The optical/IR counterpart to the newly-discovered X-ray source EXO 2030+375

M. J. Coe,1 A. Longmore,2 B. J. Payne1 and C. G. Hanson1,3

1Physics Department, The University, Southampton SO9 5NH
2Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ
3Max-Planck-Institut für Extraterrestrische Physik, 8046 Garching bei München, Federal Republic of Germany

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Summary. Near-infrared ($JHK$) photometry and 5000–7000 Å optical spectrometry have been obtained of possible counterparts of the newly discovered X-ray source, EXO 2030+375. A study of the EXOSAT error circle has revealed two possible candidates. Using the combined optical-to-IR data the most probable counterpart has been identified from the shape of the spectrum, and from the $L_X/L_{\text{opt}}$ ratio. The system bears certain similarities to V0332+53.

1 Introduction

In 1985 May, the bright transient X-ray pulsar EXO 2030+375 was discovered by EXOSAT (Parmar et al. 1985). Over the 3-month period 1985 May 19–August 25, the X-ray flux was seen to decrease steadily from an initial level of $\sim 1.5 \times 10^{-11}$ W m$^{-2}$ (700 mCrab), until it became undetectable at $< 2 \times 10^{-14}$ W m$^{-2}$ (1 mCrab). Analysis of the $\sim 42$ s pulse period revealed Doppler variations which constrain the orbital period to the range 25–45 days. This is an amendment by Parmar et al. (in preparation) to the earlier report of a 37.9-day period of White et al. (1985). Parmar et al. also report another outburst from this source in 1985 November.

An optical search of the preliminary EXOSAT error circle of radius 15 arcsec (Parmar et al. 1985) uncovered four stellar-type sources of magnitude $V = 18.5–21.5$ (Robin et al. 1985). Of these, the brightest and bluest was suggested by these authors as the most probable counterpart. Recently, however, Motch & Janot-Pacheco (1987) have reported these data in more detail and no longer favour this object to be the counterpart. Subsequently the EXOSAT error circle was reduced in size and moved approximately 15 arcsec north-east (Parmar et al., in preparation). The revised error circle now excludes all but one of the observed optical candidates; the one preferred by Robin et al. lies outside this circle.

IR and optical observations of the candidate inside the new error circle and the candidate of
Robin et al. have been obtained. The comparison of the spectra of these candidates with those of V0332+53 and other similar hard X-ray transients allows the most probable counterpart to be identified.

2 Observations

2.1 Infrared Photometry

Five sets of IR observations have been obtained from the 3.8-m United Kingdom Infrared Telescope (UKIRT) over a 2-yr period. The first was on the night of 1985 July 23, when the X-ray flux had dropped to ~5 per cent of its initial value. An exploratory raster-scan of a 30×30 arcsec region which included the revised EXOSAT error circle was carried out. Only two significant sources were found and these corresponded to the two brightest objects reported by Robin et al. (1985). Several further observations through JHKL' filters over the next 2 yr show no significant change in the luminosity of either candidate (see Table 1). The positions of these stars, together with the revised error circle, are shown in Plate 1, which are red (E) and IR prints taken from the Palomar Sky Survey. The object labelled 1 is the candidate favoured by Robin et al. and the object labelled 2 is the one now suggested by Motch & Janot-Pacheco (1987).

In addition to the IR photometry, a search for regular pulsations of the IR flux at or close to the 41.38 s pulse period was carried out, in the hope of distinguishing between the two main candidates. Data were collected with 1 s integrations in runs of 2048 samples, and a period search over the full range of 2–2000 s was performed. The search proved negative, and a conservative upper limit of 0.5 per cent modulation may be set based on a previous calibration of the technique as described in Coe et al. (1987).

2.2 Optical Observations

The region containing the two candidates was observed with the Isaac Newton Telescope on 1986 September 7 using the IPCS with the Intermediate Dispersion Spectrograph. A 2200-s exposure produced well-exposed spectra of Candidates 1 and 2 and a very weak spectrum of a third object lying between these two candidates. This third object is visible in Plate 1 lying almost 15 arcsec due south of Candidate 2. All three spectra were spatially separated on the image, but little more can be said about the third object because of the weak exposure. The spectra of the two main candidates are shown in Fig. 1. It is immediately apparent that Candidate 1 exhibits a normal reddened stellar spectrum while Candidate 2 is distinguished by strong Hα emission and a very

<table>
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Table 1. Journal of the IR observations carried out from UKIRT of the two most probable candidates for the X-ray source EXO 2030+375. The errors on the measurements are all 0.03 except where stated otherwise.
Plate 1. The field of EXO 2030+375. (a) Red (E) print and (b) corresponding IR print taken from the Palomar Survey showing the two major optical candidates discussed in the text. The X-ray error circle comes from Parmar et al. (in preparation). The large reddening towards Candidate 2 is evident by comparing the two photographs. Copyright by the National Geographic Society – Palomar Observatory Sky Survey. Reproduced by permission from the Hale Observatories.

[facing page 866]
redden spectrum. The H\alpha profile has an equivalent width of 15±1 Å and a FWHM corresponding to 640 km s\(^{-1}\). This value for the equivalent width is similar to that observed in V0332+53 while in its active state (see Coe et al. 1987 and references therein). Because no blocking filter was used during the observations of the reference stars, second-order contamination of the spectra of these objects at the red end of the spectra prevents us from absolutely flux-calibrating our candidates’ spectra. Around 5500 Å however, there is no such contamination and our estimates of the V-band fluxes agree with those of Motch & Janot-Pacheco (1987).

2.3 SPECTRAL MODELLING AND INTERSTELLAR REDDENING

From the X-ray properties of this system, Parmar et al. (in preparation) predict that we are dealing with an eccentric binary system consisting of a Be star and a neutron star similar to the V0332+53 system. On this assumption we can examine our prime target, Candidate 2, to see how well it agrees with such a model. Using the optical photometry of Motch & Janot-Pacheco (1987)
we can estimate the reddening to Candidate 2. From their data we can determine that the observed colour index, $B-V=3.34$, if combined with the expected colours of a B0 star, produces an $E(B-V)=3.74$. The justification for the assumption that an early B-type star is associated with this X-ray source is described in detail in Section 3. Taking this value for the reddening and applying appropriate corrections to all the available photometric data using the extinction curve of Rieke & Lebofsky (1985) gives the results presented in Table 2. Also given in Table 2 are the expected magnitudes of a B0 star from Johnson (1966). It is immediately apparent that there exists an infrared excess over and above the normal colours of a B0 star. This result is also illustrated in Fig. 2 where we have plotted the dereddened photometric magnitudes against the expected model atmosphere of a B0 type star. The model atmosphere used is from Kurucz (1979) and corresponds to a temperature of 25 000 K and log $g=4.0$.

We can also examine the colours of Candidate 1. From the optical colours of this candidate Motch & Janot-Pacheco deduce that it is a A2–A4 main-sequence star with a corresponding value for $E(B-V)=1.6$. Applying this to the combined optical–IR photometric data and fitting a Kurucz model atmosphere with $T=10 000$ K and log $g=4.0$ results in a good fit thereby confirming the stellar classification. There is no evidence of any IR excess in this candidate.

Finally, we can check our value for the reddening of Candidate 2 by comparing it with the X-ray absorption. Parmar et al. (1985) quote a value for the X-ray column density of $2.5\times10^{22}$ hydrogen

![Figure 2](https://example.com/figure2.png)

**Figure 2.** A Kurucz model atmosphere of temperature 25 000 K and log $g=4.0$ compared to the dereddened photometric data from this paper and from Motch & Janot-Pacheco (1987).
atom cm$^{-2}$. Using the relationship of Ryter, Cesarsky & Audouze (1975) and the above $E(B-V)=3.7$ predicts that the X-ray column density should be $(2.5\pm0.6)\times10^{22}$ cm$^{-2}$. This agreement is surprising in view of the fact that the neutron star is expected to be heavily shrouded in material accreting from the Be star companion which fuels the X-ray emission. From this we must conclude that there is very little intrinsic extinction.

3 Discussion

The optical/IR and X-ray data offer two lines of approach for the identification of the most probable optical counterpart to EXO 2030+375. The fact that Candidate 2 is the only star within the revised EXOSAT error circle is alone compelling evidence for its selection. But the X-ray observations provide further clues as to the nature of the companion star. There is no doubt that the EXO 2030+375 system belongs to the class of massive X-ray transients such as 4U1145−619, A0535+26, A1118−616 and V0332+53 (Bradt & McClintock 1983; Coe et al. 1987). These are all examples of X-ray sources with Be star companions: in these, the irregular transient behaviour is a consequence of the tendency of Be stars towards unstable mass loss. Taking $1.4\,M_\odot$ as the mass of the neutron star, the mass function $f(M)=5\,M_\odot$ (White et al. 1985) implies $M=8\,M_\odot$ for the stellar companion. This is consistent with the idea that the companion is a Be star, rather than an OB supergiant for which $M\gtrsim 15\,M_\odot$. Furthermore, it has been shown that the orbital periods of the Be/X-ray binaries are all $>15$ days, whereas the massive OB/X-ray binaries have periods in the range 1.4–9 days (Rappaport & van den Heuvel 1982). The orbital period of EXO 2030+375 deduced from the X-ray measurements of Parmar et al. (in preparation) is 25–45 days. Thus, taken together, the weight of circumstantial evidence seems conclusively in favour of an emission-line companion star.

The ratio of the X-ray-to-optical luminosity has also been shown to be a useful parameter for distinguishing between the high- and low-mass binary systems (e.g. Bradt & McClintock 1983). For massive systems, the ratio is typically 0.001–10, whereas for the low-mass systems it is in the range 100–10 000. For Candidate 2, even with EXO 2030+375 at X-ray maximum, $L_X$ (2–10 keV) over $L_{\text{opt}}$ (4000–8000 Å) is 2.8. Candidate 1 is again ruled out because the ratio would be 221. Therefore only Candidate 2 is consistent with the predicted high-mass system of White et al. (1985). From the results presented in Coe et al. (1987) for V0332+53 this may be determined to be 1.1 for this system. This further confirms the similarity of the V0332+53 and EXO 2030+375 systems.

The spectral features characteristic of Be stars are an IR excess over the normal photospheric continuum, and strong H$\alpha$ and H$\beta$ line emission (Underhill & Doazan 1982). Both these features originate in a large circumstellar disc which is formed because of the high rotational velocity of the star. The IR component arises through free–free transitions in the ionized plasma of the disc. As has been shown in Section 2.3, of the two main candidates only Candidate 2 shows evidence for an infrared excess, as well as strong H$\alpha$ emission. The corroboration of the optical/IR properties of Candidate 2 with the features predicted from the X-ray data may thus be taken as final confirmation of the proposed candidate.

It is of interest to address the question as to whether the presence of the X-ray binary system actually distorts the observed properties of the Be star and its circumstellar envelope. We can compare our observations (and those of other such binary systems reported in the literature) with the behaviour of isolated Be stars. If we take the data of Ashok et al. (1984), Dachs & Wamsteker (1982) and Dachs et al. (1981) we can construct a similar diagram to that produced by these authors relating the equivalent width of H$\gamma$ to an IR colour index. This IR colour index, taken here as $J$–$K$, represents a direct measure of the excess flux in these objects. All the data taken from these authors are presented in Fig. 3 together with similar data from EXO 2030+375 (this
Figure 3. Comparison of the IR colours and Hα equivalent widths of Be stars in X-ray binary systems (○) with isolated Be stars (*). See text for references.

paper), V0332+53 (Coe et al. 1987), Gamma Cas (Slettebak 1978), A0535+26 (Wade & Oke 1977; Janot-Pacheco, Motch & Mouchet 1987) and GT 0236+61 (D’Amico et al. 1987), Gregory et al. 1979). As can be seen from this figure there is a suggestion that the IR excess is larger in these systems, but this is largely dominated by the colour index of A0535+26. If we ignore this object then one can deduce that there is, at the most, little difference between isolated Be stars and those in X-ray binaries. Since the observations in the case of V0332+53 also include the source in an active X-ray state, then we must conclude that there can be little contribution to the IR and Hα emission from any accretion disc around the neutron star.

Finally, the lack of IR pulsations fails to support the model of Gneden, Khozov & Larionov (1981), in which masering on the neutron star polar caps is predicted to result in a modulation of the IR signal.

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References

Counterpart to EXO 2030+375