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LETTER

Letter to the Editor

The isolated neutron star candidate RBS1223 (1RXS J130848.6+212708)

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Abstract. In the ROSAT Bright Survey (RBS) we have almost completely optically identified the brightest ∼2000 high-galactic latitude sources from the ROSAT All-Sky Survey Bright Source Catalogue (1RXS). A small number of sources has empty X-ray error circles on optical images. ROSAT HRI follow-up observations of RBS1223 (=1RXS J130848.6+212708), a soft object with extreme X-ray to optical flux ratio, have confirmed a relatively bright X-ray source, whose position could be determined to an accuracy of 1.6 arcsec (90%) due to the presence of a nearby, X-ray detected bright star. Deep Keck R- and B-band images of the field were taken, but the refined X-ray error circle remains empty to a limiting magnitude $B \sim 26^m$. With an X-ray to optical flux ratio of $\log(f_X/f_{\rm opt}) > 4.1$ this object is almost certainly an isolated neutron star, similar to the two so far best-known examples RX J1856.4–3754 and RX J0720.4–3125. We discuss limits on the number of similar objects in the RBS catalogue.

Key words: accretion, accretion disks – stars: neutron – X-rays: stars – stars: individual: RBS 1223

1. Introduction

The statistics of radio pulsars and supernova explosions as well as the abundance of heavy elements suggests that about 10^9 neutron stars must have been born in our Galaxy throughout its life (Narayan & Ostriker 1990, van den Berg & Tamman 1991). As young objects, $< 10^4$ yrs, neutron stars appear as rotation-powered bright X-ray and Gamma-ray sources or radio pulsars. At intermediate ages, $< 10^6$ yrs, nearby neutron stars can be detected by radiation from their cooling surface. At even later times, $> 10^6$ yrs, isolated neutron stars (INS) become too cold to be detected as a result of internal processes and could eventually only be seen through their photospheric emission in the X-ray band, if they accrete enough interstellar matter to heat their surface (Ostriker, Rees & Silk 1970). Depending on the assumption about their space velocity distribution, several thousand old INS could be detectable e.g. in the ROSAT All-Sky-Survey (RASS) (Treves & Colpi 1991; Blaes & Madau 1993; Madau & Blaes 1994).

Recently, two very good INS candidates have been reported: RX J1856.5–3754 (Walter et al. 1996), RX J0720.4–3125 (Haberl et al. 1997). Both of them were detected in the RASS as relatively bright sources (see Table 1) with soft, blackbody-like spectra and little interstellar absorption. Pointed follow-up observations with the ROSAT PSPC and/or HRI yielded very small X-ray error circles which put stringent constraints on possible optical counterparts. Walter & Matthews (1997) could identify RX J1856.5–3754 with a faint blue object in an HST observation ($V = 25\overset{\rm m}{.}8, U = 24\overset{\rm m}{.}5$). The extremely large X-ray to optical flux ratio $\log(f_X/f_{\rm opt}) = 4.8$ excludes anything other than an isolated neutron star for this object. Recent observations of the likely counterpart of RX J0720.4–3125 (star X1) reveals $B = 26\overset{\rm m}{.}1$ (Motch & Haberl 1998) and $B = 26\overset{\rm m}{.}6$ (Kulkarni & van Kerkwijk 1998, KvK98). With $B > 26^m$ the inferred ratio $\log(f_X/f_{\rm opt}) > 5.3$ again indicates an INS origin for the X-ray emission. On long time scales the X-ray emission of the two INS candidates is almost constant. However, most remarkably, pulsations with a period of 8.4 seconds were detected for RX J0720.4–3125, which, under the assumption of accretion, indicate a low magnetic field (∼10^{10} G) and a small space velocity (∼10 km s^{-1}) for the neutron star (Haberl et al. 1997). A third, fainter candidate INS, RX J0806.4–4123, also detected in the RASS has been reported by Haberl et al. (1998). Its optical counterpart has $B > 24^m$ such that $\log(f_X/f_{\rm opt}) > 3.4$.

Assuming that only two INS with count rates ∼2 PSPC cts s^{-1} exist in the RASS, we expect a number of order 20 over the whole sky with count rates ∼0.2 cts s^{-1} (c.f. Neuhäuser & Trümper 1998).

2. The ROSAT Bright Survey (RBS)

In order to improve the determination of the X-ray luminosity function of X-ray emitting source classes, mainly AGNs, galax-

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Table 1. Summary of isolated neutron star candidates

Name	PSPC [cts s^{-1}]	HR1[1]	HR2[2]	$kT_{\rm bb}$ [eV]	N_H [10^{20} cm^{-2}]	B [mag]	log $f$xo[3]	Reference
RX J1856	3.64 ± 0.15	-0.73 ± 0.04	-0.92 ± 0.07	~ 57	1	25.8^4	4.8	Walter et al. (1996)
RX J0720	1.69 ± 0.07	-0.57 ± 0.03	-0.87 ± 0.12	~ 79	1	>26	>5.3	Haberl et al. (1997)
RX J0806	0.38 ± 0.03	-0.53 ± 0.07	-0.73 ± 0.18	78 ± 7	2.5 ± 0.9	>24	>3.4	Haberl et al. (1998)
RBS1556	0.88 ± 0.04	-0.70 ± 0.03	-0.58 ± 0.10	100 ± 10	< 1	>22	>3.5	this paper
RBS1223	0.29 ± 0.02	-0.20 ± 0.08	-0.51 ± 0.11	118 ± 13	$0.5 - 2.1$	>26	>4.1	this paper

[1] Standard ROSAT hardness ratio HR1: $((0.5 - 2\,{\rm keV}) - (0.1 - 0.4\,{\rm keV}))$ / $((0.5 - 2\,{\rm keV}) + (0.1 - 0.4\,{\rm keV}))$
[2] Standard ROSAT hardness ratio HR2: $((0.9 - 2\,{\rm keV}) - (0.5 - 0.9\,{\rm keV}))$ / $((0.9 - 2\,{\rm keV}) + (0.5 - 0.9\,{\rm keV}))$
[3] X-ray to optical flux ratio $\log(f_{\rm X}/f_{\rm opt})$
[4] V-magnitude

ies and clusters of galaxies, we have almost completed a program of optical identifications of bright, high-galactic-latitude X-ray sources, termed the ROSAT Bright Survey RBS. The goal is to completely identify all bright X-ray sources, > 0.2 PSPC cts s^{-1}, detected in the ROSAT All-Sky Survey (1RXS catalogue, Voges et al. 1996) at galactic latitudes $|b| > 30^o$, excluding LMC, SMC and the Virgo cluster (Hasinger et al. 1997; Fischer et al. 1998; Schwope et al. 1998).

The RBS is already to 98% spectroscopically complete. We find a total of 757 stars, 659 AGN, 297 clusters of galaxies, 171 BL Lac candidates, 43 Galaxies, 49 Cataclysmic variables or X-ray binaries. Only 36 of the more than 2000 sources in the sample are not yet identified. Among the known types of X-ray emitters, the BL Lac objects are those with the most extreme X-ray to optical flux ratio. Yet the optically faintest BL Lac objects at $V \simeq 20\overset{\rm m}{.}5$ have $f_{\rm X}/f_{\rm opt} < 10^2$ (Fig. 3 shows the ratio $f_{\rm X}/f_{\rm opt}$ for BL Lac objects, INS candidates and unidentified RBS sources).

For all unidentified X-ray sources we have produced finding charts from the ROE/NRL and APM digitised sky survey catalogues. The position errors of bright RASS-sources are of sufficient quality that we can immediately localize X-ray sources with empty RASS error circles on the sky survey plates. For quite a number of such objects we have been awarded short follow-up observations with the ROSAT HRI in the last years or looked in the archive, in order to investigate whether the source is a fluke or has an exceptionally large X-ray position error (a number of such objects existed in the first processing of the all-sky-survey, RASS-I). Another possibility is that the X-ray source is extended (cluster or group) and therefore has a formally empty error circle. Finally, in one case so far the HRI confirmed the position and flux of the X-ray source and has put very strong constraints on the magnitude of an optical counterpart.

3. X-ray observations of RBS1223

The field of RBS1223 has been observed with the ROSAT HRI on June 13, 1997 at 19:58 UT for a net exposure time of 2218s. We have corrected the individual X-ray photons for the HRI plate-scale factor of 0.9972 (Hasinger et al. 1998) and then analysed the data using the standard interactive analysis system EXSAS (Zimmermann et al. 1994). The HRI observation showed a point-like X-ray source consistent with the position of 1RXS J130848.6+212708. Positions of ROSAT pointed sources have a routine accuracy of $\sim$10$''$ due to inherent attitude errors. The HRI position of RBS1223 however, could be related to an absolute celestial reference system through the fortuitous detection of a second, fainter HRI source about 4.5 arcmin west of RBS1223, which could be identified with the bright ($V = 8\overset{\rm m}{.}2$) star AG+21 1341 (using SIMBAD). The X-ray position of the second HRI source is within $0.8 \pm 0.7''$ of the optical position of AG+21 1341, as determined from the APM catalogue. We did not consider it necessary to correct for this shift. The final position of RBS1223 is therefore RA(2000)= $13^h08^m48.17^s$, DEC(2000)= $21^o27'07.5''$. Taking into account the statistical accuracy of the centroiding for both sources, the 90% position error for RBS1223 is 1.6 arcsec. Fig. 1 shows a superposition of the X-ray contours of the RBS1223 field on a digitised copy of the POSS-II plate, clearly indicating an empty error box down to the plate limit.

The HRI count rate of RBS1223, 0.12 ± 0.01 cts s^{-1}, is comparable to the PSPC count rate of 0.29 ± 0.02 cts s^{-1}. RBS1223 has PSPC hardness ratios which can be fit with a blackbody temperature of 118 ± 13 eV, and an interstellar absorption column density of $N_{\rm H} = (0.5-2.1) \times 10^{20}$ cm^{-2}, consistent with the total galactic value in this direction, $N_{\rm H,gal} = 2.1 \times 10^{20}$ cm^{-2}. The unabsorbed blackbody flux at earth is about 4.5×10^{-12} erg cm^{-2} s^{-1}. We have analysed the ~ 266 HRI photons from RBS1223 for periodicities in the X-ray flux, but did not detect any significant signal in the Fourier transform of the data.

4. Optical observations of RBS1223

Images of the RBS1223 field have been obtained with the Low Resolution Imaging Spectrometer (Oke et al. 1995) at the Cassegrain focus of the Keck II telescope on the photometric night of March 19th, 1998. The 2048×2048 pixel Loral CCD was read out in single amplifier mode. A 15 min exposure

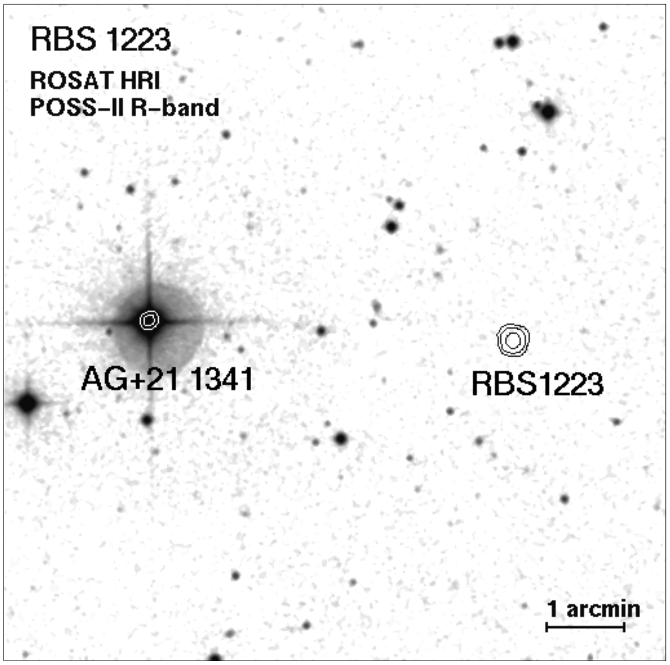

Fig. 1. ROSAT HRI X-ray contours of the observation of RBS1223 superposed on the digitised Poss-II R-band image. A second HRI source 4.5 arcmin to the East of RBS1223 could fortuitously be identified with the 8th magnitude star AG+21 1341

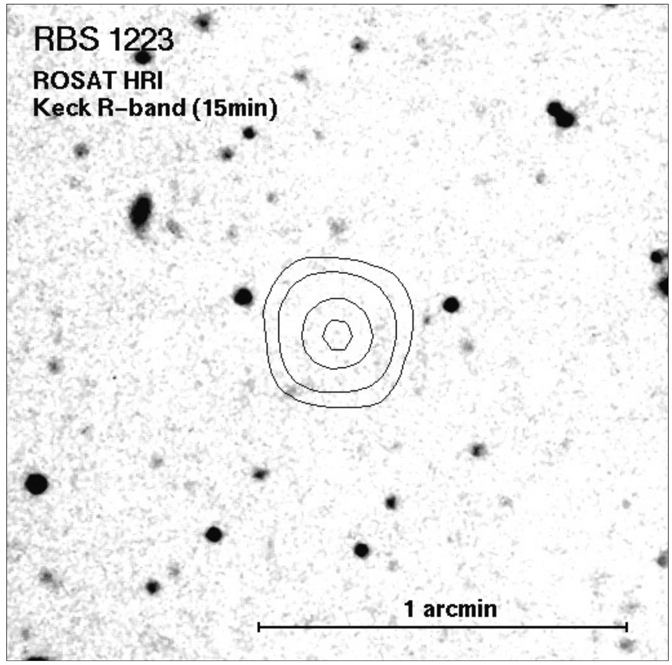

Fig. 2. ROSAT HRI contours of RBS1223 superposed on a 15 min R-band Keck II exposure. Contours are at 4, 11, 45 and 90% of the peak emission. The radius of the innermost contour is about 2.5 arcsec, i.e. larger than the actual error circle. No optical counterpart is seen to the plate limit of $R \sim 26$

through the R filter was taken at 13:33 UT and a 15 min exposure through the B filter at 13:52 UT. The reduction was done using MIDAS. The two frames were bias subtracted, cleaned of cosmic rays and flat-fielded using twilight flats. No photometric standards were taken. Using the brightness limits derived by KvK98 for the same instrumental setup and same observing conditions we estimate the limiting magnitude of our images at about 26^m by scaling with the sqaureroot of the integration time. For our estimate of the X-ray to optical flux ratio we used the conservative limit of $B = 25.^{\rm m}5$. Fig. 2 shows the HRI X-ray contours of RBS1223 superposed on the R Keck image. No optical counterpart is detected in the X-ray error circle in either the R or the B image. Using the observed X-ray flux from above we derive a lower limit of $\log(f_{\rm X}/f_{\rm opt} > 4.1$, using the relation $f_{\rm opt} = 10^{-0.4(V+13.42)}$ (Maccacaro et al. 1988) under the assumption of $V = B$.

5. Discussion

RBS1223 has all properties that single out the new class of isolated neutron stars identified by ROSAT: a very high X-ray to optical flux ratio, a rather soft X-ray spectrum and a constant X-ray flux over long time scales. With its very small X-ray error box it will provide a further challenge for optical identification. Scaling from the counterpart of RX J1856.5–3754 (Walter & Matthews 1998) we expect its optical magnitude in the range $R = 28^m - 29^m$, within reach of the HST and ground-based 8–10m telescopes. The direct prediction of the optical brightness assuming pure blackbody radiation with the spectral parameters of Table 1 gives only $V = 31.^{\rm m}5 - 32.^{\rm m}5$, beyond the limit of current telescopes.

Fig. 3 shows the extreme position of RBS1223 and the other INS candidates of Table 1 plotted in a kind of X-ray/optical colour-colour diagram together with the otherwise most extreme point-like RBS sources, the BL Lac objects. Only sources with a very peaked X-ray-optical spectrum can be in the upper left corner of this diagram. RBS1223 is the faintest of all known INS candidates and has also the highest X-ray temperature. Among the 36 unidentified RBS sources, there is only a handful of objects with X-ray hardness ratios consistent with INS. (We have, however, to be careful about possible misidentified objects in X-ray surveys). The next best INS candidate from the ROSAT Bright Survey is RBS1556, which lies in the same part of the diagram. At somewhat lower values of $\log(f_{\rm X}/f_{\rm opt})$ there are a number of unidentified objects, which could be either BL Lac candidates or INS. Assuming between 2 and 10 candidate objects in the RBS, a rough estimate of the surface density of INS brighter than 0.2 PSPC cts/s is $0.5 - 1.8$ sources sr^{-1}. The lower and upper limit can provide strong constraints on the INS $\log N - \log S$ function and therefore on the nature of the population as a whole.

The accreting old neutron star scenario was recently criticized because of a number of highly uncertain assumptions or unlikely requirements (see the discussion in KvK98; Wang et al. 1998). A very low magnetic field is required to overcome the propeller effect and allow accretion. ISM accretion would most likely be highly variable on time-scales of months

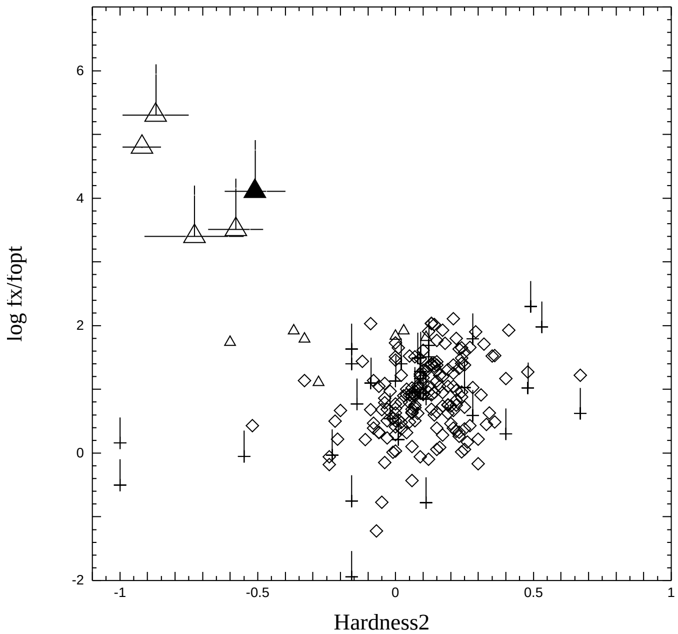

Fig. 3. X-ray/optical colour colour diagram for selected point-like RBS sources. $\log(f_{\rm X}/f_{\rm opt})$ is plotted against the hardness ratio HR2, defined in the standard ROSAT way (see Table 1). Diamonds are BL Lac objects (or candidates) and plus signs are unidentified objects. For the latter the optical magnitude of the brightest object in the error circle, or $V = 20\overset{\rm m}{.}5$ for empty error circles has been assumed. The INS objects (or candidates) listed in Table 1 are shown with large triangles (filled symbol for RBS1223). Other INS candidates from the RBS are shown with small triangles

to years. Finally, accreting neutron stars would quickly build up a hydrogen-rich envelope, which should appear much brighter in the optical band than is detected for INS (Wang et al. 1998).

Several authors have therefore proposed alternatives or variants for the nature of isolated neutron star candidates. Haberl et al. (1997) suggest a connection of RX J0720.4–3125 to the class of anomalous pulsars (Mereghetti & Stella 1995) which might be born with low space velocities and magnetic fields. KvK98 discuss the interesting possibility that the INS candidates are cooling magnetars, very high magnetic field isolated neutron stars with long spin period, which are associated with soft gamma ray repeaters. At any rate, the detection of more objects of this class and their detailed study with existing and upcoming X-ray and optical instruments is of vital importance for the understanding of their nature.

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