A State Change in the Missing Link Binary Pulsar System PSR J1023+0038


Published in:
Astrophysical Journal

DOI:
10.1088/0004-637X/790/1/39

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
A STATE CHANGE IN THE MISSING LINK BINARY PULSAR SYSTEM PSR J1023+0038


1 Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
2 ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands
3 Astronomical Institute A. Pennekoek, University of Amsterdam, 1098XH, Amsterdam, The Netherlands
4 Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA
5 McGill University, 3600 University Street, Montreal, QC H3A 2T8, Canada
6 Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, The Netherlands
7 Space Radiation Laboratory, California Institute of Technology, 1200 East California Boulevard, MC 249-17, Pasadena, CA 91125, USA
8 W. W. Hansen Experimental Physics Laboratory, KIPAC, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
9 Faculty of Physical and Applied Sciences, University of Southampton, Highfield, Southampton, SO17 1BJ, UK

Received 2013 November 29; accepted 2014 May 22; published 2014 July 1

ABSTRACT

We present radio and γ-ray observations, which, along with concurrent X-ray observations, reveal that the binary millisecond pulsar (MSP)/low-mass X-ray binary transition system PSR J1023+0038 has undergone a transformation in state. Whereas until recently the system harbored a bright millisecond radio pulsar, the radio pulsations at frequencies between 300 to 5000 MHz have now become undetectable. Concurrent with this radio disappearance, the γ-ray flux of the system has quintupled. We conclude that, though the radio pulsar is currently not detectable, the pulsar mechanism is still active and the pulsar wind, as well as a newly formed accretion disk, are together providing the necessary conditions to create the γ-ray increase. This system is the first example of a compact, low-mass binary which has shown significant state changes accompanied by large changes in γ-ray flux; it will continue to provide an exceptional test bed for better understanding the formation of MSPs as well as accretion onto neutron stars in general.

Key words: binaries: eclipsing – pulsars: individual (PSR J1023+0038) – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

The pulsar “recycling” scenario (Alpar et al. 1982; Radhakrishnan & Srinivasan 1981) proposes that the rapid rotation rates of millisecond pulsars (MSPs10) originate from a period of mass accretion from a binary companion in a low-mass X-ray binary (LMXB). The idea that such systems could also result in the complete ablation of the companion star and produce isolated MSPs—like the first MSP discovered, PSR B1937+21 (Backer et al. 1982)—seemed to be confirmed by the discovery of the first eclipsing “black widow” pulsar PSR B1957+20 (Fruchter et al. 1990). The eclipses of the radio pulsations in this system showed that mass was being ablated from the very low mass (M* ≲ 0.1 M⊙) companion (Ryba & Taylor 1991), however the mass loss rate appeared to be insufficient to ever completely destroy the companion. The LMXB and ablation phases were expected to be short-lived and so the subsequent discovery of another black widow, PSR J2051−0827 (Stappers et al. 1996), seemed to challenge the connection between these systems and the isolated MSPs. Nonetheless, clear evidence that MSPs are indeed spun-up in LMXBs came with the discovery of coherent X-ray pulsations at a period of 2.5 ms from the LMXB SAX J1808.4−3658 during an X-ray outburst (Wijnands & van der Klis 1998). To date, there are some 15 of these accreting X-ray millisecond pulsars (AMXPs) known (Patruno & Watts 2012).

With the rapid rate of MSP discoveries in the last few years (Ransom 2013, see his Figure 1), the diversity of MSP binary companions has continued to grow beyond the standard low-mass white dwarf or ultra-low-mass black widow companions that were initially found. This variety has shown that the pulsar recycling process produces a rich array of systems, some of which are exceedingly exotic (e.g., Bailes et al. 2011; Ransom et al. 2014). Furthermore, some of these new systems are excellent case studies for better understanding the accretion-induced spin-up of neutron stars.

Recently, a completely different class of eclipsing binary MSP systems, dubbed “redbacks,” with more massive (M* ≳ 0.1 M⊙) and likely non-degenerate companions have been discovered in the Galactic field (Roberts 2011 and references therein; such systems are also known in globular clusters (GCs) and were discovered earlier, e.g., D’Amico et al. 2001). Targeted searches for radio pulsars in unassociated Fermi γ-ray sources have been particularly fruitful, producing the majority of these discoveries (e.g., Ray et al. 2012; Hessels et al. 2011). Such searches have also found many more examples of the previously known black widow systems. It has also been shown that during the accretion stage the companion star can be ablated down to the mass of a planet (Bailes et al. 2011; van Haften et al. 2012) while at the same time (barely) surviving complete destruction via ablation. This again suggests that in some cases the companion does not survive and an isolated MSP is left behind.

With the wide variety of MSP systems now known, it is necessary to better understand the various potential accretion and ablation processes in LMXBs and eclipsing binary MSPs. While

10 We use the term MSP for a neutron star rotating with a period $P_{\text{spin}} \lesssim 30$ ms and with an inferred surface magnetic field $B_{\text{surf}} \lesssim 10^{10}$ G. Such sources derive their power from the star’s rotational kinetic energy loss and necessarily produce observable radio pulsations. In an increasing number of cases, pulsed magnetospheric emission is also detected in keV X-rays and MeV–GeV γ-rays.
most MSP systems are clearly well past any accretion episode, the redbacks and black widows appear to provide the closest available link to the LMXBs. There are now two exceptional systems, the Galactic field binary pulsar J1023+0038 (hereafter J1023; Archibald et al. 2009) and PSR J1824−2452/IGR J18245−2452 (hereafter M28I; Papitto et al. 2013), located in the GC M28. Both are providing us with a detailed look at the transition between these two phases. In fact, the behavior of these two systems in the last decade has made it abundantly clear that the transition between an LMXB and an MSP is not a sudden or unidirectional transformation.

J1023 was discovered in 2007 as a 1.7 ms radio pulsar in a 4.8 hr, circular-orbit eclipsing binary system. It was soon recognized to be the same source as FIRST J102347.6+003841, which had originally been identified as a magnetic cataclysmic variable (Bond et al. 2002) but was subsequently identified as possibly being an LMXB with an accretion disk during 2001 (Thorstensen & Armstrong 2005). Later optical and X-ray observations indicated that the source no longer possessed an accretion disk (Woudt et al. 2004; Homer et al. 2006; Archibald et al. 2009, 2010; Bogdanov et al. 2011). It was therefore identified as the first object to have been seen to transition from an LMXB-like state to an MSP. Archibald et al. (2013) also show that since its discovery as a pulsar this “original Galactic field redback” has exhibited radio behavior typical of this class of eclipsing binary MSPs. During this phase, X-rays are produced by the system (Archibald et al. 2010; Bogdanov et al. 2011) but they originate from a combination of pulsed magnetospheric emission and an intra-binary shock between the companion and MSP winds.

M28I links LMXBs and MSPs in a complementary, and even more direct, way because it has been seen to transition from a radio emitting MSP to an AMXP and back again: i.e., it has shown accretion-powered pulsations at the same rotational period as the previously known radio pulsar (Riggio et al. 2013; Papitto et al. 2013). Moreover, it was suggested that this object has been seen to swing between these states several times over the past decade.

Here we report a sudden change of state in J1023, starting in 2013 June. This change was heralded by the cessation of detectable pulsed radio emission from the MSP and coincides with a dramatic, five-fold increase in the γ-ray flux from the system. Along with the reported changes in the X-ray behavior (Patruno et al. 2014) and the emergence of double-peaked optical spectral lines (Halpern et al. 2013), this points to an accretion disk having re-formed in the system but with a still-active pulsar mechanism also present.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Radio Observations

As part of a campaign to track the spin and orbital evolution of the J1023 system, we are regularly observing it with the 76 m Lovell Telescope (LT) at Jodrell Bank in the United Kingdom and the 94 m (equivalent) Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands. We observed using the LT on average once every 10 days, with a typical duration of 30 minutes. Since 2013 July, we are observing with 1 hr integrations approximately weekly. The LT observations are centered at 1500 MHz and were recorded using both a digital filter bank (DFB) and, as of 2011 April, a coherent dedispersion system (ROACH) in parallel. The DFB and ROACH both provide 384 MHz of usable bandwidth after interference excision; the primary advantage of the ROACH data is simply that it provides higher effective time resolution after dedispersion using D$\$PSR (van Straten & Bailes 2011). We used the WSRT in tied-array mode (where the signals from all the available dishes are summed in phase) at central frequencies of 350 and 1380 MHz with respective bandwidths of 80 and 160 MHz. For both observing bands the data were coherently dedispersed using the PuMaII backend (Karuppusamy et al. 2008). Typically, we observed for 25 minutes, but since 2013 July a number of longer observations, up to a full orbit, have been made. For both the LT and WSRT, data inspection and post-processing, including dedispersion optimization and interference removal, is done using the PSRCHIVE11 package (van Straten et al. 2012). The archived data products have 10 s time resolution to search for short timescale changes in brightness.

In addition to our regular LT/WSRT monitoring, we have taken two long observations using the Green Bank Telescope (GBT) on 2013 August 11 and the Arecibo telescope (AO) on 2013 August 28, at central frequencies of 2 GHz and 4.5 GHz, respectively. At the GBT, we used the GUPPI pulsar backend to coherently dedisperse an 800 MHz band. The accumulated profiles were written to disk every 2.64 s. With AO, we ran seven Mock spectrometers, each recording 172 MHz, in parallel which spanned the total available 1 GHz band after removing overlap. The band was divided into 256 channels, recorded every 32.768 µs. D$\$PSR was used to incoherently dedisperse the data and fold it into 32 pulse phase bins, writing out a profile every 100 s. The various radio observing systems are summarized in Table 1.

2.2. Gamma-Ray Observations

J1023 is spatially associated with a γ-ray source detected while J1023 was active as a radio MSP (2FGL J1023.6+0040; Tam et al. 2010; Nolan et al. 2012; Archibald et al. 2013). In light of this association, and hypothesising a possible change due to the disappearance of the radio pulsar signal, we investigated the γ-ray light curve. We retrieved the Fermi Large Area Telescope (LAT; Atwood et al. 2009) Pass 7 reprocessed photons with energies of 100 MeV–300 GeV from the time range 2008 August 9–2013 November 18. We used the Fermi science tools version v9r32p5 for our analysis. We selected those photons with the SOURCE event class, and maximum zenith angle 100◦ to reduce contamination from atmospheric γ-rays. The light curve analysis was then performed using two approaches, which we now describe in turn.

The first approach follows the Fermi Cicerone12 on aperture photometry. We selected the >1 GeV photons, for which the point-spread function radius is ≲1′ (Ackermann et al. 2012), that were within 1′ of J1023. For reference, the nearest source in the 2FGL catalog is 2′ away. We then applied a region of interest (ROI) cut, filtered by the data selection (DATA_QUAL==1)

11 http://psrchive.sourceforge.net/
12 http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/
Poisson errors. We binned the resulting photons into 500 ks time bins and used the gtxposure tool with the P7REP_SOURCE_V15 instrument response functions, assuming a spectral index of 2.5 (the 2FGL catalog gives a spectral index for the associated source of 2.5 ± 0.3; Nolan et al. 2012), to compute the effective exposure within each bin. This left us with 260 photons before the radio pulsar disappearance and 63 after. We then re-binned the light curve and exposure values to compute the effective exposure within each bin. This left us with live time cubes, exposure maps, and source maps for a 40 deg sub-selection, along with long-term average fluxes and their uncertainties. We computed good time intervals (GTIs) to all our photons. We constructed likelihood fitting. We again applied the same ROI cut, data indexing for the associated source of 2

\[ \gamma \rightarrow \textrm{P7REP_SOURCE_V15} \]


\[ \text{LAT_CONFIG} \]

\[ \text{ABS(ROCK_ANGLE)} \]

\[ \text{16 Number(s) shown in parentheses represent the statistical uncertainty in the last digit(s) quoted. We do not expect systematic uncertainties to dominate and therefore do not consider them.} \]

\[ \text{15 While the WSRT is a synthesis telescope and could in theory make an image of the source, it is an east–west array and the source is located at the celestial equator which, when combined with our relatively short integration times, makes imaging almost impossible.} \]

\[ \text{14 Extensible Markup Language.} \]

\[ \text{http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/} \]
Figure 1. Timeline for the state change in J1023. Top panel: radio observations of J1023 with the LT at 1500 MHz and WSRT at 1380 MHz (black symbols), WSRT at 350 MHz (red symbols), GBT at 2 GHz (triangles) and Arecibo at 4.5 GHz (squares). The observations are plotted against time and orbital phase, where an orbital phase of zero has the pulsar passing the ascending node. The left panel shows data from 2009 to 2013, while the right panel shows the data from 2013. Observations where the pulsar was not detected are denoted by pluses, triangles and squares, while detections are shown by circles, with the circle size indicating the signal-to-noise of the detection. The horizontal lines show the average eclipse duration at 1380 and 1500 MHz (black) and 350 MHz (red). The vertical dashed lines indicate the last confirmed detection on 2013 June 15 of the pulsed signal and the first non-detection outside the known eclipse region on 2013 June 30. Bottom panel: 1–300 GeV $\gamma$-ray photon flux computed with aperture photometry. The steps (solid line) show the flux averaged over 2.5 Ms segments, with Poisson errors. The gray lines show the result of taking the same 2.5 Ms averages with intermediate starting points, effectively convolving the photon arrival time series with a 2.5 Ms top-hat function. (A color version of this figure is available in the online journal.)

$2.22(14) \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$, while the post-disappearance average flux is $6.9(9) \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$.

To better determine when the $\gamma$-ray flux started increasing, we used our aperture-photometry data and combined 2.5 Ms chunks starting every 500 ks. The results are plotted in the lower panel of Figure 1. This procedure unavoidably smoothes all features by 2.5 Ms (about 1 month). Nonetheless, it is clear that the $\gamma$-ray flux began rising at approximately the same time that the radio pulsations disappeared. It is unclear, however, whether the flux rose abruptly and then remained constant or whether it rose gradually and is possibly continuing to rise.

To look for spectral changes in a nearly model-independent way, we computed “hardness ratios” before and after the radio disappearance. Examination of the aperture photometry photons revealed that about half of them were above 1.6 GeV, so we simply performed aperture photometry as described above but with separate energy ranges of 1–1.6 GeV and 1.6–300 GeV. A “hardness ratio” would then be a ratio of (exposure-corrected) count rates in these two energy ranges. The hardness ratio before the radio disappearance was $1.10(12)$, while after the disappearance it was $1.4(3)$. We do not claim any significant change in hardness. Because of the low number of photons, we were not very sensitive to spectral changes.

We investigated orbital modulation of the $\gamma$-ray emission by using $\text{tempo}2$ (Hobbs et al. 2006) with the $\text{fermi}$ plugin to assign the corresponding orbital phase to each probability-tagged photon. We used the weighted H test (Kerr 2011) to look for periodic modulation, obtaining a false positive probability of 0.66—that is, for purely random phases there is a 66% probability of having greater deviation from uniformity than we detect. Testing with a simulated signal in which all source photons are distributed according to a sine wave produced a median false positive probability of 0.08. In other words, even with this very strong modulation, we would have had only a 50% chance of obtaining a detection better than 1.4$\sigma$. So although we have tested for orbital modulation, our non-detection rules out...
only very sharply peaked orbital modulation. We investigated modulation at the pulsar period using tempo2 to assign a pulse phase to each photon, then testing for periodicity as above. The false positive probability we obtained was 0.997. This method has the same lack of sensitivity as our search for orbital pulsations, but it also has another limitation: because our orbital ephemeris for J1023 was last updated before its disappearance in radio, and because J1023 undergoes apparently random orbital period variations (Archibald et al. 2010, 2013), we should expect phase prediction errors as large as ~0.2 turns to smear out any high harmonic content. It is therefore difficult to rule out even very sharply peaked pulsations.

4. DISCUSSION

We report that, sometime between 2013 June 15 and June 30, pulsations from the MSP in the J1023 binary system disappeared at radio frequencies where they are otherwise easily detectable. Concurrent with this disappearance we find that the \(\gamma\)-ray flux of J1023 has increased five-fold. Subsequent optical, UV and X-ray observations have shown that an accretion disk has formed in the binary system (Halpern et al. 2013; Patruno et al. 2014), signifying that J1023 has undergone a transition from a binary MSP to a state that is not accretion driven like an LMXB, but has properties similar to those seen in a state referred to as a quiescent low-mass X-ray binary (qLMXB). The present transition appears similar to that of 2000/2001; the archival study by Archibald et al. (2009) shows the system transitioning from a radio point source and G-type optical colors to having an accretion disk.

We are now fortunate to observe two redback systems that have transitioned multiple times between LMXB and MSP states. Although its 2013 outburst is a uniquely observed event for a known MSP, as a radio pulsar M28I is fairly typical in a population of about 11 known GC redbacks.\(^{17}\) This suggests that other similar pulsars in the Galactic GC system will also undergo such events in the coming years and decades. These sources remain challenging to study at optical and radio wavelengths, however, because of the relatively large distance to the most massive GCs (~5–10 kpc). Also, because stellar interactions are common in GCs the evolution of these systems will be modified compared to those in the field and in some cases exchange interactions will result in some GC redbacks hosting neutron stars no longer being orbited by their original binary companions. In contrast, the known field redbacks, of which J1023 was the first discovered, are typically significantly less distant (<2 kpc) and offer better potential for detailed multi-wavelength study. The GC and field redbacks both provide us interesting test beds for studying the accretion process and give us different views on how these systems can form and evolve.

There are now at least 7 redbacks and 17 black widow systems known in the field, thanks in large part to targeted searches of unassociated \textit{Fermi} sources (Ray et al. 2012). Again, as a radio pulsar, J1023 is no longer very atypical, with several similar examples, such as PSR J2215+5135 (Hessels et al. 2011), which has nearly identical orbital parameters and a likely similar, Roche-lobe-filling companion (Breton et al. 2013). Here as well, given proper radio, optical, and X-ray monitoring, it is expected that it may not be long before these similar systems show transitions like those we have observed from J1023. If, not, then the distinction of J1023 needs to be considered more carefully.

Though J1023 and M28I show many striking similarities in their X-ray behavior (Patruno et al. 2014), the former has yet to enter a truly energetic outburst state in which the accretion flow is reaching the neutron star surface. Indeed, the 2013 June to October activity of J1023 is arguably very similar to its past 2001 state (though no targeted X-ray data was available at that time). An energetic outburst like that seen in M28I (Papitto et al. 2013) can be ruled out for J1023 since 1996 because it would have triggered an all-sky X-ray monitor. M28I has also been observed for ~200 ks by \textit{Chandra} in 2008 (Linares et al. 2013), switching several times between a bright “active” (4 \(\times\) 10\(^{33}\) erg s\(^{-1}\)) and a faint “passive” state (6 \(\times\) 10\(^{32}\) erg s\(^{-1}\)). Therefore M28I can undergo rapid X-ray flux variations similar to those currently seen in J1023.\(^{18}\) If the X-ray flux variations observed in M28I in quiescence (i.e., the 2008 \textit{Chandra} data, for which no simultaneous radio observation is available) can be ascribed to the presence of an accretion disk, then there is no specific reason to presume that these two systems are fundamentally different.

Shvartsman (1970) proposed that an active radio pulsar in a contact binary is able to prevent the formation of an accretion disk.

\(^{17}\) http://www.naic.edu/~pfreire/GCpsr.html

\(^{18}\) Papitto et al. (2013) describes the 2008 \textit{Chandra} active and passive states as an “outburst” followed by a “total quenching” of the X-ray luminosity. We clarify, however, that the active/passive states cannot be considered as a standard outburst/quiescent cycle. The active state is indeed too faint and within the range of quiescent luminosities of LMXBs. Furthermore the passive state displays a significant X-ray luminosity well above the background level and therefore cannot be truly defined as quenching (see Linares et al. (2013) for an extended discussion.)
If the rotation-powered pulsar is still active, enshrouding of the system by intra-binary material, causing severe scattering and/or absorption, is the logical explanation for the absence of radio pulsations. This would make J1023 a so-called hidden radio MSP, as hypothesized by Tavani (1991). In this scenario, the MSP is completely enshrouded in the prodigious outflow from its close companion star, rendering the pulsar perpetually eclipsed at radio frequencies (see, e.g., Thompson et al. 1994; Iacolina et al. 2009 for possible mechanisms). At the same time, the system generates strong un-pulsed shock emission in X-rays and y-rays, due to the interaction of the pulsar wind with the outflow of matter (Tavani 1993). Other recently discovered eclipsing MSPs also exhibit compelling evidence for enshrouding (Romani & Shaw 2011; Ray et al. 2013), though J1023 is the first instance where we see a sudden increase in the high-energy emission, correlated with a radio disappearance. Together, these systems support previous arguments that a non-negligible fraction of MSPs may often be non-detectable at radio wavelengths because of enshrouding. There is also some evidence that this becomes more problematic for the fastest-spinning MSPs (Burderi et al. 2001; Hessels et al. 2006, 2008).

Spin-down luminosity is a sensitive function of spin period ($E \propto P^{-3}$) and hence this may explain this trend, all other factors, like orbital separation and companion type, being equal. Indeed this could be one reason for the absence of a discovery of a sub-millisecond pulsar thus far, in spite of reasonable sensitivity to such sources in modern large-scale pulsar surveys, such as the PALFA survey (Cordes et al. 2006), the HTRU survey (Keith et al. 2010) and the aforementioned LAT-directed searches. On the other hand, the existence of many such “hidden” fast radio MSPs is problematic in light of the absence of detections of accreting MSPs with frequencies higher than 619 Hz, in spite of there being no obvious selection effects against finding them with X-ray telescopes (Chakrabarty et al. 2003). J1023 is a 1.7 ms pulsar, the fifth fastest spinner known in the Galactic field. Of the five fastest-spinning MSPs in the field, three are known to eclipse and the other two are isolated.

With the re-appearance of an accretion disk, J1023 also resembles a number of qLMXB systems containing AMXPs. It has been suggested that some AMXPs reactivate as rotation-powered pulsars in quiescence (Stella et al. 1994; Campana et al. 1998; Burderi et al. 2003; Campana et al. 2004). Apart from M28I, no radio pulsations have been detected from any AMXP in quiescence, although this could be a consequence of enshrouding as well (Burgay et al. 2003; di Salvo et al. 2008). In addition, none has yet been detected as y-ray source with Fermi LAT (Xing & Wang 2013), although they are all significantly more distant than J1023. It is thus plausible that quiescent AMXPs may also be “hidden” MSPs.

Given the nature of the enhanced y-ray emission that has appeared from J1023, one may consider what similarities exist with the small population of y-ray binaries, where a compact object is orbited by a massive OB star (e.g., Dubus 2013). Still the best understood high-mass gamma-ray binary is PSR B1259–63, which contains a relatively rapidly rotating ($P = 47$ ms) young radio pulsar; its pulsar has $E \sim 20$ times higher than that of PSR J1023+0038 yet has shown y-rays $\sim 200$ times brighter, achieving near 100% efficiency in converting spin-down power

---

19 Nonetheless, despite observational biases against finding fast-spinning MSPs as well as a possible population of fast-spinning, “hidden” MSPs, the spin frequency distribution of MSPs is clearly seen to drop off rapidly toward higher frequencies (Hessels et al. 2007, see his Figure 4.)
to γ-rays near periastron, when the pulsar’s wind is shocked closest to the pulsar. Though the orbital compactness and companion mass in the case of J1023 is quite different when compared with such systems, there may be similarities in some of the physical mechanisms at play. This suggests PSR J1023+0038 could indeed continue to brighten. It may also serve a similar prototype role for a new class of low-mass γ-ray binaries. We note that given its increased γ-ray luminosity, its present γ-ray efficiency, assuming an isotropic luminosity and taking $\dot{E} = 4.3 \times 10^{34} \text{erg s}^{-1}$ (Deller et al. 2012), is 0.14. We therefore expect that the γ-ray luminosity will rise at most another factor of seven, as beyond that it would exceed the available energy from pulsar spin down.

Regardless of J1023’s upcoming X-ray behavior, when it returns to an MSP state then it will be possible to compare the radio pulsar timing before and after the current active state. J1023 benefits greatly in this regard from its relative brightness and the high cadence of our recent radio monitoring observations. It also does not suffer from the contaminating influence of acceleration in a GC gravitational potential, as in the case of M28I. After being spun-up to millisecond periods, an accreting neutron star should enter a spin-down phase where the mass transfer rate decreases due to the progressive detachment of the donor radius from its Roche lobe. During this final evolutionary phase, the neutron star magnetosphere expands substantially and a large fraction of the neutron star rotational energy is lost via a propeller-like mechanism (Tauris 2012). It is possible therefore that what we are observing in J1023 is indeed this very last phase of its life as an qLMXB. If this were the case and a propeller-like mechanism does occur before the source re-appears as a periodic emitter at any wavelength, then it should be possible to observe a strong spin down during this active phase, i.e., well in excess of the pulsar magnetic dipole spin down. Even if no accretion-powered X-ray pulsations are detected, this test can be performed once the active phase is over by comparing the pre- and post-active phase radio timing solutions.

In conclusion, we have demonstrated a new stage in the back-and-forth transitioning that seems to characterize the redback class of MSPs. For the first time, we have seen a bright radio MSP become undetectable while at the same time the system becomes γ-ray bright. We argue that the pulsar mechanism remains active in this system, but that the radio pulsations are obscured. While our higher-frequency radio observations have also been unsuccessful, there is perhaps potential for detecting pulsed X-rays (not generated by accretion) that will further confirm the continued activity of the pulsar itself. The detection or lack of accretion-powered X-ray pulsations in forthcoming X-ray observations can easily disprove or strengthen such an hypothesis. Similarly, planned radio interferometric observations to look for a continuum radio source are also important in this regard.

The analogy with the wider-orbit, much more massive companion γ-ray binaries is tantalizing. A multi-wavelength campaign that follows J1023 back into its radio MSP state may better resolve the state transition and associated radio/optical/X-ray/γ-ray phenomenology. Long-term, phase-coherent timing will also shed light on the accretion torques experienced while the radio pulsar was undetectable.

We thank H.A. Krimm for kind support in the use of the Swift/BAT data. A.P. acknowledges support from the Netherlands Organization for Scientific Research (NWO) Vidi fellowship. A.M.A. and J.W.T.H. acknowledge funding for this work from an NWO Vrije Competitie grant. J.W.T.H. also acknowledges funding from an NWO Vidi fellowship and ERC Starting Grant “DRAGNET” (337062). The WSRT is operated by ASTRON with support from NWO. Pulsar observations with the Lovell Telescope are funded through a consolidated grant from STFC. The Fermi LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan, and Sweden. The GBT is operated by the National Radio Astronomy Observatory (NRAO). NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc. The Arecibo Observatory is operated by SRI International under a cooperative agreement with the NSF (AST-1100968), and in alliance with Ana G. Méndez-Universidad Metropolitana, and the Universities Space Research Association. The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States; CEA/Irfu and IN2P3/CNRS in France; ASI and INFN in Italy; MEXT, KEK, and JAXA in Japan; and the K. A. Wallenberg Foundation, the Swedish Research Council, and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

REFERENCES

Dubus, G. 2013, A&ARv, 21, 64
Halpern, J. P., Gaidos, E., et al. 2013, ATel, 5514, 1