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DISCOVERY OF THE OPTICAL COUNTERPARTS TO FOUR ENERGETIC *FERMI* MILLISECOND PULSARSR. P. BRETON^{1,2}, M. H. VAN KERKWIJK², M. S. E. ROBERTS^{3,4}, J. W. T. HESSELS^{5,6}, F. CAMILO^{7,8},
M. A. McLAUGHLIN^{9,13}, S. M. RANSOM¹⁰, P. S. RAY¹¹, AND I. H. STAIRS¹²¹ School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK; r.breton@soton.ac.uk² Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada³ Eureka Scientific Inc., 2452 Delmer Street, Suite 100, Oakland, CA 94602-3017, USA⁴ Ithaca College, 205 Williams Hall, Ithaca, NY 14850, USA⁵ ASTRON, The Netherlands Institute for Radio Astronomy, Postbus 2, 7990-AA Dwingeloo, The Netherlands⁶ Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Science Park 904, 1098-XH Amsterdam, The Netherlands⁷ Columbia Astrophysics Laboratory, Columbia University, 550 West, 120th Street, New York, NY 10027, USA⁸ Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612, USA⁹ Department of Physics, White Hall, West Virginia University, Morgantown, WV 26506, USA¹⁰ National Radio Astronomy Observatory, Charlottesville, VA 22903, USA¹¹ Space Science Division, Naval Research Laboratory, Code 7655, 4555 Overlook Avenue SW, Washington, DC 20375, USA¹² Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada

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ABSTRACT

In the last few years, over 43 millisecond radio pulsars have been discovered by targeted searches of unidentified γ -ray sources found by the *Fermi Gamma-Ray Space Telescope*. A large fraction of these millisecond pulsars are in compact binaries with low-mass companions. These systems often show eclipses of the pulsar signal and are commonly known as *black widows* and *redbacks* because the pulsar is gradually destroying its companion. In this paper, we report on the optical discovery of four strongly irradiated millisecond pulsar companions. All four sources show modulations of their color and luminosity at the known orbital periods from radio timing. Light curve modeling of our exploratory data shows that the equilibrium temperature reached on the companion’s dayside with respect to their nightside is consistent with about 10%–30% of the available spin-down energy from the pulsar being reprocessed to increase the companion’s dayside temperature. This value compares well with the range observed in other irradiated pulsar binaries and offers insights about the energetics of the pulsar wind and the production of γ -ray emission. In addition, this provides a simple way of estimating the brightness of irradiated pulsar companions given the pulsar spin-down luminosity. Our analysis also suggests that two of the four new irradiated pulsar companions are only partially filling their Roche lobe. Some of these sources are relatively bright and represent good targets for spectroscopic follow-up. These measurements could enable, among other things, mass determination of the neutron stars in these systems.

Key words: binaries: general – pulsars: general – pulsars: individual (PSRs J1810+1744, J0023+0923, J2215+5135, J22561024, B1920+57, J1023+0038)

Online-only material: color figure, machine-readable table

1. INTRODUCTION

The *Fermi Gamma-Ray Space Telescope* (hereafter simply *Fermi*) has discovered hundreds of unidentified point sources whose positional uncertainties are small enough to enable deep targeted pulsar searches with the world’s largest radio telescopes. These searches have resulted in the discovery of 43 energetic millisecond pulsars (MSPs) to date (Cognard et al. 2011; Hessels et al. 2011; Kerr et al. 2012; Ransom et al. 2011; Ray et al. 2012). Intriguingly, many of these are “black widow” and “redback” systems, of which previously only a handful were known—*Fermi* has so far increased their number to over 20 (Roberts 2013).

Black widows are energetic MSPs (spin-down luminosity $\dot{E} \sim 10^{34-35}$ erg s⁻¹) with very low mass (few 0.01 M_{\odot}) companions in compact, few-hour orbits. The original black widow, PSR B1957+20 (Fruchter et al. 1988b), and other members of the class derive their name from the fact that their strong relativistic wind ablates the surface of the companion star, which might have been significantly more massive in the past (Fruchter et al. 1988b). Redbacks, on the other hand, have similar pulsars but more massive companions, of $\sim 0.2 M_{\odot}$. As

yet, is it not clear whether redbacks are the close progeny of accreting X-ray systems, nor whether they can evolve into black widow systems. The evidence that the prototype redback PSR J1023+0038 accreted matter not long ago is suggestive of the former at least (Archibald et al. 2009).

Because of their “cannibalistic” behavior, it has been proposed that some black widows eventually completely ablate their companion (Kluźniak et al. 1988; van den Heuvel & van Paradijs 1988). If this is the case, it could at least partially resolve the conundrum of the existence of isolated MSPs, since these sources clearly appear to have evolved in binary systems despite the fact that they are now isolated. It appears, however, that at least for the original black widow pulsar, PSR B1957+20, the evaporation is too slow (Eichler & Levinson 1988; Eichler & Gedalin 1995). Hence one has to wonder whether the known black widows are somewhat special (and less extreme than the isolated millisecond progenitors) or whether the scenario is simply wrong. Recent work suggested that evolution in a triple system might provide a viable formation channel to explain a small fraction of the isolated MSPs and peculiar binary pulsars (Portegies Zwart et al. 2011; Freire et al. 2011). Nonetheless, the ablation mechanism still appears as the most plausible general scenario for creating isolated MSPs.

¹³ Also an Adjunct Astronomer of the National Radio Astronomy Observatory.

Black widows and redbacks usually display extended eclipses at radio wavelengths, which are accompanied by rapid variations of the dispersion measure (DM; Stappers et al. 1996). At X-ray energies, persistent emission is often visible in addition to pulsations, which likely results from the shocked relativistic wind colliding with the companion (Stappers et al. 2003; Tavani 1993). Black widows and redbacks were thought to be a relatively small fraction of the total MSP population, but it has become clear that previous wide-field pulsar surveys have missed many sources (e.g., because of eclipses). In contrast, since energetic MSPs are efficient γ -ray emitters, targeted radio searches of γ -ray sources are biased toward finding them, especially since repeated searches of the same source have a better chance of catching it out of eclipse. About one-third of the pulsars discovered by targeting γ -ray sources have been black widows or redbacks (Ray et al. 2012). In the light of these discoveries, black widows might after all offer a viable channel for the formation of at least some of the isolated MSPs.

Optical and near-infrared observations of black widows and redbacks are an important probe of the state of the companion and the energetics of the system (see, e.g., Fruchter et al. 1988a; van Paradijs et al. 1988; Stappers et al. 2001). The optical light is dominated by the companion—the pulsar contributes a negligible amount—and shows significant flux and color variations. Mostly, these reflect strong irradiation of the hemisphere facing the pulsar, but superposed on this are ellipsoidal variations due to the tidal distortion. Combined, these allow one to constrain the inclination and other physical parameters (Stappers et al. 2001; Reynolds et al. 2007). Combined with phase-resolved spectroscopy, this can be used to determine the component masses (e.g., van Kerkwijk et al. 2011; Romani & Shaw 2011; Romani et al. 2012). Using this technique, van Kerkwijk et al. (2011) inferred that PSR B1957+20 is likely very massive, $\sim 2.40 \pm 0.12 M_{\odot}$. Similarly, Romani et al. (2012) find evidence that PSR J1311–3430 is also heavyweight—perhaps as much as $\sim 2.7 M_{\odot}$. These large masses suggest that mass transfer was relatively effective, in contrast to what is inferred for other pulsar binaries (e.g., Lin et al. 2011; Antoniadis et al. 2012), posing both an interesting quandary as to why this might be the case and an opportunity to probe the upper mass limit of neutron stars.

While this kind of light curve modeling is also possible in other types of binary neutron star systems (see, e.g., Muñoz-Darias et al. 2009; Wang et al. 2013 for low-mass X-ray binaries), black widows and redbacks are much cleaner systems. Indeed, the only source of optical light is the companion since there is no accretion disk or jet.¹⁴ Also, the irradiation is due to relativistic photons/particles which penetrate several optical depths inside the companion’s photosphere. As a result, the atmosphere remains in quasi-equilibrium and this avoids the formation of prominent emission line features. Finally, because the neutron star is a pulsar, the radio timing provides a set of accurate orbital parameters.

We have searched for the optical counterpart to four of the new black widow/redback systems, using *Gemini* data complemented by New Technology Telescope (NTT) and archival *Swift* data. In this paper, we present the optical discovery of these companions (Section 2) and use their light curves to constrain the system parameters by modeling them using the synthesis code *Icarus* (Section 3). We find that the temperature increase

on the dayside of the irradiated pulsar companions typically corresponds to a conversion efficiency $\sim 15\%$ of the incident energy available from the host pulsars’ rotational spin-down (Section 4).

2. OBSERVATIONS AND ANALYSIS

We were awarded 7.67 hr on *Gemini North* (program GN-2010B-Q-77) to search for the counterparts of four energetic binary MSPs with the GMOS-N instrument (Hook et al. 2004): PSRs J1810+1744, J0023+0923, J2215+5135, and J2256–1024. The first three pulsars were found in a targeted Robert C. Byrd Green Bank Telescope (GBT) search of unidentified *Fermi* point sources¹⁵ (P. Bangale et al., in preparation; J. W. T. Hessels et al., in preparation; Hessels et al. 2011) while the last one was discovered during the 350 MHz GBT pulsar drift scan survey¹⁶ (Boyles et al. 2013; Lynch et al. 2013; I. H. Stairs et al., in preparation). Table 1 presents the main properties of the targets, and a detailed discussion about each source follows in Section 4. Our observing program had two main goals: detect the pulsar companions and, if they are detected, identify variability at the orbital period. Our observing strategy consisted of collecting data at four different epochs, with each observing session consisting of a 320 s *i*-band, 620 s *g*-band, and 320 s *i*-band exposure sequence. Since we observed under non-photometric conditions (cloud cover: 90%, image quality: 85%, sky background: 80%, water vapor: any), resolution was not an issue and we binned the EEV CCD detector by a factor 2×2 in order to reduce the readout time to 35 s per exposure (fast mode) while still properly sampling the point-spread function. Using this strategy, we were expecting to find interepoch variability and, given the short orbital periods of these binaries, maybe even intraepoch variations (for the *i* band).

We reduced the data following standard procedures, implemented using custom Python scripts. We used standard *Gemini* nightly calibration data to remove the bias and flat field our science frames. We registered our frames astrometrically relative to the UCAC3 catalog for PSRs J1810+1744, J0023+0923, and J2215+5135, and relative to Sloan Digital Sky Survey (SDSS) for PSR J2256–1024 (the only source that falls within the coverage of SDSS Data Release 7 (DR7)). For all but PSR J0023+0923, a few tens of reference stars fall within the central frame of the CCD detector and hence our calibration yielded positional uncertainties dominated by systematic uncertainties, of $0''.07$ and $0''.1$ in UCAC3 and SDSS DR7, respectively. For PSR J0023+0923, only three UCAC3 stars fall on the central CCD chip. In this case, we calibrated the image that looked the cleanest using the UCAC3 catalog, and then calibrated the other images in the same band relative to the reference one using a list of bright stars found in all images. The measured optical positions are reported in Table 1 and agree with the radio position derived from the timing.

We performed aperture photometry using an extraction radius of 5 pixels (i.e., 0.73 arcsec at the plate scale of 0.146 arcsec per binned pixel), and sky inner and outer annuli of 10 and 15 pixels, respectively. We calibrated our photometry against bright, non-saturated stars appearing in the SDSS DR7 catalog for PSR J2256–1024, and USNO-B1 in the case of the three other targets. For USNO-B1, we converted the catalog magnitudes from the photographic *B*, *R*, and *I* magnitudes to the *ugriz* system using the transformation of Jordi et al. (2006),

¹⁴ PSR J1023+0038 was observed to have a disk before but it has since disappeared (see, e.g., Archibald et al. 2009).

¹⁵ Proposal IDs: GLST031123 (GBT), GLST041200 (GBT), GBT11A-063.

¹⁶ Proposal IDs: GBT09B-031, GBT09C-072.

Table 1
Measured and Inferred Source Parameters

Quantity	J0023+0923 ^a	J2256–1024 ^b	J1810+1744 ^a	J2215+5135 ^a	B1957+20 ^c	J1023+0038 ^c
Measured						
Right Ascension ^d	00 ^h 23 ^m 16 ^s .89(2)	22 ^h 56 ^m 56 ^s .39(1)	18 ^h 10 ^m 37 ^s .28(1)	22 ^h 15 ^m 32 ^s .68(1)	19 ^h 59 ^m 36 ^s .77	10 ^h 23 ^m 47 ^s .69
Declination ^d	09°23′24″.18(20)	−10°24′34″.37(12)	17°44′37″.38(7)	51°35′36″.45(10)	20°48′15″.12	00°38′41″.15
Gal. longitude (deg)	111.38	59.23	44.64	99.87	59.20	243.49
Gal. latitude (deg)	−52.85	−58.29	16.81	−4.16	−4.70	45.78
$f_{\gamma,0.1-100\text{ GeV}}$ ($10^{-12}\text{ erg s}^{-1}\text{ cm}^{-2}$)	10.7 ± 1.5	10.1 ± 1.4	25.5 ± 2.1	10.9 ± 1.6	16.7 ± 1.9	5.4 ± 1.0
P_{spin} (ms)	3.1	2.3	1.7	2.6	1.61	1.69
P_{orb} (h)	3.3312	5.1092	3.5561	4.1401	9.1672	4.7543
$T_{\text{asc,node}}$ (MJD (TDB))	55186.11343	54853.22391	55130.04813	55186.16449	48196.06352	54801.97065
x (lt-s)	0.035	0.083	0.095	0.47	0.089	0.343
DM (pc cm ^{−3})	14	14	40	69	29.12	14.33
A_V^e	0.37	0.14	0.43	1.15	...	...
Inferred						
d_{DM} (kpc) ^f	0.69	0.65	2.00	3.01	2.49	0.62
M_c^{min} (M_{\odot}) ^g	0.017	0.030	0.045	0.213	0.022	0.138
$L_{\text{sd},\dot{p}}$ ($10^{34}\text{ erg s}^{-1}$) ^h	1.51	3.95	3.97	5.29	16.0	9.82
L_{γ} ($10^{33}\text{ erg s}^{-1}$) ⁱ	1.28	1.21	3.05	1.30	2.00	0.65
a (R_{\odot}) ^j	1.27	1.69	1.33	1.53	2.49	1.65
R_L (R_{\odot}) ^k	0.13	0.22	0.19	0.36	0.29	0.34
Light curves (Minimum/Maximum/Quadrature) ^l						
i band	24.3/21.7/22.7	24.3/20.8/22.1	22.3/19.5/20.3	19.5/18.6/18.9	...	...
g band	28.0/23.4/25.0	28.0/22.2/26.8	23.2/19.2/20.2	19.9/18.1/18.7	...	...
Light curve fitting						
Inclination (deg)	58 ± 14	68 ± 11	48 ± 7	66 ± 16	...	...
Filling factor	0.30 ± 0.30^m	0.40 ± 0.20	0.80 ± 0.30	0.99 ± 0.03	...	...
T_{night} (K)	2900 ± 700	2450 ± 350	$\sim 4600^n$	4800 ± 450	~ 2500	~ 5600
T_{day} (K)	4800 ± 2000	4200 ± 700	$\gtrsim 8000^n$	6200 ± 500	~ 5800	~ 6650
T_{irr} (K)	4600	4100	7800^n	5550	5750	5580
ϵ_{irr}	0.17	0.07	0.60^n	0.15	0.15	0.09

Notes.

^a Timing data (P_{spin} , P_{orb} , x , DM, and $L_{\text{sd},\dot{p}}$ from J. W. T. Hessels et al. (in preparation).

^b Timing data (P_{spin} , P_{orb} , x , DM, and $L_{\text{sd},\dot{p}}$ from I. H. Stairs et al. (in preparation).

^c PSRs B1957+20 and J1023+0038 are shown for comparison. Data from the ATNF Pulsar Catalogue (Manchester et al. 2005; <http://www.atnf.csiro.au/research/pulsar/psrcat>).

^d Positions derived from optical astrometry. Uncertainties are dominated by the catalog systematics of 0′.07 in UCAC3 (J0023+0923, J1810+1744, and J2215+5135) and 0′.1 in SDSS DR7 (J2256–1024).

^e Total reddening along the line of sight (see Section 3).

^f Distance based on the dispersion-measure NE2001 model (Cordes & Lazio 2002).

^g Minimum companion mass assuming a $1.4 M_{\odot}$ pulsar and a 90° orbital inclination.

^h Spin-down luminosity inferred from P_{spin} and its derivative, and a moment of inertia of 10^{45} g cm^2 .

ⁱ γ -ray luminosity estimated from the γ -ray flux and dispersion-measure distance.

^j Orbital separation $a = x(1 + 1.4/M_c^{\text{min}})$.

^k Companion Roche radius $R_L = 0.46a[M_c^{\text{min}}/(M_c^{\text{min}} + 1.4)]^{1/3}$.

^l The reported magnitudes are inferred from the light curve modeling presented in the text.

^m The probability distribution for this parameter is highly non-Gaussian, and hence the value must be taken with caution. The median value is 0.40, the mode at ~ 0.15 and the distribution extends with a heavy tail all the way to unity.

ⁿ As explained in Section 3.3, we believe that our analytic estimate is more robust than the numerical values for the case of PSR J1810+17. Hence, we present the analytic results in this table.

$i - I = (0.247 \pm 0.003)(R - I) + (0.329 \pm 0.002)$, for the i band, and from Lupton (2005), $B - g = 0.3130(g - r) + 0.2271$ and $R - r = -0.1837(g - r) - 0.0971$, for the g band. In the case of PSR J1810+1744, there is a neighboring star that might contaminate our aperture photometry. For this reason, we performed point-spread function photometry using a Moffat profile $f(r) \propto (1 + r^2/\sigma^2)^{-\beta}$, with $\beta = 3$ and σ optimized using a set of bright, non-saturated stars for each frame. Reference stars were fitted individually while the immediate vicinity of PSR J1810+1744 was simultaneously fitted for

the source and the two other stars located east and northeast from it.

Our complete photometric results for the pulsar companions are available in Tables 2–5, as well as for a set of comparison field stars in Table 6. Our photometric errors were calculated by adding in quadrature the sky background, the photon counting noise, and the intraband relative zero point. The zero-point calibration errors correspond to the standard deviation of the mean of the zero-point calibration for each band to the reference catalog stars,

Table 2
Photometry of PSR J0023+09

Time (MJD)	Orbital Phase ^a	Flux (μ Jy)	Flux Error ^c (μ Jy)	Magnitude ^b	Magnitude Error ^c
g-band, GMOS					
55445.513890	0.6410	0.989	0.065	23.908	0.070
55449.575790	0.9056	0.024	0.057	26.756	0.511
55449.587001	0.9863	0.001	0.065	26.964	0.599
55449.612403	0.1693	0.106	0.062	26.099	0.428
i-band, GMOS					
55445.507793	0.5970	6.397	0.252	21.883	0.043
55445.519981	0.6848	4.368	0.224	22.296	0.055
55449.569694	0.8616	0.956	0.239	23.889	0.244
55449.581881	0.9494	0.637	0.240	24.266	0.330
55449.606307	0.1254	1.715	0.238	23.295	0.146
55449.618493	0.2132	3.027	0.242	22.691	0.086

Notes.

^a Orbital phases are measured from the companion's inferior conjunction.

^b AB magnitudes in the Lupton system, $m = m_0 - 2.5 \log b' - (2.5 \log e) \sinh^{-1}(f/2b')$, using softening parameters $b' = 0.059$ and 0.233μ Jy for the g and i band, respectively, and zero-point $m_0 = -48.6$.

^c The flux and magnitude errors represent the formal uncertainties. One should also add in quadrature the zero-point calibration errors, which are 0.319 and 0.757 mag in g and i band, respectively.

Table 3
Photometry of PSR J2256–10

Time (MJD)	Orbital Phase ^a	Flux (μ Jy)	Flux Error ^c (μ Jy)	Magnitude ^b	Magnitude Error ^c
g-band, GMOS					
55428.546679	0.2850	1.871	0.060	23.219	0.035
55449.283273	0.6936	1.835	0.029	23.241	0.017
55454.418742	0.8170	0.284	0.026	25.256	0.098
55469.350249	0.9567	0.020	0.024	27.478	0.483
i-band, GMOS					
55428.540594	0.2564	6.770	0.130	21.823	0.021
55428.552779	0.3136	10.368	0.125	21.360	0.013
55449.277175	0.6649	9.902	0.088	21.410	0.010
55449.291633	0.7328	5.578	0.069	22.033	0.013
55454.412643	0.7884	3.321	0.078	22.596	0.026
55454.424831	0.8456	1.559	0.074	23.416	0.051
55469.344150	0.9280	0.867	0.067	24.049	0.083
55469.356340	0.9853	0.816	0.062	24.114	0.081
g-band, ULTRACAM					
55323.421265	0.4664	3.979	1.606	22.245	0.335
z-band, ULTRACAM					
55323.421265	0.4664	45.700	5.609	19.733	0.129

Notes.

^a Orbital phases are measured from the companion's inferior conjunction.

^b AB magnitudes in the Lupton system, $m = m_0 - 2.5 \log b' - (2.5 \log e) \sinh^{-1}(f/2b')$, using softening parameters $b' = 0.025$, 0.064, 1.673 and 5.845 μ Jy for the g (GMOS), i , g (ULTRACAM) and z band, respectively, and zero-point $m_0 = -48.6$.

^c The flux and magnitude errors represent the formal uncertainties. One should also add in quadrature the zero-point calibration errors, which are 0.104, 0.119, 0.010 and 0.010 mag in g (GMOS), i , g (ULTRACAM) and z band, respectively.

which were added in quadrature to the catalog systematic calibration. In the case of PSR J0023+0923, very few catalog stars overlap with our field and hence the band calibration is poorer than for the other systems analyzed here. The SDSS systematic calibration error is 0.02 mag (for PSR J2256–1024), while that of USNO-B1.0 is 0.3 mag (for PSRs J1810+1744, J0023+0923, and J2215+5135).

The field of PSR J2215+5135 was also serendipitously observed by the UVOT instrument on board *Swift* while it

was monitoring a nearby gamma-ray burst. We performed photometric reduction of the publicly available data,¹⁷ which were all obtained in the $uvw1$ band (Poole et al. 2008; $\lambda_c = 260$ nm, $\Delta\lambda = 69.3$ nm). For the UVOT data, we used a 5 pixel aperture (i.e., 5 arcsec at 1.004 arcsec pixel⁻¹) and sky inner and outer annuli of 15 and 30 pixels, respectively. We took the photometric zero point from Breeveld et al. (2011),

¹⁷ <http://heasarc.gsfc.nasa.gov>

Table 4
Photometry of PSR J1810+17

Time (MJD)	Orbital Phase ^a	Flux (μ Jy)	Flux Error ^c (μ Jy)	Magnitude ^b	Magnitude Error ^c
<i>g</i> -band, GMOS					
55442.236873	0.7092	40.430	0.119	19.883	0.003
55443.292770	0.8355	11.639	0.053	21.235	0.005
55446.293441	0.0870	6.537	0.061	21.861	0.010
55447.310477	0.9509	1.066	0.049	23.828	0.050
<i>i</i> -band, GMOS					
55442.230765	0.6680	42.101	0.141	19.839	0.004
55442.242953	0.7502	29.091	0.124	20.240	0.005
55443.286671	0.7943	20.585	0.132	20.616	0.007
55443.298861	0.8766	8.369	0.107	21.593	0.014
55446.287344	0.0458	5.916	0.120	21.969	0.022
55446.299530	0.1281	14.863	0.126	20.969	0.009
55447.304378	0.9098	5.780	0.095	21.995	0.018
55447.316567	0.9920	3.715	0.107	22.474	0.031

Notes.

^a Orbital phases are measured from the companion's inferior conjunction.

^b AB magnitudes in the Lupton system, $m = m_0 - 2.5 \log b' - (2.5 \log e) \sinh^{-1}(f/2b')$, using softening parameters $b' = 0.051$ and 0.099μ Jy for the *g* and *i* band, respectively, and zero-point $m_0 = -48.6$.

^c The flux and magnitude errors represent the formal uncertainties. One should also add in quadrature the zero-point calibration errors, which are 0.301 and 0.308 mag in *g* and *i* band, respectively.

Table 5
Photometry of PSR J2215+51

Time (MJD)	Orbital Phase ^a	Flux (μ Jy)	Flux Error ^c (μ Jy)	Magnitude ^b	Magnitude Error ^c
<i>g</i> -band, GMOS					
55531.246057	0.1970	82.000	0.232	19.115	0.003
<i>i</i> -band, GMOS					
55531.192316	0.8855	59.559	1.180	19.462	0.022
55531.238446	0.1529	71.956	0.607	19.257	0.009
55531.252146	0.2323	95.277	0.448	18.952	0.005
55531.256359	0.2567	102.023	0.443	18.878	0.005
<i>uvw1</i> -band, UVOT					
55399.269193	0.1227	0.670	2.759	22.979	0.749
55399.335860	0.5092	4.868	2.407	22.036	0.417
55399.402162	0.8936	-1.056	2.269	23.450	0.603
55399.536221	0.6707	2.450	2.136	22.525	0.499
55399.602885	0.0572	-1.364	2.157	23.531	0.561
55399.665753	0.4216	5.503	2.026	21.930	0.325
55399.730436	0.7966	2.269	2.144	22.568	0.511
55399.799357	0.1961	-0.123	1.893	23.196	0.521
55399.865723	0.5808	5.094	2.032	21.997	0.342
55399.933775	0.9753	-0.077	1.976	23.183	0.544

Notes.

^a Orbital phases are measured from the companion's inferior conjunction.

^b AB magnitudes in the Lupton system, $m = m_0 - 2.5 \log b' - (2.5 \log e) \sinh^{-1}(f/2b')$, using softening parameters $b' = 0.242$, 0.462 and 1.972 μ Jy for the *g*, *i* and *uvw1* band, respectively, and zero-point $m_0 = -48.6$.

^c The flux and magnitude errors represent the formal uncertainties. One should also add in quadrature the zero-point calibration errors, which are 0.302 and 0.302 mag in *g* and *i* band, respectively.

$zpuvw1 = 18.95 \pm 0.03$ (AB system), to convert our count rate to magnitude. Note that the aperture correction is negligible for our aperture size.¹⁸

We also obtained some exploratory exposures during an observing run at the NTT using the tri-band ULTRACAM

imager (Dhillon et al. 2007) and managed to obtain an additional *z*-band and *g*-band images for PSR J2256–1024. The data processing was performed using the ULTRACAM data reduction pipeline.¹⁹

¹⁸ http://heasarc.gsfc.nasa.gov/docs/swift/analysis/uvot_digest/apercor.html

¹⁹ <http://deneb.astro.warwick.ac.uk/phsaap/software/>

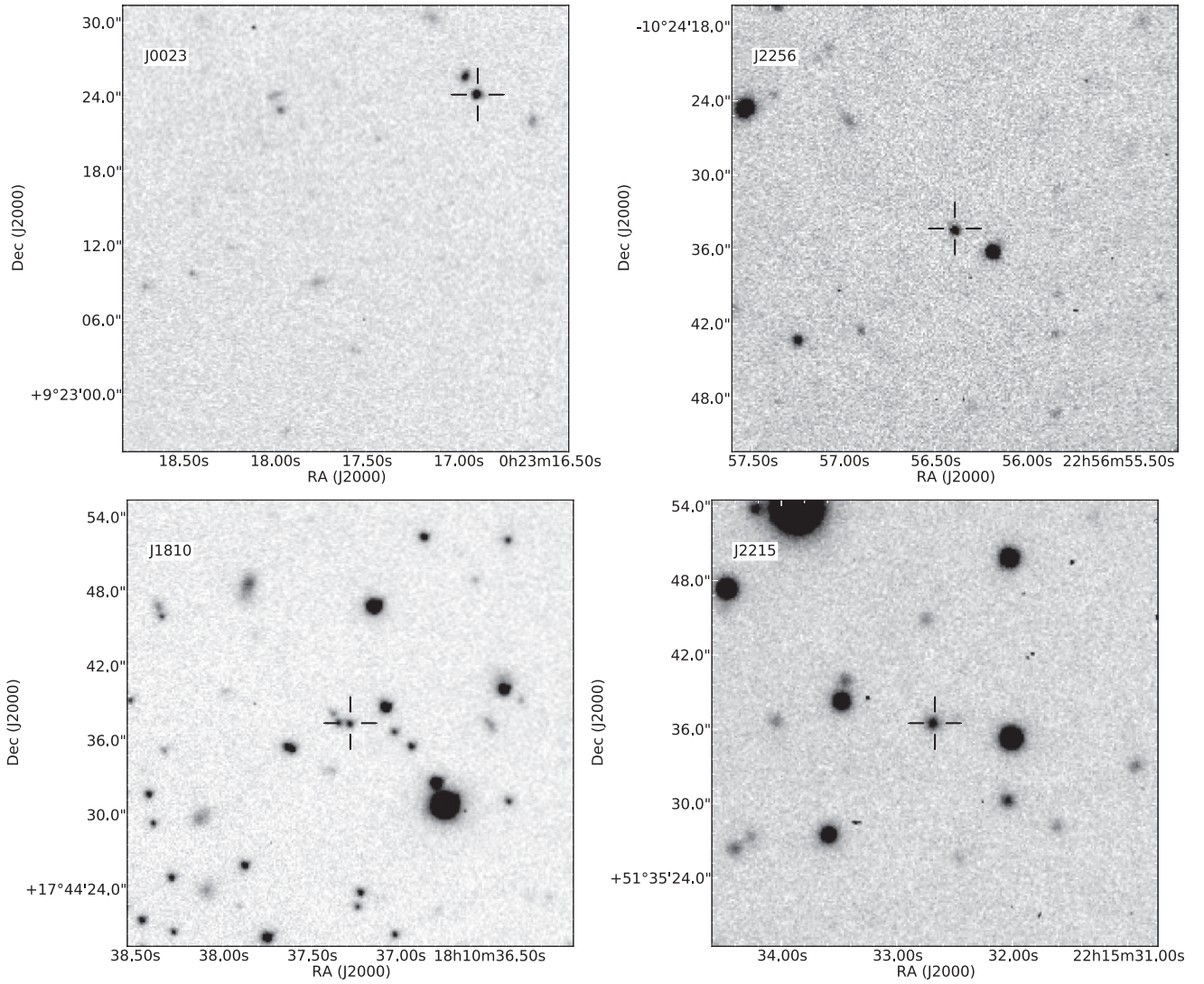


Figure 1. Finding chart of the four irradiated pulsar companions presented in this paper, observed in the *i* band with GMOS-North. In each panel, the location of the counterpart is indicated with crosshairs.

Table 6
Photometry of PSR J0023+09's Field

R.A. ($^{\circ}$)	Decl. ($^{\circ}$)	F_g (μ Jy)	δ_{F_g} (μ Jy)	F_i (μ Jy)	δ_{F_i} (μ Jy)	<i>g</i> Mag. ^a	<i>g</i> Mag. Error ^b	<i>i</i> Mag. ^a	<i>i</i> Mag. Error ^b
5.8186	9.33167	17.866	0.461	37.066	14.874	20.770	0.028	19.977	0.436
5.8316	9.32724	43.987	5.481	531.848	275.488	19.791	0.135	17.085	0.562
5.8362	9.32149	13.635	0.354	169.842	69.976	21.063	0.028	18.325	0.447
5.8478	9.30288	26.704	0.680	202.056	88.088	20.333	0.028	18.136	0.473

Notes.

^a AB magnitudes in the Lupton system, $m = m_0 - 2.5 \log b' - (2.5 \log e) \sinh^{-1}(f/2b')$, using softening parameters $b' = 0.059$ and 0.233μ Jy for the *g* and *i* band, respectively, and zero-point $m_0 = -48.6$.

^b The flux and magnitude errors represent the formal uncertainties. One should also add in quadrature the zero-point calibration errors, which are 0.319 and 0.757 mag in *g* and *i* band, respectively.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. RESULTS

We found optical counterparts to all four pulsar binaries (see Figure 1). The association of the optical counterparts with the irradiated pulsar companions was confirmed in all cases by variability at the known orbital periods, as can be seen in the light curves shown in Figure 2.

As discussed in Section 1, the light curves can be used to constrain several parameters of the system. The orbital modulation is caused by a combination of irradiation, which produces a maximum at the superior conjunction of the companion, and ellipsoidal variations, which yield maxima at quadrature. From the colors at superior and inferior conjunction of the companion, one can constrain the dayside and nightside temperatures and

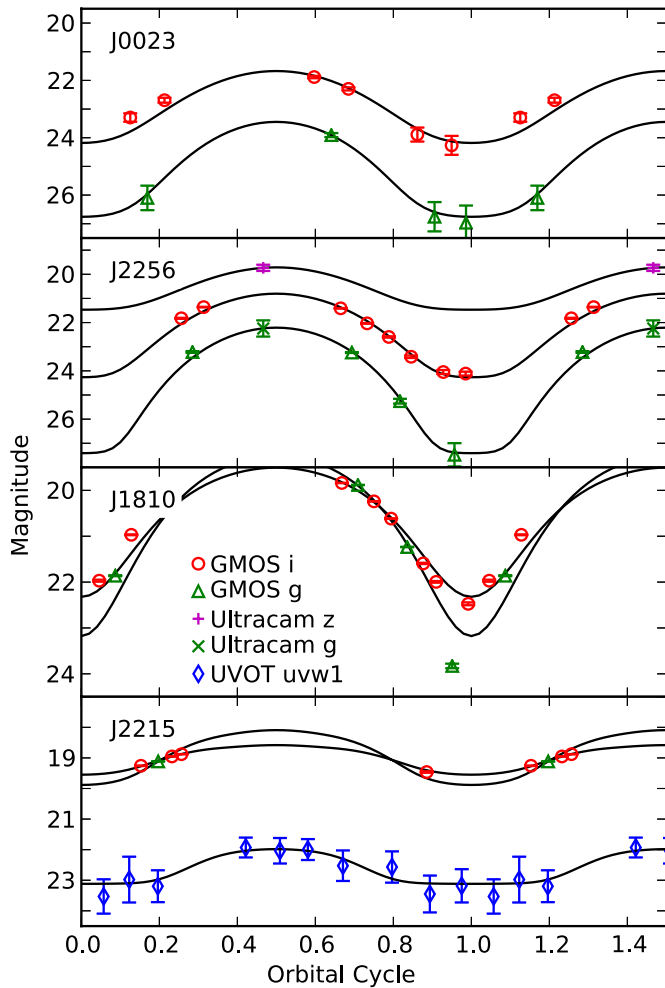


Figure 2. Light curves of the four irradiated pulsar companions. GMOS *i*, GMOS *g*, ULTRACAM *z*, ULTRACAM *g*, and UVOT *uvw1* bands are marked by red circles, green triangles, magenta plus signs, green crosses, and blue diamonds, respectively. The black lines display the best-fit light curve calculated using *Icarus*.

(A color version of this figure is available in the online journal.)

thus irradiation. For poorly sampled data like ours, the nightside temperature cannot be constrained very well, since it is degenerate with the orbital inclination. Good coverage is required to distinguish between the high-inclination case of seeing only the brighter, unirradiated nightside at inferior conjunction of the companion, or the low-inclination case where one observes a dimmer nightside combined with a sliver of the irradiated side. However, for strongly irradiated systems, where the dayside is much hotter than the nightside, the irradiated temperature can be determined relatively securely from just the colors near superior conjunction of the companion. The amplitude of ellipsoidal variations directly depends on the filling factor of the companion. Since the amplitude is small relative to irradiation, one must possess good quality sampling near quadrature in order to constrain the filling factor accurately. However, the physical size of the star is also directly related to its apparent luminosity given its distance, and thus any independent information on the latter, such as from the DM, can be used to constrain the filling factor. For small filling factors,²⁰ below ~ 0.55 , the scaling between filling factor and distance is linear (as expected), but

²⁰ We define the filling factor as the ratio of the volume-averaged stellar radius and the volume-averaged Roche lobe radius.

for larger filling factors its dependence becomes sub-linear, as the ellipsoidal variations and gravity darkening start to counteract the irradiation at maximum light (superior conjunction), leading to a $\sim 20\%$ reduction relative to the linear extrapolation when the companion fills its Roche lobe. Finally, we note that constraining parameters such as inclination and filling factor is generally limited by the quality of the sampling and the uncertainty on individual data points, whereas the determination of the temperatures are mostly affected by the absolute calibration of each band.

To get first-order estimates of the system parameters, we modeled the light curves of these irradiated binaries using *Icarus*²¹ (Breton et al. 2011) along with BTSettl atmosphere models (Allard et al. 2003, 2007, 2011) available through the Phoenix Web simulator.²² The free parameters in the model are the mass ratio q , the orbital inclination i , the distance d , and reddening A_V to the system, the companion’s filling factor $f = R/R_L$ (where R is the volume-averaged radius and R_L is the volume-averaged radius of the Roche lobe), and its dayside and nightside temperatures T_{day} and T_{night} . We assumed that the companion is tidally locked to the pulsar and added Gaussian priors on the distance and reddening. We set the mean of the distance priors to the values inferred from DM using the NE2001 model (Cordes & Lazio 2002), and, since our sources are well outside the dust layer, we estimated the reddening as being equal to the total along each line of sight as inferred by Schlegel et al. (1998; see values in Table 1). In both cases, we took standard deviations corresponding to 25% relative uncertainties. Also, since the mass ratio is unconstrained without spectroscopic information, we imposed that the mass of the pulsar lies in the range $1\text{--}3 M_{\odot}$. For the model fitting, we used the uncertainties from Tables 2 to 5 on individual data point, and a band-to-band uncertainty corresponding to our band calibration errors to which we added in quadrature an additional 0.1 mag to account for systematics in the zero-point calculation inherent to the atmosphere models (this is important only for PSR J2256–1024 for which the photometry could be accurately tied to SDSS). In the following subsections, we discuss the main results of the light curve modeling (see Figure 2 for best-fit light curves).

3.1. PSR J0023+0923

PSR J0023+0923 stands out from other black widows in its relative long spin period, and thus relatively low spin-down luminosity, which makes the expected irradiation effects on the companion relatively mild. The data constrain the colors at maximum and minimum light well, with $g - i \simeq 1.5$ and 3.0, respectively. These correspond to flux-averaged temperatures of ~ 4500 and 3200 K, respectively, close to what we infer from our models: 4800 ± 2000 and 2900 ± 700 K, respectively. Note that the latter dayside temperature is strictly for the part directly facing the pulsar, hence quite a bit higher than the flux-averaged temperature inferred from the color. The substantial change in color shows that much of the irradiated side must be hidden at inferior conjunction of the companion, and our models demonstrate that this excludes orbital inclinations lower than $i \lesssim 40^\circ$; the preferred value is $i = 58^\circ \pm 14^\circ$.

The filling factor appears relatively small at 0.30 ± 0.30 , though one must be cautious since the probability distribution is highly non-Gaussian with a mode at ~ 0.15 and an extended heavy tail all the way to a filling factor of unity (median value

²¹ <https://github.com/bretonr/Icarus>

²² <http://phoenix.ens-lyon.fr/simulator/>

at 0.40). This could imply a much smaller companion than inferred for the prototype black widow, PSR B1957+20, which has a filling factor fairly close to unity (Reynolds et al. 2007). Indeed, the nominal implied size, of $\sim 0.05 R_{\odot}$ is smaller than is possible for a solar-composition object, suggesting that the filling factor is on the upper end of our inferred range (and thus the distance somewhat larger than inferred from the DM; see Section 4). However, indirect evidence that the companion is not close to filling its Roche lobe comes from the fact that this source shows no radio eclipses at 350 MHz,²³ unlike most black widows (J. W. T. Hessels et al., in preparation; though we could also be seeing the system relatively face-on).

3.2. PSR J2256–1024

This system appears to be quite similar to PSR J0023+0923, showing slightly redder colors. Near maximum, the fortuitously phased ULTRACAM points yield $g - z \simeq 2.5$, while near minimum, the Gemini data yield $g - i \simeq 3.5$, corresponding to flux-averaged temperatures of ~ 3700 and 3100 K, respectively. Since for PSR J2256–1024 our photometric calibration is more secure, our fits yield well-constrained day and nightside temperatures, of 4200 ± 700 and 2450 ± 350 K, respectively. The modeling favors an intermediate orbital inclination, $i = 68^{\circ} \pm 11^{\circ}$.

Like for PSR J0023+0923, the best-fit filling factor is small, 0.40 ± 0.20 , although since the orbit is somewhat wider, the inferred radius of $0.09 R_{\odot}$ is not inconsistent with a solar-composition, degenerate object. Contrary to PSR J0023+0923, however, this system shows radio eclipses, suggesting that, perhaps, the size is underestimated because the distance derived from the DM is too small (see also Section 4), and/or that it is simply closer to being observed edge-on. The latter explanation appears slightly unlikely though given that our light curve fitting yield similar orbital inclination ranges (see Table 1).

3.3. PSR J1810+1744

Like PSRs J0023+0923 and J2256–1024, this system is a canonical black widow. One should expect a larger irradiation than in the case of PSRs J0023+0923 and J2256–1024, given the combination of a compact 3.6 hr orbit and a more energetic pulsar (in fact, this is the fourth fastest-spinning pulsar known in the Galactic field). Its light curves are quite puzzling since we did not find a combination of parameters that successfully account for all the data points. Indeed, the i -band light curve in particular seems inconsistent with being symmetric around minimum light, being dimmer before minimum than after. Asymmetric light curves have also been seen for PSR J2051–0827 (Stappers et al. 2001), though in that case the source was brighter before minimum than it was afterward, and the light curve showed variations between different sets of observations (in contrast to what is seen for PSR B1957+20; e.g., Reynolds et al. 2007). In the g -band light curve, the data point near minimum is significantly offset from the predicted value. As we mentioned in Section 2, particular care was taken for the flux extraction of this source. Hence we believe that the pulsar companion was intrinsically faint at this orbital phase. We note that some irradiated pulsar companions, such as PSR J1311–3430 (Romani et al. 2012), display flares so it is not impossible that PSR J1810+1744 also shows variability. Further observations

with better orbital coverage should help in understanding the odd behavior of this source.

As a result of the poor fit, we can only give qualitative constraints on the parameters. Given the large modulation, the inclination has to be relatively large, though the lack of flattening near minimum implies that the dayside has to remain partly visible; we find $i \simeq 48^{\circ} \pm 7^{\circ}$. Our best-fit model also yields a very hot dayside, with $\sim 10,000$ K, and a much colder nightside, with $\sim 3100 \pm 850$ K. Given the larger distance to the system, ~ 2 kpc, a larger filling factor can be accommodated. Our data are consistent with a Roche lobe-filling star, though the poor fit and the lack of photometric coverage near maximum yields large uncertainties, hence explaining a heavy tail in the distribution of possible filling factor at lower values. The inferred filling factor of 0.80 ± 0.30 , which implies a companion radius of $0.15 R_{\odot}$.

Given the poor fit, however, we caution that the above results cannot be taken at face value. In particular, while our data cover minimum and thus directly constrain the nightside temperature (for $g - i \simeq 1.3$, one infers a flux-averaged temperature of ~ 4600 K), maximum is not covered and hence we have no direct constraints on the dayside temperature. Nevertheless, the dayside must be relatively hot, since the source has $g - i \simeq 0$ near quadrature, implying a flux-averaged temperature of ~ 7500 K. For many black widows, the color does not vary strongly between quadrature and maximum—see PSRs J0023+0923 and J2256+1024 above, as well as PSR B1957+20 (Callanan et al. 1995). Given a dayside color of $g - i \lesssim 0$, and taking into account that the dayside temperature is somewhat hotter than the flux-averaged one, we infer a lower limit to the dayside temperature of $\gtrsim 8000$ K. We will use this limit below. Using these values also reduces the irradiation efficiency from the formal best-fit value of 1.5–0.60, which make it more plausible energetically.

3.4. PSR J2215+5135

Unlike the systems we have already discussed, PSR J2215+5135 has a significantly more massive companion and is best characterized as a redback, with orbital properties similar to the prototype, PSR J1023+0038 (Archibald et al. 2009). Like PSR J1023+0038, it shows only modest brightness variability. The Gemini data give only a single color, $g - i \simeq 0.3$, implying a flux-averaged temperature of ~ 6600 K near quadrature. The presence of UVOT data proves to be valuable at constraining parameters of this system, with the caveat that ultraviolet data are sometimes contaminated by chromospheric emission if the companion is magnetically active. The system appears to be viewed at an intermediate orbital inclination ($\sim 70^{\circ}$) and a dayside temperature of 6200 ± 500 K. Like other redback companions, the nightside is much hotter (~ 4800 K) than that of black widow companions. The filling factor is very tightly constrained to being Roche lobe filling, which is consistent with the occurrence of radio eclipses for $\sim 50\%$ of the orbit (J. W. T. Hessels et al., in preparation).

4. DISCUSSION

As can be seen in Figure 2, the model light curves generally agree well with our data. While our light curves are not sufficiently well sampled to produce strong constraints on the system parameters, they allow us to address two interesting aspects: the efficiency of the irradiation and the extent to which the companion fills its Roche lobe.

²³ Radio eclipses are strongly radio-frequency dependent, being more dramatic at lower frequencies (see, e.g., Archibald et al. 2009; Stappers et al. 1996).

To estimate the efficiency of the irradiation, i.e., the effective fraction ϵ_{irr} of the spin-down luminosity incident on the companion that is absorbed and re-radiated, we assume that the irradiating flux is thermalized and re-radiated locally, i.e., that it simply adds to the intrinsic flux wherever it impinges. Then, from the hottest point, one can derive a characteristic “irradiation temperature” $T_{\text{irr}}^4 = T_{\text{day}}^4 - T_{\text{night}}^4$, which is related to the pulsar’s spin-down luminosity, L_{sd} , as $\epsilon_{\text{irr}} L_{\text{sd}} = 4\pi a^2 \sigma T_{\text{irr}}^4$, where a is the orbital separation and σ is the Stefan–Boltzmann constant. Note that we implicitly assume that the pulsar spin-down energy is isotropically radiated.

In Table 1, we list our inferred irradiation temperatures as well as the implied irradiation efficiencies. With the exception of PSR J1810+1744, which we will discuss below, we find that the typical values of the irradiation efficiency of the new systems presented in this paper are consistent with those of PSRs B1957+20 and J1023+0038. Moreover, the other known irradiated pulsar systems (PSRs J2051–0827, J1311–3430, J2339–0533; Stappers et al. 2001; Romani et al. 2012; Romani & Shaw 2011) also display similar efficiencies ($\gtrsim 30\%$, $\sim 30\%$, and $\sim 15\%$, respectively).²⁴ We conclude that the typical irradiation efficiency factor in these systems lies in the range 10%–30%, with 15% being a representative figure. Note that the intrinsic spread in values might be smaller if one compensates for the fact that the orbital separation is poorly known given the uncertainties in the inclination, the pulsar mass, and its moment inertia.

The energetics derived from the irradiation of the companions are consistent with the idea that the relativistic wind, which is powered by the rotational spin down of the neutron star, is the major driver of the heating mechanism. The case of PSR J1810+1744 is, however, puzzling. Its rather large inferred irradiation efficiency not only departs from the other known irradiated pulsar systems but it also implies an input energy larger than the nominal spin-down luminosity (though our analytic estimate of the lower limit of ~ 0.60 is below unity). One cause may be that our assumption of an isotropic wind is not justified. For instance, if the pulsar is aligned with the orbit and emits its wind preferentially in the equatorial plane (as is the case for, e.g., the Crab and Vela pulsars), the irradiation efficiency would be reduced. From our Gemini data, there is a clear indication that both g - and i -band light curves are not symmetric, with the companion being brighter after its inferior conjunction (phases ~ 0.0 – 0.15) than before (phases ~ 0.85 – 1.0). This could be an indication of non-isotropic heating or heat redistribution at the surface of the star. More detailed light curves of this system would help resolve these issues.

Radio eclipses are observed in three out of four of these systems (J. W. T. Hessels et al., in preparation; I. H. Stairs et al., in preparation) and large increases in the DM at the ingress and egress in similar systems indicates total intrabinary electron column densities of $N_e \sim 10^{16} \text{ cm}^{-2}$ (see, e.g., Fruchter et al. 1988b). Given that eclipses are coincident with the inferior conjunction of the companions, plasma must certainly be surrounding them and hence some form of mass loss from the companion is required. In the case of a nearly Roche lobe-filling star, material is loosely bound to the surface and can be peeled off easily when exposed to a relativistic pulsar wind. Our work suggests that, however, some of the irradiated

pulsar companions that we have studied (PSRs J0023+0923 and J2256–1024) are not close to filling their Roche lobe.

As mentioned in the previous section, a first possibility is that the distances inferred from the DMs of these pulsars are underestimated. It is now well established that for pulsars located far off the Galactic plane, the measured parallactic distances tend to be larger than the DM distances (see, e.g., Gaensler et al. 2008; Roberts 2011). Roberts (2011) shows that based on 13 sources with measured parallax and Galactic latitude larger than 10° , $d_{\text{DM}}/d_{\text{parallax}} = 0.66 \pm 0.26$. Since the filling factor is correlated with the distance, we ran another set of fits using priors on the distance rescaled using the above conversion factor and error. As a result, we found that the typical filling factor for PSRs J0023+0923, J1810+1744, and J2256–1024 did not change significantly.²⁵ This comes from the fact that the dayside temperature is not very precisely constrained due to the large systematic uncertainties in the absolute calibration of the bands. Consequently, the larger distance priors tend to increase the dayside temperatures rather than changing the filling factors as one would expect. We also ran another set of fits, this time by holding the filling factor of the companions to unity and removing the distance priors in order to see how much further these systems would need to be located in order to match the observed fluxes. We found that the DM distances would need to be off by a factor 8.5, 1.2, and 2.3 for the three above sources, respectively.

While it is not excluded that our distance estimates are wrong, it appears unlikely that PSRs J0023+0923 and J2256–1024’s companions are Roche lobe filling. Whether nearly Roche lobe-filling stars are required in order to explain the radio eclipses of the pulsars is uncertain since neither the mechanism supplying particles to the plasma nor the role of the pulsar in triggering it are understood. Caution should be taken before drawing definitive conclusions and precise distance constraints from parallactic measurements would help shed light on this. Better-quality multi-color light curves will improve the measurement of the orbital inclination and address the contribution of ellipsoidal variations, hence also help to constrain the filling factor. It is worth mentioning that the second black widow system to be found, PSR J2051–0827, also displays puzzling light curves. Previous work highlighted an ambiguous behavior either indicating a filling factor near unity or closer to 50% (Stappers et al. 2001).

A common feature of black widow and redback systems is the presence of non-secular orbital period derivatives in the radio timing (see, e.g., Arzoumanian et al. 1994; Lazaridis et al. 2011; Archibald et al. 2009). It has been suggested that gravitational quadrupole coupling of the companion with the orbit might explain the orbital variability (Applegate & Shaham 1994). The dissipated tidal energy would drive convection, which would power a dynamo-induced magnetic field and provide a significant source luminosity. While such a mechanism would be compatible with the amplitude of the orbital variations of PSR B1957+20 and the luminosity of its companion (Applegate & Shaham 1994), it would require some fine tuning—namely, a $\sim 50\%$ filling factor—in order to work for PSR J2051–0827 (Lazaridis et al. 2011). These newly discovered irradiated pulsar systems could therefore provide extended leverage to test the gravitational quadrupole theory, since the Roche lobe underfilling systems are predicted to display smaller orbital variability.

²⁴ PSR J2051–0827 has a somewhat large value efficiency. The efficiency of PSR J2339–0533 is based on the radio timing from P. S. Ray et al. (in preparation).

²⁵ PSR J2215+5135 is already constrained to be Roche lobe filling.

5. CONCLUSION

Our view of the binary pulsar population is currently shifting toward a new paradigm. Until the launch of *Fermi*, the bulk ($\sim 90\%$) of the known population in the Galactic field consisted of pulsar–white dwarf systems (Lorimer & Kramer 2004), while the remaining pulsar binaries had neutron star, main sequence, very low mass star, or planet companions. Only about four of the known binary pulsars in the Galactic field were irradiated systems like those presented here. As of today, the number of irradiated systems has increased to over 20 members and candidates, which implies that they now account for about 10% of the binary pulsar population outside of globular clusters (based on the ATNF catalog; Manchester et al. 2005). It is clear that a large selection bias against finding these binaries in classical radio surveys existed until high-energy missions were added in the picture—and yet they still remain challenging to find. New radio pulsar surveys, benefiting from multibeam receivers and larger bandwidth, are also contributing to finding irradiated systems in blind searches, as was the case for PSR J2256–1024. Black widows and redbacks therefore constitute a fundamental component of the pulsar ecosystem, a component that dominates among the fastest-spinning MSPs (Hessels 2008).

The work presented here shows that the spin-down luminosity of pulsars is a good indicator of the level of irradiation sustained by their companions. We found that these systems display a rather universal irradiation efficiency $\epsilon_{\text{irr}} \sim 10\%–30\%$ for reprocessing the incoming energy flux from the pulsar’s spin-down into heat on the companion’s surface. As a result, one may easily estimate the brightness and amplitude of the optical light curves due to irradiation in these pulsar binaries, provided an orbital separation, if the pulsar spin-down luminosity is known from timing or, alternatively, from the γ -ray luminosity.

The typical reflection albedo of stars with temperatures in the range 2000–10000 K is between 0.5 and 1.0 (Claret 2001) for atmospheres that are convective and in radiative equilibrium, respectively. Given the above 15% irradiation efficiency, the above albedos imply that 10%–30% of the energy from the spin-down luminosity would actually reach the companion. It is worth noting that the temperature of PSR J1810+1744 suggests that its outer envelope might be radiative, as opposed to convective in the other systems presented here. If so, the observed irradiation efficiency would be a factor two larger because of the difference in the stellar albedo and this could partly explain why it appears unusual. If further studies of these systems find bow shock nebulae (like for PSR B1957+20), it would allow an independent measurement of the energy loss by the pulsar, which would make for an interesting comparison with that inferred from the irradiated companion (see, e.g., van Kerkwijk & Ingle 2008).

The possibility that some of these pulsar companions do not fill their Roche lobe leads one to ponder the underlying cause for radio eclipses in these systems. What is the mechanism responsible for replenishing the plasma responsible for the eclipses? Other missing pieces of the evolutionary puzzle are: Were these companion stars closer to filling their Roche lobe in the past or have they contracted thermally since the mass transfer episode has terminated? Can black widows and redbacks completely destroy their companion and eventually become the isolated MSPs that we observe? Or, are we simply observing the systems that are incapable of destroying their companions on a relatively short timescale?

The fact that some of these irradiated systems are relatively bright also offers an interesting opportunity for spectroscopic

follow-up. Radial velocity curves should allow for the measurement of the component masses, and test whether these neutron stars typically are more massive, as found for the single system studied so far. Further, detailed photometry work will also allow one to investigate the possible asymmetry in the light curves of PSR J1810+1744 and the reason for its anomalously large dayside temperature.

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Facilities: *Fermi*, GBT, Gemini:Gillett, NTT, *Swift*

APPENDIX

FIELD PHOTOMETRY

Table 6 contains the field photometries of PSR J0023+09, PSR J2256–10, PSR J1810+17, and PSR J2215+51.

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