OPTICAL/INFRARED OBSERVATIONS OF THE ANOMALOUS X-RAY PULSAR 1E 1048.1–5937 DURING ITS 2007 X-RAY FLARE

ZHONGXIANG WANG,1 Cees Bassa,1 Victoria M. Kaspi,1 Julia J. Bryant,2 and Nidia Morrell3

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ABSTRACT

We report on optical and infrared observations of the anomalous X-ray pulsar (AXP) 1E 1048.1–5937 made during its ongoing X-ray flare that started in 2007 March. We detected the source in the optical $J$ and near-infrared $K_s$ bands in two ground-based observations and obtained deep flux upper limits from four observations, including one with the Spitzer Space Telescope at 4.5 and 8.0 μm. The detections indicate that the source was approximately 1.3–1.6 mag brighter than in 2003–2006, when it was at the tail of a previous similar X-ray flare. Similar related flux variations have been seen in two other AXPs during their X-ray outbursts, suggesting common behavior for large X-ray flux variation events in AXPs. The Spitzer flux limits are sufficiently deep that we can exclude mid-infrared emission similar to that from the AXP 4U 0142+61, which has been interpreted as arising from a dust disk around the AXP. The optical/near-infrared emission from 1E 1048.1–5937 probably has a magnetospheric origin. The similarity in the flux spectra of 1E 1048.1–5937 and 4U 0142+61 challenges the dust disk model proposed for the latter.

Subject headings: infrared: stars — pulsars: individual (1E 1048.1–5937) — stars: neutron — X-rays: stars

1. INTRODUCTION

Supported by extensive observational studies over the past few years, it is generally believed that anomalous X-ray pulsars (AXPs) are magnetars—young neutron stars possessing ultrahigh $\sim 10^{14}$ G magnetic fields. While AXPs are primarily known as X-ray sources, exhibiting a variety of variability behavior related to their magnetar nature (Woods & Thompson 2006; Kaspi 2007), we now know that 5 of 10 identified AXPs—4U 0142+61, 1E 1048.1–5937, RXS J170849–400910, XTE J1810–197, and 1E 2259+586—are bright at near-infrared (NIR) wavelengths (Woods & Thompson 2006; McGill AXP online catalog). Among them, the AXP 4U 0142+61 is detected from optical to mid-infrared (MIR) wavelengths, indicating a spectral energy distribution (SED) that can be described by a two-component model: one a power-law spectrum over optical $VRI$ and NIR $J$ bands, presumably arising from the magnetosphere, and one thermal blackbody-like over the 2.2–8 μm range (Wang et al. 2006), arising from a debris disk. The discovery of such an optical/IR SED from the AXP was unexpected, and the two-component model remains controversial (e.g., Durant & van Kerkwijk 2006b). Ideally, in order to understand the optical/IR emission mechanism for AXPs and in particular determine whether the IR emission from 4U 0142+61 is unusual or generic among AXPs, SEDs of other AXPs must be observed. However, most known AXPs are highly extincted in the optical range and often extremely faint in the IR.

Among the known AXPs, 1E 1048.1–5937 is peculiar in that it has exhibited two long-term X-ray flares (Gavriil & Kaspi 2004; Tam et al. 2008), which have not been seen from other AXPs thus far. Monitored with the Rossi X-Ray Timing Explorer (RXTE), the first flare was found to start in 2002 April and lasted approximately 2 yr. At the beginning of the flare, the NIR counterpart was discovered (Wang & Chakrabarty 2002), and in observations more than 1 yr later, the counterpart was found to be approxi-
Observatory (ESO) and the 8 m Gemini South Telescope at the Gemini Observatory. Both telescopes are located in Chile.

The VLT observation was made on 2007 May 7, the same night that the second Magellan NIR image was obtained. The instrument used was the Focal Reducer and Low-Dispersion Spectrograph (FORS2; Appenzeller et al. 1998), which consists of two 2k × 4k MIT CCDs and has a FOV of 6.8′ × 6.8′. The CCD detectors were 2 × 2 binned, having a pixel scale of 0.25″ pixel⁻¹. We obtained 15 3 minute I-band images of the field, resulting in a 45 minute total exposure. The telescope was dithered in a 3 × 5 grid, with offsets of 5″ × 2.5″. The conditions were excellent, with 0.5″ seeing.

The Gemini imaging observations were made on 2007 June 24 and July 15. The instrument was Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004). The detector array of GMOS consists of three 2048 × 4608 EeV CCDs. The pixel scale is 0.073″ pixel⁻¹, while we used a detector binning of 2 pixels for the observations. In the first observation, we obtained eight r′ and five i′ images, with exposure times of 5 and 3 minutes, respectively. The telescope was dithered for the exposures, with offsets of 10″. The seeing was approximately 0.9″ during the observations. In the latter observation, we obtained 16 5 minute r′ and four 3 minute i′ images, with the same observing strategy. The seeing was approximately 0.8″.

2.1.3. Data Reduction

We used the IRAF data analysis package for data reduction. The images were bias subtracted and flat fielded. In addition, because the Gemini GMOS detectors have significant fringing in i′ band, a fringe frame provided by the Gemini Observatory was used for subtraction of the fringes in our i′ images. 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. A summary of the images that we obtained is given in Table 1.

2.2. Spitzer 4.5/8.0 μm Imaging

We also observed 1E 1048.1−5937 on 2007 August 10 with the Spitzer Space Telescope. 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 wavelengths are InSb and Si:As devices, respectively, with 256 × 256 pixels and a plate scale of 1.2″ pixel⁻¹. The FOV is 5.2′ × 5.2′. The frame time was 100 s, with 96.8 s 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 53.2 minutes at 4.5 μm and 51.5 minutes at 8.0 μm.

The raw image data were processed through the IRAC data pipelines (ver. S16.1.0) 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 details of the data reduction in the pipelines can be found in the IRAC Data Handbook (ver. 3.0; Reach et al. 2006).

3. RESULTS

3.1. Ground-based Observations

The counterpart to 1E 1048.1−5937 was detected in both NIR observations made on 2007 April 4 and the optical observations made on 2007 May 7. We performed PSF-fitting photometry to measure the brightness of the source. The nearby star X5 was used for flux calibration in the Ks and I bands (Durant & van Kerkwijk 2005). The source’s magnitudes were Ks = 19.9 ± 0.1 and I = 24.9 ± 0.2. We did not detect the source in the other observations. Using the X5 star for flux calibration (Wang & Chakrabarty 2002) we derived 3 σ limiting magnitudes for the Magellan Ks and Gemini r′ and i′ images. The results are given in Table 1.

3.2. Spitzer IRAC Observations

We did not detect the source in the Spitzer IRAC 4.5 and 8.0 μm images, and the derived 3 σ flux upper limits were 5.2 and 21.8 μJy, respectively. The fluxes correspond to limiting magnitudes of 18.9 and 16.2 mag, for the 0 mag fluxes of 179.7 and 64.1 Jy (Reach et al. 2005) at the Spitzer IRAC 4.5 and 8.0 μm bands, respectively. These results are also given in Table 1. The source region has been observed previously with IRAC at the same wavelength bands in 2005, with no counterpart found either
obtained at the tail of the first X-ray flare. We note that second (Predehl & Schmitt 1995). Also, we note that even though our upper limits are approximately 2 times deeper.

The optical/NIR counterpart of 1E 1048.1–5937 was observed a few times during 2003–2006 after the discovery of the counterpart, and the source’s brightness had been low (e.g., $K_s \approx 21.0$–21.5; see Tam et al. 2008 for details). Compared to the flux measurements, particularly those obtained in 2003 April and June when the counterpart was detected in both the optical and NIR/JKs bands (Durant & van Kerkwijk 2005; also see Table 2), our results clearly indicate an optical/NIR brightening during the 2007 X-ray flare. Indeed, assuming $A_V = 5.4$ mag, the unabsorbed optical/NIR–to–X-ray flux ratios for 2003 and our measurements are nearly identical (see Fig. 1). In this comparison, the unabsorbed 2–10 keV X-ray fluxes at 2 epochs given in Table 2 are used, and $A_V$ is estimated from $N_H = 9.7 \times 10^{21}$ cm$^{-2}$ (Tam et al. 2008) by using the relation $A_V = N_H/1.79 \times 10^{21}$ cm$^{-2}$ (Predehl & Schmitt 1995). Also, we note that even though our second $K_s$ measurement was an upper limit ($K_s > 20.1$), it was only 0.1 mag smaller than that obtained from a detection two days later by Israel et al. (2007). Thus, in these two sets of observations, the optical/NIR and X-ray fluxes appeared to be correlated.

However, as shown by Tam et al. (2008), the observed NIR brightening at the beginning of the 2002 X-ray flare preceded the pulsed X-ray flux peak by ~2 months. If we assume that the relation between the pulsed flux $F_p$ and total flux $F_t$: $F_p \propto F_t^{1.54}$ (Tam et al. 2008) is generally true for this AXP, the 2–10 keV unabsorbed total flux derived at the NIR observation time would have been $\approx 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, 3.6 times lower than the 2007 peak flux. As a result, the 2002 NIR–to–X-ray flux ratios would be approximately 6 times higher than that shown in Figure 1 (note $K_s = 19.4$ in the 2002 detection). This would indicate that the NIR and X-ray fluxes were not correlated all the time. We note that since the $F_p$ and $F_t$ relation is mainly based on the total flux measurements obtained during the 2007 flare and there were not such measurements for the 2002 flare, it is possible that the total flux was much larger at the start of the 2002 flare and not reflected in the RXTE pulsed flux measurements. In any case, we confirm that in this AXP, the large optical/NIR flux variations were related to the X-ray flares. Similar related NIR brightening has been seen in 1E 2259+586 and XTE J1810–197 during their X-ray outbursts (Tam et al. 2004; Camilo et al. 2007), suggesting common behavior for emission from AXPs. However, for 4U 0142+61, while its X-ray flux has been relatively stable (Gonzalez et al. 2007), its optical and NIR flux was found to have large, rapid variations (Durant & van Kerkwijk 2006b).

(Wang et al. 2007). Comparing to the previous results, our 2007 upper limits are approximately 2 times deeper.

4. DISCUSSION

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This limits the related NIR/X-ray behavior to only large X-ray flux variation events.

It is instructive to compare 1E 1048.1–5937 to 4U 0142+61, since the latter has well-measured fluxes from the optical to MIR. In Figure 1 we compare the optical/IR fluxes and flux upper limits of 1E 1048.1–5937 to those of 4U 0142+61, with each set of data points normalized by the approximately contemporaneous unabsorbed 2–10 keV X-ray flux of each source. The optical $Y/R$ and NIR $JKs$, fluxes for 4U 0142+61 are from Durant & van Kerkwijk (2006b); because of relatively large flux variations from the source, we show the range of the flux found in each band in the figure), the two MIR data points at 4.5 and 8.0 μm are the 2005 flux measurements in Wang & Kaspi (2008), and the unabsorbed 2–10 keV X-ray flux used is 6.6 × $10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, obtained on 2004 July 24 (Gonzalez et al. 2007). As can be seen from the figure, while the flux ratios of 1E 1048.1–5937 that we use for the comparison.

This strongly suggests that our target does not have similar MIR emission. This difference in the MIR is not very sensitive to uncertainties on the reddening to the two sources, since MIR emission is only weakly extincted by the interstellar medium. The X-ray flux from 4U 0142+61 has been stable (Gonzalez et al. 2007). A possible explanation could be the nonsimultaneous X-ray flux of 1E 1048.1–5937 that we use for the comparison. However, RXTE X-ray monitoring observations of the source have indicated that the pulsed flux, which is found to trace the total flux (Tam et al. 2008), has remained stable and high during our observations (Dib et al. 2008, in preparation). In order to raise the 4.5 μm upper limit to the flux ratio of 4U 0142+61, the X-ray flux would have had to have been as low as $11 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$, only 40% larger than the average quiescent flux (7.7 × $10^{-12}$ ergs s$^{-1}$ cm$^{-2}$) of the source and approximately one third of those obtained in 2007 April (Tam et al. 2008).
The lack of MIR emission similar to that of 4U 0142+61 from 1E 1048.1—5937 seems robust. In the dust disk model proposed for 4U 0142+61 (Wang et al. 2006), the MIR flux, arising from X-ray irradiation of the disk, is proportional to the X-ray flux of the pulsar. Therefore, even though our deep 4.5 μm limit was obtained during the X-ray flare, we can exclude the existence of a similar disk around 1E 1048.1—5937. However, since a disk could be further away from the central source, deep observations at longer wavelengths are needed in order to exclude the existence of a disk more conclusively. The MIR nondetection may suggest that debris disks are not commonly found around AXPs, and thus the putative disk in 4U 0142+61 is unique. Two other AXPs have also been observed by Spitzer with no detection; however, the derived upper limits are far above the MIR–to–X-ray flux ratio of 4U 0142+61 (Wang et al. 2007).

The optical and NIR emission from 1E 1048.1—5937 probably has a magnetospheric origin, given that the flux spectrum is similar to that of 4U 0142+61 (Wang & Chakrabarty 2002; Durant & van Kerkwijk 2005). For the latter source, its optical emission is known to be pulsed at the spin period and has a pulsed fraction much higher than that in X-rays, excluding a disk origin (Kern & Martin 2002; Dhillon et al. 2005). Details of how optical and NIR emission is produced in the magnetosphere of a magnetar are not known, although possible radiation mechanisms have been suggested (e.g., Beloborodov & Thompson 2007). We note that in the disk model for 4U 0142+61 (Wang et al. 2006), the K-band flux primarily arises from the disk, not from the magnetosphere. Therefore, the similarity in the K-band–to–X-ray flux ratios for the AXPs (Durant & van Kerkwijk 2005), including 1E 1048.1—5937 as confirmed by our measurements, challenges the disk model. The K-band emission thus should originate from the magnetospheres, which may be supported by the fact that in the absence of X-ray variability, strong K-band variability is seen in 4U 0142+61 (Durant & van Kerkwijk 2006b).

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