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ROSAT and follow-up infrared observations of the X-ray burster KS 1731-260

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Abstract. We report on the ROSAT HRI (High Resolution Imager) observation of the X-ray burster KS 1731-260. The observation was split in two parts; the first took place in 1995, March 16 lasting for $\sim$ 1 kilosecond and the second one between September 3rd and 14th, 1996 for about 5 kiloseconds. In both observations, KS 1731-260 was clearly detected with a count rate of 0.82 and 7.9 ctss respectively. From the first observation we found that the X-ray source is located at a position $\alpha = 17^{h}\ 34^{mn}\ 13.5^{s}$ and $\delta = -26°\ 05'\ 16.8''$ (equinox 2000) with an associated error radius of 10.1 arcsec (90% confidence level combining the attitude and centroid uncertainties). The position derived from the second part of the observation is consistent with the previous one. The ROSAT HRI position rules out the two counterparts that have been proposed so far. Our CFHT J and H infrared imaging of the HRI error box reveals at least 13 possible candidates. As expected from a comparison with other X-ray bursters, the upper limits derived for the infrared brightness of KS 1731-260 imply the presence of a low mass companion for the neutron star.

We also report on a refined spectral analysis of the PSPC data taken during the all sky survey in September 1990. These data, together with data recorded by TTM and PCA/RXTE indicate that the column density towards KS 1731-260 varies between $\sim$ 1 to 6 $\times 10^{22}$ H atoms cm^{-2}; thus suggesting that the source is characterized by variable intrinsic absorption. The change in the HRI count rate could be better explained by a change in the column density between the two observations rather than by a true source intensity variation. The numerous detections of the source since its discovery in 1988 together with its recent monitoring by the RXTE/ASM show that KS 1731-260 is a persistent source rather than a soft X-ray transient, as originally thought.

Key words: Galaxy: center – X-rays: stars – stars: individual: KS 1731-260 – star: neutron – infrared: stars

1. Introduction

KS 1731-260 was discovered on October 1988 by the coded-mask imaging spectrometer TTM on the MIR-KVANT Observatory (Sunyaev et al. 1989; Sunyaev et al., 1990a,b). It is located in the Galactic center region; about five degrees from the Galactic nucleus ($\sim$ 600 pc), and very close to the X-ray binary pulsar GX1+4 (less than 1 degree). In August 1989, TTM observed KS 1731-260 for 15 days while the source intensity varied from 50 to 100 mCrab in the 2–27 keV band (average around 80 mCrab). The corresponding time-averaged spectrum was best fit by a thermal Bremsstrahlung model of temperature (kT) 5.7 ± 0.3 keV absorbed through a column density (NH) of $2.2 \pm 0.2 \times 10^{22}$ H atoms cm^{-2}. The averaged 1-20 keV flux was then 2.7×10^{-9} ergs s^{-1} cm^{-2} (Sunyaev et al., 1990a, In't Zand, 1992). Several X-ray bursts with intensities up to 1.2 Crab were also recorded during the same TTM observations (Sunyaev et al. 1990a, In't Zand, 1992). Since KS 1731-260 was not known prior to TTM, in particular it had not been detected by experiments such as UHURU, HEAO2, Ariel V, it was naturally classified as a soft X-ray transient (Sunyaev et al., 1990a).

However, following the TTM observations, the source was detected twice in 1990 (April 4 and August 23) by the ART-P X-ray telescope aboard GRANAT at a luminosity-level similar to that observed by TTM (Sunyaev et al., 1990c). KS 1731-260 was subsequently detected during the GINGA/LAC scans of the Galactic center region performed from March 1988 through March 1990 (Yamauchi and Koyama 1990) and during the ROSAT all sky survey (Predehl and Schmitt 1995, see below). On March 14, 1992, the source was detected by the SIGMA telescope at energies above 30 keV with a 40-150 keV luminosity of 9×10^{36} ergs s^{-1} (at 8.3 kpc). KS 1731-260 then became one of the first X-ray bursters and hence neutron star

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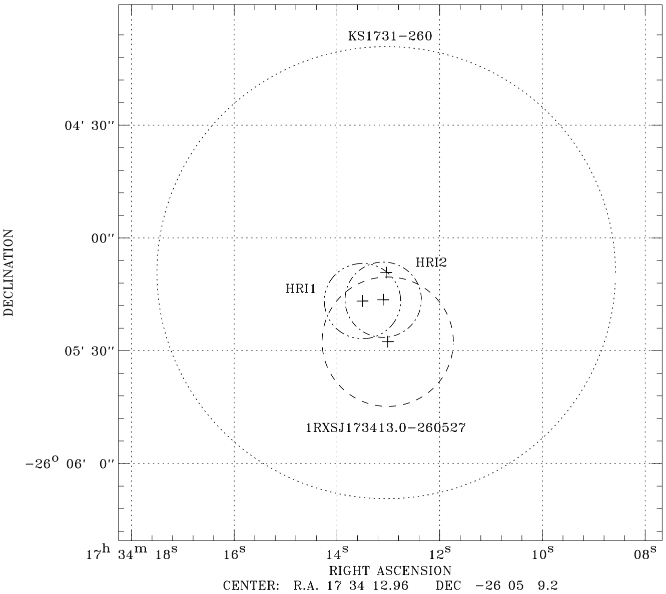

Fig. 1. The TTM (KS 1731-260 ; Sunyaev et al. 1989, dotted line), PSPC all sky survey (1RXSJ173413.0-260527; Voges et al. 1996, dashed line) and HRI positions for the first (HRI1, dot-dot-dot dashed line) and second part (HRI2, dot-dashed line) of the observation. The associated error boxes are given at the 90% confidence level (1 arcmin, 17.2 arcsec, 10.1 arcsec and 10.1 arcsec respectively).

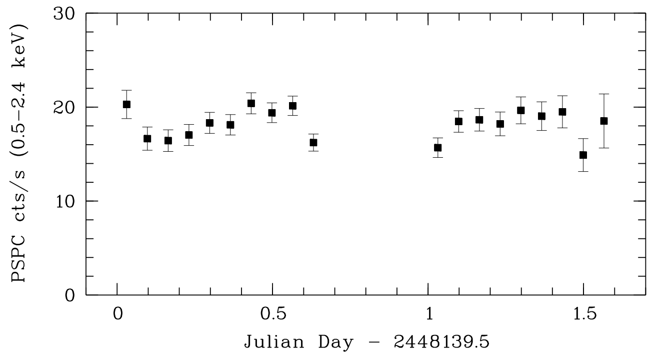

Fig. 2. The ROSAT PSPC all sky survey light curve. The energy range is 0.1-2.4 keV. KS 1731-260 was observed between September 5th and 6th, 1990.

systems detected in hard X-rays (Barret et al., 1992). Finally KS 1731-260 is also present in the KVANT-TTM maps of the Galactic Center region obtained in May 1994 (Aleksandrovitch et al. 1995), and September 26-28 1994 (Borozdin et al. 1995). All these detections spanning over six years clearly argued against the pure transient nature of the source. Not surprisingly KS 1731-260 is now being monitored by the All Sky Monitor (ASM) aboard the *ROSSI X-ray Timing Explorer* and appears as a persistent source in the 2 to 12 keV band (RXTE). Recently in a short pointed observation performed with the RXTE/*Proportional Counter Array (PCA)*, a periodic signal at 524 Hz was detected during the peak of a type I X-ray burst. This result was interpreted as KS 1731-260 containing a rapidly rotating neutron star with a spin period of 1.91 milliseconds (Morgan and Smith 1996). Furthermore this burst showed photospheric radius expansion (Smith et al. 1997). Assuming that the burst peak luminosity corresponds to the Eddington limit for a $1.4 M_{\odot}$ neutron star, Smith et al. (1997) derived a distance of 8.3 ± 0.3 kpc for KS 1731-260. For the persistent X-ray emission, the PCA spectrum was found to be very similar to the TTM spectrum (a fit by a thermal Bremsstrahlung yields a temperature of 5.5 keV), the main difference being that the NH observed by the PCA ($6.0 \pm 0.3 \times 10^{22}$ H atoms cm^{-2}) is three times larger than the one observed by TMM.

Using the TTM error box (1 arcmin radius) Cherepashchuk et al. (1994) proposed two counterparts for KS 1731-260: the first one is a 18th B magnitude (the bluest object they found in the error box on the POSS E chart), the second one is a variable star designated as object No 2547 in Terzan and Gossett (1982). The latter lies also inside the error box of the IRAS source IRAS 1731-2604.

Having some doubts about the transient nature of the source, we proposed KS 1731-260 for a short ROSAT HRI observation in order to accurately determine its position and to test the optical counterparts proposed by Cherepashchuk et al. (1994). In this paper, we first present results from a refined analysis of the ROSAT PSPC all sky survey data (Sect. 2.1), already used by Predehl and Schmitt (1995) for their study of scattering halos around bright X-ray sources. Then we report on the results of our HRI observation (Sect. 2.2). We describe in Sect. 2.3 the results of an infrared investigation conducted in the ROSAT HRI error box. Finally in Sect. 3 we show that the HRI position rules out the two proposed optical counterparts, and discuss on the nature of the source in view of our recent infrared observations.

2. Observations and results

Let us start with the PSPC observation which was performed earlier than our HRI observations.

2.1. PSPC all sky survey observations

The source was first detected by ROSAT between September 5th and 6th, 1990 during the PSPC all sky survey. The position was retrieved from the 1RXS bright source catalog (Voges et al. 1996). KS 1731-260 is identified as 1RXS J173413.0-260527 at the position $\alpha = 17^{h}\ 34^{mn}\ 13.0^{s}$ and $\delta = -26^{\circ}\ 05'\ 27.5''$ (equinox 2000) and has an associated error radius at the 90% confidence level of 17.2 arcsec. As shown in Fig. 1, this position is consistent with the HRI positions derived below.

As shown in Fig. 2 in the PSPC data, the source flux does not show any significant time variability. By selecting only photons from the inner region of the detector (i.e where vigneting corrections are unimportant), the source count rate was 18.2 cts s^{-1}. Note that the value listed in the 1RXS catalog is only 14 cts s^{-1}; in the 1RXS analysis the whole detector area is taken and an improper exposure time correction at the edge of the detector can cause systematic errors of the order of 20% (Voges, private communication). A refined spectral analysis has been performed in

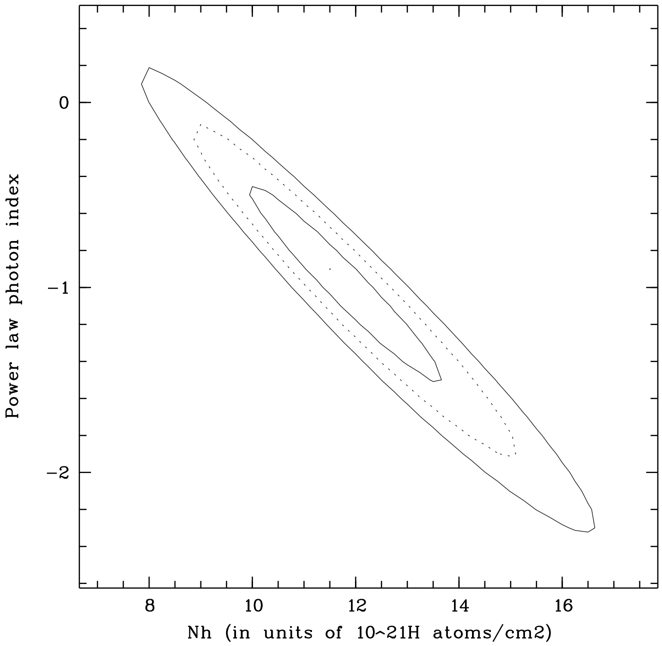

Fig. 3. Allowed grid of variations of the power law index and the column density (Nh). The contours encompass the 68%, 95% and 99% confidence levels. Note in particular that the NH measured by TTM (2.2×10^{22} H atoms cm^{-2}) is excluded at more than 99% confidence level.

order to determine NH towards the source. Unfortunately, the limited energy range of the PSPC does not allow to distinguish between soft (blackbody) and hard models (Bremsstrahlung and power law). However, in all three models, the NH derived is consistent with a value of $\sim 1.3 \times 10^{22}$ H atoms cm^{-2} with an error of about 0.3. This is about a factor of two lower than the value observed by TTM and a factor of five lower than the PCA value. The difference between the TTM and RXTE values, together with this result strongly suggest that KS 1731-260 is characterized by variable intrinsic absorption. In Fig. 3 we show the allowed grid of variations of the power law index and NH. As can be seen, KS 1731-260 is characterized by a very hard spectrum in the PSPC range (photon index around 1.). The PSPC count rate corresponds to a flux in the 0.1-2.4 keV range of $\sim 1.8 \times 10^{-9}$ ergs s^{-1} cm^{-2} for the power law model.

2.2. HRI observations

The ROSAT-HRI observation of KS 1731-260 was split in two parts: KS 1731-260 was first observed between March 16, 1995 (09:38:11) and March 16, 1995 (22:28:12) for a total exposure time of 1080 seconds, and later between September 3, 1996 (12:27:44.2) and September 14, 1996 (22:34:52) for about 4600 seconds. In both observations, the HRI field was centered on the TTM position. The observations were analyzed with the PROS software for the first one and with the EXSAS package for the second one. The source is clearly detected in both observations with a count rate of 0.82 ± 0.03 and 7.7 ± 0.09 cts s^{-1}, respectively. The best fit positions derived are $\alpha = 17^{h}\ 34^{mn}\ 13.5^{s}$ and $\delta = -26°\ 05'\ 16.8''$ (equinox 2000), and for the second observation $\alpha = 17^{h}\ 34^{mn}\ 13.1^{s}$ and $\delta = -26°\ 05'\ 16.5''$ (equinox 2000). The error on the centroid position is ~ 1 arcsec (90% confidence level). Unfortunately, no other X-ray sources were detected during our short observation and therefore no boresight corrections could be made. In a conservative way, we set up the boresight uncertainty to 10 arcsec (David et al. 1996). This combines with the centroid error to give a 90% confidence error radius of 10.1 arcsec. The two positions are perfectly consistent with each other as shown in Fig. 1.

In both observations, the source does not show any variability nor X-ray bursts. Given the possibility that KS 1731-260 is characterized by variable intrinsic absorption as discussed above, conversion of the HRI count rate into unabsorbed X-ray flux may be misleading. However, taking the spectral parameters derived by Smith et al. (1997), the HRI count rate of the second observation corresponds to a 0.1-2.4 keV unabsorbed flux of 1.9×10^{-7} ergs s^{-1} cm^{-2}. At 8.3 kpc, this flux translates to an X-ray luminosity about a factor of 10 larger than the Eddington limit for a 1.4 $M_{\odot}$ neutron star. On the other hand, decreasing the NH down to 10^{22} H atoms cm^{-2}, the 0.1-2.4 keV unabsorbed flux decreases by a factor of ~ 50 and becomes comparable to the value expected from the TTM/RXTE observations. This suggests that the change by a factor of ~ 10 in the source counting rate may be associated with a change in the NH between our two observations, and thus may not reflect a true change in the source intensity.

2.3. CFHT infrared observations inside the ROSAT HRI error box

Infrared J and H images were obtained at CFHT on 1996 June 1st using the OSIS instrument equipped with the Redeye and Nicmos 256×256 camera. In this configuration, the pixel size is 0.5″ on the sky. The total exposure time was 180 s in J and 210 s in H. Raw images were corrected for dark and flat-field using standard MIDAS procedures. Observations of photometric standard stars allowed to derive absolute J and H photometry with a 1σ systematic error of less than 0.04 mag in both bands. We show in Fig. 4 the H and J filter images with the HRI error circle overlayed. The infrared images reveal the presence of at least two tens of possible candidates in the small 10.1 arcsec radius HRI error circle derived from the first part of the observation. For indications, only objects C, D, G, H, K are included in the overlapping region of the error boxes (90% confidence level) of the PSPC and HRI positions. In Table 1 we list the magnitudes of the brightest objects located in and close to the HRI error circles.

With our observations, we also confirm the identification of IRAS 17311-2604 with variable star 2547 from Terzan & Gosset (1992). Our J and H images (not shown) reveal a bright infrared source at a position consistent with that of the optically variable star. The infrared source is unfortunately so bright that saturation prevents from deriving reliable J and H magnitudes.

Table 1. Infrared magnitudes, colors and positions of the brightest objects located in or close to the HRI error circle (equinox 2000). The error on the position is $\sim 0.5''$.

Object	J	J−H	RA (17h 34m ...s)	DEC (-26d 05′ ...″)
A	13.23 ± 0.04	0.88 ± 0.06	13.66	06.4
B	14.19 ± 0.07	1.09 ± 0.08	13.96	12.0
C	15.35 ± 0.13	1.21 ± 0.19	13.42	11.5
D	17.06 ± 0.90	2.27 ± 0.92	13.34	12.5
E	15.64 ± 0.10	1.20 ± 0.15	14.15	14.9
F	15.26 ± 0.10	1.26 ± 0.12	13.89	18.0
G	15.09 ± 0.10	1.25 ± 0.12	13.65	16.8
H	16.06 ± 0.30	1.07 ± 0.34	13.35	18.0
I	15.36 ± 0.10	0.98 ± 0.12	14.30	24.1
J	15.56 ± 0.50	0.42 ± 0.54	13.54	27.3
K	14.61 ± 0.08	0.97 ± 0.09	13.12	23.7
L	14.16 ± 0.05	0.97 ± 0.08	12.90	27.5
M	14.60 ± 0.04	1.21 ± 0.06	13.79	32.8

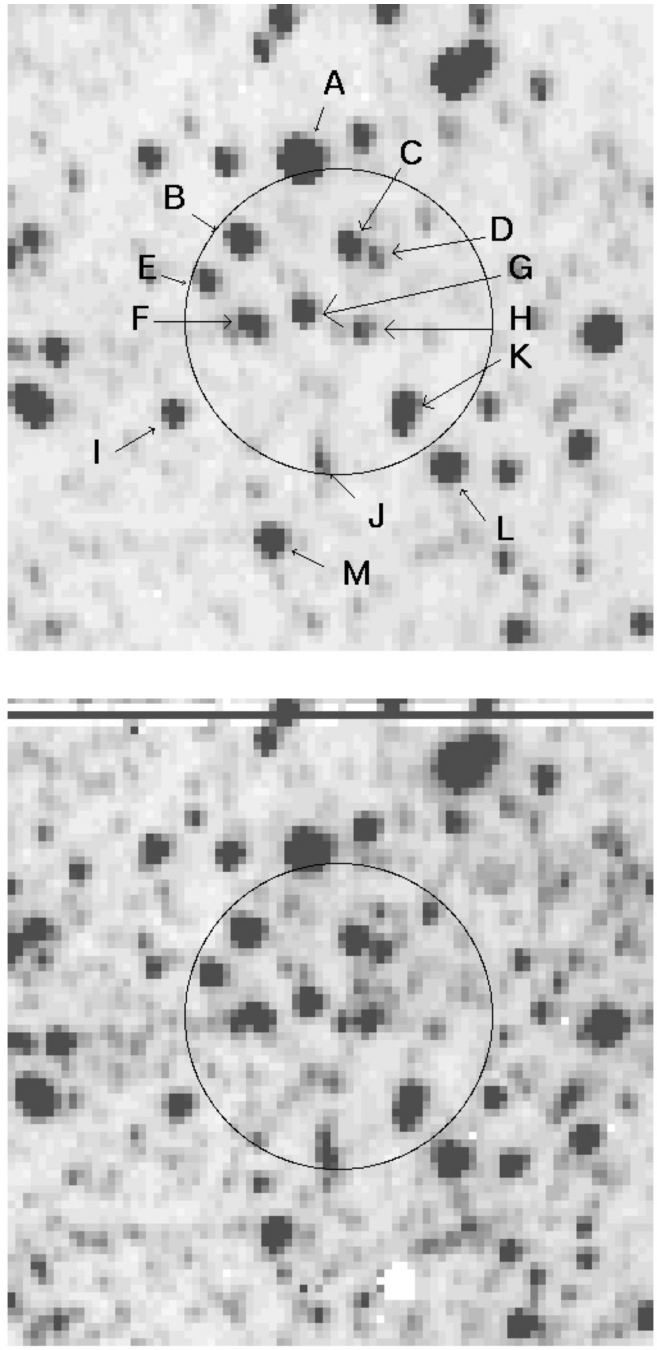

Fig. 4. The H (top) and J (bottom) images of the HRI error box of KS 1731-260 (see Table 1 for list of objects found in or around the error box on image H). The circle represents the error box as derived from the first part of the HRI observation (error box of HRI1 on Fig. 1).

3. Discussion

RXTE-ASM monitoring shows that KS 1731-260 is a source of persistent X-ray emission. This is not too surprising given the repeated detections of the source since its discovery in 1988. The RXTE-ASM 2-12 keV light curve of KS 1731-260 is shown in Fig. 5. The mean count rate (150 mCrab; 2-12 keV) translates to a 1-20 keV flux of $\sim 5.6 \times 10^{-9}$ ergs s^{-1} cm^{-2} comparable to those measured by TTM and ROSAT. Assuming a distance of 8.3 kpc and the spectral parameters observed by RXTE (Smith et al. 1997), this flux corresponds to a persistent X-ray luminosity of about 5.2×10^{37}ergs s^{-1}. This relatively high luminosity is associated with a soft spectrum and no hard X-ray emission. For indication, the RXTE spectrum which is well fit by a 5.5 keV thermal Bremsstrahlung model (Smith et al. 1997) predicts a hard X-ray flux which is about three orders of magnitude below the 40-150 keV flux observed by SIGMA (Barret et al. 1992). In its five year monitoring of the Galactic center region, SIGMA detected a hard X-ray tail from KS 1731-260 during only one one-day observation (Barret et al. 1992; Goldwurm et al. 1994). Since in X-ray bursters hard X-ray emission seems to be associated with low luminosity states (e.g. 4U1608-522: Zhang et al. 1996), both the SIGMA and RXTE results suggest therefore that KS 1731-260 spends most of its time in a high/soft luminosity state.

As said above, the main goal of our HRI observation was to accurately locate the source in order to test the two optical counterparts proposed by Cherepashchuk et al. (1994). We show in Fig. 6 the ROSAT HRI error box overlayed on ESO R plate No 520. The photographic plate was scanned at the MAMA with a pixel size of $0.675''$ and retrieved at CDS using the ALADIN interactive sky atlas (Bartlett et al. 1994). A set of local PPM standards allowed the absolute positioning of the HRI center with an accuracy of $\approx 0.3''$. None of the two former proposed candidates, objects 1 and 2 listed by Cherepashchuk et al. (1994) is now compatible with the improved HRI position. In particular, object 2, identified with variable star No 2547 from the catalogue of Terzan & Gosset (1992) cannot be associated with KS 1731-260.

Assuming that the photoelectric absorption seen in the soft X-ray band by ROSAT is entirely of interstellar origin implies $A_V \approx 7.2 \pm 1.1$ (Predehl & Schmitt 1995). This corresponds to $A_R \approx$5-6 for the effective wavelength of the ESO R plate but only $A_J \approx 2.0 \pm 0.3$ and $A_H \approx 1.25 \pm 0.20$ in the infrared bands.

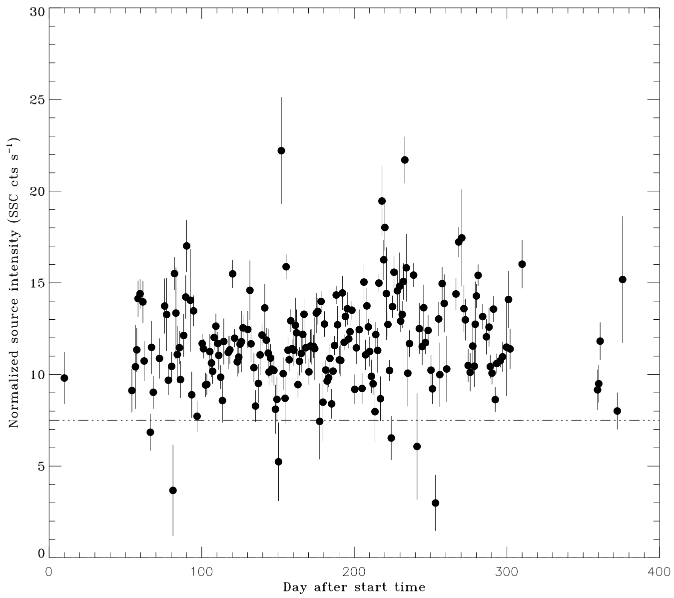

Fig. 5. The 2-12 keV light curve of KS 1731-260 as observed by the All Sky Monitor aboard the ROSSI X-ray Timing Explorer. The whole set of data spans a year (from 1997/1/6 to 1996/1/13) and shows that KS 1731-260 is a persistent X-ray source at the level of $\sim$ 150 mCrab. Each point is a 1-day average. The dot-dashed line corresponds to the flux of a 100 mCrab source for the ASM. Data have been retrieved from the Web site http://space.mit.edu/XTE/ASM-lc.html at Massachussets Institute of Technology. The first gap in the data is caused by the problems encountered by the ASM at the beginning of the mission. The second gap (from MJD 50395 to 50442) is caused by the sun traversing the Galactic Center region. During this interval, the sun was too close to KS 1731-260 for the ASM to observe it.

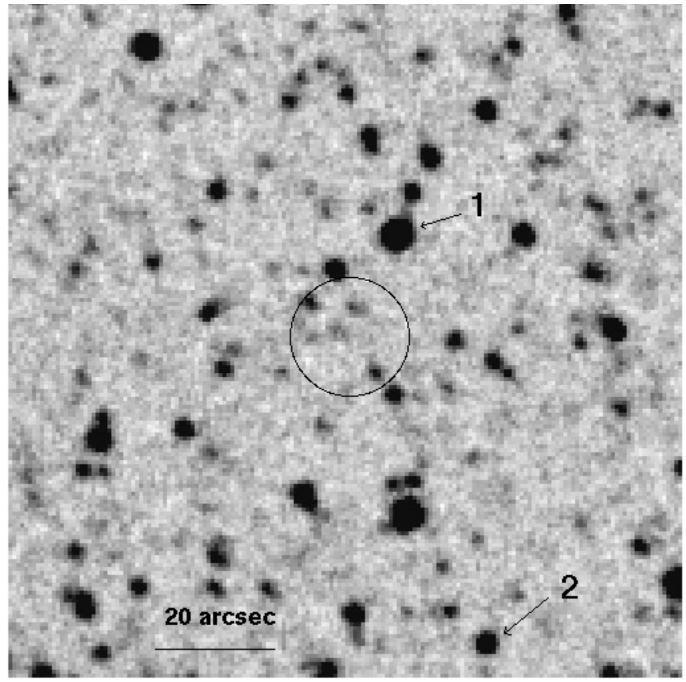

Fig. 6. The HRI error circle (for HRI1) overlayed on ESO R plate No 520. Objects 1 and 2 quoted as possible candidates by Cherepashchuk et al. (1994) are now excluded from the improved HRI error circle. North is at top and East to the left.

Unfortunately, no photometric calibration is yet available for the photographic plate. However, with an estimated R (630-690nm) limiting magnitude of $\approx$ 21-22 (West 1984), the faintest objects in the error circle seen on the ESO plate have R-J $\approx$ 6 or more, indicating a high reddening in the field, probably consistent with that assumed for KS 1731-260.

If the intrinsic J-H colors of KS 1731-260 are those of a hot OB star ($(J-H)_0 = -0.16$, Koorneef 1983), the counterpart should have a reddened J-H = 0.59 $\pm$ 0.11. This assumption holds independently from the low or high mass X-ray binary nature of the source since X-ray heating in a low-mass system probably still dominates near-infrared emission. Among the objects listed in Table 1, only D, H and J may have large enough errors on their J-H color index to be compatible with those of the expected blue counterpart. This would imply that the counterpart is fainter than H $\approx$ 14.8 and has an absolute H magnitude fainter than -1.0 (d = 8.3 kpc). Ignoring any constraints on the infrared colors, the H magnitude of the brightest candidate in the error circle (object B) implies an absolute H magnitude fainter than -2.7 (d = 8.3 kpc). These upper limits on the infrared brightness of KS 1731-260 clearly argue in favour of a low-mass companion as for all other X-ray bursters. With an absolute R magnitude of M_V = 0 to 6 (corresponding to M_H = -1 to 5) observed for X-ray bursters (van Paradijs & Mc Clintock 1994) the optical counterpart may have H magnitude in the range of 14 to 21 at a distance of 8 kpc and could therefore be within the reach of H band spectroscopy.

4. Conclusions

With the ROSAT-HRI, we have accurately determined the position of KS 1731-260 and showed that its error box does not contain any of the two proposed optical counterparts. On the other hand, our infrared imaging of the HRI error box reveals a large number of possible counterparts, all arguing in favour of a low mass system. H band spectroscopy could be performed and should eliminate some of them and reveal the true counterpart of the source. KS 1731-260 which is a persistent X-ray source since at least 1988 is going to be observed with RXTE during the second cycle of the guest investigator program. These observations will be useful is several ways; first to address the origin of possible intrinsic NH variations within the system (obscuration of the X-ray source by a disk corona, the outer disk, etc..). Secondly X-ray burst studies might help us to set even better constraints on the source distance and confirm the recent detection of millisecond pulsations.

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