A search for the optical counterpart to the magnetar CXOU J010043.1−721134.

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ABSTRACT

After our tentative detection of an optical counterpart to CXOU J010043.1−721134 from archival Hubble Space Telescope (HST) imaging, we have followed up with further images in four bands. Unfortunately, the source originally identified is not confirmed. We provide deep photometric limits in four bands and accurate photometry of field stars around the location of the magnetar.

Subject headings: pulsars: individual (CXOU J010043.1-721134)

1. Introduction

Magnetars are neutron stars that derive their large X-ray luminosity from the decay of a super-strong magnetic field or the order 10^{15} G (and even greater internally), many orders greater even than normal radio pulsars and accreting X-ray sources (Woods & Thompson, 2006). They are found preferentially in the Galactic plane, in accordance with their presumed youth and high-mass progenitors (e.g., Figer et al., 2005). This makes observations in soft X-rays and the optical difficult, due to the large columns of extincting material to each of the objects (Durant & van Kerkwijk, 2006a).

For the nearest of the magnetars, 4U 0142+61, an intriguing break was seen in the broad-band optical spectrum between the B and U bands (Hulleman et al., 2004). Due to the faintness and extinction to this source, it has not proved possible so far to further characterize the optical feature.

A source for which the extinction will be much less of an issue is CXOU J010043.1−721134, a magnetar in the Small Magellanic Cloud. This source was detected by *Chandra* as a slow-spinning X-ray source, with a bright thermal or power-law spectrum (Lamb et al., 2002). Although relatively faint in the first observations by Lamb et al. and Majid et al., in later *Chandra* and *XMM* observations, the object had brightened somewhat towards a similar luminosity to the other Anomalous X-ray Pulsars ($\sim 2 \times 10^{35}\,\mathrm{erg\,s^{-1}}$, 0.5–10 keV range; McGarry et al., 2005). The AXPs (the more stable type of magnetar) all seem to have the same 2–10 keV luminosity ($\sim 1 \times 10^{35}\,\mathrm{erg\,s^{-1}}$; Durant & van Kerkwijk, 2006b).

In Durant & van Kerkwijk (2005a, hereafter DvK05), we presented evidence for the detection of an optical counterpart to CXOU J010043.1-721134 in archival Hubble Space Telescope imaging with the Wide Field/Planetary Camera 2 (WFPC2). The serendipitous detection was based on a single exposure from a survey of the SMC (Tolstoy, 1999). Although a faint source, the detection parameters and statistics of non-detections in the field pointed to it likely being a true detection.

Here we present deeper HST imaging of the field of CXOU J010043.1−721134 in four bands to attempt to confirm the tentative detection presented in DvK05.

2. Observations

Following the failure of the Advanced Camera for Surveys (ACS), we planned an imaging campaign with the Wide Field/Planetary Camera 2 (WFPC2) on board the Hubble Space Telescope (HST), aiming first to confirm the detection in DvK05, and second for broad-band photometry to measure the spectral energy distribution throughout the optical and into the ultra-violet. We used the filters F336W, F439W, F606W and F814W and the wide-field chips, for reduced read-out noise across the PSF area. Exposures were dithered by non-integer pixel shifts, in order to sample the PSF and decrease the sensitivity to bad pixels. We obtained 6 exposures in F336W (total time: 8400 s), 6 exposures in F439W (3400 s), 2 exposures in F606W (800 s) and 4 exposures in F814W (2600 s).

The images were analyzed with the `HSTphot` package (Dolphin, 2000), which handles bad pixel rejection, sky level estimation, cosmic ray identification, image alignment, PSF analysis and photometry for the ensemble image set.

To stack together images (for display and astrometry only), we over-sampled each frame by a factor of two, and aligned and added these, removing cosmic rays in the process. See Figure 1 for co-added images in each band. Clearly the source named Star X DvK05 is not present at the same location.

To register the images to the ICRS, we searched the astrometric catalogs for references in the field. Both the USNO B1.0 (Monet et al. 2003) and GSC II (STScI, 2006) have substantial scatter in star locations compared to the images and to each other in this crowded field. The UCAC catalog (Zacharias et al., 2003), generally regarded as having more precise positions, has too few stars in the field for an astrometric solution. We used the 2MASS (Cutri et al., 2003) catalog, primarily on the F439W image (in which the 2MASS stars were not saturated). 11 2MASS stars were matched on the WF3 chip, of which 9 were usable to fit for rotation, scale and offset. Final residuals were $\sim 0.08''$in each coordinate. The systematic uncertainty of the 2MASS positions is estimated to be 0.1–0.2″; if we assume the worst case, then the 0.6″*Chandra* positional uncertainty (90% confidence) translates into a 0.72″positional uncertainty (90% confidence) on our images. Transferring the astrometric solution from the F439W image to the other images incurred negligible additional uncertainty.

Table 1 lists the positions and magnitudes of stars around the inferred X-ray position of CXOU J010043.1−721134. Comparing to the images in Figure 1, one can see that some of these sources are not good detections.

The 3σ photometry limits for the field were: 24.2 in F334W, 25.6 in F439W, 26.2 in F606W and 25.9 in F814W. These magnitudes are *flight system*: defined such that a star of zero color in the Johnson-Cousins UBVRI system has zero color in any pair of WFPC2 filters, and the F555W magnitudes $m_{555} = V$ (Holtzman et al. 1995). A color-magnitude diagram of stars in the field is shown in Figure 2 for the two filters F606W and F814W, which have the highest number of detections. All of the detected stars are consistent with being part of the normal stellar population in the field.

3. Discussion

Given the non-detection probability of $\sim 1.5\%$ estimated in DvK05, it is rather surprising that the deeper observations presented here failed to detect the same source. The estimate was based on the number of good detections in the field which would also have been considered interesting (by color), had they fallen within the positional error circle. Only one new source is detected within the positional error circle, Star 6, and this is red enough in $m_{606} - m_{814}$ to appear as a normal star on the color-magnitude diagram, Figure 2

Star Y does not appear to have varied significantly between the two observations in either filter where it was detected, and Star Z is still consistent with a bright early-type star.

Two distinct possibilities exist for the non-detection of the counterpart to CXOU J010043.1−721134 proposed in DvK05: the original detection was false, or the detection was real, but the source has faded considerably in the intervening time. For the detected object to physically leave the positional uncertainty circle at the distance of the SMC, or even by a foreground white dwarf is not possible, the proper motion required would be too great.

One obvious solution is that the detection in DvK05 was, in fact, a cosmic ray or some other artifact. `HSTphot` rejects detections as cosmic rays if they are much sharper than typical stars, and this source was, if anything, more diffuse. Some objects were, however, in the same part of the color-magnitude diagram as Star X, so there is a small but non-negligible chance that this was a mere fluke. In this deeper set of observations, there remain a few detections of similar brightness in m_{606} and blueness in $m_{606} - m_{814}$ as the original detection. The large scatter at the bottom of Figure 2 is not significant in this respect, as these sources (including the couple near the error circle) are more poorly measured than Star X appeared to be in DvK05.

Although the detection in DvK05 is clearly in doubt following these observations, it is possible that the object faded considerably in the optical, and became undetectable. The only AXP that has been detected multiple times in the optical, 4U 0142+61, does at times show large variations in flux, and the X-ray to optical flux ratio inferred in DvK05 was much larger for Star X than it had typically been for 4U 0142+61. Assuming that none of the sources detected is the counterpart to CXOU J010043.1−721134, we derive a limit on the flux ratio $f_X/f_V > 114$ (with $V \approx m_{606}$, $A_V = 0.3$ from Hilditch et al., 2005; and X-ray flux in the 2–10 keV range from Woods & Thompson, 2006), which compares to a typical value of 460 for 4U 0142+61. Thus, the general consistency found between different AXPs (Durant & van Kerkwijk, 2005b) could still hold for this source as well.

To summarize, follow-up HST/WFPC2 observations of the field of CXOU J010043.1−721134 have failed to confirm our earlier tentative detection of an optical counterpart. No convincing counterpart is seen, with much better limiting magnitudes than before. The absence of a detection could either mean that the original detection was false, or that the counterpart has faded significantly. If the latter, its X-ray to optical flux ratio could now be the same as for 4U 0142+61.

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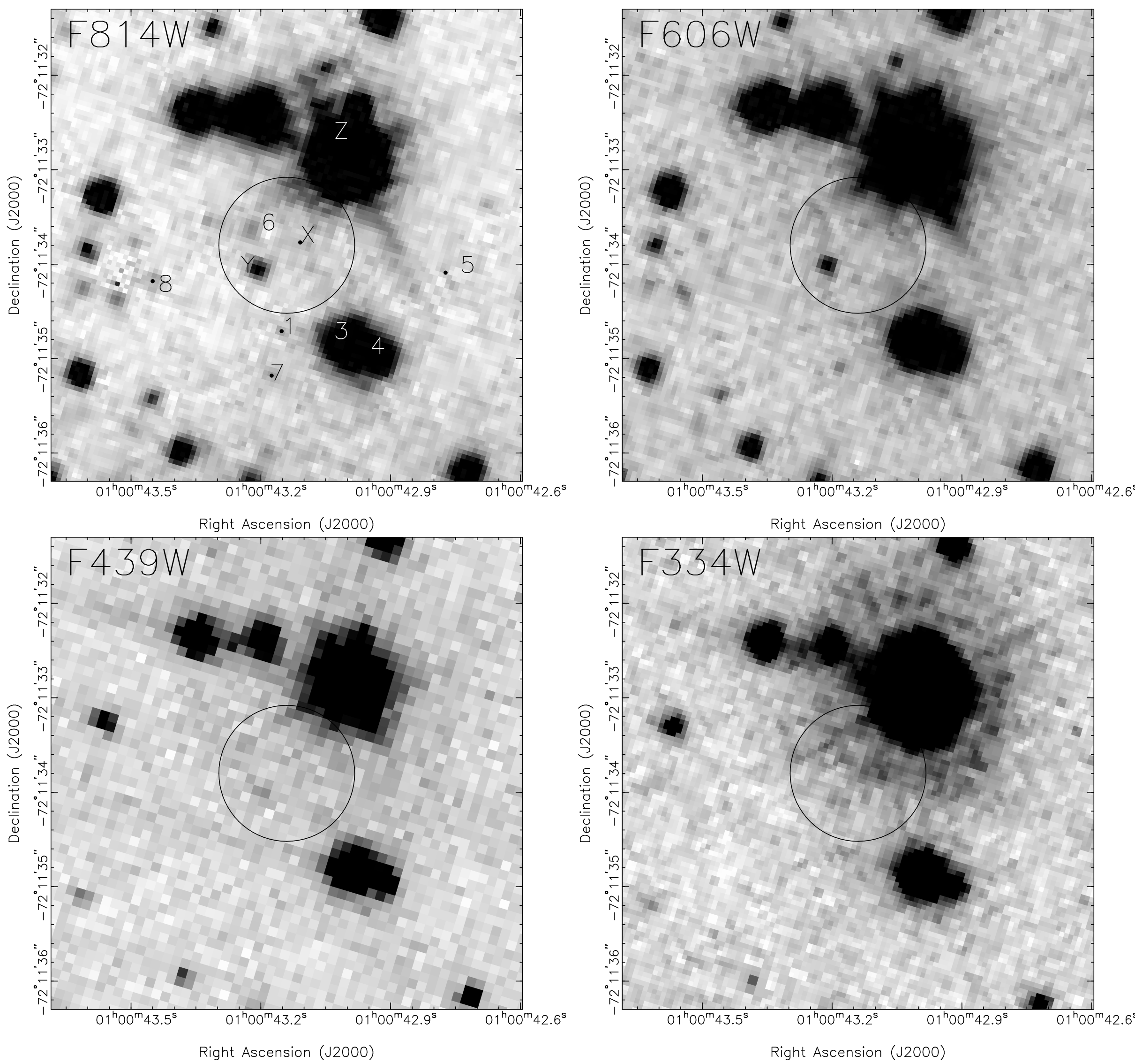

Fig. 1.— Images of the field of CXOU J010043.1−721134 in the F814W, F606W, F439W and F334W filters (left to right, top to bottom). The positional 90% confidence circle based on the *Chandra* detection is shown, and the stars listed in Table 1 are labelled.

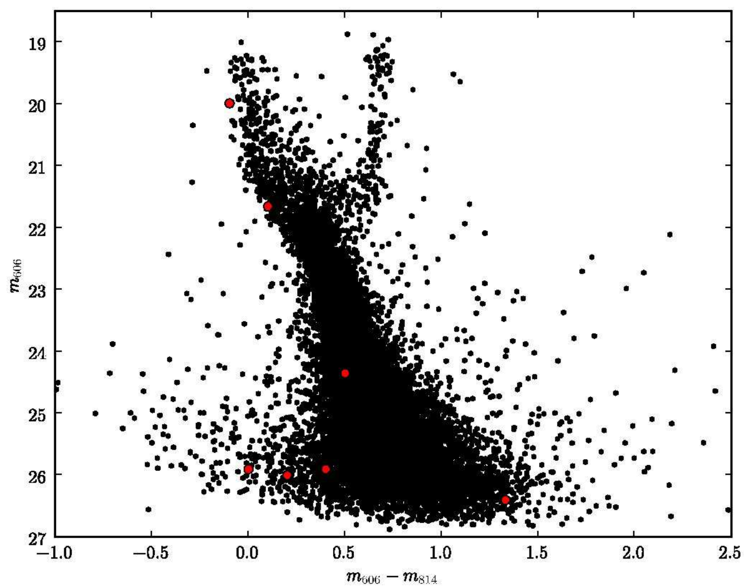

Fig. 2.— Colour-magnitude diagram of stars in the field of CXOU J010043.1−721134, for the filters F606W and F814W. Circular markers represent the few sources near to or in the positional error circle with measured magnitudes.

Table 1. Photometry of field stars

Label	RA	dec	m_{334}	m_{439}	m_{606}	m_{814}
1	1:00:43.152	-72:11:34.71	24.2±0.3	>25.6	26.2±0.3	>25.9
Y	1:00:43.209	-72:11:34.09	24.1±0.3	24.81±0.15	24.35±0.08	23.85±0.06
3	1:00:42.995	-72:11:34.92	19.031±0.005	19.966±0.006	19.986±0.007	20.084±0.005
4	1:00:42.926	-72:11:35.03	21.73±0.03	21.858±0.017	21.653±0.011	21.551±0.012
5	1:00:42.773	-72:11:34.09	>24.2	>25.6	26.4±0.3	>25.9
6	1:00:43.221	-72:11:33.64	>24.2	>25.6	25.9±0.2	25.07±0.14
10	1:00:43.175	-72:11:35.18	>24.2	>25.6	25.9±0.2	25.8±0.3
Z	1:00:43.001	-72:11:32.94	···	17.783±0.002	···	···
12	1:00:43.450	-72:11:34.18	>24.2	>25.6	26.1±0.2	25.9±0.3

Note. — See Figure 1 for the locations of the stars in the field. Uncertainties are formal 1σ errors, limits are 95% confidence. Magnitudes are Flight-System (Dolphin, 2000), some are clearly spurious (see text).