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Optical/infrared observations of the X-ray burster KS1731–260 in quiescence

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ABSTRACT

Aims. We performed an optical/infrared study of the counterpart of the low-mass X-ray binary KS 1731–260 to test its identification and obtain information about the donor.
Methods. Optical and infrared images of the counterpart of KS 1731–260 were taken in two different epochs (2001 and 2007) after the source returned to quiescence in X-rays. We compared these observations with those obtained when KS 1731–260 was still active.
Results. We confirm the identification of KS 1731–260 with the previously proposed counterpart and improve its position to α = 17:34:13.46 and δ = −26:05:18.60. The *H*-band magnitude of this candidate showed a decline of ∼1.7 mag from outburst to quiescence. In 2007 April we obtained $R = 22.8 \pm 0.1$ and $I = 20.9 \pm 0.1$ for KS 1731–260. Similar optical brightness was measured in June 2001 and July 2007. The intrinsic optical color $R - I$ is consistent with spectral types from F to G for the secondary although there is a large excess over that from the secondary at the infrared wavelengths. This may be due to emission from the cooler outer regions of the accretion disk. We cannot rule out a brown dwarf as a donor star, although it would require that the distance to the source is significantly lower than the 7 kpc reported by Muno et al. (2000, ApJ, 542, 1016).

Key words. astrometry – X-rays: binaries – stars: individual: KS 1731–260

1. Introduction

Low-mass X-ray binaries are systems in which a low-mass companion star transfers material onto a neutron star or black hole. In these compact binaries, the intense X-ray irradiation usually overwhelms the light from the donor (e.g. Charles & Coe 2006). There are, however, some systems, the so-called X-ray transients, in which substantial X-ray activity (10^{36}–10^{38} erg s^{-1}) only occurs during well-defined outbursts. The outbursts typically last from weeks to months and are usually separated by long intervals (years to decades) of very low X-ray luminosity (10^{30}–10^{34} erg s^{-1}). During these intervals of quiescence, the emission from the accretion flow fades to the point the companion star is clearly visible and is nearly undisturbed by irradiation; hence, it can be studied to derive the parameters of the binary. Most of the low-mass X-ray binaries have orbital periods of a few hours to days and contain ordinary hydrogen-rich donor stars. The so-called ultra compact binaries, however, have orbital periods shorter than 80 min. The small period implies such a small Roche lobe that the donor star must be hydrogen poor (e.g. Nelson et al. 1986).

The transient KS 1731–260 was discovered with the Mir/Kvant instrument in August 1989 (Sunyaev 1989). The presence of type-I X-ray bursts coming from the system indicates

that its compact object is a neutron star (Sunyaev 1989; Sunyaev et al. 1990) and places an upper limit on the distance to the source of 7 kpc (Muno et al. 2000) and 7.8 kpc (Galloway et al. 2008) assuming a pure helium photosphere for a 1.4 $M_\odot$ and $R = 10$ km neutron star. The corresponding distances for a 2 $M_\odot$ neutron star would be 9% greater. The Galloway et al. (2008) best estimations are 7.2 ± 1 kpc for pure helium and 5.6 ± 0.7 kpc for material with cosmic abundances (hydrogen fraction $X = 0.7$). In contrast to most X-ray transients, KS 1731–260 did not disappear after a few weeks to months, but it could be observed continuously at high luminosities. However, in February 2001, after having actively accreted for over a decade, the source suddenly turned off. A *Chandra* observation of the source was performed a few months after this event and an X-ray luminosity of only 2×10^{33} erg s^{-1} could be measured (Wijnands et al. 2001b).

Several authors tried to identify the optical counterpart of KS 1731–260 during its long active episode. In the error circle obtained with Kvant, many optical stars were present, but Cherepashchuk et al. (1994) identified two promising stars on the red Palomar Survey plate. However, using the significantly higher spatial resolution of the *ROSAT/HRI*, Barret et al. (1998) demonstrated that those stars could not be identified with KS 1731–260 and suggest 13 possible candidates, which were later ruled out by the analysis of the *Chandra* image made by Revnivtsev & Sunyaev (2002). These authors propose

a likely counterpart, although it could not be conclusively identified because of the lack of observations in quiescence. Finally, Wijnands et al. (2001a) made observations when the source turned off and identified the counterpart of KS 1731–260 as a very weak optical source in the *Chandra* error circle. However, no optical magnitudes could be measured. The only optical/near-IR magnitude measured for KS 1731–260 in quiescence was obtained by Orosz et al. (2001) who reported $J = 18.62 \pm 0.21$ in 2001 July 13.

In this paper we present the optical and infrared observations of the counterpart of KS 1731–260. This is an important issue since this source is only one of a few sources where crustal cooling has been observed in quiescence (Cackett et al. 2006, and references therein). Knowledge of the neutron star mass helps to set the timescale of this cooling, as higher mass neutron stars have a thinner crust, hence would cool more quickly (Brown & Cumming 2009). In addition, KS 1731–260 is one of the few sources showing superbursts (Kuulkers et al. 2002). Therefore, any information on the nature of the donor star may give us a clue to what kind of material is accreted onto the neutron star.

2. Observations and reductions

Infrared *H* and *K* images of KS 1731–260 were obtained on the 3.8 m United Kingdom Infrared Telescope (UKIRT) with the UKIRT Fast Track Imager (UFTI) on UT 2001 July 9. Seeing during the observations was measured at 0.9 arcsec. For both the *H*- and *K*-band images of the target, a series of five consecutive 60 s exposures were obtained with offsets of 20 arcsecs between each exposure. Observations of a photometric standard star were obtained in a similar way, with 5 s exposure time and using a subarray of the detector (47 arcsec^2 field of view). For both the target and the standard stars, the position of the object on the array was moved between exposures so that the group could be median-stacked to produce a sky flat. Basic data reduction was performed using the ORAC-DR online reduction system at UKIRT. The magnitudes were derived from IRAF/daophot point-spread function (psf) fitting with an aperture correction.

Optical images of the field of KS 1731–260 in Sloan *r'*, *i'* and *z'* (see e.g. Fukugita et al. 1996) were obtained on UT 2001 June 28 on the 6.5 m Magellan Walter Baade telescope at Las Campanas Observatory (Chile) and the MagIC camera with 600 s of exposure time in each filter. We also observed in Johnson/Bessel *R* and *I* on UT 2007 April 26 and 27 with the same telescope but equiped with the IMACS detector and with 900 s of total exposure in each band. Finally, we obtained images in Johnson/Bessel *R* and Gunn *i* on UT 2007 June 16 on the 3.6 m telescope at La Silla Observatory in Chile with 1800 s exposure time in each filter.

In none of the above nights were standard stars observed, so we calibrated a set of 15 faint stars in the field of view of KS 1731–260 in an independent run on UT 2007 April 25 on the 1.5 m telescope at San Pedro Mártir Observatory in Mexico. We performed a color-dependent *BVRI* calibration using several standard stars from four Landolt plates (Landolt 1992). The conversion to the Sloan filter set was made using the empirical transformations given in Jordi et al. (2006). KS 1731–260 was not detected that night. In the rest of the nights we performed aperture photometry on our object and in the set of previously calibrated comparison stars. All the optical images were corrected for bias and flat-fielded in the standard way using IRAF[1] tasks. An observing log is presented in Table 1.

Table 1. Log of the observations.

Date	$n \times$ exp. time (s)	Filter	Telescope
2001 June 28	1×600	r'	6.5 m Magellan
	1×600	i'	
	1×600	z'	
2001 July 09	5×60	H	3.8 m UKIRT
	5×60	K	
2007 April 25	3×900	V	1.5 m San Pedro Mártir
	3×600	R	
	3×600	I	
2007 April 26	3×300	R	6.5 m Magellan
2007 April 27	3×300	I	6.5 m Magellan
2007 July 16	1×1800	R	3.6 m La Silla
	1×1800	i	

3. The position of KS 1731–260

The *Chandra*/ACIS-S observation on KS 1731–260 was obtained on 2001 March 27 00:17-06:23 UTC (only a few months after the source turned off) for a total onsource time of ~20 ks. For details about this observation and the discussion of the result obtained from the spectral analysis of the data, we refer the reader to Wijnands et al. (2001b,a). Two CIAO tools are usually used to determine the presence of X-ray sources in *Chandra* fields and to obtain their positions: *celldetect* and *wavdetect*. Both tools detected two X-ray sources in our field (see also Wijnands et al. 2001b,a), but although the obtained coordinates were very similar for both tools, they differ slightly (by 0.1 arcsec). We also used the IRAF tool *daofind* to obtain the coordinates, and these coordinates were slightly different from those obtained with the CIAO tools. The statistical errors on the position are very small, but the spread in the coordinates as obtained with the different tools can be used as a good indication of the accuracy of the coordinates. As expected, the spread is greater for the extra *Chandra* source (designated CXOU J173412.7-260548) because of its lower number of counts compared to KS 1731–260.

The pointing accuracy of the satellite is approximately 0.6 arcsec, but the astrometric accuracy of the coordinates can be improved if it is possible to tie the *Chandra* coordinate frame with others (such as 2MASS with an astrometric accuracy 0$.''$2). We only have CXOU J173412.7-260548 to try to obtain better astrometric accuracy, but in the 2MASS catalog a star (2MASSI J173412.7-260548) was present with very similar coordinates to CXOU J173412.7-260548; the coordinates are 0.4 arsec off. Therefore, we identify CXOU J173412.7-260548 with the 2MASS star. This is the only star above the 2MASS detection limit into the Chandra error circle. To estimate the probability that an unrelated source has fallen in the X-ray error circle by chance, we note that there are 7 stars of similar brightness or brighter to 2MASSI J173412.7-260548 within a 1 arcmin circle, so we estimate a 7×10^{-4} probability that an unrelated object is falling by chance into the 0.6 arcsec Chandra error circle. CXOU J173412.7-260548 has an offset with respect to 2MASSI J173412.7-260548 of 0.016, 0.024, and 0.001 sec in right ascension and 0.12, 0.03, and 0.15 s in declination for the *celldetect*, *wavdetect*, and *daofind* tool, respectively. We applied the same offsets for the position obtained for KS 1731–260. By combining these offsets we derived a best position of KS 1731–260 of $\alpha = 17{:}34{:}13.47$ and $\delta = -26{:}05{:}18.8$, with an accuracy of 0.4 s.
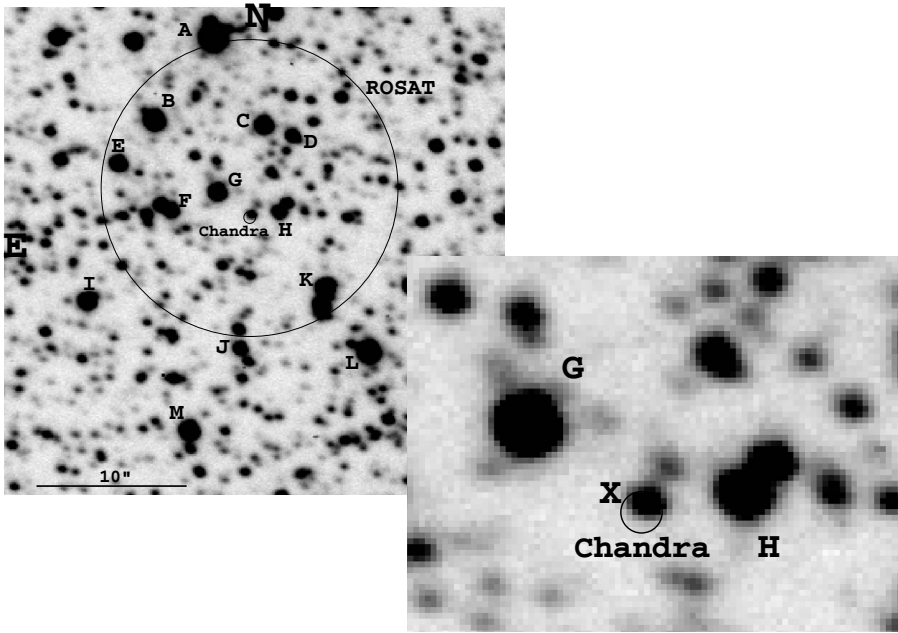
Fig. 1. A Magellan *I* image of the ROSAT error box (10 arcsec radius) of KS 1731–260 (*left*) and a close-up of the Chandra position (0.4 arcsec) with star "X" as our proposed optical and infrared counterpart (*right*). Star labeling is as in Barret et al. (1998). North is upwards and east is to the left.

In Fig. 1 we show the Magellan *I* image, taken 2007 April 25, with the ROSAT and *Chandra* 0.4 s diameter error circle. To obtain a precise astrometric solution, we used the positions of the astrometric standards selected from the USNO-B1 astrometric catalog[2] with a nominal 0″.2 uncertainty. A hundred reference objects can be identified in our field but, to minimize potential positional uncertainties caused by overlapping stellar profiles, we selected only 28 isolated stars, discarding the stars with significant proper motions. The IRAF tasks ccmap/cctran were applied for the astrometric transformation of the images. Formal rms uncertainties of the astrometric fit for our images are ≲0″.15 in both right ascension and declination, which is compatible with the maximum catalog position uncertainty of the selected standards. It is clear that only one viable candidate counterpart is left within the *Chandra* error box. This image, taken with good seeing conditions (∼0″.5), reveals a faint nearby star at northwest of the target. Finally, we measured the center of the source "X" by fitting a Gaussian to the star profile and improve the position of KS 1731–260 to $\alpha = 17{:}34{:}13.46$ and $\delta = -26{:}05{:}18.60$ with a conservative estimate of our 3σ astrometric uncertainty of ≲0″.2 in both RA and Dec.

4. Photometry

Infrared *H* and *K* images of KS 1731–260 in quiescence were obtained on UT 2001 July 9. We compared the brightness of the stars in the field of KS 1731–260 obtained on 1996 June by Barret et al. (1998) with our 2001 UKIRT observations (see Fig. 2). In Table 2 we give the old *H*-band magnitudes, from the original Barret et al. (1998) paper, and new ones, as well as our $(H - K)$ 2001 colors. Stars have been labeled as in Barret et al. (1998). We also included the most likely counterpart of KS 1731–260 (source "X"). The source "X" was not measured by Barret et al. (1998), so we determined its *H*-band magnitude from the original observations. Because of the faintness of target "X", we first cleaned the contamination of nearby stars by

using the IRAF allstar task, which subtracts the best PSF fit of the set of contaminating stars. This step was iterated to minimize the residuals after PSF subtraction. Although there is a scatter of 0.17 rms in the *H* band magnitudes as derived from the Barret et al. (1998) CFHT image and the new UKIRT observations, only target "X", of the sources near the Chandra error circle, shows a substantial variation. For this object $H = 17.70 \pm 0.20$ in 2001, that is, it has declined by ∼1.7 mag between both observations. The large change in *H*-band magnitude between burst and quiescence, together with its location in the *Chandra* error circle, leads us to conclude that source "X" is indeed the infrared counterpart to KS 1731–260.

We observed KS 1731–260 in three different epochs when the target was in quiescence: in 2001 in Sloan r', i', z', in April 2007 in Bessel *R* and *I*, and in June 2007 in Bessel *R* and Gunn *i*. To obtain reliable magnitude measurements of our very faint target, we cleaned the contamination of the stars near KS 1731–260 (G and H in Fig. 1) by subtracting the best PSF. Photometric error estimates on the optical magnitudes are based on a combination of Poisson statistics and the error contribution of the stars used for calibration. For the optical magnitudes in different nights, we refer to Table 3.

5. Discussion

Table 3 summarizes the magnitudes of KS 1731–260 measured in quiescence including the *J* magnitude of Orosz et al. (2001). The *J* and *H*-band magnitudes of this candidate show a decline of ∼1.3 and 1.7 mag, respectively, from outburst (1996 June) to quiescence (2001 July). In the *K*-band, however, the source is only ∼0.6 mag fainter compared with the *K′* magnitude obtained by Mignani et al. (2002) in 1998 July. This could mean either that the system faded in infrared from 1996 to 1998, when it was actively accreting or that the disk emission is lower in *K* so, after the X-rays turn off, the disk has become much less luminous, so the *J* and *H* magnitudes dropped.

In 2007 KS 1731–260 had the same optical brightness, within the errors, as in 2001. To determine the nature of its companion, we plot the *RIJHK* spectral energy distribution (SED) for various main-sequence type stars along with that of KS 1731–260 (Fig. 3). The absolute magnitudes and the colors
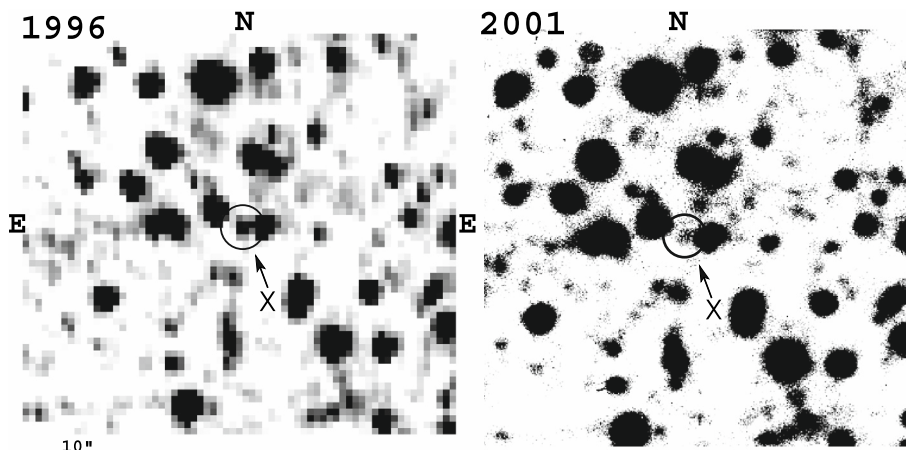
Fig. 2. *H*-band images of the field around the proposed counterpart "X" obtained in 1996 with CFHT (*left*) and 2001 with UKIRT (*right*). North is upwards and East is to the left.

Table 2. *H*-band magnitudes and colors of isolated stars near the *Chandra* error circle.

Star	H(CFHT)	H(UKIRT)	$(H - K)$(UKIRT)
A	12.35 ± 0.06	11.91 ± 0.10	0.71 ± 0.10
B	13.10 ± 0.08	13.12 ± 0.10	0.70 ± 0.10
C	14.14 ± 0.19	14.01 ± 0.10	0.71 ± 0.10
D	14.79 ± 0.92	15.29 ± 0.15	0.71 ± 0.15
E	14.44 ± 0.15	14.33 ± 0.10	0.76 ± 0.10
F	14.00 ± 0.12	14.33 ± 0.11	0.76 ± 0.11
G	13.84 ± 0.12	13.89 ± 0.10	0.76 ± 0.10
H	14.99 ± 0.34	15.07 ± 0.11	0.72 ± 0.11
I	14.38 ± 0.12	14.24 ± 0.10	0.70 ± 0.10
J	15.14 ± 0.54	15.25 ± 0.15	0.75 ± 0.15
K	13.64 ± 0.09	13.83 ± 0.10	0.77 ± 0.10
L	13.19 ± 0.08	12.94 ± 0.10	0.67 ± 0.10
M	13.39 ± 0.06	13.18 ± 0.12	0.79 ± 0.12
X	16.00 ± 0.60	17.70 ± 0.20	1.00 ± 0.30

Notes. CFHT and UKIRT observations were obtained on 1996 June and 2001 July, respectively. Star labeling is as in Barret et al. (1998) and Fig. 1.

Table 3. Magnitudes of KS 1731–260 for the three epochs in quiescence.

Date	mag
2001 June 28	$r' = 23.6 \pm 0.4$
	$i' = 22.3 \pm 0.4$
	$z' = 21.0 \pm 0.4$
2001 July 09	$H = 17.7 \pm 0.2$
	$K = 16.7 \pm 0.3$
2001 July 13	$J = 18.6 \pm 0.2$ [*]
2007 April 26	$R = 22.8 \pm 0.1$
2007 April 27	$I = 20.9 \pm 0.1$
2007 July 16	$R = 23.0 \pm 0.3$
	$i = 22.5 \pm 0.2$

Notes. [*] Magnitude J from Orosz et al. (2001).

of the stars are taken from Leggett (1992) and Allen (1976), whereas the apparent magnitudes were calculated using the extinction laws of Cardelli et al. (1989) assuming a reddening of $A_V \sim 6$ obtained from the spectral fits to the combined *Chandra/XMM-Newton* data (Wijnands et al. 2002) and a distance of 7 kpc (upper limit from Muno et al. 2000). The error bars for these apparent magnitudes account for the uncertainty in the reddening. The optical color $R - I$ of KS 1731–260 is consistent with spectral types from F to G. However, the infrared colors ($J - K = 0.9$ and $H - K = 0.6$) are much higher than expected even for a late M star.

Observations of transients in quiescence have predominately been carried out in the optical, and in this wavelength range the accretion disk is known to contribute significantly to the observed flux. Typically it is assumed that the disk spectrum is a featureless continuum and that it marginally contributes to the overall light in the infrared. Therefore, many authors have used infrared observations, rather than optical, to determine the ellipsoidal variability and constrain the mass ratio and the inclination angle in these systems (see e.g. Charles & Coe 2006, for a review). If we consider the infrared data alone, assuming that the near-infrared magnitudes are completely dominated by the light of the secondary, we cannot rule out a brown dwarf as donor star ($J - K \geq 1$; Cruz et al. 2009). The possibility that KS 1731–260 is an extremely narrow binary system with an orbital period of ~1 h has been suggested by Muno et al. (2000)

based on their analysis of the burst pulsations of this system and the spin-frequency interpretation. Kuulkers et al. (2002) also report a twelve-hour long X-ray flare from this source. Cumming & Bildsten (2001; see also Strohmayer & Brown 2002) pointed out the unstable carbon burning in a layer beneath the (un)stable hydrogen/helium or helium layer, deeper in the neutron star, as a possible mechanism to explain these events. Obviously, for this to work, the ashes of the burning hydrogen/helium layer need to contain carbon. One way to achieve this is to have stable burning of helium so the donor star should be helium-rich. However, a brown dwarf donor would require that the distance is lower than 500 pc, well below the estimation based on radius-expansion X-ray bursts (Muno et al. 2000; Galloway et al. 2008).

Nevertheless, there is no reason to argue that the nonstellar contribution to the near infrared flux is minimal and consistent throughout quiescence. On the contrary, optically thick material (hence thermal infrared flux) at the outer regions of the accretion disk is theoretically plausible (Hynes et al. 2005). Furthermore, infrared flickering has been recently detected in the X-ray Transients (and black hole candidates) J0422+32 (Reynolds et al. 2007) and A0620-00 (Cantrell et al. 2008) in quiescence. In A0620-00 system a jet was seen in the radio band (Gallo et al. 2006). The synchrotron spectrum, which is thought to be the jet signature, is frequently seen at radio but also up to higher frequencies in the infrared. Finally, the analysis of the SEDs of a sample of quiescent transients (one of them containing a neutron star) have shown an infrared excess probably due to the presence of a cool disk component (Reynolds et al. 2008). Hence, a nonstellar infrared component superimposed on a main sequence, F to G type, stellar
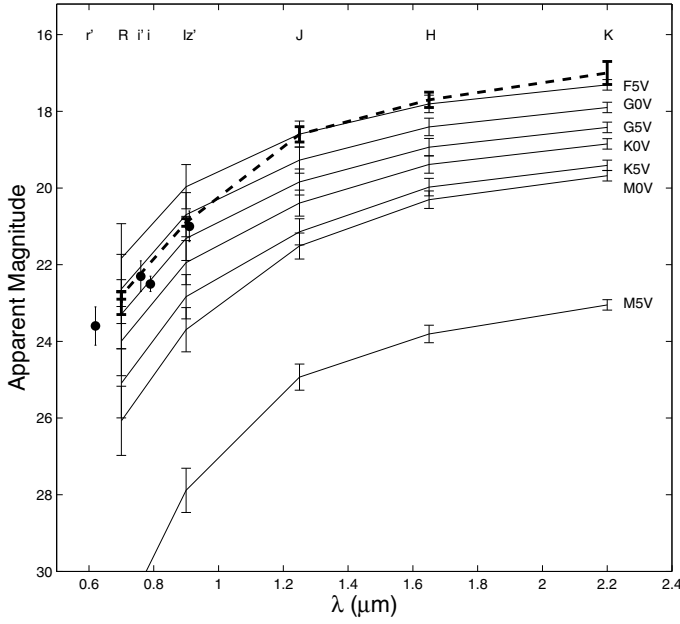
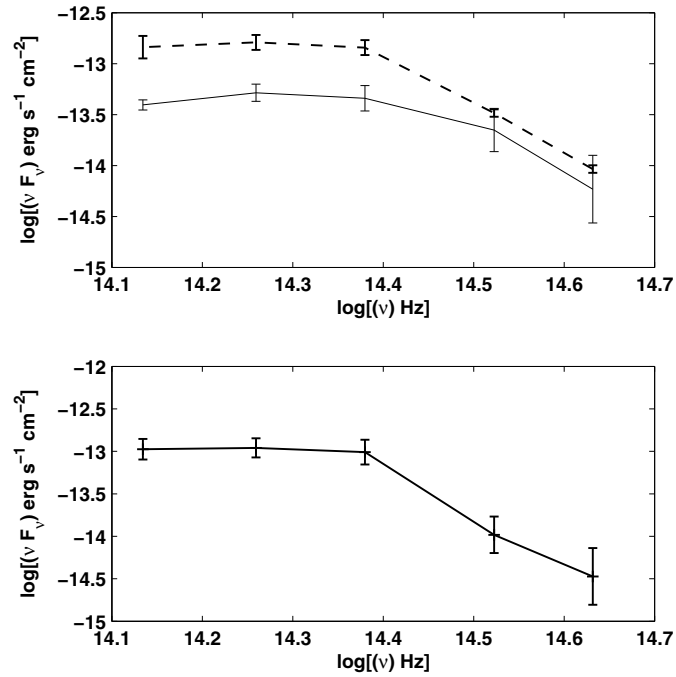**Fig. 3.** *RIJHK* SED for various type stars and KS 1731–260 (dashed line).

Fig. 4. *Top panel*: SEDs of KS 1731–260 (dashed line) and a G5V star (solid line) assuming a reddening of $A_V \sim 6$ and a distance of 7 kpc. *Bottom panel*: spectrum of the nonstellar component obtained by subtracting the G5V colors from the KS 1731–260 colors.

spectrum can explain our SED. The distance to the system would be then ~5 kpc for a late G star and ~12 kpc for a late F. Assuming a distance to the source of 7.2 kpc (Galloway et al. 2008) the optical counterpart is more consistently a early G type star. To recover the broadband spectrum of the nonstellar component we subtracted the companion star, using the apparent magnitudes of a G5V star assuming a reddening of $A_V \sim 6$ and a distance of 7 kpc, from the KS 1731–260 colors

(Fig. 4, top panel). Again, the error bars for these apparent magnitudes account for the uncertainty in the reddening. The resultant component (Fig. 4, bottom panel) is far from the canonical $F_\nu \propto \nu^{1/3}$ accretion disk spectrum. However, fitting the infrared alone we find a flat spectrum with $\alpha = -0.1 \pm 0.1$ where $F_\nu = \nu^\alpha$. The very flat infrared SED ($F_\nu \sim$const.) could naturally be interpreted as a mixture of an optically thick disk spectrum and flat spectrum emission, possibly synchrotron (Fender et al. 2000). Therefore, we favor an H-rich system instead of an ultra compact binary.

Combining Paczyński (1971) expression for the averaged radius of a Roche lobe with Kepler's Third Law, we get the well-known relationship between the secondary's mean density and the orbital period: $\rho = (110/P_{\rm h}^2)\,{\rm g\,cm}^{-3}$, where ρ is the mean density and $P_{\rm h}$ the orbital period in hours. From this expression we estimated an orbital period of about 10 h for a G type star.

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