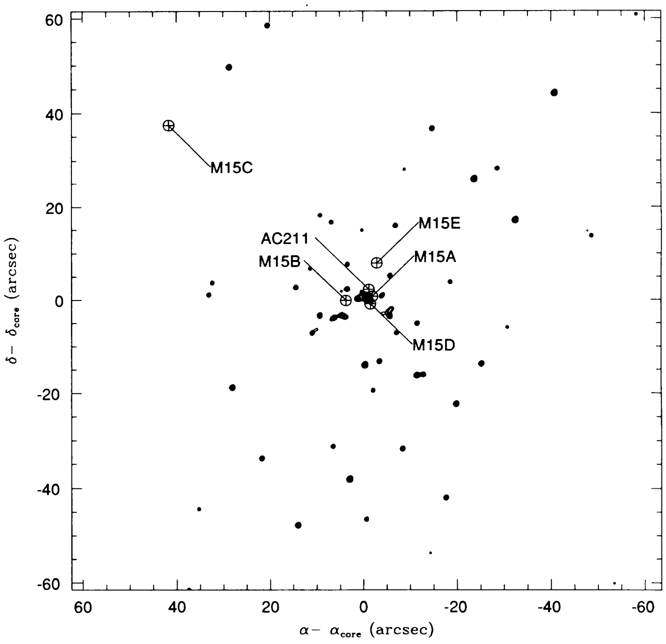

FIG. 2.—Optical image of the globular cluster M15 with the positions of the five known pulsars and the X-ray binary X2127+11/AC 211 indicated relative to the cluster core, $\alpha_{\rm core} = 21^{\rm h}27^{\rm m}33^{\rm s}.35$ and $\delta_{\rm core} = 11°56'48''.8$ (Shawl & White 1986). The position of AC 211 is from Geffert et al. (1989). Positions of PSR 2127+11A, B, C, D, and E (=M15A, B, C, D, and E) relative to the cluster core are ($-1''.9$, $0''.8$), ($3''.8$, $-0''.3$), ($41''.7$, $37''.5$), ($-1''.4$, $-0''.9$), and ($-2''.7$, $8''.0$) respectively, accurate to within $0''.3$ in all cases.

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known neutron stars in M15. Assuming a distance of 10 kpc, the minimum radial distance of PSR 2127+11C from the cluster center is 2.7 pc, significantly larger than the core radius ($\lesssim 0.13$ pc; Lauer et al. 1991).

3. DISCUSSION

Table 1 gives the reduction in the spin rate, $\dot{P}$, from which we find that PSR 2127+11C has a characteristic age, $\tau_c \equiv P/2\dot{P}$ of 1×10^8 yr, and a dipole magnetic field strength, $B_9 \equiv 12$, where $B_9 \equiv B/10^9$ G, and the field strength is estimated from the usual dipole formula, $B_9^2 = 10^{21} P\dot{P}$. This combination of low magnetic field strength and rapid rotation strongly suggests that PSR 2127+11C belongs to the group of pulsars which have been spun up by accretion of matter from a companion star—the so-called "recycled" pulsars.

The low stellar density at the radius of PSR 2127+11C implies a time scale of at least 10^{11} yr for either tidal capture or exchange reactions. Since at least one such event likely occurred within τ_c to form the currently observed PSR 2127+11C system, it is almost certain that it was formed not at its current location but rather in the highly concentrated core of this PCC globular cluster (King 1985). Possible scenarios for ejection from the core are the following: (1) the 30.5 ms pulsar collided with a preexistent binary system and replaced one of the components or (2) a preexistent binary containing the 30.5 ms pulsar collided with an isolated star or another binary system, with a possible exchange of companion. Note that in either case a high density of degenerate stars is indicated in the core of M15 and the involvement of at least one binary system is required. The fact that four out of the five known pulsars in M15 are single supports scenario 1. It has been suggested that single recycled pulsars in clusters are the result of catastrophic tidal encounters of neutron stars with main-sequence stars (Phinney & Kulkarni 1991).

Either of the two formation scenarios for PSR 2127+11C requires a collision involving a binary system. The PSR 2127+11C system is thus likely to be a direct manifestation of processes predicted to occur in globular clusters, namely, the heating of the cluster core through release of binary binding energy (Elson et al. 1987). Core collapse of dense globular clusters is an inevitable consequence of dynamical evolution. The collapse is halted by the formation of tidal binaries and the release of energy through additional close interactions which cause a decrease in the binary semimajor axis ("hardening"), thereby releasing binding energy. For close binaries, exothermic interactions are kinematically favored over endothermic reactions which tend to disrupt the binary. The highly eccentric PSR 2127+11C system is likely to have resulted from such an exothermic collision, with the potential energy released in the collision being converted into kinetic energy, resulting in the ejection of PSR 2127+11C from the core. If the products of such collisions do not escape the cluster, their excess kinetic energy is eventually distributed to other stars in the core upon subsequent passes through it, thus contributing to the overall heating of the core.

With the exception of PSR 2127+11C, all the cluster pulsars known to date and the dozen cluster low-mass X-ray binaries are located within the core of clusters, or within a few core radii. It is highly unlikely that PSR 2127+11C is on an escape trajectory from the cluster because of the very short time to escape to its current radius ($<10^5$ yr). Rather, it is almost certainly in a highly eccentric orbit with its pericenter in the cluster core (see Phinney 1991 for a discussion of the distribution and evolution of orbits of ejected pulsars). However, a slightly larger initial velocity kick ($\gtrsim 60$ km s^{-1} for M15; Phinney 1991) would have resulted in escape from the cluster, raising the possibility that other systems such as the remarkably similar binary pulsar 1913+16 may have been formed in and ejected from a cluster and are currently masquerading as field binary pulsars. PSR 2127+11C was found during a systematic search of globular clusters observable from Arecibo, most of which are in the range $-30° \lesssim l \lesssim 70°$ in Galactic longitude. Given the relative volumes probed by this survey and the Galactic plane survey which discovered PSR 1913+16, and given the characteristic ages of the pulsars, a birthrate for compact binary systems may be crudely estimated for each of the two systems separately. Assuming that several binaries are ejected for every binary like PSR 2127+11C retained by the cluster, the birthrates are the same within an order of magnitude. Globular clusters may thus turn out to be a significant source of compact binary pulsars. We further note that the proper motion measured for PSR 1913+16 (Taylor & Weisberg 1989) is consistent with it originating in a globular cluster several kiloparsecs from its present position.

In addition to position information, the timing solution for PSR 2127+11C also yields new information concerning the nature of the companion to the pulsar and therefore on its evolutionary history. Interpretation of the observed orbital precession as a general relativistic (GR) advance of periastron at a mean rate of $\dot{\omega} = 4\overset{\circ}{.}46 \pm 0\overset{\circ}{.}01$ yr^{-1} (Table 1) implies a total mass of $2.71 \pm 0.01\ M_\odot$ for the binary system. It is necessary, however, to consider alternative classical explanations which, if present, would corrupt the above mass estimate. In particular, significant classical contributions can be expected if the companion star is an extended object with either a tidally or a rotationally induced gravitational quadrupole moment. A main-sequence star companion is ruled out, since it would induce a rate of precession $O(10^3)$ times that observed (Masters & Roberts 1975). A helium star companion is also excluded, since the current maximum mass of a helium star in M15 is of order 0.38 $M_\odot$ or less (Iben & Tutukov 1985), more massive stars having completed their evolution in the $\sim 10^{10}$ yr age of the cluster, implying a pulsar mass less than 0.22 $M_\odot$ and a rate of precession based on the structure of helium stars (Roberts, Masters, & Arnett 1976) substantially different from that observed.

In the case of a white dwarf companion, a gravitational quadrupole moment might arise from rapid rotation. However, given the lack of an observed variation in the projected semimajor axis $a_1 \sin i$, a limit of $\sim 0\overset{\circ}{.}001$ yr^{-1} may be placed on the precession of the orbital inclination angle. This in turn places a limit on a classical contribution to $\dot{\omega}$ due to a quadrupole moment (Smarr & Blandford 1976). For instance, a rotating white dwarf companion generating more than a 1% classical contribution to the observed $\dot{\omega}$ would need to have its spin axis aligned to better than $\sim 1\overset{\circ}{.}5$ of the orbital plane or its normal vector (or a similar restriction on the dynamical longitude). Such an alignment seems unlikely given the nearly uniform a priori distribution of orientations expected from the collisional interaction which resulted in the observed binary system. In summary, we conclude that the current companion is either a white dwarf, a neutron star, or a black hole, and is not significantly contributing to the observed rate of precession. Hence, the total mass of the system is 2.71 $M_\odot$.

One consequence of the large total mass and the small characteristic age of this system compared with the age of M15 is

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that the current companion could not have been the mass donor responsible for the "recycling" of the pulsar. For, unless the pulsar mass alone exceeds 2.1 $M_\odot$ (a value which seems unlikely given the mass measurements of PSR 1913+16 (Taylor & Weisberg 1989) and X-ray binary systems (Rappaport & Joss 1983), the mass of the progenitor of the presumed white dwarf companion would exceed the 0.8 $M_\odot$ turnoff mass of the cluster, i.e., the companion star would have evolved off the main sequence and initiated mass transfer prior to the inferred pulsar age τ_c. As a result of this, unless PSR 2127+11C was orbiting a star with just the right mass to evolve and initiate mass transfer during the last $\sim 10^8$ yr, it has undergone at least two collisional interactions in the last $\sim 10^8$ yr—the first to "recycle" it and the second to replace the mass donor with a degenerate star (neutron star or white dwarf) and eject it from the core.

PSR 2127+11C provides yet another astronomical system in which the effects of GR can be observed along the lines of PSR 1913+16 (Taylor & Weisberg 1989), with two caveats: (1) The radio flux density at 430 MHz of PSR 2127+11C is 1 mJy, considerably smaller than the 6 mJy of PSR 1913+16, resulting in noisier TOAs (70 μs versus 15 μs for PSR 1913+16). (2) The pulsar parameters of PSR 2127+11C will be perturbed by gravitational effects of the cluster stars. The latter is an intrinsic effect and arises from an unknown gravitational acceleration of the binary system from both nearby stars and a cumulative effect from the cluster as a whole. Using the equation for the acceleration along the line of sight given in Phinney (1991), we find that the maximum acceleration that PSR 2127+11C may be undergoing due to the cluster potential is of order $\sim 1 \times 10^{-7}$ cm s^{-2}; (the perturbation from neighboring stars is only $\sim$4% of this value). This corresponds to a 1.7% corruption of $\dot{P}$ (rotational spin decay) and a 2.1% corruption of $\dot{P}_b$ (orbital period decay). Observations of PSR 2127+11C over the next few years will thus allow a quantitative test of GR in the strong-field limit accurate to $\sim$2% (compared with the 0.8% now obtained by PSR 1913+16 and the even better accuracy expected for PSR 1534+12; Wolszczan 1991). Conversely, one may assume that GR is the correct theory and use any observed deviation in $\dot{P}_b$ to determine the line-of-sight acceleration and hence the intrinsic $\dot{P}$. This may then be used to infer the correct characteristic age of the system as well as information on the mass distribution of the cluster. Higher order time derivatives of the observed parameters will be dominated by the cluster environment (Blandford, Romani, & Applegate 1987) and, rather than yielding new information about the pulsar, will provide interesting information on the gravitational potential of the globular cluster.

We are grateful to J. H. Taylor for supplying the TEMPO software package; E. S. Phinney for stimulating discussions; S. Djorgovski for an optical image of M15; and Jose Navarro for help in observations. This work was supported by the National Science Foundation, the US Department of Energy, and the Alfred P. Sloan Foundation.

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