PSR J0636+5128: A Heated Companion in a Tight Orbit

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Abstract

We present an analysis of archival Gemini g', r', K and Keck H, Ks imaging of this nearby short-period binary (\(P_B = 5.8\) minutes) 2.87 ms pulsar. The heated companion is clearly detected. Direct pulsar heating provides an acceptable model at the revised >700 pc parallax distance. The relatively shallow light curve modulation prefers an inclination \(i < 40\)°; this high-latitude view provides a likely explanation for the lack of radio signatures of wind dispersion or eclipse. It also explains the low minimum companion mass and, possibly, the faintness of the source in X-rays and \(\gamma\)-rays.

Key words: gamma rays: stars – pulsars: general – pulsars: individual (PSR J0636+5128)

1. Introduction

PSR J0636+5128 (hereafter J0636) is a \(P = 2.87\) millisecond pulsar (MSP) binary discovered in the Green Bank Northern Celestial Cap Pulsar Survey (Stovall et al. 2014). It was originally designated PSR J0636+5129, but improved timing astrometry requires an official name change. It has the third shortest orbital period (\(P_B = 5750\) s) of any confirmed pulsar binary, and a small mass function indicating a minimum companion mass \(m_{c,\text{min}} = 0.0070\, M_\odot\). This is likely a member of the “black widow” (BW) class of evaporating pulsars, although no radio eclipses or orbital modulation of dispersion measure (DM) are seen. With DM = 11.1 cm\(^{-3}\) pc one infers a distance of \(\sim 500\) pc (NE2001, Cordes & Lazio 2002). A recent timing parallax indicates \(d > 700\) pc Arzoumanian et al. (2018), so the Stovall et al. (2014) parallax estimate of \(d = 203\pm 11\) pc was evidently in error. The proper motion is small and the Shklovskii-corrected spindown power is \(E = 5.6 \times 10^{33}\) J s\(^{-1}\), for a neutron star moment of inertia \(10^{35} I_{55}\) g cm\(^2\). This is a relatively low spindown power for a companion-evaporating pulsar. The binary is detected in the X-rays by Chandra, but must be relatively faint in the \(\gamma\)-rays as it is not in the 8 years Fermi Large Area Telescope catalog (FL8Y).

We found observations of the field of the pulsar in the Keck and Gemini archives. The companion is clearly detected at the radio-determined position, is brightest at the expected maximum phase, and is substantially variable (Figure 1). We used these data to measure and fit the companion light curve.

2. Archival Data—Optical GMOS Images

The Gemini Science archive contained 10 420 g' exposures and nine 420 s r' images, taken on 2014 December 21 under program GN-2014B-Q-81 (PI: K. Stovall). Images in the two bands had FWHM median 0"91 and 0"89, respectively. We downloaded these data along with associated calibration frames and standard fields from the Gemini archive and subject them to standard Gemini IRAF calibrations. All frames were registered to a common position and we performed Gaussian-weighted aperture photometry at the maximum light pulsar position. After some experimentation to optimize the signal-to-noise ratio (S/N), we adopted a Gaussian weight \(\sigma = 1.4\times\) the individual frame’s FWHM and an extraction aperture 1.7\times\) this FWHM; we used a local annular background. We calibrated by using matched weighted extractions of field stars, whose g' and r' magnitudes were determined from the Sloan Digital Sky Survey (SDSS) catalog. The pulsar was detected in all frames with reasonable statistical significance. However, a faint extended source, likely a background galaxy, lies \(\sim 1/5\) to the southwest (SW; Figure 1, lower left panel). In the g' frame at minimum, which suffered relatively poor seeing, this may provide a systematic contamination, so our measurement might best be considered an upper limit (Figure 2). We estimate the zero point errors as \(\lesssim 0.03\) mag, insignificant except for the very highest S/N points.

After barycentering the time of the frame midpoints, we plotted the measured magnitudes folded on the orbital ephemeris of Stovall et al. (2014; Figure 2). The source is brightest at pulsar inferior conjunction (\(\phi_0 = 0.75\)) when we are best viewing the heated face of the companion. The orbital coverage is incomplete, and there appear to be fluctuations about the overall quasi-sinusoidal modulation.

3. Archival Data—Near-infrared (IR) Gemini NIRI and Keck NIRC2

The same Gemini program includes 60 s K integrations, taken with NIRI+AO+LGS on 2014 November 05 (21 exposures) and December 08 (24 usable exposures). The typical (adaptive optics (AO)-assisted) FWHM were 0"19 and 0"14 on the two nights. Again optimal extraction provided estimated photometry for the two nights. The K magnitudes were calibrated against the \(K = 1.38\) star Two Micron All-Sky Survey (2MASS) J06360673+5129070. In a few frames this star was saturated or too near the image edge and so we bootstrapped the calibration via objects common to the unsaturated frames.

The Keck archive contained NIRC2+AO frames of the field (program C222N2L, PI: Kulkarni) with \(27 \times 60\) s in \(H\) and \(28 \times 60\) s in \(K\) taken on 2013 March 1. The frame FWHM was 0"18–0"21 in \(H\) and 0"14–0"19 in \(K\). For these data relative unweighted aperture photometry proved to be the most stable. Again we calibrated against 2MASS J06360673+5129070, correcting for the slow transparency variations through the observation.

The near-IR fluxes still showed occasional outliers, even after this flux calibration. Accordingly, we chose to adopt the median of each set of three images in the IR pointing dithers. In
Figure 1. Upper left panel: NIRC2 K image of PSR J0636+5128 (median of frames). Lower left panel: GMOS r image at maximum. Upper right panel: GMOS g image at maximum. Lower right panel: GMOS g image at minimum.

Figure 2. GMOS-N/NIRI/NIRC2 light curves. The data are phased to the ephemeris of Stovall et al. (2014), with \( \phi = 0 \) at the pulsar ascending node; two periods are plotted for clarity. For the second period, the infrared points are the medians of the magnitudes during individual dither pointings. The model is an ICARUS direct heating fit to the data. Note the appreciable data fluctuations about the light curves, suggesting variability or finer substructure.

Figure 2. The near-IR light curves show the individual points in the first cycle and the median points in the second period. Together, the Gemini and Keck K magnitudes cover nearly a full orbit. Where these overlap, the Keck magnitudes appear fainter, but with substantial scatter. Given the evident variation about the sinusoidal light curve, we cannot differentiate between photometric errors or companion brightening. The overall K light curve, however, has a shallow minimum at phase \( \phi = 0.25 \).

With \( \Delta m < 2 \) mag the optical light curves are relatively shallow for a classical BW. However, the deeper modulation in the g’ band gives the signature of companion heating. The light curves show evidence of non-sinusoidal variability in all four bands. Some short-period companion-evaporating pulsars show stochastic variability, likely due magnetic flares on the companions (Romani et al. 2015). So until we have many

\[ \text{Table 1 Binary Model Fits} \]

| Parameter | Direct | IBS-B |
|-----------|--------|-------|
| \( i \) (deg) | 24 ± 2 | 40 ± 6 |
| \( f_{d1} \) | 0.83 ± 0.10 | 0.97 ± 0.08 |
| \( L_{d1}/10^{32} \text{erg s}^{-1} \) | 9.0 ± 0.2 | 8.0 ± 0.4 |
| \( L_{d2}/10^{30} \text{erg s}^{-1} \) | 1.1 ± 0.4 | |
| \( T_{L} (\text{K}) \) | 2420 ± 220 | 2650 ± 340 |
| \( d \) (kpc) | 1.06 ± 0.05 | 0.99 ± 0.05 |
| \( \chi^2 (\chi^2/\nu) \) | 106 (2.04) | 84 (1.75) |
| \( T_{\nu} (\text{K}) \) | 3890 | 3880 |
| \( M_e (M_\odot) \) | 0.019 | 0.013 |
| \( R_e (R_\odot) \) | 0.104 ± 0.013 | 0.093 ± 0.005 |
| \( q \) | 81.6 | 132. |
| \( K(\text{km s}^{-1}) \) | 250 | 399 |

Notes.
\( ^a \) Magnetic axis at \( \theta_B = 22^\circ ± 5^\circ, \phi_B = 229^\circ ± 8^\circ \).
\( ^b \) Flux-averaged "day"-side temperature.
\( ^c \) Volume equivalent radius in \( R_e \) for \( f_{d1} \).
\( ^d \) Expected K-band radial velocity for \( M_{\text{NS}} = 1.5 M_\odot \).

orbits of J0636 photometry, we cannot establish a full quiescence light curve.

4. System Modeling and Conclusions

We fit these data with the ICARUS modeling code (Breton et al. 2013), optionally including the extensions to compute the IntraBinary Shock (IBS) and its radiative heating (Romani & Sanchez 2016) and the ducting of IBS particles to the companion surface by magnetic fields (Sanchez & Romani 2017). The extinction in this direction is modest, with the Green et al. (2015) dust maps giving \( A_V \approx 0.22 \pm 0.06 \) at 0.5 kpc and \( \approx 0.26 \pm 0.06 \) by 1.0 kpc. The basic fit considers direct illumination by the pulsar. Lacking optical radial velocity information, we do not have enough constraints for a meaningful fit to the neutron star mass, so it is fixed at \( M_{\text{NS}} = 1.5 M_\odot \). The primary fit parameters are the inclination \( i \), the distance \( d \), the Roche lobe fill factor \( f_{d1} \) (ratio of nose radius to the \( L_1 \) position, which determines the companion radius), \( T_{\nu} \) the temperature of the unheated (Night) side of the companion, and \( L_d \) the direct heating power.

The basic fit is summarized in Table 1. A distance \( d > 1 \) kpc is preferred. If \( A_V \) is allowed to vary it tends toward zero, so we fix it at the lower limit for the 1 kpc distance. The model requires a small inclination \( i < 30^\circ \) to match the shallow light curve. The fill factor gives a companion radius (volume equivalent Roche lobe radius) of 0.10 \( R_\odot \). The direct heating power \( \sim 9 \times 10^{32} \text{erg s}^{-1} \) is comfortably less than the spin-down power \( 5.6 \times 10^{33} \text{erg s}^{-1} \). This fit is quite satisfactory except for the relatively large \( \chi^2/\nu \approx 2 \), evidently the result of the substantial scatter especially in the K points.

In evaluating this fit, we should check consistency with other observables. First, the relatively large distance is consistent with the revised parallax. At this distance the companion flux gives a radius 0.10 \( R_\odot \). BW companions appear to be inflated by the heating and should hence be somewhat larger than the \( R = 0.0126 (M/M_\odot)^{-1/2} R_\odot \) radius of a cold (degenerate) H-poor remnant of a stellar core. With our fit inclination \( i \) and the pulsar \( x_0 = a_0 \sin i = 0.00899 \text{lt-s} \) one obtains a mass \( M_e = 0.019 M_\odot \). This would have a minimum cold radius 0.047 \( R_\odot \), so the companion is appreciably inflated. Thus, the
observed rather low $x_2$ and minimum companion mass is a result of the low inclination $i$; the actual companion mass is quite typical of other BW pulsars.

Note that the original parallax estimate of 203 pc is impossible to accommodate in a direct heating model, as to match the observed companion flux and maximum temperature the effective radius of the star would be 0.019 $R_\odot$, less than half the size of smallest plausible (cold degenerate) radius. This supports the general conclusion of Sanchez & Romani (2017) that direct heating models often indicate relatively large distances and luminosities. There we showed that if the heating is particle-mediated and the particles precipitate to a magnetic cap, smaller luminosities and distances are acceptable.

The absence of a source at this position in the Third Fermi-LAT Gamma-ray Source Catalog (3FGL; Acero et al. 2015) or FLSY surveys gives an upper limit on the gamma-ray flux (the dominant radiative output) of $f_\gamma < 5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. If the pulsar were an isotropic emitter, then we would infer a gamma-ray heating power (at $d = 1.07$ kpc) $< 7 \times 10^{32}$ erg s$^{-1}$. This is slightly less than the required direct heating. However, there is good evidence (e.g., Watters et al. 2009) that pulsar $\gamma$-rays are preferentially beamed toward the spin equator. If, as expected, the pulsar is spin-aligned with the binary orbit at our inferred high inclination, the Earth should detect a lower gamma-ray flux than that illuminating the companion.

Spiewak et al. (2016) detected the pulsar system in a 15 ks X-ray Multi-Mirror Mission (XMM) exposure. The limited X-ray counts do not allow a detailed spectral analysis, but with an assumed $N_H = 3.3 \times 10^{20}$ cm$^{-2}$ (consistent with DM and $A_V$), they infer a power law index $\Gamma = 2.6$ and an unabsorbed flux $f_{2-10\, \text{keV}} = 5.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. At the 203 pc distance, this would have been an anomalously low X-ray luminosity, but at our optically fit distance the inferred $L_{2-10\, \text{keV}} = 7 \times 10^{29}$ erg s$^{-1}$ is low but within the dispersion of the $L_X - E$ relations of Possenti et al. (2002) and Li et al. (2008). As this $\Gamma$ is relatively large for BW non-thermal emission, the observed X-spectrum may be composite, with soft emission from a heated polar cap contributing at low energies. Deeper X-ray exposure will be needed to make a detailed spectral measurement and to constrain possible orbital modulation.

The relatively large $\chi^2$/DoF of the fit implies that something must be present in addition to the simple direct heating. IBS-accelerated particles may be significant, and $\chi^2$ can be lowered at the cost of additional parameters. Table 1 includes an example IBS fit, where in addition to direct heating we have a typical IBS front ($\beta = 0.2$, ratio of companion wind momentum to pulsar wind momentum) interacting with a companion magnetic field (dipole axis at $\theta_B = 29^\circ$ to the line of centers). Although the model does have an improved $\chi^2$/DoF, the fit is not especially compelling as small-scale variations in the light curve are not matched. The general conclusions of the direct heating fit are preserved, with a small inclination angle, acceptable direct heating flux, $\sim$kpc distance, and substantial filling factor suggesting companion inflation. The particle heating is a small fraction of the direct (gamma-ray) luminosity.

The measured flux departures from the basic heating model look largely random. Clearly we will require many orbits of high-quality photometry to see what emission is variable and what is systematic. One intriguing feature is the excess at $\phi = 0.1$–0.2, with high points in $g$ and $r$ and a (variable?) excess in $K$. This is too narrow to be thermal emission from a hot spot. However, if the IBS itself radiates sufficient optical synchrotron flux, one may have narrow peaks from the emission beamed from the relativistic plasma flowing on the IBS surface. Such emission would, however, tend to be weak at the low $i$ indicated by the surface heating.

In the present fits, the high-latitude view means that the Earth line-of-sight apparently passes above the equatorial ionized outflow from the companion wind, so no radio eclipses are seen. The small $i$ also implies a mass ratio $q \sim 100$ and a relatively large companion mass. This (despite the short orbital period) makes it more likely that the binary is a classical BW rather than the extreme mass ratio ($q \sim 200$) Tidarren’s-like PSR J1311–3430 (Romani et al. 2016). With J0636’s faint optical magnitude and low temperature, a spectral check of the prime Tidarren signature (an H-free atmosphere) is likely not feasible. However near-IR spectra might be able to provide a radial velocity, which can help constrain the system mass and inclination; predicted values for the models are given in the table. Higher S/N multicolor photometry, especially with multiple epochs to isolate the quiescence light curve, can also help in understanding heating in this very short-period system.

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