DISCOVERY OF TWO RADIO PULSARS IN THE GLOBULAR CLUSTER M15

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ABSTRACT

We report the discovery of two radio pulsars, 2127+11B and 2127+11C, in the globular cluster M15 (NGC 7078), which also contains the 110-ms pulsar 2127+11A (Wolszczan *et al.* 1989). Although only twenty globular cluster pulsars are known at present, the detection of three pulsars in a single cluster suggests that there might be a large total population of these objects, which would make them powerful probes of the dynamics and evolution of globular clusters. One of the new pulsars, 2127+11C, is in a highly eccentric binary system with an 8-hour period. It is thus similar to the famous PSR 1913+16 system (Taylor and Weisberg 1989) and study of the pulse arrival times can be expected to provide tests of general relativity, including gravitational wave emission. The companion of PSR 2127+11C is probably either another neutron star or a massive white dwarf, suggesting that the core of M15 contains a high density of massive stellar remnants.

1. OBSERVATIONS

The initial observations were made using the 305 m Arecibo radio telescope at a central frequency of 430 MHz and a 10 MHz receiver bandwidth. The data were sampled at an effective rate of 1.974 kHz using the Arecibo 40 MHz, three-level correlation spectrometer in a manner identical to that employed in the discovery of PSR 2127+11A (Wolszczan *et al.* 1989). The discovery observations were made on 26 December 1988 starting at 18:51 UT. The pulse search was carried out on the Caltech nCUBE/10, a concurrent computer having 512 Central Processing Units (CPUs) with hypercube interconnection topology. A 16 Megasample de-dispersed time series was formed by padding the observed 10.9 million samples out to 2^{24} samples and by assuming a dispersion measure of $67.25\,\mathrm{cm}^{-3}\,\mathrm{pc}$ determined from earlier observations of PSR 2127+11A (Wolszczan *et al.* 1989). The power spectrum was calculated using a concurrent implementation of the Fast Fourier Transform (FFT) algorithm (Fox *et al.* 1988) and searched for families of significant harmonic peaks.

2. RESULTS

Table 1 and Figure 1 give the parameters and pulse profiles of the three pulsars detected in the 430 MHz observations. PSR 2127+11A was clearly detected in our first analysis of the December 1988 data. Further inspection revealed PSR 2127+11B with a period of 56 ms but approximately two times fainter than PSR 2127+11A. Subsequent timing measurements spanning 230 days indicate that PSR 2127+11B is an isolated pulsar with a period derivative ($\dot{P}$) of $9 \times 10^{-18}\,\mathrm{s\,s^{-1}}$, implying a characteristic age of 1×10^{8} yr, if the observed $\dot{P}$ is due solely to magnetic braking. If, on the other hand, one assumes that the dominant effect is acceleration due to the local gravitational field, as in the case of PSR 2127+11A (Wolszczan *et al.* 1989), then the magnitude of the acceleration is $5 \times 10^{-8}\,\mathrm{m\,s^{-2}}$. The errors quoted for PSR 2127+11B in Table 1 are three times the formal errors given by the temporal fitting program used in the analysis (TEMPO). The accuracy of these measurements are limited by the coupling of the timing residuals due to a position error (a one year period sine wave) and a $\dot{P}$ error (quadratic drift) over the limited 230 day observation period.

TABLE 1
Pulsar Parameters

Timing Parameter		2127+11A	2127+11B	2127+11C
Epoch (JD)	T_0	2,447,213.15	2,447,632.9906	2,447,660.9089
Pulse Period (ms)	P_0	110.66470954(1)	56.13303358(1)	30.529(1)
Period Derivative ($10^{-18}\,\mathrm{s\,s^{-1}}$)	$\dot{P}$	-20 ± 1	8.8 ± 1.1	—
Right Ascension (″)*	α_{core}	$-1.95 \pm .15$	$+3.86 \pm .15$	—
Declination (″)*	δ_{core}	$+0.6 \pm .3$	$-0.8 \pm .6$	—
Dispersion Measure ($\mathrm{cm^{-3}\,pc}$)	DM	67.25 ± 0.05	67.25 ± 1.0	67.25 ± 1.0
Flux Density (mJy)	S_{430}	$1.7 \pm .4$	$1.1 \pm .4$	$0.6 \pm .2$
Orbital Period (s)	P_b	—	—	$28{,}969 \pm 1$
Semi-Major Axis (ls)	$a_1 \sin i$	—	—	$2.52 \pm .01$
Eccentricity	e	—	—	$0.680 \pm .003$
Longitude of Periastron (deg)	ω_0	—	—	316.4 ± 1.0
Epoch of Periastron (JD)	T_0	—	—	2,447,632.46720(5)
Mass Function ($\mathrm{M_\odot}$)	f	—	—	0.15

Numbers in parenthesis indicate the uncertainty in the last significant digit.

The values given for PSR 2127+11A are those reported by Wolszczan *et al.* (1989) and are consistent with the results of our 430 MHz observations. The values for PSR 2127+11B are based on 430 MHz observations spanning 230 days. The Keplerian orbital parameters for PSR 2127+11C are based on 17 days of pulse arrival time analysis.

* Positions are relative to the centre of globular cluster M15 ($\alpha = 21^{\mathrm{h}}\,27^{\mathrm{m}}\,33^{\mathrm{s}}\!.35$ and $\delta = 11^\circ\,56'\,48''\!.8$) (Shawl and White 1986).

PSR 2127+11C was discovered using an algorithm specifically developed for detection of pulsars in binary orbits. The variable Doppler shift due to the orbital acceleration can spread the signal power over

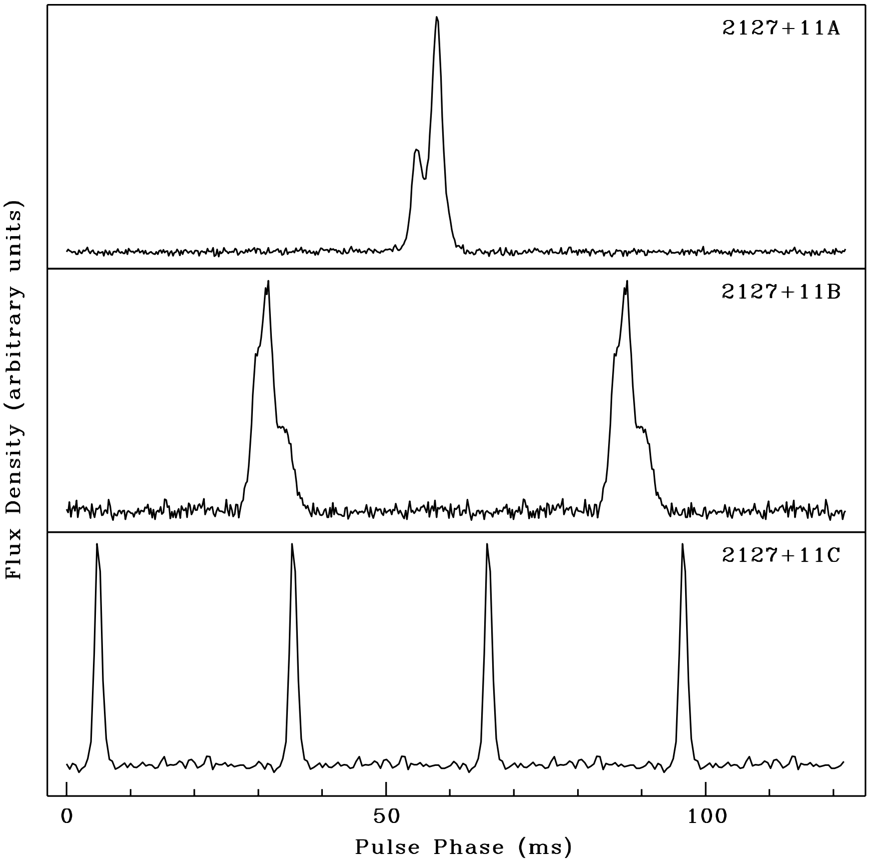

Figure 1: Average pulse profiles for the three known radio pulsars in globular cluster M15. The time resolution is $500\,\mu$s.

multiple frequency bins, resulting in a loss in sensitivity, particularly for fundamentals or harmonics with millisecond periods. In our algorithm, samples were inserted or deleted in the time series to compensate for a presumed acceleration. To reduce the computational demands of the search, we assumed a constant acceleration. A range of accelerations from $-19.2\,\mathrm{m\,s^{-2}}$ to $+19.2\,\mathrm{m\,s^{-2}}$ was explored using 2^{24}-point transforms, corresponding to the acceleration experienced by a pulsar in a circular orbit with 1 d period and a $1\,\mathrm{M}_\odot$ companion. A series of 2^{22}-point transforms was also calculated for accelerations of magnitude $203\,\mathrm{m\,s^{-2}}$, corresponding to a $1\,\mathrm{M}_\odot$ companion and a 4 hr circular orbit. PSR 2127+11C, with a period of 30.5 ms, was initially found in a 16 Megapoint transform at an acceleration of -9.5 m/s^2.

Timing measurements were begun to determine the Keplerian parameters of the PSR 2127+11C orbit. Recording of the raw data stream on magnetic tape allowed us to extract timing information for all three

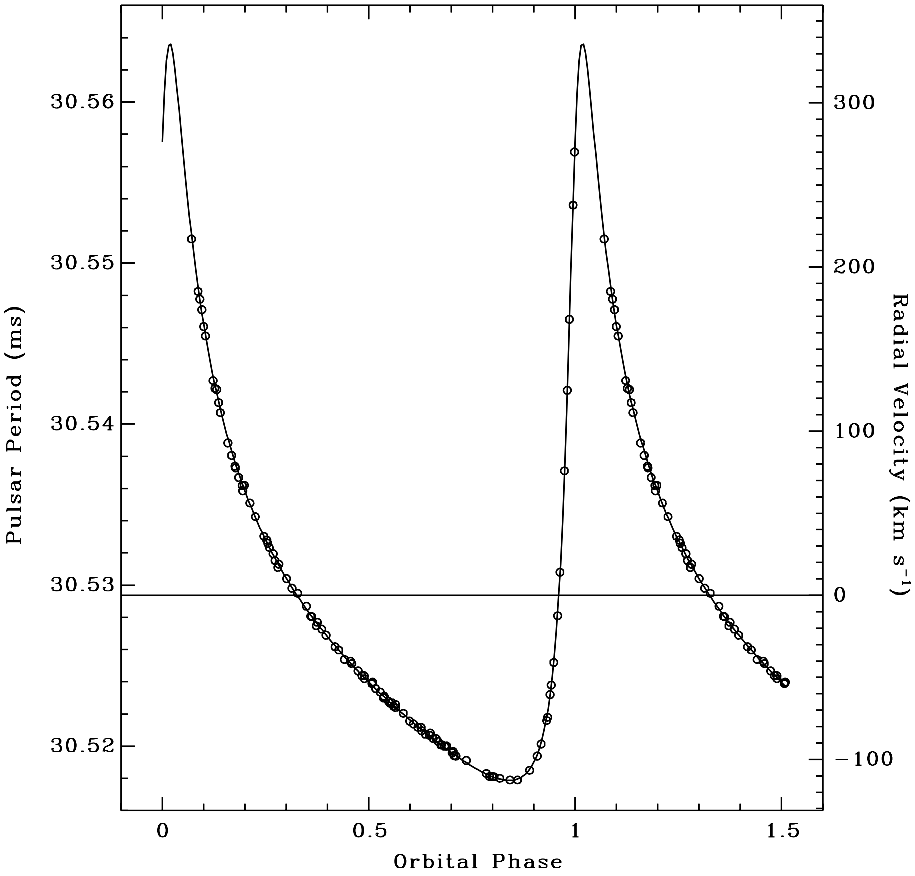

Figure 2: Velocity profile and observed Doppler shifted pulse periods as a function of orbital phase for PSR 2127+11C.

pulsars from the same data. Because of the faintness of PSR 2127+11C, an integration time of $\gtrsim 10$ minutes was required for detection. This necessitated an acceleration search for each observation to compensate for orbital motion and to obtain the correct apparent pulsar period. The determination of the orbital period was also complicated by the limited duration (3 hr) over which the cluster can be observed by the Arecibo telescope. The orbital period was found to be 8 hr 3 m, indicating that it would take a minimum of six weeks for a complete cycle of observable orbital phase. In Figure 2, we display the apparent pulsar period at the midpoint of each observation as a function of the orbital phase for observations taken primarily over an eight week period. The eccentricity of the orbit is immediately apparent.

Using the velocity curve in Figure 2 for an initial estimate of the orbit, pulse arrival time analysis has been performed on 17 observations taken during May 1988. The resulting Keplerian parameters, surprisingly similar to those of 1913+16 (Taylor and Weisberg 1989) are given in Table 1. If the secondary is another neutron star, the estimated orbital decay time and the advance of periastron will be 2×10^8 yr and $4\,^\circ\,\mathrm{yr}^{-1}$, similar to those of PSR 1913+16. The PSR 2127+11C system should thus provide tests of general relativity in the strong field limit, including gravitational wave emission, comparable to those of PSR 1913+16. The errors quoted in Table 1 are our best estimates of the uncertainty due to the limited time span of observations used in this analysis and the possibility of pulse numbering ambiguities. A significantly more accurate measurement of the pulsar parameters, including a precise determination of the advance of periastron, is in progress using approximately nine months of timing observations.

Constraints can be placed on the the pulsar and companion masses (m_p and m_c) by determining the mass function f, which depends on the apparent size of the pulsar's orbit and the orbital period. The value of the mass function for the 2127+11C system is $f(m_p, m_c) = (m_c \sin i)^3/(m_p + m_c)^2 = 0.15\,\mathrm{M}_\odot$. Assuming $m_p = 1.4\,\mathrm{M}_\odot$ for PSR 2127+11C, the minimum mass of the companion is $0.94\,\mathrm{M}_\odot$. For $m_p = m_c = 1.4\,\mathrm{M}_\odot$, the inclination angle i of the orbital plane to the line of sight would be 49°, close to the median inclination angle of 60°. Given the measured orbital parameters, the distance of closest approach is of the order of $1\,\mathrm{R}_\odot$ for inclination angles corresponding to a $1\,\mathrm{M}_\odot$ companion. Consequently, a main-sequence companion is ruled out, and the companion is most likely a second neutron star or a massive white dwarf.

3. DISCUSSION

The discovery of three pulsars within a single cluster suggests that pulsars are abundant in globular clusters. Kulkarni, Narayan, and Romani (1990) have quantitatively analyzed the results of the major cluster pulsar surveys and conclude that a typical rich cluster contains about 100 active pulsars, most of which will be undetectable owing to the great distances to the clusters. Assuming a distance of 10 kpc to M15, the radio luminosities of PSR 2127+11A, B and C are respectively 170 mJy kpc^2, 110 mJy kpc^2 and 60 mJy kpc^2. These luminosities are well above the minimum luminosity of 1 mJy kpc^2 for field pulsars. Hence with increased sensitivity, additional pulsars ought to be detectable in M15. We are now in the process of analyzing all our data, over 50 hr of observations, in an effort to locate fainter pulsars.

The discovery of the binary pulsar 2127+11C strongly suggests an abundance of massive stellar remnants in the core of M15. According to the standard scenario, in some previous phase, PSR 2127+11C must have been in a binary system with a non-degenerate companion. We rule out PSR 2127+11C being a primordial binary because the formation of such systems is inevitably associated with a large systemic motion ($\gtrsim 200\,\mathrm{km\,s}^{-1}$) (Cordes and Dewey 1988; Dewey and Cordes 1987; Verbunt and Hut 1987) which would have resulted in the expulsion from the cluster. Consequently, the companion is likely the result of a capture interaction. Alternatively, PSR 2127+11C could have been a solitary, spun-up pulsar (like PSR 2127+11B) which experienced an exchange collision with a binary system. The large observed eccentricity indicates that an exchange may have taken place recently.

Various authors have argued for a scenario of pulsar formation by accretion-induced collapse (AIC) of white dwarfs (Michel 1987; Chanmugam and Brecher 1987; Bailyn and Grindlay 1990). AIC scenarios invoke massive C+O white dwarfs or O-Ne-Mg white dwarfs and thus, even if AIC mechanism were to be operative, see (Verbunt, Lewin, and van Paradijs 1989) for a discussion of the considerable theoretical and observational difficulties with this mechanism), the discovery of PSR 2127+11C implies an abundance of these white dwarfs. Such white dwarfs evolve from massive main-sequence stars ($M \lesssim 8\,\mathrm{M}_\odot$). Thus in the framework of either the standard or the AIC model we conclude that, in the past, M15 contained many massive stars. To achieve reasonable rates for exchange or capture interactions, the remnants of these massive stars must have aggregated in the core of M15 by mass segregation. Enen taking this effect into account, very steep initial mass functions ($\propto M^{-\alpha}$, $\alpha \geq 3.5$) are ruled out for M15 because they predict insufficient numbers of massive white dwarfs and neutron stars. A flatter IMF also explains the large abundance of pulsars inferred from other observations (Kulkarni, Narayan, and Romani 1990). However, we note that some recent theoretical studies (Chernoff and Weinberg 1990) suggest steep IMFs for most clusters which survive to the present date.

Most tidal-capture binaries, i.e., captures resulting from the transfer of kinetic energy to stellar deformation, are expected to be formed with an orbital radius of $\sim \mathrm{R}_\odot$, and thus an orbital period of a fraction of day. A small fraction (10% to 30%) are expected to be wide binaries ($P_{orb} \sim 100\,\mathrm{d}$) formed by capture of giants. The formation of single pulsars like 2127+11A,B is easily understood as resulting from the breakup of a wide binary by passing stars (Verbunt *et al.* 1987; Romani, Kulkarni, and Blandford 1987). Rappaport, Putney, and Verbunt (1989) have shown this to be a very effective mechanism for breaking up wide binaries in the especially high-density collapsed core of M15. The tidal interaction model predicts that there should be between 3 to 10 times more compact binaries than isolated or wide-orbit binaries, whereas we detected only one compact binary and two isolated pulsars. Selection effects may have prevented detection of a larger number of short orbital period systems in our current survey. A quantitative analysis of selection effects is beyond the scope of this letter and will be presented elsewhere.

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