A DEEP INFRARED SEARCH FOR AXP 1E 1841−045

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ABSTRACT

Multicolor (JHKs) imaging and photometry of the field of the anomalous X-ray pulsar (AXP) 1E 1841−045 is analyzed in the light of accurate new coordinates from Chandra. From excellent quality images, we find multiple sources in and around the position error circle. Of these, none can be confidently identified as the infrared counterpart. The limiting magnitudes reached were J = 22.1, H = 20.7, and KS = 19.9 (95% confidence).

Subject heading: pulsars: individual (1E 1841−045)

1. INTRODUCTION

The anomalous X-ray pulsars (AXPs) are a small group of young, energetic neutron stars, whose luminosity is thought to be powered by the decay of a superstrong magnetic field, i.e., magnetars (Thompson & Duncan 1996). Since the discovery of the first optical counterpart to an AXP (Hullemann et al. 2000), searches have been undertaken to identify further optical and infrared counterparts in different colors. Due to the large extinction to most of these sources, the infrared has proved the more successful route. See Woods & Thompson (2004) for a review of the AXPs and their counterparts to date.

1E 1841−045 is located within the supernova remnant (SNR) Kes 73, and has a pulse period of 11.8 s and a soft X-ray spectrum well-fitted by either a blackbody plus power law or the sum of two blackbodies, with a fitted hydrogen absorption column of N_H = 2.5 × 10^{22} cm^{-1} (Morii et al. 2003; Gotthelf et al. 2004). Surprisingly, this source was found by Kuiper et al. (2004) to have hard, pulsed X-ray emission with a rising power-law spectrum out to about 100 keV. Since this dominates the emission energetics, it has prompted an ongoing revision of magnetar spectra; Martini et al. 2004), the 1k × 1k infrared imaging array with 0.125 pixels on the Magellan Clay Telescope,1 under excellent conditions. The total integration times were 1125 s in J, 1825 s in KS, and 1825 s in H, at a seeing of ≈0.35. A second J-band integration was performed, but the seeing had deteriorated, and so this is not included in the analysis.

Standard reduction was carried out to flat-field and combine the frames using IRAF. The flat fields were derived by median combining many images in each filter of a less crowded field. This proved more successful than either screen flats or median images from the data frames themselves. Photometry was performed using DAOPHOT II (Stetson 1987).

In order to calibrate the frames, we obtained short-exposure images of standard stars, from Persson et al. (1998). Because of some light cloud in patches on the night in question, it was found more reliable to use standards from the following night and find the magnitude transformation from one night to the next using fields that were imaged on both nights (see Durant & van Kerkwijk 2005). The offsets were small in each band, ≲0.03 mag. The standards were taken at a range of air masses so that the zero point at the appropriate air mass could be found (the variation with air mass is slight in the infrared in any case).

The magnitudes found for stars in the field tend to be fainter than those found by Wachter et al. (2004) and Mereghetti et al. (2001) by typically 0.3 mag for their faintest stars (note that there are also some substantial differences in the magnitudes presented by these two sets of authors). This can be attributed to the better seeing conditions, which allowed sources to be separated that would otherwise have been blended in this extremely crowded field. Many of the stars measured by Mereghetti et al. (2001) are saturated on our deeper images, and so cannot be compared. We believe that the better separation of sources entirely explains the discrepancy in measured magnitudes.

An astrometric solution was found for the images based on Two Micron All Sky Survey (2MASS) sources (Cutri et al. 2003) in the field. We matched 86 stars for J in the ±2′ × 2′ field, and after rejecting large residuals, the rms deviation in each coordinate was ≲0.1 with 71 points. The error in connecting this image to the others is negligible in comparison. The astrometric uncertainty arises in connecting our images to the 2MASS reference frame. Since Wachter et al.’s coordinates are also based on

1 See http://www.ociw.edu/lco/magellan/instruments/PANIC/panic/.
Fig. 1.—Images of the field of 1E 1841−045 in the $K_s$ (top left), $H$ (top right), and $J$ bands (bottom). In the top left image are labeled the stars whose magnitudes are presented in Table 1.
2MASS stars, there should be no additional uncertainty in the astrometry.

3. RESULTS

Figure 1 shows the stacked images, with the position error circle of radius 0.09 (3σ confidence) derived by Wachter et al. (2004) overlaid. Table 1 gives the magnitudes of stars in and around the circle, as labeled on the images, and Figure 2 shows those stars with three measured magnitudes on a color-color diagram compared to the rest of the stars in the field.

From Figure 2, one sees that, of the stars near the positional error circle (see Fig. 1), none have colors significantly different from those of other stars in the field. Note that the large scatter is due to the extreme crowding in the field, particularly in $K$. This means that the measured magnitude of a given star can be strongly affected by the halo of a neighboring brighter star. The magnitude limits reached at 95% confidence are $J = 22.1$, $H = 20.7$, and $K_s = 19.9$.

By fitting the X-ray spectrum with an absorbed blackbody plus power-law spectrum, a value for the hydrogen column density can be derived. Assuming the Predehl & Schmitt (1995) relationship, this translates to an extinction toward the source of $A_V \approx 14$. With the caveat that the intrinsic X-ray spectrum is not known, this number provides an approximate measure of reddening. Figure 2 shows that the effect of extinction means that one cannot distinguish between an intrinsically hot but highly extincted source and an intrinsically cool (i.e., red) source. Also note that, since the main sequence is known to start around (0,0) on this diagram, the bluest sources here have $A_V \approx 2$, although extinction is known to increase rapidly in this direction (e.g., Drimmel et al. 2003).

Although an outlier on Figure 2, star F is consistent with being a very highly reddened red supergiant. Dereddening it with $A_V = 14$ would not place it below the bulk of the stars, as is the case with 4U 0142+61 ($H - K_s = 1.0 \pm 0.1$, $J - H = 1.2 \pm 0.2$; Israel et al. 2004; Hulleman et al. 2004). Whether these two objects would be expected to have the same spectrum is an open question, as is the appropriate value of reddening. The AXPs with confirmed infrared counterparts appear to have similar X-ray to infrared flux ratios (Durant & van Kerkwijk 2005), and star F would have both a much brighter counterpart and a much lower X-ray to infrared flux ratio than 4U 0142+61. Although stars with colors as red as star F are rare in the field, it cannot be presented as a likely counterpart. It is worth mentioning that star B, if close to the magnitude limit in $J$, would fall in the right region of Figure 2, but again this can hardly be more than a suggestion of a candidate counterpart.

Comparing with the spectrum of 4U 0142+61 again (the brightest and best-measured AXP, $J = 22.3 \pm 0.1$, $H = 21.1 \pm 0.1, K_s = 20.15 \pm 0.08$), one would expect 1E 1841−045’s magnitudes to fall beyond the magnitude limits given above, especially if the nominal reddening values to the two sources are to be believed (which would make the above magnitudes fainter by about 2.5, 1.7, and 1.1 mag, respectively). Thus a nondetection here does not imply that the two spectra are necessarily different, but does demonstrate that this part of the sky is so crowded that finding the counterpart will prove very difficult.

In conclusion, we have found the magnitudes of several sources in or near the accurate Chandra error circle for the position of 1E 1841−045. Despite the depth and quality of the images, we find no source that can be confidently presented as the likely counterpart. Extremely deep images with narrow point-spread functions will be required in order to find the counterpart to this AXP.
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