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A search for the IR counterpart of the black hole candidate 4U 1630-47

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Abstract. We present the first attempt to localize the IR counterpart of the recurrent, ultra soft X-ray transient 4U 1630-47. We have obtained two sets of K band images of this highly obscured region, during both outburst and quiescence. The recent radio position reported by Hjellming et al. (1999) allow us to perform accurate astrometry on the field. We discuss three stars which lie near the radio position: although two have colours which appear to be consistent with the reddening towards 4U 1630-47, neither are strongly variable. Deeper IR monitoring, during both outburst and quiescence, is required to reliably identify an IR counterpart.

Key words: stars: binaries: close – stars: individual: 4U 1630-47 – infrared: stars – X-rays: stars

1. Introduction

4U 1630-47 is a highly obscured X-ray transient first discovered by $Uhuru$ (Jones et al. 1976). In contrast to most other X-ray transients, more than a dozen outbursts from this object have been observed so far: by comparison, typical recurrence timescales for other systems are $\sim$10–50 years. Furthermore, the outbursts of 4U 1630-47 appear to occur quasi-periodically, consistent with a $\sim$600 day ephemeris. This ephemeris is not exact, however, and the times of two of the most recent outbursts have been inconsistent with it (Kuulkers et al. 1997b; Kuulkers 1998).

The general X-ray properties of 4U 1630-47 (i.e. the ultra-soft X-ray spectrum in outburst, the non-detection of any X-ray bursts or coherent periodicities) suggest that it may well be a black hole binary (e.g. see the review by van Paradijs & McClintock 1996). However, without an optical (or IR) identification and subsequent radial velocity measurements, such evidence remains circumstantial.

Interest in this system has increased further with the discovery by Kuulkers et al. (1997a) of rapid X-ray variability in 4U 1630-47 akin to that of GRO J1655-40 and GRO J1915+105, the Galactic "superluminal" jet sources. The temporal evolution of several 4U 1630-47 outbursts also resembles the outburst behaviour of these two sources.

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The optical/IR identification of 4U 1630-47 is especially challenging as (a) the high extinction towards this object (A_v $\geq$13) makes an optical identification extremely difficult, and (b) the position until recently was only known to 10$''$ (Parmar et al. 1986). However, Hjellming et al. (1999) locate a radio transient within the X-ray error circle to within 0.3$''$ (1σ: Sood priv. comm.), using data from the Australia Telescope Compact Array (see also Buxton et al. 1998): this detection was simultaneous with an X-ray outburst observed by the X-ray Timing Explorer (XTE). Such a position finally allows accurate optical and IR astrometry to be performed.

Here we present the first attempt to identify this system using K band photometry. We observed 4U 1630-47 in the IR during June 1995, 1996 and 1998. No X-ray outburst was reported during the first and last observation, consistent with the ephemeris of Parmar et al. (1997). Fortuitously, however, our 1996 observations did coincide with the peak of an outburst detected with the All Sky Monitor on board XTE (see Fig. 1). We present these observations in Sect. 2, and in Sects. 3 and 4 discuss the implications of these for the nature of 4U 1630-47.

2. Observations and analysis

4U 1630-47 was observed using the the Cerro Tololo Infrared Imager (CIRIM) on the 1.5-m at CTIO. This is a 256x256 HgCdTe NICMOS 3 array with a variable pixel scale. For the observations presented here the scale used was 0.65 arcseconds per pixel, yielding a field of view of 166 arc seconds. This value was chosen as a compromise between the smaller scale required for optimum image sampling, and the larger scale required for reliable background determination (especially in crowded fields).

A detailed observing log is presented in Table 1. During each observing run, the field of 4U 1630-47 was observed using a series of 9 image grids: the background was derived using the median of these images and subtracted from each frame. Each were then flatfielded, registered and co-added. Both the image reduction and astrometry (see below) were performed using $IRAF$. Seeing during both runs was $\sim 1.5''$: only the 1998 run (and the last 1996 observation) was photometric. These data were calibrated using the UKIRT Faint Standard catalogue (Casali & Hawarden 1992).

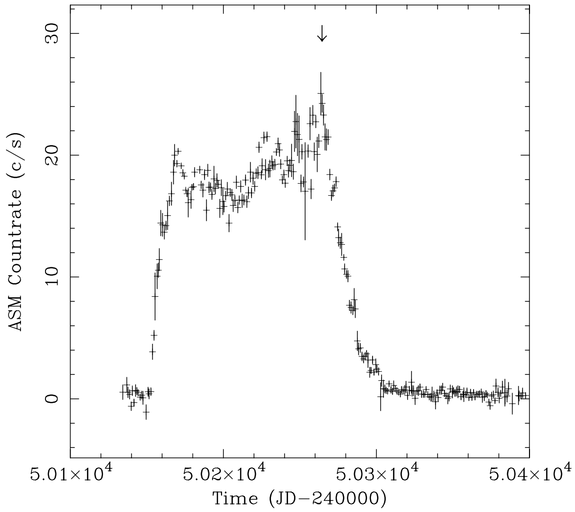

Fig. 1. The XTE ASM light curve of the June 1995 outburst of $4U1630-47$. The epoch of the CTIO observations is arrowed.

Table 1. Observing Log

Date	Filter	Exposure time (s)
1995 June 13.155	K_s	675
1995 June 14.102	K_s	675
1995 June 14.112	J	270
1996 June 30.045	K_s	810
1996 June 30.080	K_s	810
1996 June 30.091	K_s	810
1996 July 02.210	K_s	810
1998 June 01.305	K_s	1080
1998 June 02.267	K_s	1080
1998 June 03.164	K_s	1080
1998 June 01.320	J	1080

Because of the reddening of the field and the relatively small area of the CIRIM detector, some care was required in locating the radio position of 4U 1630-47 on the IR image: we proceeded as follows. First, an I-band image of the field was kindly obtained for us by Stefan Collier using the CCD imager on the 1-m telescope at the South African Astronomical Observatory during 1998 April 25 (see Fig. 2). Six stars from the USNO-A2.0 star catalogue (Monet et al. 1998) were identified in this image and our J and K$_s$ (2.0–2.3μm) band images. The centroids of these stars on the I-band and K$_s$ band images were then estimated, and the relationship between pixel and celestial coordinates determined. The rms of the fit to these positions in our K$_s$ band image was $0.4''$, comparable to the error in the radio position.

3. Results

3.1. Variability

The radio position, superimposed on our K$_s$ band image, is plotted in Fig. 3: the radius of this error circle is a 2σ error incorporating both our astrometric error (from the rms above) and the radio error, added in quadrature. Three stars lie near the boundary of this error circle. To study these we first summed the data, creating an "on-state" (1996) and "off-state" (1995 and 1998) image, and then used DAOPHOT (Stetson 1987) to measure the magnitudes of these stars relative to star A (marked on Fig. 3). We show the results of this photometry in Table 2. We did not detect star 2 in the J band, to a limiting magnitude of ∼18. A significant contribution to measurement error for the fainter stars arises from the large plate scale and crowded nature of the field. In uncrowded regions, the images reach a limiting magnitude of K$_s$ ∼17.5. No significant variability was observed between these two datasets. The very marginal evidence for

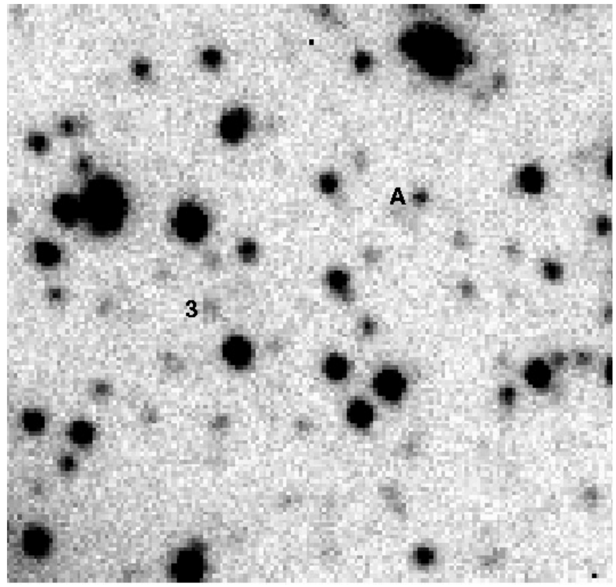

Fig. 2. The SAAO I-band image of the $4U\ 1630-47$ field. North is up and East to the left: the field of view is $\sim1' \times 1'$.

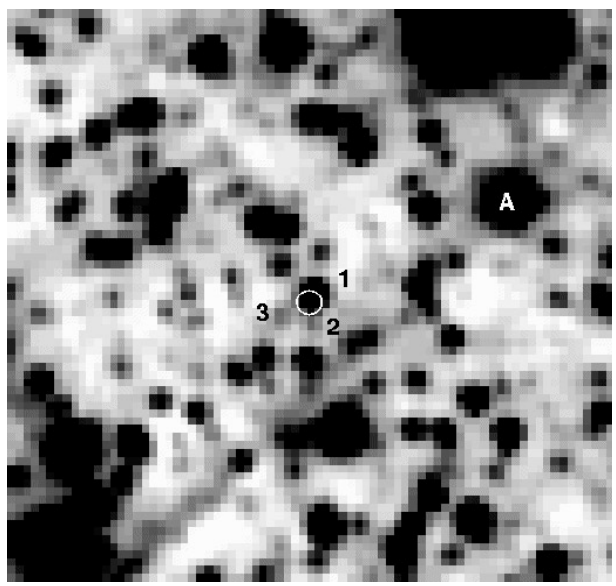

Fig. 3. The CTIO K$_s$ band image of the field in Fig. 2.

variability for star 2 could easily be due to systematic errors arising from its proximity to star 1. Note that the "off-state" data are somewhat deeper, and should be the more reliable. Finally, we cannot exclude the possibility that some of these stars are themselves blends of unresolved stars, at the $< 1''$ level.

3.2. Colours

We now consider the interstellar reddening towards 4U 1630-47. HI radio surveys in this direction (Dickey & Lockman 1990) yield a hydrogen column (N_H) of 2.1×10^{22} cm^{-2}, implying E_{B-V} =4.2 (assuming N_H/E_{B-V} $=5\times10^{21}$ cm^{-2} mag^{-1}; Savage & Mathis 1979). X-ray measurements of the column towards 4U 1630-47 are typically higher than this: the best (i.e. lowest reduced χ^2) *Ginga* and *ASCA* fits to the outburst spectra yield values for N_H between 6.4 and 9.5 $\times10^{22}$ cm^{-2} (Parmar et al. 1997), corresponding to 13$<$ E_{B-V} $<$19. For the discussion that follows we take $E_{B-V} = 4.2$, bearing in mind that the X-ray spectra indicate that it could be substantially higher. Using this value, we show in Table 2 the dereddened colours of the stars near the radio position, taking E_{J-K} =2.3, (from the interstellar extinction laws derived by He et al. 1995). Now, the J-K colours for the "bluest" stars to be found in the tabulation of Johnson (1966) are never less than –0.2. Hence it is clear that only stars 1 and 2 have colours that may be compatible with the interstellar reddening towards 4U 1630-47. The nature of star 2 in particular is poorly constrained: for example, a late B/early A V star at 10 kpc would be consistent with both the observed (dereddened) magnitude and colour limit. In what follows, however, we discuss stars 1 and 2 in the context of the IR properties of X-ray binaries.

4. Discussion

4.1. Could 4U 1630-47 be a Low Mass X-ray Binary?

The subset of Low Mass X-ray Binary most closely resembling 4U 1630-47 is probably the Soft X-ray Transients/X-ray Novae. If so, how much IR variability might we expect to see from such a system? Unfortunately, for an X-ray heated disk with T_{eff} =25,000 K, some ∼30 times less flux is generated in the K band than in the V: hence the IR response of such a system to X-ray heating is considerably less dramatic than that at optical wavelengths. To be more specific, we consider two possibilities:

4.1.1. 4U 1630-47 as a short period X-ray transient

The quiescent K band counterpart of A0620-00 (P_{orb} = 7.8 hr) has a magnitude of ∼14.5 (Shahbaz et al. 1994a) at a distance of ∼1 kpc: at a distance of 10 kpc and A_K =1.2 it would be well below our limit of sensitivity. Hence, neither star 1 nor star 2 in the "off-state" image can be the quiescent counterpart to this type of system.

The V band outburst amplitude for A0620-00 ∼7 (e.g. van Paradijs & McClintock 1996). For the K band, we use the outburst measurement of Kleinmann et al. (1976: K= 10.2), and the quiescent measurements of Shahbaz et al. (1994a). These yield an amplitude reduction between the two bands of ∼3 magnitudes, comparable to that discussed in the foregoing section.

Table 2. 4U 1630-47 Photometry

Star	on-state K_s	off-state K_s	off-state J	dereddened J-K (mean)
1	13.64±0.05	13.65±0.05	16.1±0.1	0.2
2	16.5±0.2	16.9±0.2	$\geq$ 18	$\geq$–1
3	16.8±0.2	16.7±0.2	17.6±0.15	–1.5
A	10.90±0.05		13.85±0.05	

Despite the reduced amplitude of variability of the IR counterpart, it should still be relatively bright (in outburst). The absolute K magnitude of Sco X-1 (P_{orb} = 18.9 hr) is ∼ –0.5, using the average K magnitude of Hertz & Grindlay (1984), and a distance of 2.8± 0.3 kpc (Bradshaw et al. 1999: this is the most accurate distance known towards any non- globular cluster/extragalactic LMXB). This yields K∼15.7 for a distance of 10 kpc: for an Eddington limited X-ray luminosity from a black hole primary, we would expect an even brighter K band magnitude. Such a counterpart would have been clearly observed in our "on-state" data set, even if spatially unresolved from star 1 and/or 2: hence, in this scenario 4U 1630-47 must be $>$ 10 kpc away and/or A_K ≫1.2 (i.e. column towards the system is considerably in excess of that implied by the radio measurements: see Sect. 3.2).

4.1.2. 4U 1630-47 as a long period X-ray transient

Here we compare 4U 1630-47 with the IR properties of V404 Cyg (P_{orb} = 155.4 hr). The quiescent counterpart of this system has a K-band magnitude of 12.4, with a significant $A_v \sim 3$, and a distance of ∼3.5 kpc (Shahbaz et al. 1994b; Wagner et al. 1994). For the parameters assumed for 4U 1630-47, this yields K∼15.6: hence, if $A_K \sim 2$, such a counterpart would be compatible with star 2. However, the outburst magnitude of V404 Cyg (K= 9.4: Gehrz et al. 1989), then yields K∼13.4 for 4U 1630-47 (with $A_K = 2$), which would also have been clearly observable. Hence we can exclude this type of system also, subject to the caveats of the last section.

4.2. 4U 1630-47 as a High Mass X-ray Binary

Although the initial discovery of a 600 day periodicity in the outburst cycle of 4U 1630-47 hinted at a binary origin, the apparent change in this periodicity (Kuulkers et al. 1997b) now appears to argue against this scenario. Nonetheless, a high mass companion in this binary cannot as yet be ruled out. Indeed, for a distance of 10 kpc and $E_{B-V} = 4.2$, the absolute magnitude and colours for star 1 are consistent with those of a Be star (Zorec & Briot 1991; Dougherty et al. 1994). The lack of any significant variability between outburst and quiescence for star 1 may not be inconsistent with this model: whereas some Be systems show ∼1 mag K band variability during outburst (e.g. 4U 0115+63: Negueruela et al. 1997), EXO 2040+375 shows little (typically $\leq$ 0.1 magnitudes: Norton et al. 1994).

5. Conclusions

Despite our serendipitous observations of 4U 1630-47 in both an "on" and "off" state, and the location of 2 possible IR candidates near the position of the radio transient, we have not yet found a convincing IR counterpart to this unusual X-ray binary. Deeper IR monitoring, during both outburst and quiescence, is required to reliably identify an IR counterpart.

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