THE ASTROPHYSICAL JOURNAL LETTERS, 892:L6 (5pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab799d

The FAST Discovery of an Eclipsing Binary Millisecond Pulsar in the Globular Cluster M92 (NGC 6341)

Zhichen Pan[1,2], Scott M. Ransom[3], Duncan R. Lorimer[4,5], William C. Fiore[4,5], Lei Qian[1,2], Lin Wang[1,2,6,7], Benjamin W. Stappers[7], George Hobbs[8], Weiwei Zhu[1,2], Youling Yue[1,2], Pei Wang[1,2], Jiguang Lu[1,2], Kuo Liu[9,1,2], Bo Peng[1,2], Lei Zhang[1,6,8], and Di Li[1,2,6]

[1] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100101, People's Republic of China
panzc@bao.ac.cn, dili@nao.cas.cn

[2] CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People's Republic of China

[3] National Radio Astronomy Observatory, Charlottesville, VA 22903, USA

[4] Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA

[5] Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV 26505, USA

[6] College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

[7] Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK

[8] CSIRO Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia

[9] Max-Plank-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Received 2020 February 22; revised 2020 February 24; accepted 2020 February 24; published 2020 March 19

Abstract

We report the discovery of an eclipsing binary millisecond pulsar in the globular cluster M92 (NGC 6341) with the Five-hundred-meter Aperture Spherical radio Telescope (FAST). PSR J1717+4308A, or M92A, has a pulse frequency of 316.5 Hz (3.16 ms) and a dispersion measure of 35.45 pc cm^{-3}. The pulsar is a member of a binary system with an orbital period of 0.20 days around a low-mass companion that has a median mass of $\sim$0.18 $M_\odot$. From observations so far, at least two eclipsing events have been observed in each orbit. The longer one lasted for $\sim$5000 s in the orbital phase range 0.1–0.5. The other lasted for $\sim$500 s and occurred between 1000 and 2000 s before or after the longer eclipsing event. The lengths of these two eclipsing events also change. These properties suggest that J1717+4308A is a "red-back" system with a low-mass main-sequence or sub-giant companion. Timing observations of the pulsar and further searches of the data for additional pulsars are ongoing.

Unified Astronomy Thesaurus concepts: Globular star clusters (656); Binary pulsars (153); Eclipsing binary stars (444); Millisecond pulsars (1062); Pulsar timing method (1305)

1. Introduction

There are currently 156 pulsars known in 29 globular clusters[10] (GCs). One of the highlights from previous discoveries in GCs is the large population of eclipsing binary pulsars, which includes the fastest spinning millisecond pulsar, Terzan 5ad (Hessels et al. 2006). This object belongs to a subset of eclipsing systems known as "red-backs" (see, e.g., Crawford et al. 2013; Roberts 2013, and references therein) Defining characteristics of red-backs include: (1) the orbital eccentricity being close to zero (noting that the largest eccentricity measured to date if $<10^{-4}$ for PSR J1740-5340 in NGC 6397; D'Amico et al. 2001); (2) a low-mass (typically 0.2–0.7 $M_\odot$) main-sequence companion star; (3) short orbital periods (among the 12 known GC red-back systems only two, Terzan 5ad and NGC 6397A, have orbital periods longer than one day); (4) ionized material from the companion star surrounding the pulsar (Bellm et al. 2016 and references therein); (5) X-ray counterpart identifications (e.g., PSR J1824-2452I or M28I, Pallanca et al. 2013; Papitto et al. 2013) or optical ones (e.g., NGC 6397A, Ferraro et al. 2001). All the GC red-backs are eclipsing binaries that have longer eclipsing durations than other eclipsing pulsars. For example, 47 Tuc V and W typically have 50% and 30% durations, respectively (Camilo et al. 2000; Ridolfi et al. 2016); Terzan 5A is typically at $\sim$30%, and sometimes is eclipsing for the whole orbit (Bilous et al. 2019). Sometimes, at both eclipse ingress and egress, the pulses exhibit excess propagation delays as the pulses pass through the atmosphere of the companion. These delays can be used to estimate the electron column density through the orbit (e.g., as seen in PSR J1701−3006B or M62B; Possenti et al. 2003). As with other binary pulsars, the orbital inclination can be calculated assuming that the companion is a low-mass main-sequence star or a white dwarf (e.g., NGC 6397A, D'Amico et al. 2001).

Pulsars in GCs are prime targets for deep radio searches with large single dishes. Located outside of Arecibo sky and with a reasonable distance, M92 was selected as one of the highest-priority targets for early science surveys with the Five-hundred-meter Aperture Spherical radio Telescope (FAST; Nan et al. 2011; Li & Pan 2016; Li et al. 2018; Jiang et al. 2019), in both drift scan surveys (see Li et al. 2018) and deep targeted searches, particularly, as the so-called Search of Pulsars in Special Populations (SP^2). M92 is a metal-poor (e.g., Roederer & Sneden 2011) GC with a distance of 8.3 ± 1.6 kpc (Rees 1992). It has been studied at optical wavelengths (see, e.g., the main-sequence color–magnitude diagram obtained by Heasley & Christian 1986). M92 has also been examined as a comparison to other clusters (e.g., with M13 and 47 Tuc, Cathey 1974, with M15 and NGC 5466, Buonanno et al. 1985), and in X-ray (e.g., Fox et al. 1996; Lu et al. 2011). According to an empirical relation (Hui et al. 2010; Turk & Lorimer 2013) contingent upon the stellar interaction rate, Zhang et al. (2016) estimated the population size of M92 pulsars to be about 13, ranking them fifth among all clusters visible to FAST.

In this Letter, we present the FAST discovery and initial timing observations of an eclipsing binary millisecond pulsar in

[10] http://www.naic.edu/~pfreire/GCpsr.html

M92, PSR J1717+4308A (hereafter M92A). In Section 2, we describe the discovery observation, along with follow-up observations with FAST and the Green Bank Telescope (GBT). We discuss the implications of this discovery in Section 3, and present our conclusions in Section 4.

2. Observation, Data Reduction, and Timing Analysis

The initial search observation of M92 was carried out on 2017 October 9 as part of a pilot survey for pulsars in GCs with FAST. An ultra-wideband receiver system was used that covered 270–1620 MHz with a ∼60 K system temperature. The two polarization channels were sampled and digitized using 8 bit precision every 200 μs. The total integration time was 30 minutes. The signal processor directly sampled the data in the 0–2048 MHz band, corresponding to 8192 channels in total and a channel bandwidth of 0.25 MHz. To avoid large time smearing at low frequency and smaller field-of-view at high frequencies, we found an optimal band between 500 and 700 MHz for subsequent processing. In this band, the beam size (FWHM) is between 4$'$.9 and 6$'$.9. The diameters of GCs, including M92, are usually larger than 10$'$, while most of them have a much smaller core radius and half-light radius. For M92, its core radius and half-light radius are 0$'$.26 and 1$'$.02, respectively (Harris 1996). Therefore, our beam covers the region of M92 in which we would expect to detect pulsars.

The search was done using the PulsaR Exploration and Search Toolkit (PRESTO;[11] Ransom 2001; Ransom et al. 2002, 2003). Assuming a distance to M92 of 8.3 kpc (Rees 1992), the dispersion measure (DM) predicted by the NE2001 model is 44 pc cm^{-3} (Cordes & Lazio 2002, 2003) and for the YMW16 model it is 35 pc cm^{-3} (Yao et al. 2017). Taking the average value between these two models, the time smearing in one channel for a signal with a DM of 39.5 pc cm^{-3} is 0.2–0.7 ms across the whole band. Given these predictions, we conservatively adopted a DM range of 0–100 pc cm^{-3} in the search. To retain sensitivity to binary pulsars, we performed 1D acceleration searches with a range of $\pm$231 m s^{-2} (assuming a 200 Hz signal) or $\pm$93 m s^{-2} for a 500 Hz signal using the PRESTO routine `accelsearch`. Details of these calculations can be found in Ransom et al. (2001). We found a signal with a period $P = 3.16$ ms with an acceleration of -15.5 m s^{-2}, and DM of 35.45 pc cm^{-3} was found, very close to the value predicted from YMW16 electron density model. The measured signal-to-noise ratio was 51. We note that without the acceleration search, the pulsar would have been undetectable.

In mid-2018, we started monitoring observations at FAST using the 19-beam L-band receiver. This system covers a band of 1.05–1.45 GHz with a beam size of about 3$'$ and a system temperature on cold sky of about 24 K (Jiang et al. 2020). For these observations, we sampled the data from two polarizations with 8 bit precision from the central beam every 49.152 μs with 4096 channels each of width 0.122 MHz. A total of 13 observations have been carried out in the 421 day period between 2018 August (MJD 58351) and 2019 October (MJD 58711). Depending on the FAST commissioning schedule, observations lasted between 0.5 and 5 hr. For each observation, we de-dispersed the data to a DM value of 35.45 pc cm^{-3}, searched for the signal, and obtained times of arrival (TOAs) for timing. The first template used for TOA generation was made from data taken on 2018 September 18 using the accelerated spin parameters determined from a search of that day's data. After determining an initial orbital solution using all of the TOAs from 2018, we folded the longest observation with that ephemeris and obtained an improved pulse profile. A Gaussian-based template, fitted to that pulse profile, was used to determine all of the TOAs for all of the other observations with FAST's 19-beam L-band receiver. With the exception of two observations where the pulsar was undetected due to eclipses, we obtained 1166 TOAs from 11observations. We normally obtained 128 TOAs from every observation, that is to say, every TOA was obtained from ∼30–60 s observation.

Table 1
Parameters for PSR J1717+4308A, M92A

Timing Observation Summary	
MJD Range	58351–58711
Data Span (days)	421
Number of TOAs	1166
Rms Timing Residual (μs)	13.4
Measured Quantities	
Pulse Frequency (Hz)	316.4836857(3)
Orbital Period, P_b	0.2008678775(8)
Epoch of Passage at Periastron, T_0 (MJD)	58353.5490817(3)
Projected Semimajor Axis, χ_p (lt-s)	0.398703(2)
Set Quantities	
R.A. (hh:mm:ss)	17:17:07.39 (J2000)
Decl. (dd:mm:ss)	+43:08:09.4 (J2000)
Reference Epoch (MJD)	53600
Dispersion Measure, DM (cm^{-3} pc)	35.45
Pulse Frequency Derivative (s^{-2})	0
Orbital Eccentricity, e	0
Longitude of Periastron, ω (deg)	0
Timing Model Assumptions	
Clock Correction Procedure	TT(BIPM)
Solar System Ephemeris Model	DE436
Binary Model	BT

We also observed the pulsar with the GBT on 2018 June 29 and 30 for 3.5 hr (across two days). These observations used the 820 MHz receiver and acquired data with the Green Bank Ultimate Pulsar Processing Instrument (GUPPI; DuPlain et al. 2008). The GUPPI data were sampled with 8 bit precision every 81.92 μs over a bandwidth of 200 MHz split into 4096 contiguous channels. We searched the data using PRESTO and the "jerk-search" functionality of `accelsearch` (Andersen & Ransom 2018), we obtained a candidate of a similar period to that seen in the FAST data. While we were able to detect the pulsar, due to the low signal-to-noise ratios of the detections and lack of detections during times where the pulsar was eclipsed, we were unable to use them to obtain a solution for the binary orbit. After we had successfully obtained a phase-connected timing solution from FAST data alone, we folded the GBT data successfully. The folded GBT observation is shown in the right panels of Figure 1 alongside a FAST observation, and highlights the stark contrast in the sensitivity of the two telescopes.

Obtaining timing solutions for red-back systems is notoriously difficult. We used the TEMPO[12] and TEMPO2 (see, e.g., Hobbs et al. 2006) software packages to carry out the timing analysis of the FAST TOAs. With only 13 observations

[11] https://www.cv.nrao.edu/~sransom/presto

[12] http://tempo.sourceforge.net

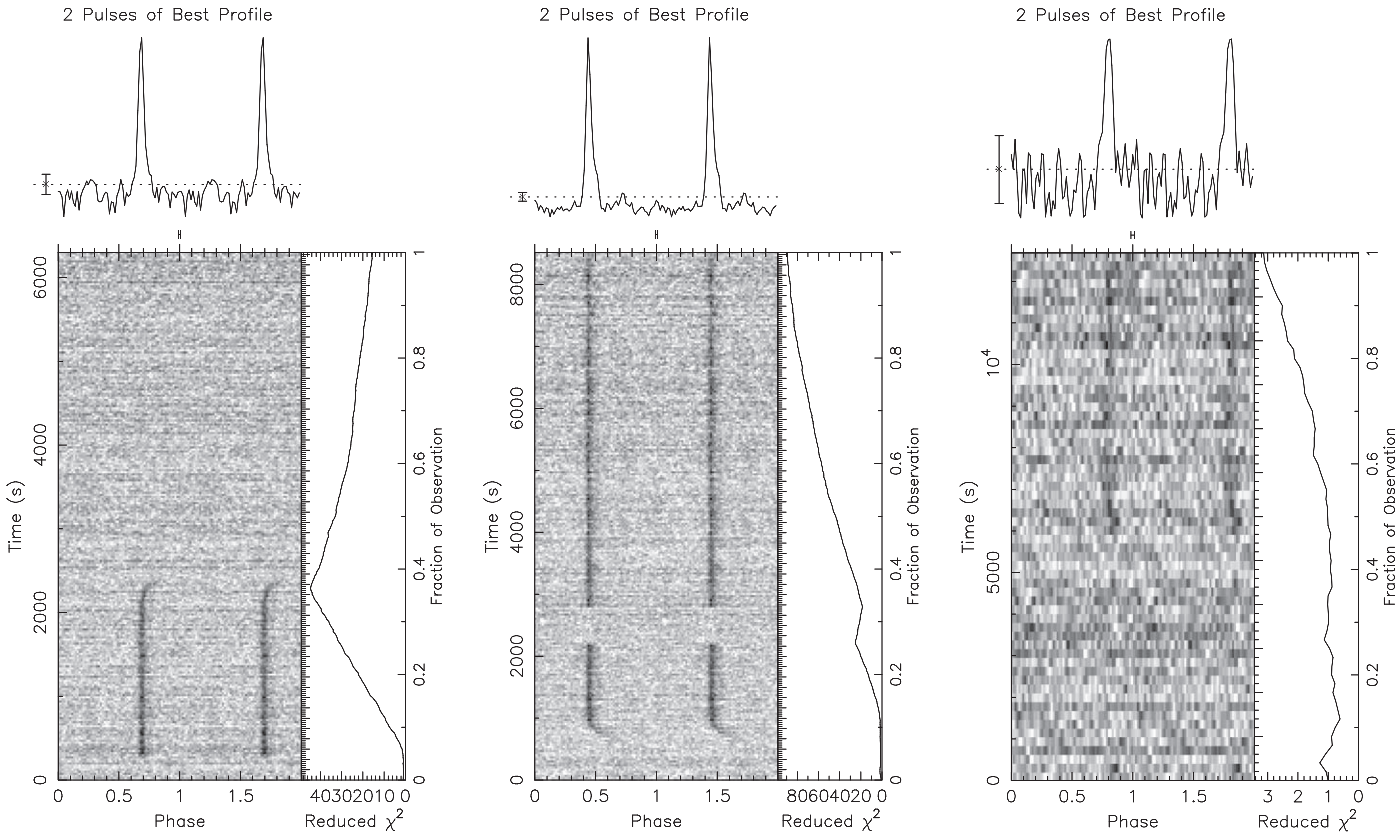

Figure 1. M92A eclipses. Left: folding result of FAST data taken on 2018 September 13. The short eclipse event happened 2000 s before the longest eclipse (at the beginning of the observation). Middle: folding result of FAST data taken on 2018 October 2. The short eclipse event happened approximately 1000 s after the longest eclipse. Right: folding of GBT data taken on 2018 June 29 to 30, showing the huge sensitivity difference between GBT and FAST.

over a 1 year period, including a gap of 9 months, the timing solution is likely not completely phase connected over the full year. We do not have a sufficient number of observing epochs to break degeneracies between the positional and spin-down parameters. However, as the orbital period is short, we are confident in the orbital parameters and the timing residuals as a function of orbital phase. These were obtained by fitting from phase offsets between each of the observations and assuming that the pulsar is at the center of the cluster (Harris 1996, 2010). In TEMPO, we put jumps between every observation, set the pulse frequency derivative and orbital eccentricity to be zero, and used the cluster center as the position for the pulsar for obtaining a timing solution. In TEMPO2, we were able to obtain "a tentative" coherent timing solution across the entire data span (without fitting for offsets between each observation) with a pulse frequency of 316.4836857767(2) Hz and no spin-down. The results from TEMPO or TEMPO2 generally agree. In Table 1 and Figure 2 we show the timing parameters and the timing residuals from obtained using TEMPO. We are continuing to observe the pulsar and a "final" coherent timing solution will be published elsewhere, along with possible multi-wavelength counterparts and better constraints on the eclipsing medium from the companion star.

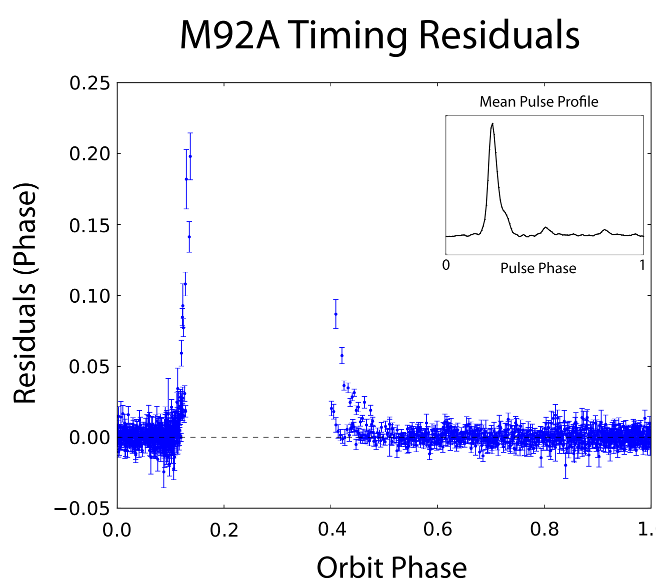

Figure 2. Timing residuals as a function of orbital phase and the mean pulse profile (upper right).

3. Discussion

We believe that the pulsar is associated with M92 for the following reasons: (1) the measured DM value is close the model predictions; (2) the properties of the pulsar (such as it being a millisecond pulsar, in a compact orbit, with a low-mass companion) are similar to many other GC pulsars. Of course, a definitive association would require the discovery of another pulsar in the cluster with similar DM. Searches are ongoing, but a second pulsar has yet to be discovered.

M92A seems to be a new GC red-back pulsar with highly variable eclipses and occasional "mini" eclipses at non-standard

Table 2
Timing Observations of M92A and Eclipsing Events

Date (YYYY MM DD)	Observation Length (hr)	Eclipsing Length (s)	Comments
2018 Aug 21	3	387	Short, before the longer one Orbit phase: 0.08–0.10 Observation ended with eclipsing
2018 Aug 23	5		Observation started and ended with eclipsing
2018 Sep 13	2		Observation started and ended with eclipsing
2018 Sep 14	2		Observation ended with eclipsing
2018 Sep 18	1		No eclipsing observed
2018 Oct 2	5	5255 591	A full observation of the longer one Orbit phase: 0.14–0.45 Short after the longer one Orbit phase: 0.52–0.56
2018 Oct 3	5	4469 627	A full observation of the longer one Orbit phase: 0.15–0.41 Short, after the longer one Orbit phase: 0.50–0.54
2018 Oct 4	0.5		Full eclipsing
2018 Jun 21	0.5		Full eclipsing
2018 Jun 25	1		No eclipsing observed
2018 Jun 27	0.5		Observation ended with eclipsing

Note. Only eclipses in which the entire eclipse duration has been observed were measured.

orbital phases in each orbit. Table 2 shows the observations and the eclipsing events observed. The longest eclipsing event lasts for 5000 s, which corresponds to ~40% of the orbit. We note that the eclipsing event in M92A has a longer duration than an event purely caused by the physical extent of the companion star, and is therefore caused by an ionized "wind." A small eclipsing event has been seen in four of our 11 observations. The event lasts for 1000–2000 s (6%–12% of the orbital period) before or after this "normal" eclipsing event. These minor eclipsing events are likely caused by anisotropic and clumpy ionized gas in the system. The length of these two eclipsing events change from orbit to orbit. Figure 1 shows two observations as examples.

Bilous et al. (2019) also reported that the intensity of the individual pulses from Terzan 5A at both eclipse ingress and egress sometimes became up to 40 times higher than average likely due to plasma lensing. Such a phenomena also happens in other eclipsing systems such as black widows. Main et al. (2018) reported plasma lensing in the original black widow, B1957+20, where the pulsar signal can sometimes be enhanced by factors of up to 70–80 at ~300 MHz. Assuming that FAST has a system temperature of 20 K and gain of 16 K Jy^{-1}, then a single pulse from a pulsar with a width 1 ms and a peak flux of 18 mJy will be detected with a signal-to-noise ratio of 6 by FAST. If plasma lensing can increase the intensity by a factor of 50, with FAST we are able to detect single pulses from millisecond pulsars down to a peak flux density of ~0.36 mJy. These results suggest that single pulse searches should also be used for GC pulsar observations to potentially aid in finding new red-backs and black widows. We have applied a single pulse search algorithm to our M92 data, but no single pulses with signal-to-noise ratio larger than 6 have yet been detected.

The timing residuals near eclipse ingress and egress also show significant dispersive delays (see Figure 2). The maximum delay estimated from the data is approximately 0.6 ms, corresponding to a DM excess of 0.3 pc cm^{-3}. This is similar to some other GC red-backs (e.g., less than 1 pc cm^{-3} for NGC 6397A; D'Amico et al. 2001) and significantly smaller than Terzan 5A (see the millisecond-duration delays in Bilous et al. 2019).

4. Conclusion

A red-back eclipsing binary millisecond pulsar, PSR J1717+4308A or M92A, with a pulse frequency of 316.48 Hz (corresponding to a pulse period of 3.1597 ms) and orbital period of 0.2 days was discovered in GC M92 with FAST. This brings the number of GCs with pulsars to 30 and the total number of GC pulsars published to 157. The pulsar's DM of 35.45 cm^{-3} pc is very close to that predicted by the YMW Galactic electron density model. Based on its orbital characteristics, the orbiting companion is most likely a main-sequence star with a mass of 0.18 $M_{\odot}$. At least two eclipses have been observed per orbital cycle. The longer of the two, between orbital phase 0.1 and 0.5, is most likely due to a companion wind. The shorter eclipse, occurring between phase of 0.06 and 0.12, lasts for less than 10 minutes.

The discovery of PSR J1717+4308A or M92A demonstrates the potential for FAST as an excellent probe of the GC pulsar population in the coming years, which suggests that the total population of pulsars in M92 should be one of the highest in the FAST sky. There are other 24 even richer clusters to be searched, including NGC 7078, NGC 7089, and Pal 2 (see Table 3 of Zhang et al. 2016 for details). A full census of the

FAST GC pulsar sample will undoubtedly lead to interesting individual binary systems.

This work is supported by the Basic Science Center Project of the National Nature Science Foundation of China (NSFC) under grant No. 11988101, the National Nature Science Foundation of China (NSFC) under grant No. 11725313, No. 11803051, No. U1631237, No. 11703047, No. 11773041, No. 11690024, No. 11743002, and No. 11873067, by National Key R&D Program of China No. 2017YFA0402600, and State Key Development Program for Basic Research No. 2015CB857100, the Strategic Priority Research Program of the CAS grant No. XDB23000000. This work made use of data from the Five-hundred-meter Aperture Spherical radio Telescope (FAST). FAST is a Chinese national mega-science facility, built and operated by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). We appreciate all of the people in the FAST group for their support and assistance during the observations. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Green Bank Observatory is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. Z.P. and Y.Y. are supported by the CAS "Light of West China" Program. S.M.R. is a CIFAR Fellow and is supported by the NSF Physics Frontiers Center award 1430284. D.R.L. acknowledges support from the National Science Foundation awards AAG-1616042, OIA-1458952, and PHY-1430284 and from the Research Corporation for Scientific Advancement. W.C.F. acknowledges the STEM Mountains of Excellence Graduate Fellowship. L.Q. is supported in part by the Youth Innovation Promotion Association of CAS (No. 2018075). W.Z. is supported by the CAS Pioneer Hundred Talents Program. K.L. acknowledges the financial support by the European Research Council for the ERC Synergy Grant BlackHoleCam (grant No. 610058), the FAST FELLOWSHIP from Special Funding for Advanced Users budgeted and administrated by Center for Astronomical Mega-Science, Chinese Academy of Sciences (CAMS), and the CAS-MPG LEGACY funding "Low-Frequency Gravitational Wave Astronomy and Gravitational Physics in Space." B.P. acknowledges the CAS-MPG LEGACY funding "Low-Frequency Gravitational Wave Astronomy and Gravitational Physics in Space."

ORCID iDs

Zhichen Pan https://orcid.org/0000-0001-7771-2864
Scott M. Ransom https://orcid.org/0000-0001-5799-9714
Duncan R. Lorimer https://orcid.org/0000-0003-1301-966X
William C. Fiore https://orcid.org/0000-0001-5645-5336
Lei Qian https://orcid.org/0000-0003-0597-0957
Lei Zhang https://orcid.org/0000-0001-8539-4237
Di Li https://orcid.org/0000-0003-3010-7661

References

Andersen, B. C., & Ransom, S. M. 2018, ApJL, 863, L13
Bellm, E. C., Kaplan, D. L., Breton, R. P., et al. 2016, ApJ, 816, 74
Bilous, A. V., Ransom, S. M., & Demorest, P. 2019, ApJ, 877, 125
Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1985, A&A, 145, 97
Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G., & Manchester, R. N. 2000, ApJ, 535, 975
Cathey, L. R. 1974, AJ, 79, 1370
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Cordes, J. M., & Lazio, T. J. W. 2003, arXiv:astro-ph/0301598
Crawford, F., Lyne, A. G., Stairs, I. H., et al. 2013, ApJ, 776, 20
D'Amico, N., Possenti, A., Manchester, R. N., et al. 2001, ApJL, 561, L89
DuPlain, R., Ransom, S., Demorest, P., et al. 2008, Proc. SPIE, 7019, 70191D
Ferraro, F. R., Possenti, A., D'Amico, N., & Sabbi, E. 2001, ApJL, 561, L93
Fox, D., Lewin, W., Margon, B., van Paradijs, J., & Verbunt, F. 1996, MNRAS, 282, 1027
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E. 2010, arXiv:1012.3224
Heasley, J. N., & Christian, C. A. 1986, ApJ, 307, 738
Hessels, J. W. T., Ransom, S. M., & Stairs, I. H. 2006, Sci, 311, 1901
Hobbs, G., Edwards, R., & Manchester, R. 2006, ChJAS, 6, 189
Hui, C. Y., Cheng, K. S., & Taam, R. E. 2010, ApJ, 714, 1149
Jiang, P., Tang, N.-Y., & Hou, L.-G. 2020, arXiv:2002.01786
Jiang, P., Yue, Y., Gan, H., et al. 2019, SCPMA, 62, 959502
Li, D., & Pan, Z. 2016, RaSc, 51, 1060
Li, D., Wang, P., Qian, L., et al. 2018, IMMag, 19, 112
Lu, T-Ni., Kong, A. K. H., Verbunt, F., et al. 2011, ApJ, 736, 158
Main, R., Yang, I.-S., Chan, V., et al. 2018, Natur, 557, 522
Nan, R., Li, D., Jin, C., et al. 2011, IJMPD, 20, 989
Pallanca, C., Dalessandro, E., Ferraro, F. R., Lanzoni, B., & Beccari, G. 2013, ApJ, 773, 122
Papitto, A., Ferrigno, C., Bozzo, E., et al. 2013, Natur, 501, 517
Possenti, A., D'Amico, N., Manchester, R. N., et al. 2003, ApJ, 599, 475
Ransom, S. M. 2001, PhD thesis, Harvard Univ.
Ransom, S. M., Cordes, J. M., & Eikenberry, S. S. 2003, ApJ, 589, 911
Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, ApJ, 124, 1788
Ransom, S. M., Greenhill Lincoln, J., Herrnstein James, R., et al. 2001, ApJL, 546, L25
Random, S. M., Hessels, J. W. T., Stairs, I. H., et al. 2005, Sci, 307, 892
Rees, R. R., Jr. 1992, AJ, 103, 1573
Ridolfi, A., Freire, P. C. C., Torne, P., et al. 2016, MNRAS, 462, 2918
Roberts, M. S. E. 2013, in IAU Symp. 291, Neutron Stars and Pulsars: Challenges and Opportunities after 80 years, ed. J. van Leeuwen (Cambridge: Cambridge Univ. Press), 127
Roederer, I. U., & Sneden, C. 2011, AJ, 142, 22
Turk, P. J., & Lorimer, D. R. 2013, NMRAS, 436, 3720
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Zhang, L., Hobbs, G., Li, D., et al. 2016, RAA, 16, 151