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The Be/X-ray transient KS 1947+300*

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Abstract. We present optical spectroscopy and optical and infrared photometry of the counterpart to the transient X-ray source KS 1947+300. The counterpart is shown to be a moderately reddened $V = 14.2$ early-type Be star located in an area of low interstellar absorption slightly above the Galactic plane. Changes in brightness are accompanied by correlated reddening of the source, as is expected in this kind of object. From intermediate resolution spectroscopy, we derive a spectral type B0Ve. If the intrinsic luminosity of the star is normal for its spectral type, KS 1947+300 is situated at a distance of ~10 kpc, implying that its X-ray luminosity at the peak of the spring 2000 X-ray outburst was typical of Type II outbursts in Be/X-ray transients. KS 1947+300 is thus the first Be/X-ray recurrent transient showing Type II outbursts which has an almost circular orbit.

Key words. stars: emission line, Be – stars: individual: KS 1947+300 – stars: binaries: close – stars: neutron – X-ray: stars

1. Introduction

The transient hard X-ray source KS 1947+300 was discovered on 8th June 1989 by the TTM coded-mask X-ray spectrometer aboard the *Kvant* module of the *Mir* orbiting space station (Borozdin et al. 1990). The source was detected at a flux of 70 ± 10 mCrab in the 2−27 keV range. Its spectrum could be approximated by a power law with $\alpha = -1.72 \pm 0.31$ absorbed by a hydrogen column density $N_{\rm H} = (3.4 \pm 3.0) \times 10^{22}$ cm^{-2} (Borozdin et al. 1990). The source was detected in three further pointings of the area during June and July 1989, but was not detected in August, when the 3-σ upper limit on the flux was equivalent to 1/7th of the flux observed in June (Borozdin et al. 1990).

The 30″ error circle contains only two bright stars, which were observed by Grankin et al. (1991, henceforth GSY). The brightest object was reported to have the colours of a reddened distant early-type star. Independently, Goranski et al. (1991, henceforth GELS) searched a larger circle ($r = 1'$) around the position of the X-ray source. They also concluded that the same star (their Star 2) was the likely optical counterpart. A spectrum of this object showed evidence for Hα emission above the night-sky level (GELS).

The transient X-ray pulsar GRO J1948+32 was detected by the BATSE detectors on board the *ComptonGRO* satellite on 6th April 1994 (Chakrabarty et al. 1995). The source displayed pulsations at 18.7 s and a hard spectrum extending up to 75 keV. It was detected during 33 days reaching a maximum flux of ~50 mCrab in the 20−75 keV range. Chakrabarty et al. (1995) observed modulation of the neutron star's pulse frequency suggestive of orbital variation. The very large error box of GRO J1948+32 (which included the TTM error circle for KS 1947+300) rendered the search for an optical counterpart unfeasible, but the overall X-ray behaviour was reminiscent of a Be/X-ray binary.

A new outburst of KS 1947+300 was detected by the All Sky Monitor (ASM) on board the *RossiXTE* satellite starting around 23rd October 2000 (Levine & Corbet 2000). Further *RossiXTE* observations revealed pulsations at $P_{\rm s} = 18.76$ s (Swank & Morgan 2000), making the identity of KS 1947+300 and GRO J1948+32 virtually certain. The outburst finished in late November 2000, but it was shortly followed by a much larger one. Analysis of PCA/*RXTE* pointed observations taken during this phase of activity has resulted in the derivation of an orbital solution with $P_{\rm orb} = 40.43$ d and $e < 0.04$ (Galloway et al. 2002).

In this paper we report on optical and infrared observations of the proposed counterpart taken during and after the

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* Partly based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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Table 1. Photometric values for the optical counterpart to KS 1947+300 derived from our observations. Uncertainties depend fundamentally on the calibration of the zero points and are upper limits.

Date	U	B	V	R	I
29/05/01	14.98 ± 0.05	15.17 ± 0.05	14.24 ± 0.08	13.53 ± 0.10	12.89 ± 0.05
03/07/01	14.76 ± 0.08	15.06 ± 0.05	14.16 ± 0.03	13.50 ± 0.02	12.77 ± 0.04

outbursts. Our observations confirm the optical counterpart and identify the system as a Be/X-ray transient.

2. Observations

2.1. Optical photometry

Observations of the field were taken in service mode on the night of 29th May 2001 using the 1.0-m Jakobus Kapteyn Telescope (JKT) in La Palma, Spain. We obtained images through *UBVRI* filters with the JAG-CCD imaging instrument equipped with a 2148×2148 SITe2 CCD. As well as individual frames covering the field of KS 1947+300, we also observed three Landolt standard fields, containing a total of nine standard stars (Landolt 1992), at a range of airmasses. Bias subtraction and flat fielding were carried out on all frames using *Starlink* CCDPACK software (Draper et al. 2000). Then, using the *Starlink* GAIA software (Draper & Gray 2000), aperture photometry was performed on all frames with background subtraction from annular sky regions around each star.

Instrumental minus catalogue magnitudes were calculated for each of the Landolt standard stars and linear fits were performed against airmass. The resulting extinction coefficient and zero point corrections were applied to the target star, resulting in the magnitudes shown in Table 1. Because the target frames were observed near the zenith, uncertainties in the extinction coefficients have negligible effect, and the uncertainties shown in the table are essentially due to zero point uncertainties only.

Observations of the field were also taken on the night of July 3rd 2001 using the 2.6-m Nordic Optical Telescope (NOT) in La Palma, Spain. We obtained images through *UBVRI* Bessel filters with the Andalucia Faint Object Spectrograph and Camera (ALFOSC), equipped with a thinned 2048×2048 pixel Loral/Lesser CCD, covering a field of view of 6.′4 × 6.′4.

As well as individual frames covering the field of KS 1947+300, we also observed three Landolt standard fields, each containing four standard stars (Landolt 1992), at a range of airmasses. Photometric reduction was carried out following an identical procedure to that described above for the JKT data. Similar comments regarding the zero point uncertainties apply.

2.2. Infrared photometry

The field of KS 1947+300 was observed in the J, H and K filters (all with 60-s exposures) on 6th December 2000 from the 1.1-m AZT–24 telescope at Campo Imperatore (Italy) equipped with the Supernova Watchdogging IR Camera (SWIRCAM), which has a 4.′4 × 4.′4 field of view and 1.″04/pixel spatial resolution). 10″ dithered images were taken in the three filters. Data analysis procedures similar to those described above were applied. A photometric standard was also observed (SAO 48300; 10 s in each filter) and used to derive absolute magnitudes. Within the X-ray positional uncertainty circle, we detected only one bright (H = 11.4) IR object, corresponding to the proposed optical counterpart to KS 1947+300, which is thus the only reddened star in the field. Its magnitudes are listed in Table 2.

Table 2. Infrared photometric values for the optical counterpart to KS 1947+300 derived from our observations at Campo Imperatore.

J	H	K
11.67 ± 0.15	11.43 ± 0.12	11.21 ± 0.12

2.3. Spectroscopy

We obtained a low resolution spectrum of the optical counterpart on December 1 2000, using the 1.82-m telescope operated by the Osservatorio Astronomico di Padova atop of Mount Ekar, Asiago (Italy). The telescope was equipped with the Asiago Faint Object Spectrograph and Camera (AFOSC) and the SiTE thinned CCD. We used grism #4 which gives a resolution of ≈8.3 Å over the $\lambda\lambda$ 3500–7500 Å range. Details of this spectrum were reported in Negueruela et al. (2000).

A second spectrum (displayed in Fig. 1) was obtained on February 8 2001 using the 2.5-m Isaac Newton Telescope (INT), located at the Observatorio del Roque de los Muchachos, La Palma, Spain. The telescope was equipped with the Intermediate Dispersion Spectrograph (IDS) with the 235-mm camera. The choice of the R400V grating and thinned EEV#10 CCD results in a nominal dispersion of ∼1.4 Å/pixel. Measurements of arc line widths indicate a spectral resolution of ≈5 Å (*FWHM*) at λ5500 Å.

Further spectra were obtained on June 19–22, 2001, using the 1.52-m G. D. Cassini telescope at the Loiano Observatory (Italy). The telescope was equipped with the Bologna Faint Object Spectrograph and Camera (BFOSC) and the new EEV camera. Several grisms were used, giving different coverages and resolutions. A detail of the higher resolution spectrum is shown in Fig. 1.

Finally spectra were obtained on the nights of July 2 2001 and December 5–8 2001 using ALFOSC on the NOT, equipped with grism #7. On the nights of July 2 and December 5, we used a 1.″8 slit width, while on December 6 and 7 the slit width was 1.″0. The resolutions achieved with these configurations are 10.6 Å and 6.6 Å respectively. Spectra taken with the 1.″0 slit have been normalised and summed and their blue end is displayed in Fig. 4.

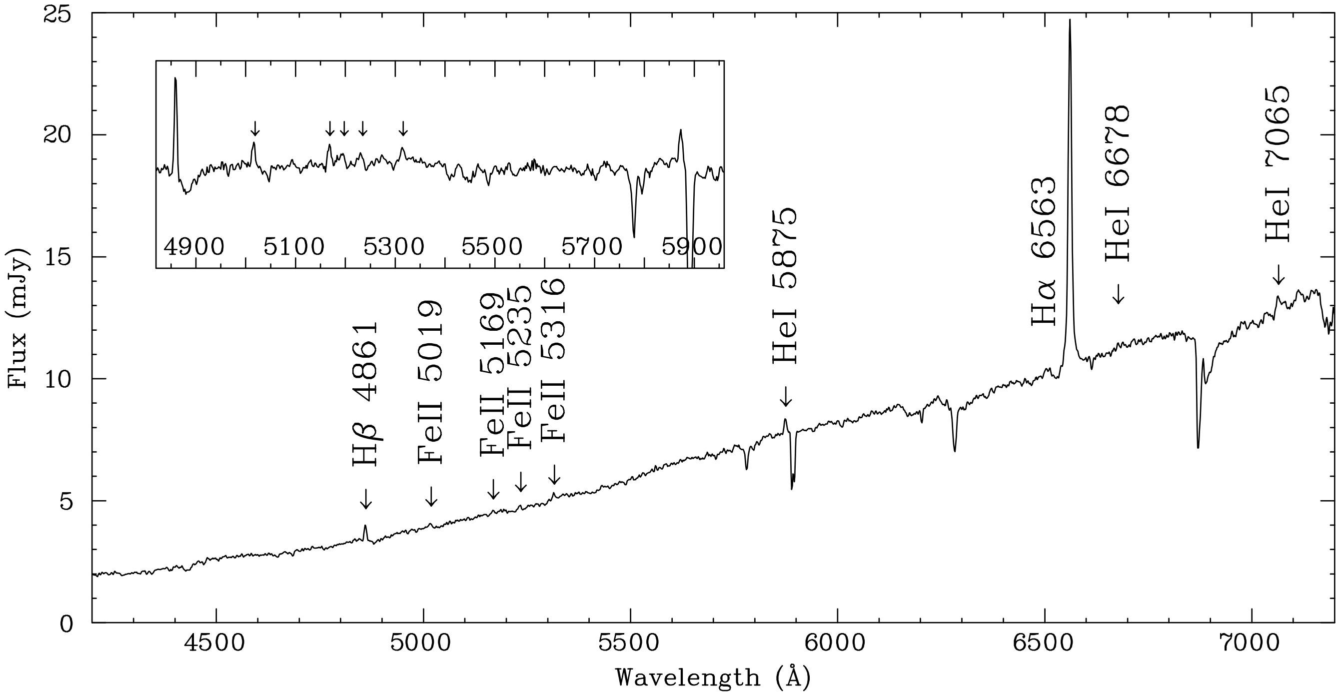

Fig. 1. Flux-calibrated low-resolution spectrum of the optical counterpart to KS 1947+300, obtained on February 8, 2001, using the INT+IDS. The calibration is not absolute due to slit losses. The inset shows in detail the emission lines in the yellow region, from a spectrum taken from Loiano on June 22, 2001, using BFOSC + grism #7. The positions of the Fe II blends at $\lambda\lambda$ 5019, 5169, 5198, 5235 & 5316 Å are indicated by arrows.

All the spectroscopic data were reduced with the *Starlink* packages CCDPACK and FIGARO (Shortridge et al. 1997) and analysed using FIGARO and DIPSO (Howarth et al. 1997).

3. Results

3.1. Previous photometric work

GSY and GELS independently observed the error box of KS 1947+300 and report several measurements of the optical counterpart. GELS obtained *UBV* photometry of the source. They give 13 data-points covering a span of 15 days starting in September 15 1990, followed by a single data-point 18 days later. GSY give 14 sets of *UBVR* data-points. Of these, the first eight cover a span of 38 days starting on October 16 1990, while the last six cover 11 days separated from the first set by a 200-d gap (i.e., in June 1991). The last point in the dataset of GELS overlaps in time with GSY's first run. The values measured by the two teams on JD 2 448 182 are compatible within the errors quoted, showing that their photometric systems are not very different.

Both sets of authors indicate that the dispersion in their measurements is compatible with observational errors, while GELS explicitly mention that they do not observe any clear correlation between the *B* and *V* bands. Close inspection of the datasets, however, shows that both sets of authors clearly underestimated the accuracy of their measurements. As can be seen in Fig. 2, measurements clearly display a very good correlation between V and $(B-V)$. GSY do not quote any errors for their photometry, but the dispersion of data-points in Fig. 2 shows that they are unlikely to be any larger than the errors in GELS's photometry. A simple linear fit to all the data-points from both papers (without consideration of errors) gives a Spearson correlation coefficient $R = 0.64$, clearly suggesting that there is an underlying correlation.

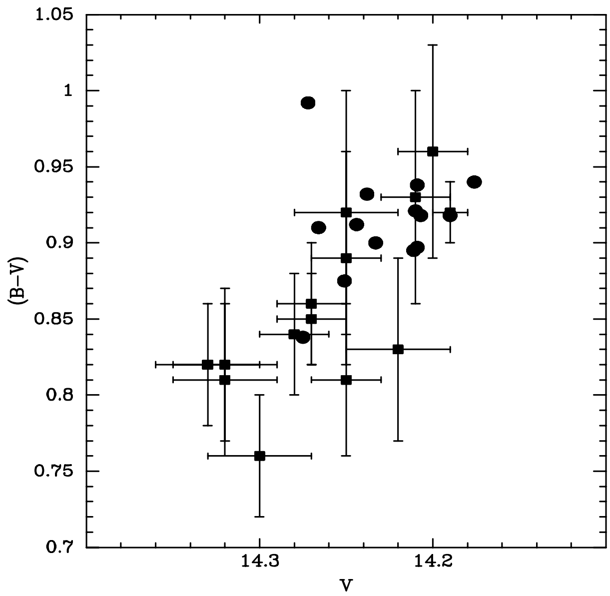

Fig. 2. A colour/magnitude plot of the photometric data presented by GELS and GSY. The data from GELS are shown as filled squares with their associated errors. The data from GSY, who do not quote errors, are shown as filled circles. A tight correlation between the *V* magnitude and the associated reddening is obvious to the eye.

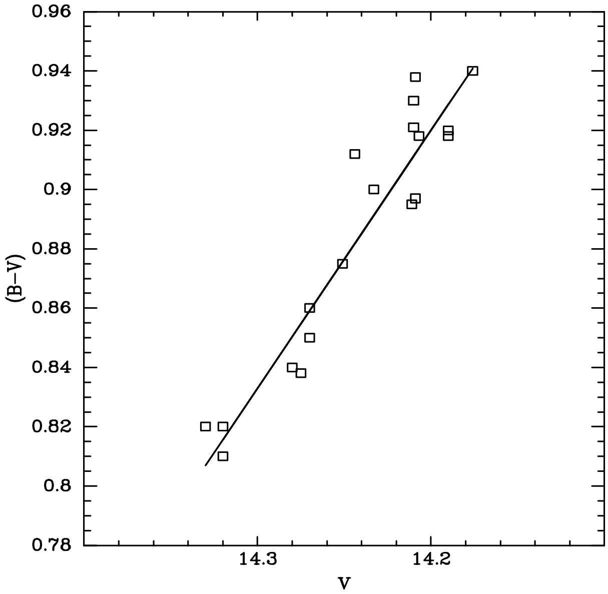

Fig. 3. Colour/magnitude plot of the combined photometric datasets of GELS and GSY. The best linear fit, corresponding to Eq. (1), is given as a straight line. The Spearson correlation coefficient for the fit is $R = 0.95$, indicating that there is a very tight correlation between V and $(B - V)$.

Even though the errors of some measurements are relatively large, none of the values deviates strongly from the general trend. As a consequence, it was thought appropriate to improve the quality of the fit by following an iterative procedure: a linear fit to all the points was obtained, the data-point that deviated most strongly from the fit was removed and the remaining points were fitted, repeating until no further improvement in the correlation coefficient was obtained. Only a few points had to be removed before the correlation coefficient was considerably improved. For example, removal of a single deviating point seen at the top of Fig. 2 improved the correlation coefficient from $R = 0.64$ to $R = 0.77$. Figure 3 shows the final linear fit to 19 data-points (taken approximately evenly from both sets). The goodness of the fit is indicated by a Spearson correlation coefficient $R = 0.95$. Interestingly, the best fit line, given by

$$(B - V) = 13.3 - 0.87V \tag{1}$$

is identical in slant and zero point to the original fit to the complete dataset, clearly showing that our selective analysis has not deleted any information contained in the plot. Such a result suggests that any dispersion in the photometry due to instrumental errors has not been systematic and the few deviating points may be attributed to low photometric quality.

From the strength of the correlation and the fact that the coefficient multiplying V is rather close to unity, it can be deduced that most of the variation in $(B - V)$ is simply due to variability in V and that the variation in B is very small in comparison. The whole behaviour is consistent with what is expected from a Be star, where the variability is due to emission from a circumstellar disk with a temperature $T_{\rm disk} \approx 0.5T_{\rm eff}$, where $T_{\rm eff}$ is the effective temperature of the star. The disk contribution to the total spectral energy distribution is very small in the B band and increases towards longer wavelengths. The spectral energy distribution (star plus disk) becomes bluer when it is fainter because the contribution from the disk decreases.

For this reason, rather than taking an average of all the photometric measurements of the star, we consider that the faintest (and bluest) points in the dataset are more representative of the intrinsic magnitudes of the Be star, since the contribution from the disk is smallest. The three points in the bottom left region of Fig. 3 average to $V = 14.32 \pm 0.02$ and $(B - V) = 0.82 \pm 0.02$, which is compatible within the errors with the linear relationship found above.

3.2. Spectral classification

An intermediate resolution spectrum of the optical counterpart to KS 1947+300 is displayed in Fig. 1. Except for some variability in the strength of the Hα line (see Sect. 3.3), all our spectra are nearly identical. The characteristics are typical of an early-type reddened distant Be star: Hα and Hβ appear strongly in emission, as also does He I λ5875 Å. He I λ7065 Å and He I λ6678 Å can be seen as very weak emission features in the spectra with highest SNR. Some Fe II lines (indicated in Fig. 1) can be seen in emission, as well. The continuum is characterised by strong diffuse interstellar bands. The presence of He I emission implies a spectral type earlier than B2, putting the source in the spectral range of counterparts to Be/X-ray binaries (Negueruela & Coe 2002).

Absorption lines typical of an early-type star can be seen in the blue part of the spectrum. A higher resolution spectrum of this region is displayed in Fig. 4. The presence of He II implies a spectral type earlier than B0.5. The ratio between He II λ4686 Å and C III λ4650 Å is only compatible with a spectral type B0 for a main-sequence object. At O9.5V, He II λ4686 Å is already stronger than the C III line (Walborn & Fitzpatrick 1990), while the presence of He II λ4200 Å is incompatible with a spectral type later than B0.2. Though the strength of the Si IV doublet on the wings of Hδ could suggest an O9.5III spectral class, the ratio between He II λ4200 Å and C III λ4187 Å and the weakness of He II λ4541 Å support the later spectral type. Therefore we adopt a B0Ve spectral type.

3.3. Evolution of Hα

Profile changes in emission lines, particularly Hα, may be used to trace the dynamical evolution of the Be envelope (e.g., Negueruela et al. 2001). Unfortunately, the resolution of most of our spectra is too low for this aim, but some information may still be collected from the evolution of the line strength.

Table 3 displays the Equivalent Width (EW) of Hα for our spectra. Though the data are sparse, it seems likely that the strength of the line must have remained relatively constant for the whole period, with a slight increase around July 2001 (i.e., after the end of the large X-ray outburst).

4. Discussion

KS 1947+300 is a transient X-ray source, which has appeared three times at very high luminosity and is at most weakly

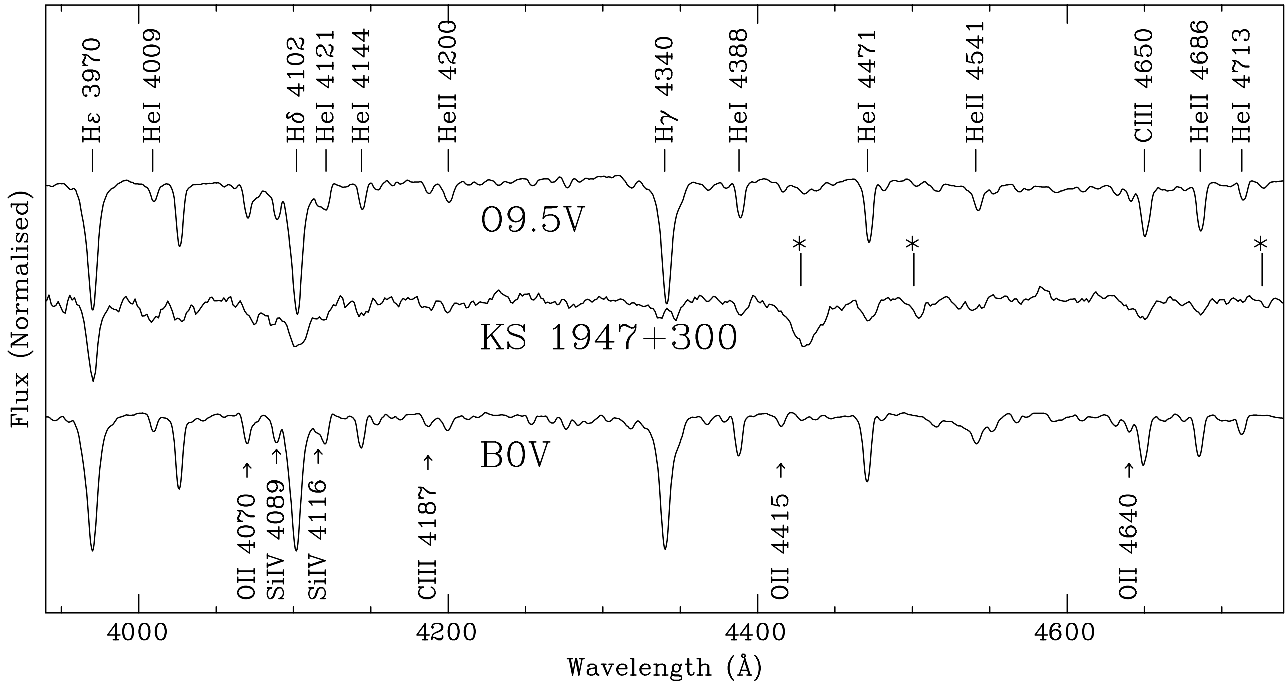

Fig. 4. Blue spectrum of the optical counterpart to KS 1947+300 compared to those of the B0V standard and the O9.5V standard artificially spun up to $v \sin i = 220\ \mathrm{km\,s^{-1}}$ in order to reproduce the very broad and shallow absorption lines in the spectrum of KS 1947+300 (as is typical in Be stars). Diffuse Interstellar Bands are marked with a "*".

Table 3. EW of Hα measured on our spectra. Errors are estimated from the spread of values obtained by using different measurement methods and selecting different continua.

Date	*EW* (Å)
Dec. 1, 2000	−14.7 ± 1.0
Feb. 8, 2001	−14.8 ± 0.5
Jun. 19, 2001	−15.1 ± 1.0
Jun. 22, 2001	−15.5 ± 0.8
Jul. 7, 2001	−16.5 ± 0.5
Dec. 7, 2001	−15.3 ± 0.5

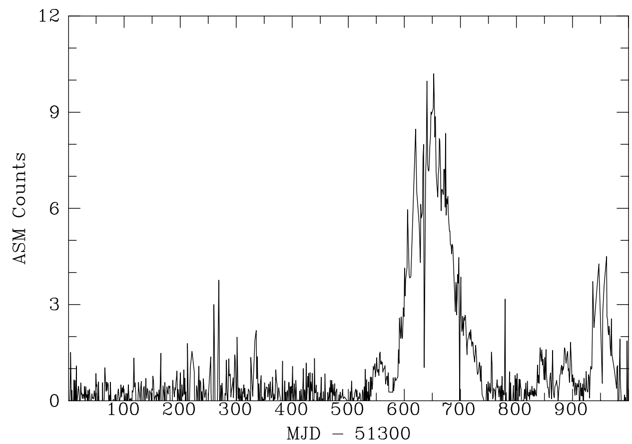

Fig. 5. *RXTE*/ASM X-ray lightcurve of KS 1947+300 between MJD 51300 (May 2, 1999) and MJD 52300 (Jan. 26 2002). Data are one-day averages of the ASM three energy-bands. Two major outbursts, centred on February 13 2001 and December 17 2001, as well as several minor flares are visible after MJD 51800.

detected (below 6 mCrab) by the *RXTE*/ASM during quiescence (Levine & Corbet 2000). This behaviour is typical of the class of Be/X-ray transients, like 4U 0115+63 or A 0535+26 (see Okazaki & Negueruela 2001). KS 1947+300 has only been observed on three occasions, in 1989, 1994 and 2000–2001. Such a recurrence timescale is typical of Type II (or giant) outbursts in Be/X-ray transients.

KS 1947+300 became active in late 2000. After a first weak outburst in November 2000, it underwent a very long giant outburst, lasting close to 150 days and reaching a flux in excess of 120 mCrab around MJD 51953 (February 13th). Two further weak outbursts and a moderate-intensity one followed during the second half of 2001 (see Fig. 5).

Our observations have shown that the optical counterpart to KS 1947+300 is a moderately reddened B0Ve star. For the adopted spectral type, an intrinsic colour $(B-V)_0 = -0.27$ may be considered (Wegner 1994). We can then assume that the observed faintest photometric dataset corresponds to the intrinsic magnitudes and colours of the star (obviously, if this is not the case, the star will be intrinsically fainter and bluer, allowing the distance derived here to be used as a lower limit). Therefore we derive an excess $E(B-V) = 1.09$. The ratio of selective to total extinction R_V in this area has been shown to be close to standard out to moderate distances (Turner 1976). Hence we will use the standard law (i.e., $R = 3.1$ – see Fitzpatrick 1999), resulting in $A_V = 3.38$. With an average absolute magnitude for B0V $M_V = -4.2$ (Vacca et al. 1996), we derive then a distance of $\approx$10 kpc to KS 1947+300.

With galactic coordinates ($l = 66\overset{\circ}{.}1$, $b = +2\overset{\circ}{.}1$), KS 1947+300 lies in an area of rather low obscuration. Extinction is moderate within one kpc of the Sun and then remains constant out to at least 5 kpc (Forbes 1985), which explains why such a distant object is moderately bright. In this area of the sky, the Perseus Arm is defined by the Vul OB2 association, which, with a dereddened distance modulus $DM = 13.2$, lies at 4.4 kpc (Turner 1980). The average reddening of six Vul OB2 stars lying at $b > 1^{\circ}$ is $E(B-V) = 0.6$ (Turner 1980). The rather larger reddening to KS 1947+300 supports a higher distance. The source is then likely to be located in the Cygnus or Outer Arm, which in this direction is located at ≈9 kpc (Taylor & Cordes 1993), in good agreement with our distance estimate. The distance estimated for KS 1947+300 is very similar to that found for the nearby source XTE J1946+274 (Verrecchia et al. 2002), which should also lie on the same arm.

Considering this distance, the peak X-ray luminosity (uncorrected for effects of circumstellar or interstellar absorption) observed by *BeppoSAX* during the March 2001 outburst was $L_{\rm x} \approx 2 \times 10^{37}$ erg s^{-1} (Rea et al., in prep.), which is a typical value for Be/X-ray transients during a Type II outburst. The occurrence of weaker outbursts after a Type II outburst is also a typical feature of a subgroup of Be/X-ray transients, characterised by close orbits with moderate and low eccentricity (Okazaki & Negueruela 2001). The only peculiarity of this outburst was its duration, rather longer than is typical in other Be/X-ray transients (typically 4−6 weeks).

The occurrence of several X-ray outbursts has not been reflected in any changes in the intensity of the Hα line during the period considered. Though obvious correlations have been seen in other systems (e.g., 4U 0115+63; Negueruela et al. 2001), such effects are likely to be strongly dependent on the relative geometry of the system: if the Be star is seen under a relatively low inclination angle, any changes in the Be disk structure would be barely reflected in the measured properties of Hα. It is a well known fact, as derived from both observations (Hanuschik et al. 1996) and modelling (Hummel & Hanuschik 1997), that at high and moderately high inclinations optically thick lines (such as Hα) show the effects of density perturbations only as relatively weak flank inflections, as the range of projected rotational velocities is small and several radiative transfer effects (such as non-coherent scattering; cf. Hummel & Hanuschik 1997) result in the broadening of features. Such inflections will certainly not be observable at the moderate resolutions used here. Higher resolution spectroscopy will be therefore necessary in order to derive a value for the counterpart's $v \sin i$.

The main difference between KS 1947+300 and other Be/X-ray transients with similar behaviour lies on its very low orbital eccentricity $e < 0.04$ (Galloway et al. 2002). Few Be/X-ray transients with low eccentricities are known. An upper limit $e \lesssim 0.09$ was set by Kelley et al. (1983) for the orbit of 2S 1553−542, an X-ray transient observed in 1975 during a single outburst, which was likely to be a Be/X-ray binary. The 27.1-s X-ray pulsar XTE J1543-568 is also likely a Be/X-ray binary. It displayed a large outburst in 2000, followed by weaker activity (In't Zand et al. 2001). XTE J1543-568 has a 75.6-d orbital period with an eccentricity $e < 0.03$. As both 2S 1553−542 and XTE J1543-568 have only been observed during one giant outburst each, KS 1947+300 is the first low-eccentricity recurrent transient displaying Type II outbursts.

Okazaki & Negueruela (2001) argued that one could debate whether the preponderance of moderately eccentric orbits among Be/X-ray transients was an observational effect or reflected the actual distribution. Since the neutron star companion is very effective at truncating the circumstellar disk of the Be star when the eccentricity is low, it could well be that low-eccentricity systems rarely display bright X-ray outbursts and are difficult to detect. The behaviour of KS 1947+300 seems to argue otherwise, since this system with a practically circular orbit has displayed 3 Type II outbursts in 11 years, a recurrence timescale comparable to those of the most active Be/X-ray transients.

The implication is then that low-eccentricity systems are as likely to display Type II outbursts as systems with moderate eccentricity and therefore the small number of low-eccentricity systems detected is actually reflecting the dominance of moderately eccentric orbits among Be/X-ray transients. This would then be one further argument in favour of supernova kicks (cf., van den Heuvel & van Paradijs 1997; Negueruela & Coe 2002).

5. Conclusions

We have shown that the optical counterpart to the recurrent X-ray transient KS 1947+300 is a B0Ve star at an approximate distance of 10 kpc. KS 1947+300 is therefore a Be/X-ray transient displaying recurrent Type II outbursts with intrinsic luminosities similar to other bright Be/X-ray transients. Among the ∼10 systems known displaying this kind of behaviour, KS 1947+300 is the first one to have an almost circular orbit. Since its existence shows that Be/X-ray binaries with very low eccentricities can be detected as bright X-ray sources, it is to be inferred that the preponderance of systems with moderate eccentricities among the observed sample reflects the actual distribution of orbital eccentricities.

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