SEARCH FOR MID-INFRARED FLUX VARIATIONS FROM THE ANOMALOUS X-RAY PULSAR 4U 0142+61

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ABSTRACT

We report on our Spitzer observations of the anomalous X-ray pulsar 4U 0142+61, made following a large X-ray burst that occurred on 2007 February 7. To search for mid-infrared flux variations, four imaging observations were carried out at 4.5 and 8.0 μm with the Infrared Array Camera from February 14 to 21. No significant flux variations were detected, and the average fluxes were 32.1 ± 2.0 μJy at 4.5 μm and 59.8 ± 8.5 μJy at 8.0 μm, consistent with those obtained in 2005. The nondetection of variability is interesting in light of reported rapid variability from this source in the near-infrared but consistent with the fact that the source already went back to its quiescent state before our observations began, as indicated by contemporaneous X-ray observations. In order to understand the origin of the near-infrared variability, frequent, simultaneous multwavelength observations are needed.

Subject headings: infrared: stars — pulsars: individual (4U 0142+61) — stars: neutron — X-rays: stars

1. INTRODUCTION

The anomalous X-ray pulsars (AXPs) are a small group of isolated, young neutron stars having X-ray luminosities greater than their rotational energy loss rates. They are believed to be magnetars, neutron stars possessing ~10^{14} G magnetic fields, with X-ray emission powered by the decay of their superstrong magnetic fields (Thompson & Duncan 1996). The magnetar nature of AXPs has been strongly supported by their high spin-down rates and radiative properties similar to soft gamma repeaters, including short X-ray bursts (Woods & Thompson 2006; Kaspi 2007). The bursting activity likely reflects structural changes in the surface magnetic field of a magnetar.

As the brightest and nearest among the currently known AXPs, 4U 0142+61 has been well studied over wavelength ranges from the X-ray to mid-infrared (MIR). Its X-ray emission in the 0.5–10 keV range can be well described by a blackbody (kT = 0.5 keV) plus power law (photon index Γ = 3.4; e.g., Patel et al. 2003), which is believed to arise from the surface and magnetosphere of the star (e.g., Thompson et al. 2002). Its optical emission is pulsed at the 8.7 s spin period (Kern & Martin 2002; Dhillon et al. 2005) and appears to have a power-law–like spectrum (Hullereman et al. 2000), likely also originating from the magnetosphere (although no apparent connection can be established between the optical and X-ray spectra). A surprise came from the detection of the source in the MIR (4.5 and 8.0 μm), which revealed a rising spectrum from the near-IR (NIR) to MIR (Wang et al. 2006). The detection can be interpreted as a surrounding debris disk (Wang et al. 2006). The putative disk, presumably formed from fallback material after the supernova explosion, is irradiated by the X-rays from the central pulsar and emits mainly in the MIR. The existence and appearance of such a disk has been predicted (e.g., Lin et al. 1991; Perna et al. 2000).

Recently, optical/NIR flux variability from 4U 0142+61 has been reported (Durant & van Kerkwijk 2006). In a total of only nine observations, significant flux variations were detected, suggesting that such variability is very common. This variability is intriguing, since no such flux changes have been detected in X-rays, even though X-ray observations of the source have been made much more frequently than the optical/NIR observations. An obvious question is whether there is similar variability in the MIR. Rapid variability in the MIR would be very hard to understand in the disk model in the absence of X-ray variability.

On 2007 February 7, a large fast-rise X-ray burst was detected during the Rossi X-Ray Timing Explorer (RXTE) monitoring observations of 4U 0142+61 (Gavriil et al. 2007). The peak flux of the burst was more than 2 orders of magnitude larger than that in the source’s quiescent state. This event provided an opportunity to test the fallback disk model, since an MIR flux increase is expected from an X-ray–irradiated disk when the input X-ray flux is increased (see Fig. 1). For the purposes of searching for variability and testing the fallback disk model, we observed 4U 0142+61 with the Spitzer Space Telescope. In this paper, we report on the results of the observations.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Spitzer/IRAC 4.5/8.0 μm Imaging

We observed 4U 0142+61 four times in 2007 February 14–21 with Spitzer, following the February 7 burst. To catch flux variations from the source and possibly constrain their timescale, the observations were scheduled to be on days 2, 4, and 7 after the first observation. The exact observation dates are given in Table 1. The imaging instrument used was the Infrared Array Camera (IRAC; Fazio et al. 2004). It operates in four channels at 3.6, 4.5, 5.8, and 8.0 μm, while two adjacent fields are simultaneously imaged in pairs (3.6 and 5.8 μm; 4.5 and 8.0 μm). We observed our target in the 4.5 (bandwidth 1.0 μm) and 8.0 μm (bandwidth 2.9 μm) channels. The detectors at the short- and long-wavelength bands are InSb and Si:As devices, respectively, with 256 × 256 pixels and a plate scale of 1.2′. The field of view is 5.2′ × 5.2′. The frame time was 100 s, with 96.8 and 93.6 s effective exposure time per frame for the 4.5 and 8.0 μm data, respectively. The total exposure times in each observation were 19.4 minutes at 4.5 μm and 18.7 minutes at 8.0 μm.

We also obtained the previous Spitzer IRAC data of 4U 0142+61 from the Spitzer archive. The observation was made on 2005 January 17 at the same wavelength bands as ours. The effective exposure times were 77.4 and 74.9 minutes at 4.5 and 8.0 μm, respectively. The results from this observation were previously reported by Wang et al. (2006).
2.2. Data Analysis

The raw image data were processed through the IRAC data pipelines (ver. S15.3.0) 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. In the post-BCD (PBCD) pipeline, radiation hits in BCD images are detected and excluded, and BCD frames are then combined into final PBCD mosaics. The detailed data reductions in the pipelines can be found in the IRAC Data Handbook (ver. 3.0; Reach et al. 2006). For our 2007 data, the target’s nearby region in the 4.5 \( \mu \text{m} \) images suffered the “column pull-down” effect, an artifact in which a column of the detector array has a reduced intensity when a place in the column reaches a level of approximately 35,000 digital numbers due to a bright star or cosmic rays. We corrected the BCD images for the artifact by using the tool cosmetic.pl. The artifact-corrected BCD images were then combined into PBCD mosaics by using the tool mosaic.pl. Both tools are provided by SSC in the MOPEX package. In our PBCD data processing, the latest 2006 June permanently damaged pixel mask (pmask) image, provided by SSC, was used.

The target field in the 4.5 \( \mu \text{m} \) PBCD images is crowded. We used DOPHOT (Schechter et al. 1993), a point-spread function (PSF) fitting program, for photometry. For the 8.0 \( \mu \text{m} \) images, in which the sky background dominates in brightness and varies substantially over the source field region, we found that aperture photometry provided more consistent measurements (this was also suggested by the Spitzer Helpdesk). The program phot in the IRAF package APHOT was used for photometry. The aperture radius was 3 pixels and background annulus radii were 3–7 pixels. The DOPHOT results were also corrected to this aperture set (Reach et al. 2006). The correction factor was derived by comparing the brightnesses resulting from the PSF-fitting photometry to those from the aperture photometry of a few well-exposed, isolated stars in the source field.

In addition, to eliminate systematic variations among the PBCD images that might be caused by changes such as in the instrument, observing conditions, or data reduction, we applied a differential photometry technique: we calibrated the brightness of our target with those of an ensemble of bright, nonvariable stars in the images. The base images were the 2005 data, which have longer exposure times and thus higher signal-to-noise ratios.

3. RESULTS

The flux density measurements are given in Table 1. As can be seen, the flux densities are consistent with being a constant within the uncertainties. No significant variations were detected from our observations. Compared to the 2005 flux densities, the upper limits (90% confidence) on the flux density changes are 13% at 4.5 \( \mu \text{m} \) and 38% at 8.0 \( \mu \text{m} \). We note that the flux densities in Table 1 for the 2005 observation are slightly lower than those previously reported, 36.3 \( \pm \) 3.6 and 51.9 \( \pm \) 5.2 \( \mu \text{Jy} \) at 4.5 and 8.0 \( \mu \text{m} \), respectively (Wang et al. 2006). For the 4.5 \( \mu \text{m} \) results, the difference is mainly caused by blending with nearby stars. A few photons from nearby stars appear within radii of 2–3 pixels from the center of our target. When aperture photometry was used (in Wang et al. 2006), the extra photons were included as the target counts. This can be verified by comparing the measurements from aperture photometry to those from PSF fitting. For example, when an aperture radius of 3 pixels is used, the ratio between the fluxes from the first and last photometry is 1.42 \( \pm \) 0.09 for our target, while the average ratio is 1.214 \( \pm \) 0.008 for a few nonblended test stars in the field. When the aperture radius is changed to 2 pixels, the flux ratios for our target and the test stars are equal (1.07 \( \pm \) 0.07 for the target vs. 1.070 \( \pm \) 0.008 for the test stars). For the 8.0 \( \mu \text{m} \) results, the difference, which is well within the uncertainties, is probably due to the different IRAC data pipelines (ver. S11.0 in Wang et al. [2006] vs. ver. S15.3.0 in this work).

We average the four 2007 4.5 \( \mu \text{m} \) fluxes, weighted by the flux uncertainties, and find a mean of 32.1 \( \pm \) 1.2 \( \mu \text{Jy} \). This value is exactly the same as the 2005 result (note that the total exposure time in each wavelength band of the 2007 observations is approximately the same as that of the 2005 observation). Adding a 5% absolute calibration uncertainty in quadrature (Reach et al. 2005, 2006), we obtain 32.1 \( \pm \) 2.0 \( \mu \text{Jy} \). The 8.0 \( \mu \text{m} \) flux densities, as shown in Table 1, have similar uncertainties, even though the exposure time of the 2005 observation is four times that of one 2007 observation. This is because the flux density uncertainties are dominated by the sky noise (e.g., Reach et al. 2005) and there were intrinsic intensity variations within the sky annulus in the aperture photometry. Therefore, the longer 2005 exposure time did not effectively reduce the sky noise. We average the four flux densities and find an average of 59.8 \( \pm \) 8.5 \( \mu \text{Jy} \), where we use the uncertainty 8.0 \( \mu \text{Jy} \) (Table 1) and add the 5% absolute calibration uncertainty to it in quadrature.

4. DISCUSSION

There are a total of 11 reported \( K \)-band observations of 4U 0142+61 in the past 9 years, and three of them were with

![Figure 1](https://example.com/image.png)
simultaneous $JH$ observations (Durant & van Kerkwijk 2006; Gonzalez et al. 2007). In the observations, the AXP exhibited large and rapid flux variations in the $K$ band, and the $JH$ fluxes correlated with the $K$ but varied less. Assuming that the $K$-band variations are sufficiently sampled, the probability of seeing a $>15\%$ flux change would be $60\%$. In one extreme case, a $40\%$ $K$ flux decrease occurred within 1 day. Our Spitzer observations were planned so that such strong variability would have been detected. Correlated flux changes between the MIR and $K$ bands are expected in the proposed dust disk model for 4U 0142+61 (Fig. 1; Wang et al. 2006), if X-ray flux changes are considered as the primary cause of the variability.

We did not detect the $K$-like flux variations in our MIR observations. The Spitzer/IRAC fluxes were consistent with being a constant within the uncertainties. Given that the upper limit on the MIR $4.5\mu m$ flux variations was $13\%$, the MIR emission variability was similar to the NIR $JH$ bands and less variable than in the $K$ band. We note that in a $K$-band observation made 1 day prior to our first Spitzer observation, the source had $K = 19.9 \pm 0.1$ mag (Gonzalez et al. 2007), approximately the average $K$-magnitude of 4U 0142+61. Because the timescale of the $K$ flux variations is not determined, this could suggest that the source was in a stable state in the NIR during our observations, which could be a reason for the absence of MIR variability. To further constrain the relation between the MIR and NIR emission, frequent, simultaneous observations are needed.

If the MIR emission is truly less variable, the restricted $K$-band variability would demand explanation. Interestingly, similar NIR variability is seen in a few dust disk systems around young stars (e.g., Eiroa et al. 2002). In those systems, the variability has been suggested to be caused by structural changes of the inner disk. If this is the case for 4U 0142+61, the properties in the source’s IR variability might be explainable. Since emission in the $K$ band would mainly arise from the inner edge of the disk and thus be more sensitive to inner disk changes, it would vary more strongly than emission in the $JH$ and Spitzer MIR bands. It is not clear what would be the cause of the structural changes in the disk in 4U 0142+61. One possibility is variable X-ray heating, such as due to burst-related X-ray brightening. However, no significant short-term flux variations have been found in the X-ray observations of the source (Durant & van Kerkwijk 2006), and thus far only a few bursts have been found in biweekly RXTE X-ray monitoring observations (Dib et al. 2007a; Gavriil et al. 2007), indicating infrequency of the burst events. Thus, in the absence of X-ray variability, the $K$-band variability challenges the dust disk model (Durant & van Kerkwijk 2006).

In addition, we did not detect any significant MIR flux changes from 4U 0142+61 in our Spitzer IRAC observations following the large X-ray burst. The $4.5/8.0\mu m$ fluxes were nearly the same as those obtained in 2005. As demonstrated by X-ray observations of the source that were made several days prior to our first Spitzer observation (Gonzalez et al. 2007), the AXP unfortunately had already returned to quiescence during our observations. Also as shown in the long-term X-ray monitoring observations, the quiescent X-ray flux of 4U 0142+61 has been nearly constant and stable over the past decade (Dib et al. 2007a; Gonzalez et al. 2007). Therefore, our nondetection is consistent with the source’s state at X-ray energies at the time.

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