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## A NEW ACCRETION DISK AROUND THE MISSING LINK BINARY SYSTEM PSR J1023+0038

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### ABSTRACT

PSR J1023+0038 is an exceptional system for understanding how slowly rotating neutron stars are spun up to millisecond rotational periods through accretion from a companion star. Observed as a radio pulsar from 2007–2013, optical data showed that the system had an accretion disk in 2000/2001. Starting at the end of 2013 June, the radio pulsar has become undetectable, suggesting a return to the previous accretion-disk state, where the system more closely resembles an X-ray binary. In this Letter we report the first targeted X-ray observations ever performed of the active phase and complement them with UV/optical and radio observations collected in 2013 October. We find strong evidence that indeed an accretion disk has recently formed in the system and we report the detection of fast X-ray changes spanning about two orders of magnitude in luminosity. No radio pulsations are seen during low flux states in the X-ray light curve or at any other times.

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

*Online-only material:* color figures

### 1. INTRODUCTION

PSR J1023+0038 (henceforth J1023) is a 1.7 ms radio pulsar in a 4.8 hr orbit with a  $\sim 0.2 M_{\odot}$  companion star (Archibald et al. 2009, 2010). Before its 2007 discovery as a radio millisecond pulsar (MSP), the source was known as a candidate quiescent low-mass X-ray binary (LMXB; Thorstensen & Armstrong 2005; Homer et al. 2006). Strong evidence for the presence of an accretion disk came from optical observations in 2000–2001 (Thorstensen & Armstrong 2005; Bond et al. 2002; Wang et al. 2009; see also Archibald et al. 2009 for an overview). Detailed optical/X-ray observations from 2002 onward suggest the absence of an accretion disk (Archibald et al. 2009, 2010; Bogdanov et al. 2011). Therefore, it is now accepted that, at least in 2001, J1023 was an accreting neutron star (NS) in an LMXB; the NS has subsequently turned on as a radio MSP between 2001 and 2007. From 2007 onward this source has been consistently observed as an eclipsing radio MSP (a so-called “redback” system; see Roberts 2011), with a low X-ray luminosity thought to be largely due to a pulsar-wind-driven shock near the inner Lagrangian point  $L_1$  (Bogdanov et al. 2011), probably with a contribution from the pulsar’s surface or magnetosphere (Archibald et al. 2010).

According to the current paradigm, MSPs are formed in X-ray binaries by accreting gas from a low-mass donor companion. The discovery of accreting millisecond X-ray pulsars (AMXPs; e.g., Wijnands & van der Klis 1998) represented a first confirmation of this “recycling” scenario (see Patruno & Watts 2012 for a review). The accreted matter spins up the NS to millisecond periods. How and when the accretion process switches off remains unknown (see, e.g., Tauris 2012). J1023 has been heralded as the “missing link” between radio MSPs and LMXBs and has given new insights into this evolutionary process.

The very recent discovery of an X-ray active phase from PSR J1824–2452I (a.k.a. IGR J18245–2452; spin period

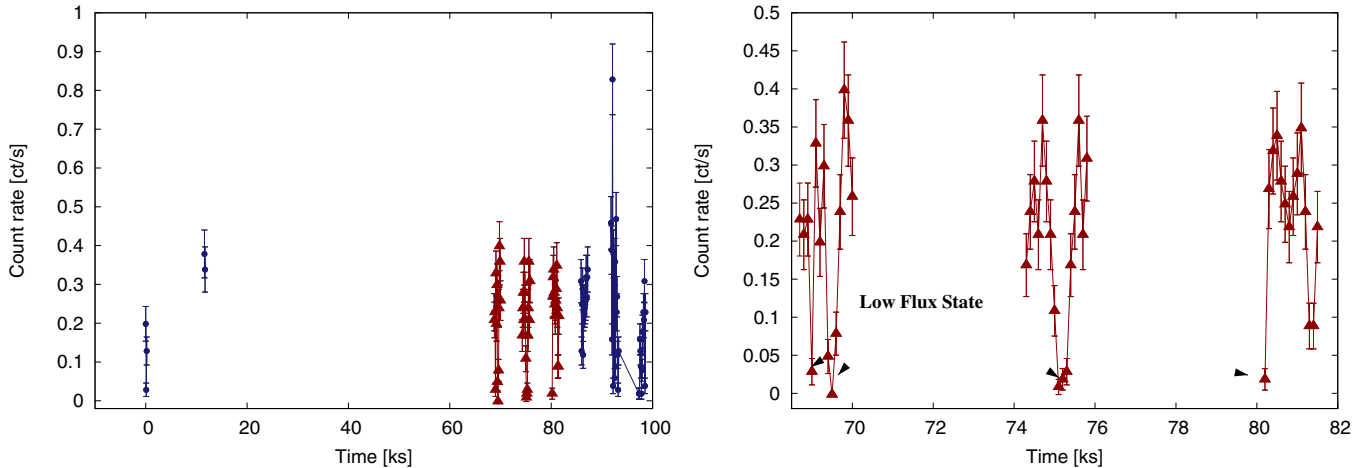
3.9 ms, orbital period 11 hr; hereafter M28I, since it is in the globular cluster M28) has again confirmed the recycling scenario. Originally discovered in 2006 as a radio MSP, M28I was observed to turn into a typical AMXP—with active accretion onto the NS surface and associated X-ray bursts—and then return surprisingly rapidly to an X-ray quiescent/radio MSP state within only a few weeks after the X-ray outburst (Papitto et al. 2013a, 2013b). There are several similarities between the J1023 and M28I systems, but the former enjoys the advantage of being at a quarter the distance and hosting a pulsar that is more than an order-of-magnitude brighter at radio wavelengths.

In the period 2013 June 15–23, J1023 switched off as a radio pulsar (Stappers et al. 2013a). Solar constraints prevented the observation of this source with most X-ray and UV/optical telescopes until mid-October. The *Swift*/Burst Alert Telescope was able to monitor the source in hard X-rays, showing non-detections throughout the monitoring with typical upper limits of  $10^{35}$  erg s<sup>-1</sup> in the 15–50 keV band (using a distance of 1.368 kpc; Deller et al. 2012).

In this Letter we report the first X-ray and UV/optical results on the radio-quiet phase of J1023 performed on 2013 October 18–19 by the *Swift* satellite. The observations show increased X-ray and UV/optical activities (Kong 2013; Patruno et al. 2013) that provide compelling evidence for the presence of a recently formed accretion disk in the system. We also report radio observations carried out with the Lovell and Westerbork Radio Synthesis Telescope that show no evidence for pulsed radio emission.

### 2. OBSERVATIONS AND DATA REDUCTION

We analyzed three targeted *Swift* observations taken on 2013 June 10, 12, and October 18/19. This last observation started with two short exposures on October 18 at UT 05:11:50 and was continued with six more exposures on October 19



**Figure 1.** Left panel: background-subtracted XRT count rate measured in the 0.5–10 keV band on 2013 October 18–19. Each data point is a 100 s average and the red triangles refer to the zoomed-in panel on the right. Right panel: example of the X-ray flickering discussed in the text. Four episodes are highlighted in the plot, corresponding to X-ray fluxes compatible with the quiescent X-ray luminosity. (A color version of this figure is available in the online journal.)

starting at UT 00:14:26. We used all data collected with the *Swift*/X-Ray Telescope (XRT) and the Ultra-Violet/Optical Telescope (UVOT). The XRT was operated in photon-counting mode (2.5 s time resolution) in all three observations, whereas the UVOT operated with the filters *UW2* (June 10), *UW1* (June 12), and *UW1/U* (October 18/19). The total on-source time was  $\simeq 14$  ks, with 10 ks on October 18/19 and  $\sim 2$  ks on each of June 10 and 12.

We reduced the data using the UVOT and XRT pipelines and applying standard event screening criteria. The October 18–19 UVOT observation started with the first two exposures taken with the *UW1* filter and the remaining six with the *U* filter. We extracted source events for each observation using circular regions with radii of 40'' (for XRT) and 8'' (for UVOT) and by using the best astrometric position available (Deller et al. 2012). We kept only X-ray photons with energies between 0.5–10 keV and then removed the background by measuring it in a 40'' region far from bright sources. We combined the UVOT exposures within each observation to provide a single high-signal-to-noise image for each filter. We also analyzed the six October 19 *U*-band exposures separately to highlight the rapid time variability of the source. We performed a power-spectral analysis of the 0.5–10 keV XRT data by creating Fourier transforms of different length, between  $\sim 130$  s (64 data points) and  $\sim 1300$  s (512 data points) all with a Nyquist frequency of  $\simeq 0.2$  Hz.

To complement these *Swift* observations, we also performed targeted observations with the Lovell and Westerbork radio telescopes. Lovell observations began on 2013 October 19 at 07:32:44 UT and were obtained using the ROACH backend, coherently dedispersing 400 MHz of bandwidth centered at a frequency of 5.1 GHz. The observations lasted 2 hr and spanned orbital phases 0.35–0.77, thus occurring away from the usual eclipse time at this high radio frequency. A total of five 15–60 minute Westerbork observations (three of which were at orbital phases where we do not expect radio eclipses) were acquired on October 16, 20, and 21 at central frequencies of 350 and 1380 MHz and with respective bandwidths of 80 and 160 MHz, using the tied-array mode and PuMaII backend (Karuppusamy et al. 2008). Data from both telescopes were folded using a recent rotational ephemeris and inspected on a variety of timescales to look for pulsed radio emission.

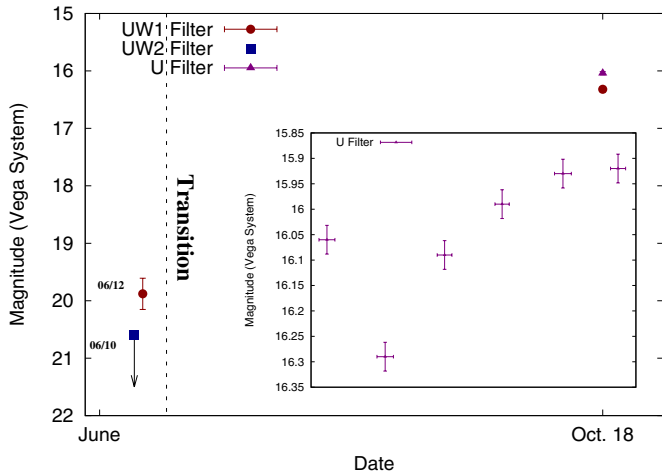
### 3. RESULTS

The *Swift* June 10/12 observations, occurring before the reported disappearance of the radio MSP, show a dim X-ray source compatible with the radio-loud state reported in Homer et al. (2006), Archibald et al. (2010), Tam et al. (2010), and Bogdanov et al. (2011). An inspection of the light curve shows a faint source with 0.5–10 keV count rate of  $\sim 0.01$  counts  $s^{-1}$  and little variation throughout the observations. The UVOT images also show marginal detections ( $\sim 20$  mag) and non-detections ( $> 20.6$  mag) in the *UW1* and *UW2* filters, respectively. In the following we focus on the October 18/19 *Swift* observations and on the radio MSP observations carried out after the disappearance of the radio MSP.

#### 3.1. X-Rays

The October 18 *Swift*/XRT observation (i.e., the first taken after June 12) shows a dramatic, 20-fold increase in the count rate (0.2 counts  $s^{-1}$ ). The average flux remains approximately stable in all eight exposures with a variation of less than a factor two in the average fluxes. We performed an X-ray spectral fit to the combined  $\sim 10$  ks of data by using an absorbed power-law model and obtained a good fit ( $\chi^2/\text{dof} = 58/61$ ) with a spectral index  $\Gamma = 1.69 \pm 0.09$ , a negligible absorption column  $N_{\text{H}} = 3.8^{+2.0}_{-1.9} \times 10^{20}$   $\text{cm}^{-2}$  (as found in Archibald et al. 2010 and Bogdanov et al. 2011) and a 0.5–10 keV luminosity of  $2.5 \times 10^{33}$   $\text{erg s}^{-1}$ . The addition of a blackbody component gives unconstraining temperatures, but fixing the emission radius to 10 km gives a  $3\sigma$  upper limit of 0.127 keV and a luminosity of  $9 \times 10^{29}$   $\text{erg s}^{-1}$ .

Inspection of the light curve on shorter timescales (10–100 s) reveals a surprising X-ray flickering with strong variability that changes the flux by one order of magnitude. In some cases the flickering is observed to happen within 10 s. Shorter timescales cannot be investigated here because of the limited count rate. The flickering is visible several times in the light curve (see Figure 1) and is observed also when dividing the light curve into two energy bands (a 0.5–2.0 keV soft and a 2.0–10 keV hard band) with similar magnitude. In one instance we observe a low-flux state followed by a strong (100 fold) increase in flux, with a peak count rate of  $\sim 1$  counts  $s^{-1}$  (Figure 1).



**Figure 2.** *Swift*/UVOT observations in the *UW1* (central  $\lambda \simeq 260$  nm), *UW2* (192.8 nm), and *U* (346.5 nm) bands. The source is not detected in *UW2* on June 10 whereas it is marginally detected in *UW1* on June 12. The error bars on the October 18/19 measurements are within the symbol size in the plot. Between June 15 and 23 the source turned off in radio (Stappers et al. 2013a). On October 18 the *UW1* filter shows a clear increase in luminosity with the source detected also in the *U* band (purple triangle). The inset shows the six *U*-filter exposures with the horizontal bars that identify the length ( $\sim 25$  minute per exposure).

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

We therefore infer an X-ray luminosity variation from  $10^{32}$  erg s $^{-1}$  up to  $10^{34}$  erg s $^{-1}$  in less than 10 s.

A power spectrum of the 0.5–10 keV light curve shows no prominent periodicity.

### 3.2. Optical/*U*

The UVOT images show that there is also a clear state change in the UV/optical emission. On October 18, the *UW1* counterpart is very luminous with magnitude of  $16.32 \pm 0.05$ , which is  $\sim 3.5$  mag brighter than the previous *UW1* observation on June 12. The *U* band shows also a bright counterpart with magnitude of  $16.04 \pm 0.03$ .

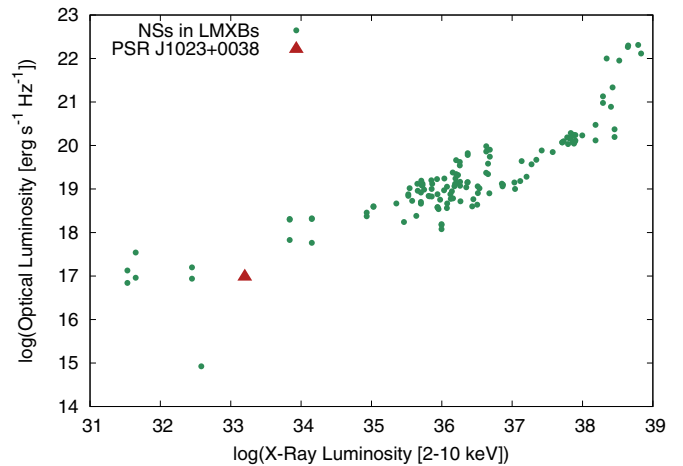
The six closely spaced exposures taken (October 19) show a *U*-band variability of  $\sim 0.3$  mag on a timescale of  $\sim 1$  hr (see Figure 2) whereas no correlation is observed between the average 0.5–10 keV X-ray luminosity and the *U* magnitude.

### 3.3. Radio

No radio emission was detected in the October observations with  $10\sigma$  flux density upper limits of 0.8 mJy, 0.2 mJy, and 0.1 mJy for the full integration times of the 350 MHz, 1380 MHz, and 5 GHz observations, respectively. These are all more than an order of magnitude lower than the measured radio fluxes prior to this current X-ray active phase (see Stappers et al. 2013b; Archibald et al. 2013). The observations at 5 GHz overlapped with two of the dips seen in the *Swift* data, (starting at MJD 56584.347264 and MJD 56584.355933) but there is no evidence of an associated short burst of pulsed radio emission. Furthermore, J1023 was previously detectable in 10 s intervals with Westerbork/Lovell at 350 and 1380 MHz. This also gives confidence that the non-detection of the radio pulsar in short sub-integrations is a significant change.

## 4. DISCUSSION

We have reported the unambiguous X-ray and UV/optical signatures of a state change in J1023, which coincide with its



**Figure 3.** X-ray/optical correlation found in NS LMXBs with the addition of J1023. The correlation exists between the reprocessed light and the X-ray emission coming from the accretion process.

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

disappearance as an observable radio MSP. This is the second time that such a state is observed in J1023 and the first time that targeted X-ray data are recorded in this state. The X-rays show a considerably softer spectrum ( $\Gamma \simeq 1.7$ ) than during the MSP state ( $\Gamma \simeq 1$ ; Archibald et al. 2010; Bogdanov et al. 2011) indicating a change in the origin of the X-ray emission.

The large UV increase between June 12 and October 18 and the rapid ( $\sim 1$  hr) changes in luminosity in the *U* band support the presence of an accretion disk in the system. Bond et al. (2002) reported both slow (hours-to-days) and rapid (minutes-to-seconds) optical flickering for J1023 in late 2000, during the previous active phase. The flickering was observed on 10 s timescales, very similar to what we now observe in X-rays. *V*-band monitoring of the source (Halpern et al. 2013) in its current state revealed a counterpart with magnitude between 16.37–16.94. The similarity of the *V*, *U*, and *UW1* magnitudes is compatible with the flatness of the continuum in a reprocessed accretion disk ( $F_\nu \propto \nu^{0.1}$ ). Halpern et al. (2013) also observed a double-peaked  $H\alpha$  line, typical of accretion disks. Such signatures were also identified by Bond et al. (2002) in the 2001 active episode. The presence of an accretion disk around J1023 does not, however, necessarily imply that material is reaching the NS. Indeed, the total 0.5–10 keV luminosity remains low, with an average value of  $2 \times 10^{33}$  erg s $^{-1}$ , which is about  $20\times$  higher than observed during the MSP phase but still within the range of luminosities of quiescent LMXBs (Bildsten & Rutledge 2001).

According to van Paradijs & McClintock (1994), the absolute visual magnitude of LMXBs correlates with the orbital period  $P_b$  of the binary and its X-ray luminosity. Russell et al. (2006) updated and revised this correlation, separating black hole and NS LMXBs. We therefore use the flux density detected in the *U* band and rescaled to the distance of the pulsar to place J1023 in the optical/X-ray diagram among the other known NS LMXBs (Russell et al. 2006, 2007). We use the *U* band even if the original correlation is calculated for the *B*, *V*, *R*, *I*, and near-IR bands because we expect a negligible difference in reddening (which is  $\sim 0.1$  mag toward J1023) and a rather flat optical spectrum.

Although there is significant scatter in the data points, J1023 fits into the X-ray/optical correlation (see Figure 3), further

strengthening the idea that most of the optical and X-ray luminosity comes from an accretion process and not from an intra-binary shock or from the spin-down luminosity of a rotation-powered pulsar.

Archibald et al. (2009) proposed that the low X-ray luminosity of the system when an accretion disk is present is due to the onset of a propeller stage. Indeed, given the spin-down-inferred  $1.1 \times 10^8$  G magnetic field, Archibald et al. estimated that the required minimum luminosity for accreting gas to overcome the magnetic centrifugal barrier is  $10^{37}$  erg s $^{-1}$ , well above the luminosities currently reached by J1023. The corotation radius  $r_c$ , where the Keplerian orbital frequency of the matter equals the rotational frequency of the NS (592 Hz here), is located at about 24 km from the NS center. The onset of the propeller stage (Illarionov & Sunyaev 1975) happens when  $r_m > r_c$ . We use the magnetospheric radius definition:

$$r_m = 23.5\xi \dot{M}_{-10}^{-2/7} M_{1.4}^{-1/7} R_{10}^{12/7} B_8^{4/7} \text{ km}, \quad (1)$$

where  $\xi = 0.3\text{--}1$  is related to the structure of the inner disk,  $B_8$  is the magnetic field normalized to  $10^8$  G, and  $\dot{M}_{-10}$  is the mass accretion rate in units of  $10^{-10} M_\odot \text{ yr}^{-1}$ . The condition  $r_m > r_c$  will be met for a mass accretion rate of approximately  $10^{-10} M_\odot \text{ yr}^{-1}$ , in line with the value estimated by Wang et al. (2009) for the previous 2001 active episode. However, as noted by Spruit & Taam (1993) and Rappaport et al. (2004), a propeller regime where matter is expelled from the system needs  $r_m \gg r_c$ . When this condition is not met, the matter will not be expelled but will accumulate at the inner disk edge possibly leading to a new disk structure, different from the standard Shakura & Sunyaev thin disk and known as a “dead disk” (Sunyaev & Shakura 1977). In certain conditions, the dead disk has the characteristic of having an inner disk radius that remains close to  $r_c$  even when the mass accretion rate drops to zero (“trapped disk”; D’Angelo & Spruit 2010, 2012).

The low flux states resemble the quasi-periodic dips observed in several LMXBs (e.g., Díaz Trigo et al. 2006), although we do not find any strict correlation between their occurrence and a specific orbital phase. The inclination of the orbit ( $\sim 46^\circ$ ; Bogdanov et al. 2011) also strongly argues against the dips interpretation. If the rapid X-ray flickering is instead due to variation in mass accretion rate at the inner disk edge, then for a standard Shakura–Sunyaev disk,  $r_m$  would move by a factor of two to three. The timescale for this drift is given by the viscous timescale:

$$\begin{aligned} \tau_{\text{visc}} \sim 3.5\alpha^{-4/5} \left[ \frac{\dot{M}}{10^{-10} M_\odot \text{ yr}^{-1}} \right]^{-3/10} \\ \times \left[ \frac{M}{1 M_\odot} \right]^{1/4} \left[ \frac{\Delta R}{10 \text{ km}} \right]^{5/4} \text{ s}, \quad (2) \end{aligned}$$

where  $\alpha \sim 0.1$  and  $\Delta R$  represents the width of the region involved. To reach a timescale of 10–100 s for  $\dot{M} \sim 10^{-10} M_\odot \text{ yr}^{-1}$  we need to have an annulus of no more than 10–100 km. Since the light cylinder radius is  $r_{lc} \simeq 80$  km, and if we assume that  $r_m$  at the maximum luminosity is located close to  $r_m \simeq r_c \simeq 24$  km, then it is likely that  $r_m$  does not lie far from  $r_{lc}$  when the system reaches the low flux state luminosity. In this case it is not unreasonable to expect that the quenching of the radio emission would stop and the pulsar would turn on again as an MSP. Our radio search for pulsations in the low flux states, however, found no detectable radio pulses

when the binary reaches the minimum X-ray flux level. If a trapped disk is actually present, then the inner disk edge will *always* stay close to  $r_c$  at about 24 km even when  $M \rightarrow 0$ . In this case the quenching will always be present during the active phase.

This radio non-detection is perhaps not surprising, since the “radio ejection” mechanism originally suggested by Shvartsman (1970) is thought to clear the disk from any system with a radio pulsar that has not been quenched by material entering its light cylinder. However, Ekşil & Alpar (2005) found that there is a region out to 2–3 light cylinder radii where a disk can withstand the wind of an active pulsar. If the disk around J1023 recedes into this regime, the radio pulsar mechanism might be active some of the time.

Indeed, Stappers et al. (2013a) reported that since 2013 June 21 the gamma-ray luminosity of J1023 has increased by a factor of five with respect to the average pre-transition luminosity. This is difficult to explain in an active accretion state but it might indicate an enhancement in the intra-binary shock emission, perhaps due to the pulsar wind running into the inner edge of the disk or expelled gas colliding with circumbinary material or the interstellar medium.

X-ray flickering, similar to that reported here, has also been observed in the AMXP M28I (Papitto et al. 2013a; Ferrigno et al. 2013). This source is so far the only AMXP known that has turned on as an active radio MSP (Papitto et al. 2013a). During M28I’s 2013 outburst, *XMM-Newton* observations showed a rapid flickering in the X-ray light curve which resembles what we observe in J1023, with the difference that the flickering there happened at luminosities two/three orders of magnitude higher than in J1023. A power spectrum showed red noise but no specific periodicity. The same source also showed fast X-ray luminosity variations during quiescence, as seen with *Chandra* (Linares et al. 2013). Such variations span a factor of seven in luminosity (between  $\sim 10^{33}$  and  $10^{34}$  erg s $^{-1}$ ) on a timescale of a few hundred seconds. The observation of more rapid timescales in quiescence is however hampered by the large distance to M28I (5.5 kpc). Linares et al. (2013) reported that M28I becomes harder when going from luminosities of  $10^{34}$  erg s $^{-1}$  down to  $10^{32}$  erg s $^{-1}$ , which is also observed in J1023. When going toward luminosities above  $10^{34}$  erg s $^{-1}$ , the spectra again become harder, suggesting that some new physical mechanism is at play.

A remaining open question is why M28I has gone through a relatively bright outburst whereas J1023 shows only very faint luminosities (so far at least). The higher spin rate of J1023 creates a faster rotating magnetic field and thus a stronger magnetic centrifugal barrier. Compared with M28I, this likely makes it easier to achieve a propeller or dead-disk phase in J1023. When J1023 returns to quiescence, radio timing observations may be able to measure any spin-down or spin-up that accumulates during this active phase, possibly distinguishing between propeller and dead-disk models.

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