INFRARED OBSERVATIONS OF THE MILLISECOND PULSAR BINARY J1023+0038: EVIDENCE FOR THE SHORT-TERM NATURE OF ITS INTERACTING PHASE IN 2000–2001

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Received 2012 September 24; accepted 2013 January 04; published 2013 February 1

ABSTRACT

We report our multi-band infrared (IR) imaging of the transitional millisecond pulsar system J1023+0038, a rare pulsar binary known to have an accretion disk in 2000–2001. The observations were carried out with ground-based and space telescopes from near-IR to far-IR wavelengths. We detected the source in near-IR JH bands and Spitzer 3.6 and 4.5 μm mid-IR channels. Combined with the previously reported optical spectrum of the source, the IR emission is found to arise from the companion star, with no excess emission detected in the wavelength range. Because our near-IR fluxes are nearly equal to those obtained by the 2MASS all-sky survey in 2000 February, the result indicates that the binary did not contain the accretion disk at the time, whose existence would have raised the near-IR fluxes to twice larger values. Our observations have thus established the short-term nature of the interacting phase seen in 2000–2001: the accretion disk existed for at most 2.5 yr. The binary was not detected by the WISE all-sky survey carried out in 2010 at its 12 and 22 μm bands and our Herschel far-IR imaging at 70 and 160 μm. Depending on the assumed properties of the dust, the resulting flux upper limits provide a constraint of \( <3 \times 10^{22} \)–\( 3 \times 10^{25} \) g on the mass of the dust grains that possibly exist as the remnants of the previously seen accretion disk.

Key words: binaries: close – stars: individual (J102347.6+003841) – stars: low-mass – stars: neutron

1. INTRODUCTION

It was quite surprising when the binary millisecond pulsar (MSP) J1023+0038 (hereafter J1023) was discovered in an untargeted radio pulsar survey (Archibald et al. 2009), because although the source was previously known to have radio emission (Bond et al. 2002), it was suggested to be a cataclysmic variable and later established that it is likely a low-mass-X-ray binary (LMXB) with a 4.75 hr orbital period and a \( \sim 0.2 \, M_\odot \) companion (Thorstensen & Armstrong 2005). Detailed analyses of an optical spectrum of J1023, taken in 2001 February by the Sloan Digital Sky Survey (SDSS), have shown that the source at the time was in a bright state and had broad, double-peaked hydrogen and helium emission lines, a typical feature of an accretion disk (Wang et al. 2009). From 2002 May onward, however, the source has been seen to be dramatically different, having only a G-type absorption spectrum (Thorstensen & Armstrong 2005) and thus indicating the disappearance of the disk approximately 1.5 yr later (for a summary of the properties of J1023 around that time, see table 1.). Combining with these observational results, the discovery of a radio pulsar has strongly suggested that this is the first such binary found at the end of its transition from an LMXB to a radio MSP. MSPs are believed to be “recycled” pulsars, formed from the evolution of X-ray binaries (Bhattacharya & van den Heuvel 1991). In such a binary with a low-mass companion, a neutron star was spun up by accretion of matter from the companion via an accretion disk. At the end of the interacting phase when the mass accretion rate in the disk was below a minimum value and thus the inner edge of the disk was truncated outside of the light cylinder of the neutron star by the neutron star’s magnetic field, the neutron star appeared at radio frequencies to be an MSP (Campana et al. 1998 and references therein). Subsequently, the disk would be disrupted due to the radiation pressure from the fast-spinning pulsar. While this model is generally accepted, there are few observational studies of the scenario due to the lack of known systems that are right at the end of the transition.

From the estimated spin-down rate of the J1023 pulsar, its rotational energy loss rate (the so-called spin-down luminosity) has been found to be \( \dot{L}_{\text{sd}} \sim 4.3 \times 10^{34} \) erg s\(^{-1}\) (Deller et al. 2012). The majority of the energy should be carried out in a magnetized, high-velocity wind, which is likely interacting with the companion causing the orbital modulation (Thorstensen & Armstrong 2005) and eclipses of the pulsar emission (Archibald et al. 2009) seen at optical and radio frequencies, respectively. The wind also plausibly caused the disappearance of the disk that existed in 2000–2001 (however, see Takata et al. 2010, 2012 for an alternative scenario). It is not clear whether the companion star in J1023 would replace its disk through repeated outflows. If it does, since the Kelvin–Helmholtz relaxation time for the companion has been much longer than 10 years since 2001 (see also Deller et al. 2012) as pointed out by Thorstensen & Armstrong (2005), J1023 would serve as a rare example for detailed studies of the transitional processes and pulsar-wind–disk interaction.

In an effort to fully study this rare system and the detailed evolutionary process of such binary systems at or right after the transition phase, we have carried out infrared (IR) observations with ground-based and space telescopes. The accretion disk that has disappeared from the optical after 2002 May might have left an IR remnant. Recent Chandra observations of the source have found orbital variability in its X-ray emission and likely revealed an intrabinary shock (Bogdanov et al. 2011). The shock, which would be produced by the interaction between the pulsar wind and outflow from the companion, might also be detectable at IR

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* Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
Our target was detected in the near-IR \textit{JHK}\textsubscript{s} bands by the 2MASS all-sky survey (Skrutskie et al. 2006) in 2000 February 6, but with relatively large uncertainties ($J = 16.30 \pm 0.10$, $H = 15.69 \pm 0.13$, and $K\textsubscript{s} = 15.9$ with no uncertainty given; Wang et al. 2009). In order to either confirm the Two Micron All Sky Survey (2MASS) results or detect any variability, we re-observed J1023 in the \textit{JH} bands using the 2.5 m Irénée du Pont telescope at Las Campanas Observatory in Chile on 2012 May 10. The camera was the RetroCam, which uses a detector of a Rockwell Hawaii-1 \textsubscript{1024} \texttimes \textsubscript{1024} HgCdTe array. The field of view (FOV) was $3.4 \times 3.4$, with a pixel scale of $0.2\text{pixel}^{-1}$. The total on-source exposure time at each band was 405 s. During an exposure, the telescope was dithered in a $3 \times 3$ grid with offsets of approximately $15\arcsec$ to obtain the measurement of the sky background. The observing conditions were good, having $0\farcs6$ seeing.

We used the IRAF data analysis package for data reduction. The images were dark subtracted and flat fielded. From each set of dithered images in one observation, a sky image was made by filtering out stars. The sky image was subtracted from the set of images, and then the sky-subtracted images were shifted and combined into one final image of the target field.

The near-IR counterpart to J1023 was well detected in both \textit{J}- and \textit{H}-band images. We performed aperture photometry to measure brightnesses of the target and other in-field sources. Flux calibration was conducted using the 2MASS sources detected in our images.

2.2. Spitzer IRAC 3.6 and 4.5 \textmu m Imaging

We observed the target four times on 2010 January 15 with the \textit{Spitzer Space Telescope} during its warm mission phase (Program ID 60197). The multiple exposures were requested in order to average out any possible orbital flux changes caused by the irradiated companion star by the pulsar. The imaging instrument used was the Infrared Array Camera (IRAC; Fazio et al. 2004). While the camera operated in four channels at 3.6, 4.5, 5.8, and 8.0 \textmu m, only the first two channels were available during the warm mission and used for our observations. The detectors at the short and long wavelengths are the InSb and Si:As devices, respectively, both with $256 \times 256$ pixels and a plate scale of $1\text{pixel}^{-1}$. The FOV is $5\times5\arcmin$. The frame time was 30 s with $23.6$ s and $26.8$ s effective integration time per frame, and the total integration times in each of our four observations were 1.97 minutes and 2.23 minutes at channels 1 and 2, respectively.

The raw image data were processed through the IRAC data pipelines (version S18.13.0) at the Spitzer Science Center (SSC). In the basic calibrated data (BCD) pipeline, standard imaging data reductions, such as removal of the electronic bias, dark sky subtraction, flat-fielding, and linearization, are performed and individual flux-calibrated BCD frames are produced. The details of the data reduction in the pipelines can be found in the IRAC Instrument Handbook (version 2.0.2). Using a MOSaicker and Point source EXtractor (MOPEX) package, provided by the SSC, we conducted further data reduction and profile-fitting photometry. In the processes, we used the MOPEX pipelines \texttt{overlap} to perform background matching between the BCD frames, \texttt{mosaic} to carry out removal of cosmic rays and bad pixels, and APEX to perform point source extraction. Also using \texttt{mosaic}, final post-BCD (PBCD) mosaics were produced by combining the BCD frames. The target was well detected in our IRAC images.

2.3. WISE Imaging

Launched on 2009 December 14, the \textit{Wide-field Infrared Survey Explorer} (WISE) mapped the entire sky at 3.4, 4.6, 12, and 22 \textmu m (called the W1, W2, W3, and W4 bands, respectively) in 2010 with FWHMs of $6\farcs1$, $6\farcs4$, $6\farcs5$, and $12\farcs0$ in the four bands, respectively (Wright et al. 2010). The WISE all-sky images and source catalog were released in 2012 March. We checked the WISE data and found that J1023 was detected in the W1 and W2 bands but not in the other two bands. We downloaded the images of the target field from the Infrared Processing and Analysis Center. The dates of the observations and the depth of coverage of the target field were between 2010 May 21–26 and 11–12 pixels (corresponding to 97–106 s on-source integration time), respectively.

2.4. Herschel PACS 70 and 160 \textmu m Imaging

We also observed J1023 on 2011 November 26 with the \textit{Herschel Space Observatory} (ObsIDs 1342233048, 1342233049). The imaging instrument used was the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010). PACS performs imaging at a blue and a red channel simultaneously, of which the central wavelengths are either 70 or 100 and 160 \textmu m, respectively. The detectors are a $64 \times 32$ and a $32 \times 16$ bolometer array for the blue and red channels, respectively, both with an FOV of $\sim1.75 \times 3.5\arcmin$. We used the mini-scan map mode of PACS for imaging at the 70 \textmu m (bandwidth 25 \textmu m) and 160 \textmu m (bandwidth 85 \textmu m) channels. The total telescope time for our observation was 1 hr with 18 minute on-source time.

The image data were downloaded from the Herschel Science Archive, which were processed from the Herschel Data Processing system at the Herschel Science Center. The target was not detected in the images. We used the background counts at the source region and estimated the flux upper limits. The values we derived were highly consistent with that given by the Herschel observation planning tool HSpot.

3. RESULTS

The flux measurements obtained for J1023 from 2MASS \textit{JHK}\textsubscript{s}, our near-IR \textit{JH}, and Spitzer/IRAC 3.6 and 4.5 \textmu m detections are listed in Table 2. We assigned a 0.3 mag uncertainty to the 2MASS \textit{K}\textsubscript{s}-band measurement. The \textit{JH} magnitudes resulting from our observation are consistent with the 2MASS values within the uncertainties. For the Spitzer observations at each IRAC channel, our four flux measurements showed $\leq1.2\%$ and $\leq3.4\%$ differences at 3.6 and 4.5 \textmu m, respectively, and the averaged values are given in the table. Considering 2.7% and 3.5% uncertainties on the measurements from photometry at the two channels, no significant flux variations were detected. We also used the orbital period and time of ascending node provided from radio timing of the pulsar (Archibald et al. 2009) and checked the phase duration of our Spitzer observations. The phase was in a range of $0.58$–$0.67$, corresponding to the range of $0.33$–$0.42$ used in Thorstensen & Armstrong (2005), during which the optical wavelengths. Our observations and data reduction are described in Section 2. The results from the observations are given in Section 3, and the implications of our results for J1023 are discussed in Section 4.
light curve (emission from the companion) of J1023 had a flat top at the V band and a V − I color variation of ≤ 0.02 mag (see Figure 4 in Thorstensen & Armstrong 2005). Since the effective temperature of the companion was probably around 5700 K (Thorstensen & Armstrong 2005) at the time of our Spitzer observations, the expected orbital flux variations should be smaller than 0.02 mag at the mid-IR wavelengths, indicating that our result of no significant flux variations is consistent.

The WISE 3.4 and 4.6 μm flux measurements from the WISE catalog are also provided in Table 2. For the non-detections of J1023 in WISE W3 and W4 bands and our Herschel images, flux upper limits were obtained and their 3σ values are given. The WISE measurements of J1023 in W1 and W2 bands, particularly the latter, have magnitudes larger than those of the IRAC (by 0.127 and 0.68 mag), although the differences are within 3σ uncertainties of the WISE measurements. It has been noted that at the faint end starting from >15 mag at W1 and W2 bands, there is a faintward bias (in average of 10%–20%) of WISE relative to IRAC measurements from the comparisons of photometry of sources in the ecliptic poles (Jarrett et al. 2011). This bias is suspected to be caused by stronger source confusion to WISE due to its relatively lower resolution. Also the comparisons show ~0.1 and ~0.2 mag ranges of scattering of the WISE W1 and W2 measurements, respectively, when sources are faint with >15 mag. Therefore, we concluded that the apparent differences of the WISE measurements of J1023 relative to that of our IRAC measurements are instrumental, due to the bias and larger scattering of the WISE W1 and W2 measurements of relatively faint sources.

3.1. Near-IR and Mid-IR detections

Optical emission from J1023 after 2002 May is known to arise from the companion star, which has a G5V-type optical spectrum and probably has a size approximately equal to that of the Roche lobe (0.4 R⊙; Thorstensen & Armstrong 2005; Wang et al. 2009). We display the optical spectrum, the same one given in Wang et al. (2009) which was averaged from 23 spectra obtained in 2003-2004 by Thorstensen & Armstrong (2005). In Figure 1, we found that the spectrum can be well fit with a G5V model spectrum (Kurucz 1993) with no reddening needed (χ² = 857 for 1498 degrees of freedom). We note that in Chandra X-ray spectroscopic studies of the source, no hydrogen column density was needed either (Bogdanov et al. 2011). At a distance of d = 1.37 kpc (Deller et al. 2012), the companion’s radius R was found to be R ≈ 0.41 R⊙. The flux densities at the near-IR 1.24 and 1.66 μm and mid-IR 3.6 and 4.5 μm wavelengths were thus derived from the model spectrum, and they are 0.498, 0.437, 0.119, and 0.076 mJy, respectively. The model flux densities are consistent with the observed values within 1σ uncertainties at near-IR wavelengths and slightly lower than that at mid-IR wavelengths (Table 2). Adding 2% systematic uncertainties to IRAC channels 1 and 2 (Reach et al. 2005), the values are consistent within approximately 2σ uncertainties. We thus conclude that the near-IR and mid-IR emission we detected likely arose from the companion star and no significant excess IR emission was detected from the source.

We estimated flux upper limits on excess mid-IR emission from J1023. Considering that near-IR and mid-IR emission detected in our ground-based and Spitzer observations came from the companion, we fit them and the optical spectrum together with the same model spectrum used above. In order to reduce the dominance of the optical spectrum, we assigned them a weight of 1/150. In addition, 2% systematic uncertainty from flux calibration at near-IR wavelengths and the systematic uncertainties of IRAC channels 1 and 2 were included. We found that R ≈ 0.42 R⊙ at d = 1.37 kpc provided the best fit, and the minimum χ² = 14.9 for 13 degrees of freedom. Assuming a detection of mid-IR emission at either 3.6 or 4.5 μm with the same uncertainty as in our Spitzer observations and fixing R = 0.42 R⊙, we increased the flux value at each wavelength until that χ² increased by 8.9 (3σ confidence; Lampton et al. 1976). The 3σ upper limits were thus found to be 0.011 and 0.006 mJy at channels 1 and 2, respectively.

3.2. Implication of the Near-IR Measurements

It was noted by Wang et al. (2009) that the 2MASS measurements of J1023 made on 2000 February 6 were consistent with being at the tail of the G5V spectrum of the companion. Combining with the mid-IR measurements, our more accurate near-IR JH measurements, which are approximately equal to the 2MASS values, confirm the 2MASS detection and the companion-star origin of the near-IR emission detected both in 2000 and at the current time. This result raises a very interesting point that in 2000 February the accretion disk did not exist. In Figure 1 we overplotted the disk model spectrum shown in Wang et al. (2009) and the combined spectrum of the disk and companion are overplotted (dash-dotted and long-dash-dotted curves, respectively). Model spectra from two sizes of dust grains are shown (dashed and long-dashed curves are for 7 and 20 μm dust grains, respectively), providing upper limits of 3 × 10⁻²² and 3 × 10⁻²³ g on the dust mass for both dust sizes.

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4 See also http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec6_3c.html.
features as the SDSS spectrum. The existence of the accretion disk thus likely started after 2000 February 6 but before May 6. A summary of the properties of J1023 known from different observations around the time is given in Table 1 (see also Archibald et al. 2009). Previously, Wang et al. (2009) found a required time of 0.5 yr for building the accretion disk in 2001 by considering the estimated disk mass of $10^{23}$ g and mass transfer rate of $10^{13}$ g s$^{-1}$. Our constraint on the starting time of the disk existence is therefore roughly consistent with their estimation. The lifetime of the interacting phase should be at most 2.5 yr from 2000 February to 2002 May, suggesting that for J1023 the interacting phase is short term in nature and that the system might repeat the short-term process in the future when the outflow from the companion could overcome the pulsar wind. Close monitoring of the binary system is warranted.

4. DISCUSSION

We have conducted multi-band imaging observations of J1023 from near- to far-IR wavelengths using ground-based and space telescopes. In the near-IR $JH$ bands and Spitzer mid-IR 3.6 and 4.5 μm channels, we have detected the source but the emission has been found to arise from the companion star of the binary and no excess IR emission was detected. The upper limits on the flux on the existence of any hot (600–800 K) dust in the system were derived and they were in the range of 0.006–0.011 mJy at the mid-IR 3.6–4.5 μm wavelengths. At the longer wavelengths, we did not detect emission from the source and the 3σ upper limits were approximately from 0.5 mJy at 12 μm to 6 mJy at 160 μm.

Constraints on the existence of relatively cold dust material in the binary system can be estimated from our results. A remnant of the accretion disk that was disrupted by either the pulsar wind (Wang et al. 2009) or γ-ray emission from the pulsar (Takata et al. 2010, 2012) might stay in the system and be illuminated by the pulsar wind. We used a simple dust model given by Foster & Fischer (1996), in which a single temperature is assumed for all dust grains, to estimate infrared emission from possible cold dust material in J1023. The spin-down luminosity of the pulsar in J1023 was recently estimated by Deller et al. (2012). Considering that a fraction of this energy output, $f = 0.01$, heats the dust of two sizes, 7 and 20 μm, we found that our IR upper limits constrain the masses of the dust to be lower than $3 \times 10^{23} (f_{0.01}/a_T a_T^2) g$ and $3 \times 10^{23} (f_{0.01}/a_T a_T^2)^2$ g, where $a_T$ and $a_T^2$ are the dust grain sizes of 7 and 20 μm, respectively. The corresponding dust temperatures are $T_D \sim 300$ K and $T_D \sim 80$ K. The model spectra are displayed in Figure 1. We note that Wang et al. (2009) have estimated a mass of $10^{23}$ g for the accretion disk seen in 2001. Assuming that 1% of the remnant’s mass is dust, the upper limits on the total mass of the remnant are $\sim 10^{24}$ g for the 300 K dust or $\sim 10^{26}$ g for the 80 K dust. The masses are substantially higher than the mass of the accretion disk, suggesting that the observations were not deep enough (particularly at 8 μm with no Spitzer observations) to detect possibly existing dust material in the system.

X-ray emission from J1023 has been detected with a dominant non-thermal component (Homer et al. 2006; Archibald et al. 2010; Bogdanov et al. 2011). Combined with the fact that orbital variability was seen in the X-ray emission, the origin of the emission is likely an intrabinary shock, produced by the outflows from the two stars of the system (Bogdanov et al. 2011; Takata et al. 2012). This shock could radiate emission in a long wavelength range from X-ray to IR wavelengths (see, e.g., Slane et al. 2008). However, assuming a single power-law emission and extending the Chandra spectrum ($\alpha = -0.2$; Bogdanov et al. 2011) to the IR wavelengths, a flux at 10 μm is predicted to be $10^{-4}$ mJy. Therefore, much deeper mid- or far-IR observations than ours are needed in order to determine possible emission properties of the putative intrabinary shock at the long wavelengths.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The publication also makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by NASA. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

### Table 1

| Date          | Measurement              | Inference       | Reference |
|---------------|--------------------------|-----------------|-----------|
| 1998 Aug 10   | $F_{1.656} = 6.56$ (mJy) | Pulsar emission | 1         |
| 1999 Mar 22   | SDSS photometry          | G dwarf color   | 1, 2      |
| 2000 Feb 6    | 2MASS near-IR photometry | G dwarf fluxes  | 3, 4      |
| 2000 May 6    | Optical spectroscopy     | Disk present    | 1         |
| 2001 Feb 1    | SDSS spectroscopy        | Disk present    | 3         |
| 2001 Dec 10   | Optical spectroscopy     | Disk present    | 2         |
| 2002 May 11   | Spectropolarimetry       | G dwarf spectrum| 5         |
| 2003 Jan 31   | Optical spectroscopy     | G dwarf spectrum| 6         |
| 2004 Jan 18–20| Optical spectroscopy     | G dwarf spectrum| 6         |
| 2004 Mar 8–9 | Optical spectroscopy     | G dwarf spectrum| 6         |
| 2004 Nov 18   | Optical spectroscopy     | G dwarf spectrum| 6         |
| 2004 Feb 16   | Spectropolarimetry       | G dwarf spectrum| 5         |
| 2005 May 23   | Optical spectroscopy     | G dwarf spectrum| 5         |
| 2007 Jan 28   | $F_{0.35 \mu m} \approx 75$ (mJy) | Pulsar discovery | 7         |
| 2008 Dec 23   | Optical spectroscopy     | G dwarf spectrum| 7         |
| 2008 Dec 25   | Optical spectroscopy     | G dwarf spectrum| 7         |

### Table 2

| Telescope/Instrument | Observation Date | Band | Magnitude | Flux (mJy) |
|----------------------|------------------|------|-----------|------------|
| 2MASS                | 2000 Feb 6       | J    | 16.30 ± 0.10 | 0.481 ± 0.045 |
|                      |                  | H    | 15.69 ± 0.13 | 0.542 ± 0.065 |
|                      |                  | $K_s$| 15.9 ± 0.3  | 0.29 ± 0.08  |
| du Pont/RetroCam     | 2012 May 10      | J    | 16.260 ± 0.024 | 0.499 ± 0.011 |
|                      |                  | H    | 15.964 ± 0.025 | 0.421 ± 0.019 |
| Spitzer/IRAC         | 2010 Jan 15      | J    | 15.862 ± 0.034 | 0.127 ± 0.004 |
|                      |                  | $K_s$| 15.813 ± 0.038 | 0.085 ± 0.003 |
| WISE                 | 2010 May 21–26   | J    | 15.989 ± 0.066 | 0.123 ± 0.008 |
|                      |                  | $K_s$| 16.49 ± 0.34  | 0.043 ± 0.014 |
|                      |                  | 12   | <12.1       | <0.4        |
|                      |                  | 22   | <8.8        | <2.6        |
| Herschel/PACS        | 2011 Nov 26      | 70   | <2.8        | <6.3        |

Notes. For non-detections, 3σ flux upper limits are given.

a 0.3 mag uncertainty is assigned by us to $K_s$.
We thank the anonymous referee for helpful comments. This research was supported by National Basic Research Program of China (973 Project 2009CB824800) and National Natural Science Foundation of China (11073042). Z.W. is a Research Fellow of the One-Hundred-Talents project of the Chinese Academy of Sciences.

**Facilities:** Du Pont (RetroCam), *Spitzer* (IRAC), *Herschel* (PACS)

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