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## MEASUREMENT OF ORBITAL DECAY IN THE DOUBLE NEUTRON STAR BINARY PSR B2127+11C

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### ABSTRACT

We report the direct measurement of orbital period decay in the double neutron star pulsar system PSR B2127+11C in the globular cluster M15 at the rate of  $(-3.95 \pm 0.13) \times 10^{-12}$ , consistent with the prediction of general relativity at the  $\sim 3\%$  level. We find the pulsar mass to be  $m_p = 1.358 \pm 0.010 M_\odot$  and the companion mass  $m_c = 1.354 \pm 0.010 M_\odot$ . We also report long-term pulse timing results for the pulsars PSR B2127+11A and PSR B2127+11B, including confirmation of the cluster proper motion.

*Subject headings:* binaries: close — globular clusters: individual (M15) — gravitation — pulsars: individual (PSR B2127+11A, PSR B2127+11B, PSR B2127+11C)

### 1. INTRODUCTION

Pulsars in binary systems with neutron star companions provide the best available laboratories for testing theories of gravity. To date, two such systems have been used for such tests: PSR B1913+16 (Taylor & Weisberg 1982, 1989), and PSR B1534+12 (Stairs et al. 1998, 2002). Both are consistent with Einstein’s general relativity (GR).

The globular cluster M15 (NGC 7078) contains eight known radio pulsars, the brightest of which are PSR B2127+11A (hereafter M15A), a solitary pulsar with a 110.6 ms spin period; PSR B2127+11B (M15B), a solitary 56.1 ms pulsar; and PSR B2127+11C (M15C), a 30.5 ms pulsar in a relativistic 8 hr orbit with another neutron star (Wolszczan et al. 1989; Anderson 1992). The Keplerian orbital parameters of M15C are nearly identical to those of PSR B1913+16, although the former did not follow the standard high-mass binary evolution (Anderson et al. 1990). With our data set spanning 12 years, M15C now provides a similar test of GR.

### 2. OBSERVATIONS AND ANALYSIS

We observed M15 with the 305 m Arecibo radio telescope from 1989 April to 2001 February, with a gap in observations between 1994 February and 1998 December roughly corresponding to a major upgrade of the telescope. All observations used the 430 MHz line feed, with 10 MHz of bandwidth centered on 430 MHz.

Observations up to 1994 January were made with the Arecibo three-level autocorrelation spectrometer (XCOR), which provided 128 lags in each of two circular polarizations and  $506.625 \mu\text{s}$  time resolution. The autocorrelation functions were transformed to provide 128 frequency channels across the band, and these data were dedispersed at the appropriate dispersion measure (DM; Anderson 1992) and folded synchronously with the pulse period for each pulsar. Observations were broken into sub-

integrations of 10 minutes for M15A and M15C and 20 minutes for the fainter M15B.

Beginning in 1999 January, we used the Caltech Baseband Recorder (CBR) for data acquisition. This backend sampled the telescope signal in quadrature with two-bit resolution and wrote the raw voltage data to tape for off-line analysis with the Hewlett-Packard Exemplar machine at the Caltech Center for Advanced Computing Research. After unpacking the data and correcting for quantization effects (Jenet & Anderson 1998), we formed a virtual 32-channel filterbank in the topocentric reference frame with each channel coherently dedispersed at the DM of M15C (Hankins & Rickett 1975; Jenet et al. 1997). The coherent filterbank data were then dedispersed and folded for each pulsar as for the XCOR data.

The folded pulse profiles were cross-correlated against a high signal-to-noise ratio standard profile appropriate to the pulsar and backend (Fig. 1) to obtain an average pulse time of arrival (TOA) for each subintegration, corrected to UTC (NIST). The standard pulsar timing package TEMPO,<sup>5</sup> along with the Jet Propulsion Laboratory’s DE405 ephemeris, was used for all timing analysis. TOA uncertainties estimated from the cross-correlation process were multiplied by a constant determined for each pulsar-instrument pair in order to obtain reduced  $\chi^2 \approx 1$ . An arbitrary offset was allowed between the XCOR and CBR data sets to account for differences in instrumental delays and standard profiles. The timing models resulting from our analysis are presented in Table 1, and postfit TOA residuals relative to these models are shown in Figure 2. All stated and depicted uncertainties correspond to 68% confidence.

### 3. DISCUSSION

#### 3.1. Post-Keplerian Observables for M15C

In addition to the five usual Keplerian orbital parameters, in the case of M15C we have measured three post-Keplerian (PK) parameters: advance of periastron ( $\dot{\omega}$ ), time dilation and gravitational redshift ( $\gamma$ ), and orbital period derivative ( $\dot{P}_b$ ). The dependence of these PK parameters on the Keplerian parameters and component masses depend on the theory of gravity;

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<sup>5</sup> See <http://pulsar.princeton.edu/tempo>.

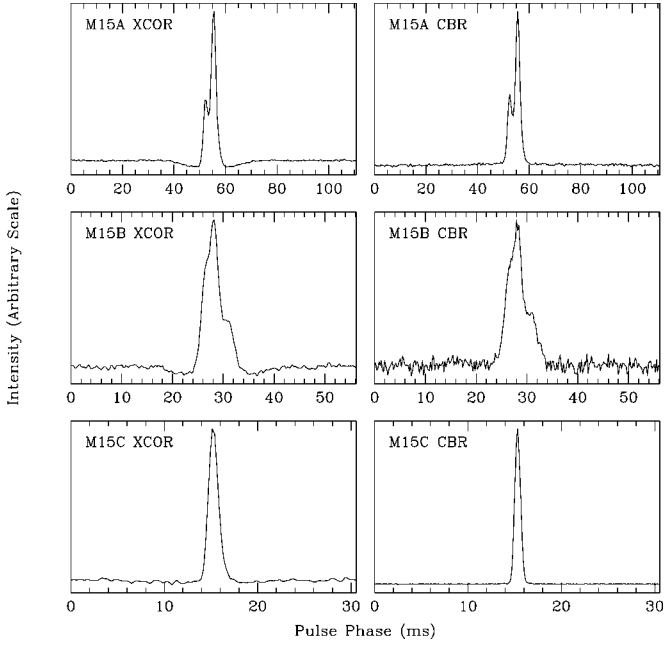


FIG. 1.—Average pulse profiles for three pulsars in M15. Average pulse profiles of M15A (top row), M15B (middle row), and M15C (bottom row) as observed with XCOR (left column) and CBR (right column). The negative dips preceding and following the main pulse in the XCOR pulse profiles are an artifact of the correlator’s coarse three-level quantization; this distortion has been corrected in the CBR data (Jenet & Anderson 1998).

in GR, these relations are (see Taylor & Weisberg 1982; Damour & Deruelle 1986; and Damour & Taylor 1992)

$$\dot{\omega} = 3G^{2/3}c^{-2}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-1}M^{2/3}, \quad (1)$$

$$\gamma = G^{2/3}c^{-2}e\left(\frac{P_b}{2\pi}\right)^{1/3}m_c(m_p + 2m_c)M^{-4/3}, \quad (2)$$

$$\begin{aligned} \dot{P}_b = & -\frac{192\pi}{5}G^{5/3}c^{-5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)^{-7/2} \\ & \times \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)m_pm_cM^{-1/3}, \end{aligned} \quad (3)$$

where  $G$  is the gravitational constant and  $c$  is the speed of light. The measurement of any two PK observables determines the component masses under the assumption that GR is the correct description of gravity; measuring the third parameter overdetermines the system and allows a consistency test of GR.

### 3.2. Kinematic Effects on Pulse Timing

The rate of change of orbital period that we observe in the M15C system,  $(\dot{P}_b)^{\text{obs}}$ , is corrupted by kinematic effects that must be removed to determine the intrinsic rate,  $(\dot{P}_b)^{\text{int}}$ . Following the discussion of Phinney (1992, 1993) regarding the parallel case of kinematic contributions to  $\dot{P}$ , we have

$$\begin{aligned} \left(\frac{\dot{P}_b}{P_b}\right)^{\text{kin}} = & \\ -\frac{v_0^2}{cR_0} \left( \cos b \cos l + \frac{\delta - \cos b \cos l}{1 + \delta^2 - 2\delta \cos b \cos l} \right) + \frac{\mu^2 d}{c} - \frac{a_l}{c}, \end{aligned} \quad (4)$$

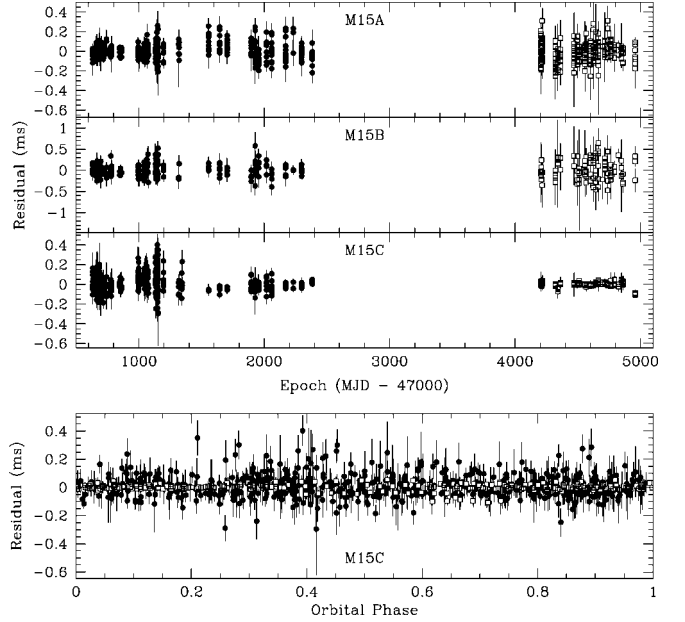


FIG. 2.—Timing residuals of M15A, M15B, and M15C. Residuals for each pulsar vs. observation epoch are shown in the top three panels, with M15C residuals vs. orbital phase in the bottom panel. Filled circles represent XCOR observations, and open squares indicate CBR data.

where  $v_0 = 220 \pm 20 \text{ km s}^{-1}$  is the Sun’s Galactic rotation velocity,  $R_0 = 7.7 \pm 0.7 \text{ kpc}$  is the Sun’s galactocentric distance,  $\delta \equiv d/R_0$ ,  $\mu$  is the proper motion,  $d = 9.98 \pm 0.47 \text{ kpc}$  is the distance to the pulsar (McNamara et al. 2004), and  $a_l$  is the pulsar’s line-of-sight acceleration within the cluster. The first term in equation (4) is due to the pulsar’s Galactic orbital motion, the second to the secular acceleration resulting from the pulsar’s transverse velocity (Shklovskii 1970), and the third to the cluster’s gravitational field.

Acceleration within the cluster may well dominate the kinematic contribution to  $\dot{P}_b$ , but  $a_l$  is an odd function of the distance from the plane of the sky containing the cluster center to the pulsar, and since we do not know if M15C is in the nearer or farther half of the cluster, we must use its expectation value,  $\bar{a}_l = 0$ . Phinney (1993) calculates a maximum value of  $|a_l|_{\text{max}}/c = 6 \times 10^{-18} \text{ s}^{-1}$ , too small for the observed  $\dot{P}$  to provide a useful constraint. However, the unknown  $a_l$  still dominates the uncertainty of  $(\dot{P}_b)^{\text{kin}}$ ; we take the median value of  $0.71 |a_l|_{\text{max}}$  as the uncertainty in  $a_l$  (Phinney 1992). Evaluating equation (4), the total kinematic contribution is

$$(\dot{P}_b)^{\text{kin}} = (-0.01 \pm 0.12) \times 10^{-12}, \quad (5)$$

and subtracting this contamination from  $(\dot{P}_b)^{\text{obs}}$  yields the intrinsic value

$$(\dot{P}_b)^{\text{int}} = (-3.95 \pm 0.13) \times 10^{-12}. \quad (6)$$

### 3.3. Component Masses of M15C and a Test of General Relativity

Solving equations (1) and (2) given the measured values of  $\dot{\omega}$ ,  $\gamma$ ,  $P_b$ , and  $e$  gives  $m_p = 1.358 \pm 0.010 M_\odot$ ,  $m_c = 1.354 \pm 0.010 M_\odot$ , and  $M \equiv m_p + m_c = 2.71279 \pm 0.00013 M_\odot$  in the framework of GR (Fig. 3). This result is consistent with, and more precise than, previous mass measurements for the neutron stars in

TABLE 1  
PULSAR PARAMETERS FOR B2127+11A–C

PARAMETER <sup>a</sup>	PULSAR		
	B2127+11A	B2127+11B	B2127+11C
Right ascension, $\alpha_{J2000.0}$ .....	21 <sup>h</sup> 29 <sup>m</sup> 58 <sup>s</sup> .2472(3)	21 <sup>h</sup> 29 <sup>m</sup> 58 <sup>s</sup> .632(1)	21 <sup>h</sup> 30 <sup>m</sup> 01 <sup>s</sup> .2042(1)
Declination, $\delta_{J2000.0}$ .....	+12°10′01″.264(8)	+12°10′00″.31(3)	+12°10′38″.209(4)
Proper motion in $\alpha$ , $\mu_\alpha$ (mas yr <sup>-1</sup> ) .....	-0.26(76)	1.7(33)	-1.3(5)
Proper motion in $\delta$ , $\mu_\delta$ (mas yr <sup>-1</sup> ) .....	-4.4(15)	-1.9(59)	-3.3(10)
Pulse period, $P$ (ms) .....	110.66470446904(5)	56.13303552473(9)	30.52929614864(1)
Reference epoch (MJD) .....	50000.0	50000.0	50000.0
Period derivative, $\dot{P}$ (10 <sup>-15</sup> ) .....	-0.0210281(2)	0.0095406(6)	0.00498789(2)
Period second derivative, $\ddot{P}$ (10 <sup>-30</sup> s <sup>-1</sup> ) .....	32(5)	...	-2.7(13)
Dispersion measure, DM (pc cm <sup>-3</sup> ) .....	67.31	67.69	67.12
Binary model .....	...	...	DD
Orbital period, $P_b$ (days) .....	...	...	0.33528204828(5)
Projected semimajor axis, $a \sin i$ (lt-s) .....	...	...	2.51845(6)
Orbital eccentricity, $e$ .....	...	...	0.681395(2)
Longitude of periastron, $\omega$ (deg) .....	...	...	345.3069(5)
Time of periastron, $T_0$ .....	...	...	50000.0643452(3)
Advance of periastron, $\dot{\omega}$ (deg yr <sup>-1</sup> ) .....	...	...	4.4644(1)
Time dilation and gravitational redshift, $\gamma$ (s) .....	...	...	0.00478(4)
Orbital period derivative, $(\dot{P}_b)^{\text{obs}}$ (10 <sup>-12</sup> ) .....	...	...	-3.96(5)
Weighted rms timing residual ( $\mu$ s) .....	58.9	103.5	26.0
Derived Parameters			
Orbital period derivative, $(\dot{P}_b)^{\text{int}}$ (10 <sup>-12</sup> ) .....	...	...	-3.95(13) <sup>b</sup>
Pulsar mass, $m_p$ ( $M_\odot$ ) .....	...	...	1.358(10)
Companion mass, $m_c$ ( $M_\odot$ ) .....	...	...	1.354(10)
Total mass, $M = m_p + m_c$ ( $M_\odot$ ) .....	...	...	2.71279(13)
Galactic longitude, $l$ (deg) .....	65.01	65.01	65.03
Galactic latitude, $b$ (deg) .....	-27.31	-27.31	-27.32
Transverse velocity, $v_\perp$ (km s <sup>-1</sup> ) <sup>c</sup> .....	210(70)	120(230)	170(40)
Intrinsic period derivative, $\dot{P}_{\text{int}}$ (10 <sup>-15</sup> ) <sup>b</sup> .....	...	...	0.00501(5)
Surface magnetic field, $B_{\text{surf}}$ (10 <sup>10</sup> G) <sup>b</sup> .....	...	...	1.237(6)
Characteristic age, $\tau_c$ (Gyr) <sup>b</sup> .....	...	...	0.097(1)

<sup>a</sup> Figures in parenthesis are 1  $\sigma$  (68%) uncertainties in the last digit quoted. Uncertainties are calculated from twice the formal error produced by TEMPO.

<sup>b</sup> Corrected for kinematic effects as described in § 3.2.

<sup>c</sup> Based on the distance measurement of McNamara et al. (2004).

the M15C system (Prince et al. 1991; Anderson 1992; Deich & Kulkarni 1996). We note that these masses are consistent with the masses of double neutron star binaries observed in the field (Thorsett & Chakrabarty 1999; Stairs 2004). M15 is a metal-poor cluster with a mean metallicity  $[\text{Fe}/\text{H}] = -2.3$  (Snedden et al. 1991), suggesting that the mass of neutron stars is not a strong function of the metallicity of their progenitors.

Our determination of a third PK parameter gives a test of GR;  $(\dot{P}_b)^{\text{int}}$  is  $1.003 \pm 0.033$  times the predicted value. While M15C provides an impressive test of GR, it is less stringent than the 1%  $\dot{\omega}$ - $\dot{P}_b$  test provided by PSR B1913+16 (Taylor & Weisberg 1989) and the 0.5%  $\dot{\omega}$ - $\dot{P}_b$  test provided by PSR B1534+12 (Stairs et al. 2002), where  $s \equiv \sin i$  is the shape parameter determined through measurement of Shapiro delay. We note that the uncertainty in the intrinsic orbital period decay is due almost entirely to the kinematic contribution, so further observations will not significantly improve our determination of  $(\dot{P}_b)^{\text{int}}$  or the quality of the test of GR it allows.

### 3.4. Proper Motion of M15

The proper motions resulting from our timing analysis give absolute transverse velocities for M15A and M15C several times greater than the cluster escape velocity. The measured proper motions for these two pulsars and M15B are shown in Figure 4, along with four published proper motion measurements for M15 based on optical astrometry. The pulsar proper motions are all consistent with each other; their average is  $\mu_\alpha = -1.0 \pm 0.4$  mas yr<sup>-1</sup>,  $\mu_\delta = -3.6 \pm 0.8$  mas yr<sup>-1</sup>. This result

is in good agreement with the cluster measurement of Cudworth & Hanson (1993).

### 3.5. Intrinsic Spin Period Derivatives

If we assume that GR provides the correct description of gravity, we can use  $(\dot{P}_b)^{\text{obs}}$  to determine the total kinematic correction to  $\dot{P}_b$  and, hence, to  $\dot{P}$  for M15C. We find

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{GR}}^{\text{kin}} = \left(\frac{\dot{P}_b}{P_b}\right)_{\text{GR}} = (-8 \pm 17) \times 10^{-19} \text{ s}^{-1}, \quad (7)$$

which corresponds to  $a_t/c = (4 \pm 17) \times 10^{-19} \text{ s}^{-1}$ . We now apply this correction to the observed value of  $\dot{P}$  and find the intrinsic value assuming GR,  $(\dot{P}_{\text{GR}})^{\text{int}} = (0.00501 \pm 0.00005) \times 10^{-15}$ . This intrinsic spin-down rate allows us to improve on the previous estimate of the pulsar's characteristic age and magnetic field strength (Anderson 1992); we find  $\tau_c = 0.097 \pm 0.001$  Gyr and  $B_{\text{surf}} = (1.237 \pm 0.006) \times 10^{10}$  G.

Our timing models for M15A and M15C include  $\ddot{P}$  (Table 1), which is unlikely to be intrinsic to the pulsars. For M15A in the cluster core, Phinney (1993) estimates the kinematic contribution to be  $|\dot{a}_t/c| \equiv |\dot{P}/P| \leq 10^{-26} \text{ s}^{-1}$  (80% confidence). This is significantly larger than the observed  $|\dot{P}/P| \sim 3 \times 10^{-28} \text{ s}^{-1}$ , so the observed  $\dot{P}$  is consistent with the expected jerk resulting from the cluster's mean field and nearby stars. For M15C, far from the cluster core, we measure  $|\dot{P}/P| \sim 10^{-28} \text{ s}^{-1}$ . We note that our measurement of  $\dot{P}$  in M15C is not of high significance

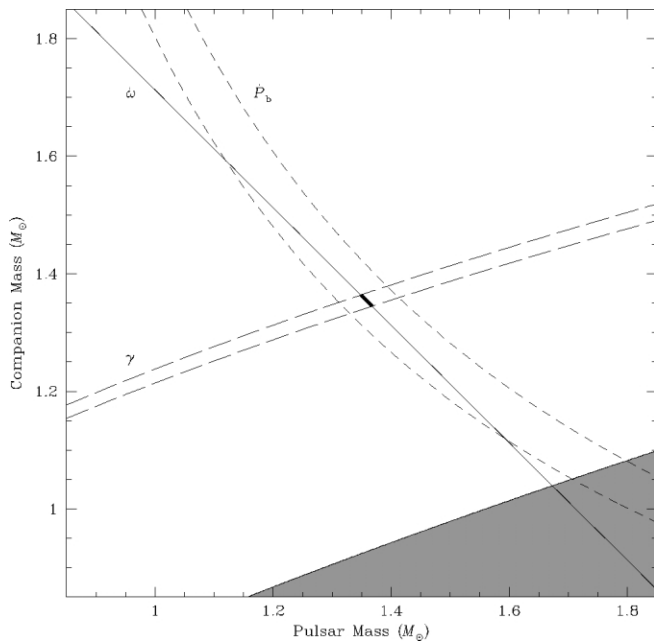


FIG. 3.—M15C mass-mass diagram. The constraints on the pulsar and companion masses in GR from the measured values of  $\gamma$  (long-dashed lines),  $\dot{\omega}$  (solid lines), and intrinsic  $P_b$  (short-dashed lines) are shown. The allowed region in mass-mass space at the intersection of these constraints is denoted by a heavy line segment near the center of the plot. The shaded region is excluded by Kepler's laws. The intersection of the constraints from the three post-Keplerian observables indicates that the behavior of this system is consistent with GR.

( $\sim 2\sigma$ ) and may be an artifact of the systematic trends apparent in our timing data (Fig. 2).

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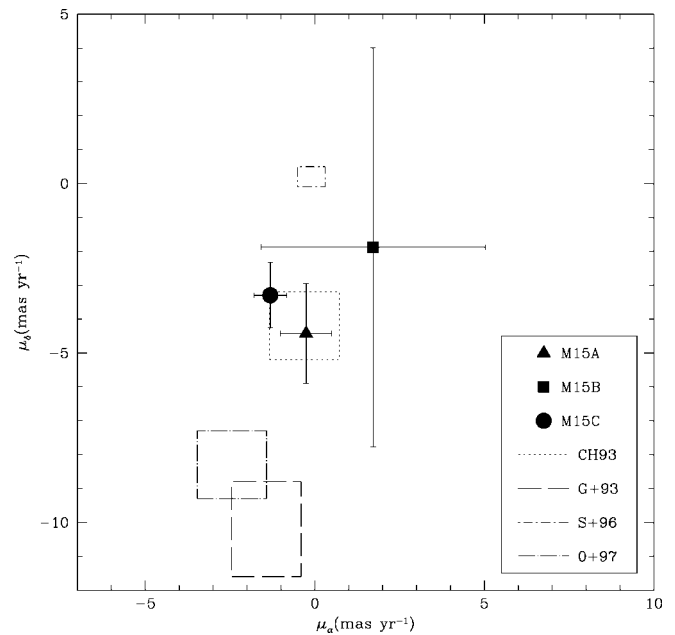


FIG. 4.—Proper motion of M15. We show the measured proper motions of M15A, M15B, and M15C in right ascension and declination, with rectangular regions indicating the published cluster proper motion measurements of Cudworth & Hanson (1993; CH93), Geffert et al. (1993; G+93), Scholz et al. (1996; S+96), and Odenkirchen et al. (1997; O+97).

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