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Letter to the Editor

On the X-ray position and deep optical imaging of the neutron star candidate RXJ1856.5-3754 ⋆

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Abstract. We present X-ray and optical studies of the ROSAT source RXJ1856.5-3754, a neutron star candidate. With recent optical observations of a potential optical counterpart to another X-ray source in the field and correcting the X-ray positions for two effects not taken into account before, we determine the ROSAT X-ray source position and its error, both different from previous work. Also, we present deep optical imaging in B and V obtained with the ESO - MPI 2.2 m telescope on La Silla and in B and R obtained with the Keck telescope.

Key words: Neutron star: individual: RXJ1856.5-3754

1. Introduction

From the rate of supernovae that produce neutron stars (NS), it is expected that the Galaxy is populated by 10^8 to 10^9 NS. However, only $\sim$ 700 radio pulsars have been discovered so far (Taylor et al. 1995). NS, which are not active as radio pulsars, may be visible as soft X-ray sources, if $T > 10^5\ K$: Old NS due to accretion of material from the interstellar medium (Ostriker et al. 1970) and young and middle-aged NS due to emission from a cooling surface (e.g. Becker 1995). Many such old NS were expected to be detectable with the ROSAT All-Sky Survey (RASS) in the 0.1 to 2.4 keV range (Treves & Colpi 1991, Blaes & Madau 1993). In the optical we expect to see the faint end of, e.g., a blackbody spectrum, i.e. old NS show very large X-ray to optical flux ratios: For an old NS near the RASS detection limit ($\sim$ 0.01 cts s^{-1}), we expect $V \approx 30$ mag, difficult to identify with the largest optical telescopes. Danner (1996) surveyed all clouds listed in Magnani et al. (1985) for old NS, which should be detectable with RASS, if they move slowly through these clouds. There are $\sim$ 90 RASS sources projected onto the clouds, but Danner (1996) did not identify any old NS candidate. Such X-ray bright, old NS may be very rare, possibly due to a large birth velocity of NS (Lorimer et al. 1995), as spherical accretion depends on the relative velocity.

Walter, Wolk, & Neuhäuser (1996, WWN96) presented the very bright, super-soft X-ray source RXJ1856.5-3754 as old NS. It was detected first by the *Einstein Observatory* slew survey, then with RASS and ROSAT pointed observations with both the Positional Sensitive Proportional Counter (PSPC) and the High Resolution Imager (HRI). For details on ROSAT, see Trümper (1983). WWN96 found no counterpart down to $V \sim 23$ mag and $f_X/f_V > 7000$. No variability on timescales from ms to yrs was found (WWN96; Neuhäuser, Walter, & Wolk 1996, NWW96; Pavlov, Zavlin, Trümper, Neuhäuser 1996, PZTN96; Campana et al. 1996, CMS96). The X-ray spectrum as observed with the 6 $ksec$ ROSAT PSPC observation shows a $kT = 57eV$ blackbody with an absorbing column density corresponding to $A_V = 0.1$ mag (WWN96). If this source is a NS, then it may well be middle-aged or old, as it cannot be associated with any SNR and it does not show pulsation. As pointed out by Bignami (1996), Caraveo et al. (1996), CMS96, and Haberl et al. (1997), the properties of RXJ1856.5-3754 are not that different from middle-aged NS, like the radio-quite Geminga or other normally behaving pulsars, so that one may not need to invoke accretion from interstellar medium as source for the strong emission instead of the hot surface of a cooling NS; e.g., RXJ0720.4-3125 is very similar to RXJ1856.5-3754, but pulsating with 8.39 s (Haberl et al. 1997).

2. The location of RXJ1856.5-3754

WWN96 have taken a 18 $ksec$ HRI observation centered on RXJ1856.5-3754 and obtained their source positions with SASS 7.5. From the small offset between a GSC star's optical and X-ray position, they conclude that the HRI X-ray position of RXJ1856.5-3754 has an error circle with a 1.5″ radius only.

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⋆ partly based on observations collected at the European Southern Observatory 1.5m and 2.2m telescopes on La Silla during programs 57.E-0646, 57.MPI-3, and 57.MPI-5

2.1. Identification and position of RXJ1855.1-3754

We reanalysed the ROSAT HRI observation using EXSAS commands for source detection (Zimmermann et al. 1994). There is only one other X-ray source (RXJ1855.1-3754 at 16.65′ off-axis) in the HRI field with an obvious near-by optical counterpart, namely GSC star 79160050. WWN96 already used the position of this GSC star to estimate the HRI bore-sight correction, which may be as large as 10″. WWN96 obtained just 0.7″ as offset between the GSC star's optical and X-ray position – concluding that the bore-sight offset is very small. With EXSAS, we obtain 4.7″ as offset between the optical position of this GSC star and the HRI source RXJ1855.1-3754, which is different from the offset obtained by WWN96 for two reasons: SASS 7.5 gives less accurate positions for faint source far off-axis compared to EXSAS, because EXSAS routines construct better background maps due to several small improvements, which have the most important effects far off-axis. And neither SASS 7.5 nor EXSAS (version Jan96 under MIDAS Nov95) correct for the fact that two pixels on an HRI image correspond to only 0.9957″ instead of 1″ as assumed so far (David et al. 1996 and G. Hasinger, private communication). In the case of RXJ1855.1-3754, the effect amounts to 4.3″ in α and 0.2″ in δ. We corrected for this effect and obtain $\alpha_{2000} = 18^h55^m12^s$ and $\delta_{2000} = -37°53'47.3''$; the statistical 1σ error of this position is $\pm 4''$, i.e. quite large as the source is faint and far off-axis. It is not possible to determine a more precise position from the PSPC pointed observation, because the source is not detected (its HRI count rate converts to a PSPC count rate just below the detection limit). The shift in α and δ between this X-ray position and the GSC star optical position is a first approximation to the bore-sight correction.

However, this GSC star may either not be the true counterpart to the X-ray source and/or have high space motion, so that it moved significantly between the observation done to obtain the GSC position and the HRI observation. To check this, we obtained optical spectra of the GSC star in order to study its nature. Optical spectra were taken in July 1996 in a program aimed at identifying T Tauri stars among ROSAT sources using the ESO 1.52 m telescope on La Silla equipped with a Boller and Chivens spectrograph. The mean resolution of $\sim$ 2.5 Å (FWHM) in the 4600 to 7000 Å spectral range allows us to resolve the Lithium absorption line at 6707 Å from the near-by Calcium line. We reduced the data with MIDAS.

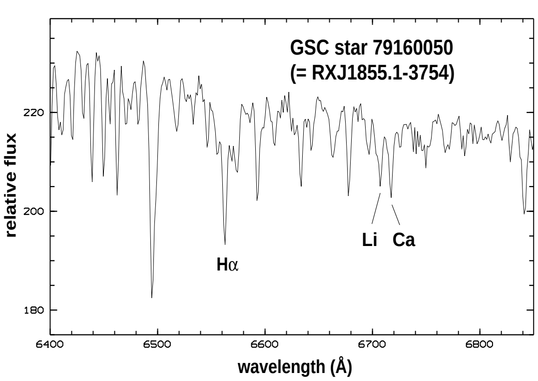

Fig. 1. Optical spectrum of GSC 79160050: The structured $H\alpha$ line (emission filling in the absorption), the Lithium (and Ca) absorption, and the spectral type K3 are all typical for T Tauri stars

The spectrum of this star (shown in figure 1 as obtained on 1996 July 21) is typical for naked weak-line T Tauri stars, low-mass pre-main sequence stars with $H\alpha$ absorption filled in with emission, Lithium 6707 Å absorption, and strong coronal X-ray emission (c.f. Appenzeller & Mundt 1989, for a review on T Tauri stars). Hence, this star is most certainly the true optical counterpart to the X-ray source. We also obtained a CCD image of this star and its surrounding with the ESO - MPI 2.2 m telescope (equipped with EFOSC 2) on La Silla on 1996 July 23. Its current position (epoch 1996.56) is not different from the positions taken for GSC (epoch 1974.56) and DSS (epoch 1987.63), i.e. this star has neglible proper motion. We measured $V = 12.98 \pm 0.02$ mag for this star consistent with $V \sim 12.75 \pm 0.4$ mag as listed in the GSC.

2.2. The X-ray position of RXJ1856.5-3754

Now, we know the offset between the HRI and the optical position (2.1″ shift in α to the west and 3.9″ shift in δ to the south). Before we can correct the central HRI source position for this bore-sight offset, we have to correct the X-ray position of this source for the pixel effect mentioned above. For the central source, we obtain with EXSAS an HRI position, which is almost the same as given by WWN96, because the source is bright and lies at only 0.12′ off-axis; its statistical 1σ error is just $\pm 0.5''$. The X-ray position obtained with the PSPC pointed observation is less accurate, but consistent with the HRI position. The central X-ray position corrected for both the pixel effect and the bore-sight offset is $\alpha_{2000} = 18^h56^m35.29^s$ and $\delta_{2000} = -37°54'34.4''$. The 1σ error of this position is $\sim 5''$, due to statistical uncertainties in the two HRI X-ray source positions and the error in the optical position of the GSC star ($\pm 0.4''$), which contributes to the error in the boresight correction. The RASS position as listed in RASS Bright Source Catalog (Voges et al. 1997) is very close to our corrected HRI position, with an offset of just $-2.2''$ in α and 0.9″ in δ, and also with an error of just 7″. The position from the ROSAT PSPC pointed observation is much less precise ($\pm 20''$), because it was far off-axis, while on-axis at several RASS scans.

The HRI observation has been performed in 128 time intervals lasting between 1 and 2128 s spread over $\sim$ 32 hours. CMS96 also analysed the X-ray position of the source and argue that the HRI position appears to be different from slot to slot, i.e. that ROSAT has had pointing or attitude problems. According to CMS96, after merging the observations from different slot together, the source appears to be elongated (20″ in NS direction). By checking the position of the central HRI source in all slots, we find that neither is the source elongated nor are there any attitude problems. The observed point spread function (PSF) of the central source is consistent with the PSF expected at the 0.12′ off-axis angle: the source is not elongated, but slightly extended in a circular fashion with the FWHM being 6.2″. We detect no variability. Also, none of all the other X-ray sources in the field appear to be elongated. The PSPC X-ray position obtained by CMS96 also is different (shifted by 18″ to the south) from positions obtained by both us and Voges et al. (1997) for RASS and from those obtained by us, WWN96, and PZTN96 for the PSPC and HRI pointings.

2.3. Is RXJ1856.5-3754 foreground to the CrA cloud ?

CMS96 also present some spectral modeling of the PSPC X-ray spectrum. Their results for the blackbody, Raymond-Smith, and power law models are essentially the same as published in WWN96, NWW96, and PZTN96. In addition to those models, CMS96 also performed another specific NS model, the Zampieri model (Zampieri et al. 1995), for which their χ^2 is slightly larger than for their black body fit. Also, they get a distance too small for the luminosity, so that they conclude that the star may have a non-neglible magnetic field. PZTN96 came to the same conclusion, as only their magnetic H model with $B = 10^{12}$ G yielding $V \approx 24$ to 26 mag at $\sim$ 12 pc cannot be excluded from the present data. For their non-magnetic H and He atmospheres, they expect magnitudes ($20 < V < 22$ mag), brigther than the observed limit (WWN96). For a non-magnetic Fe atmosphere, they predict V = 27.5 mag, but their best fit distance is larger than the distance to the CrA cloud.

However, both PZTN96 and CMS96 argue that their fits yielding distances larger than towards the CrA dark cloud may still be correct, if the object is seen either through a hole in the cloud or just off the cloud borders. To investigate this possibility, we plot IRAS 100 μm contours (levels 12, 20, and 30) of the CrA cloud (figure 2). However, from this figure, the situation as to whether or not the source is foreground, is inconclusive. As the column density is $A_V \sim 3$ mag towards the center of the CrA dark cloud and $A_V \sim 0.7$ mag towards the cloud filament at the position of RXJ1856.5-3756 (Rossano 1978), the source may well be foreground to the CrA cloud, i.e. at less than $\sim$ 130 pc distance (Marraco & Rydgren 1981).

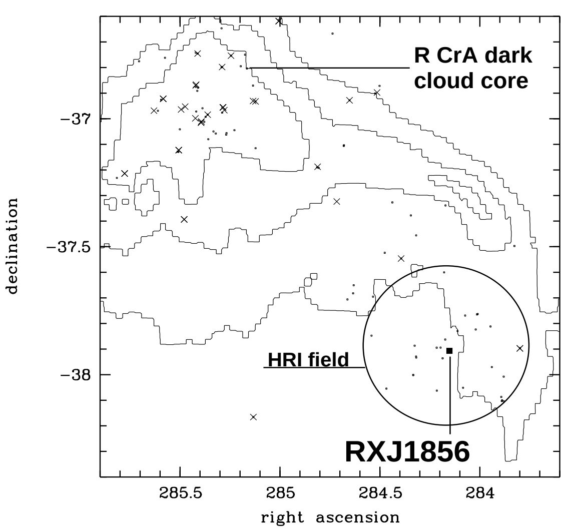

Fig. 2. The IRAS map around RXJ1856.5-3754: Three IRAS 100 μm contour levels are shown for the CrA cloud complex, with the dark cloud core and a filament typical for a star forming region. Crosses are T Tauri stars, small dots are PSPC and HRI pointed sources, the large circle is the HRI field, and the square indicates the field around the central X-ray position shown in figure 3

3. Optical Imaging

We obtained deep optical images in V and B of the field around RXJ1856.5-3754 at the ESO - MPI 2.2 m telescope equipped with EFOSC 2. The V image consists of 33 exposures with 6930 s total exposure, the B image of four exposures with total exposure of 1200 s, all obtained between 1996 July 11 to 20. The seeing was $\sim 1''$ during most observations and our limiting magnitudes are $V \sim 25$ mag and $B \sim 22.5$ mag. We were also able to obtain two CCD frames in the Kron-Cousins R and B band with the 10 m W.M. Keck telescope. The data were taken on 1995 June 3 with the LRIS instrument in its imaging mode. We integrated for 360 s in R and 600 s in B. Limiting magnitudes are $B \sim 24$ mag and $R \sim 24$ mag. Observing conditions were photometric with seeing between $1.0''$ and $1.5''$. We reduced all our images with standard MIDAS proceedures and used different Landolt fields for calibration. Magnitudes are compiled in Table 1; B magnitudes obtained for several stars with both the ESO - MPI 2.2 m and the Keck telescope agree very well within our errors; CMS96 also have done optical imaging (ten times less deep than ours), they used the Gunn filters g, r, and i. We present in figure 3 our deep optical image, which was obtained by adding up all our images in B, V, and R in order to get as deep as possible.

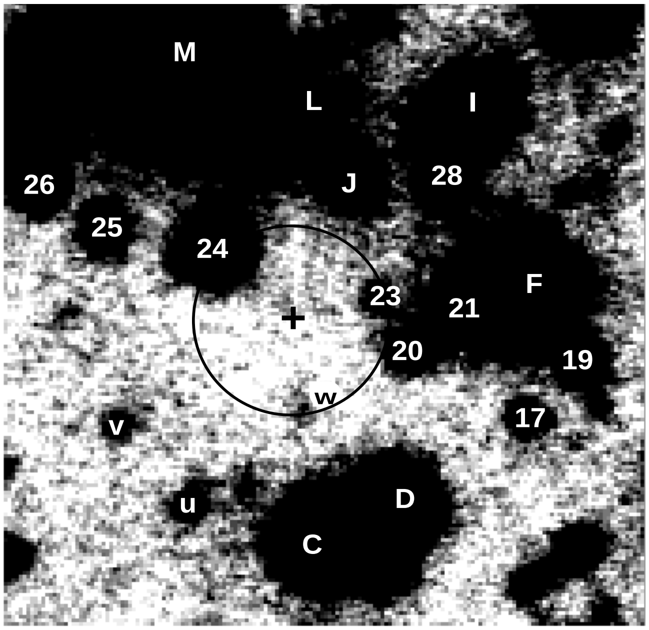

Fig. 3. Deep B+V+R image of the RXJ1856.5-3754 field. North is up, east to the left. Designations follow those by WWN96 (capital letters) and CMS96 (numbers), objects labeled with small letters are new detections. We show our central HRI position (+) corrected for pixel effect and bore-sight offset and its $5''$ error circle

4. Summary, discussion and conclusions

To estimate the bore-sight correction of the ROSAT HRI observation of the neutron star candidate RXJ1856.5-3754, we identified another X-ray source in the field and confirmed that its proper motion is neglible, both done with optical follow-up observations. Also, we took into account that two pixels on the HRI do not correspond to exactly one arc second. Thus, we could obtain a very precise X-ray position of RXJ1856.5-3754 and its error. We tried to identify the optical counterpart by deep imaging. If RXJ1856.5-3754 is a NS, its optical counterpart may be blue ($B-V \approx -0.3$ mag and $V-R \approx -0.3$ mag). However, the middle-aged NS Geminga and PSR0656+14 are not blue (Bignami et al. 1996, Pavlov et al. 1996).

Table 1. Magnitudes of objects near RXJ1856.5–3754. No entry means 'not detected'. The precision for ESO data for objects brighter than $\sim$ 20 mag is $\pm$0.02 in V and $\pm$0.05 in B; for objects with magnitude between 20 and 23, the error is $\pm$0.05 in V and $\pm$0.1 in B; for even fainter objects, the errors are $\pm$0.2. The precision for Keck data is $\pm$0.05 for objects brighter than 22 mag, $\pm$0.2 for objects between 22 and 24 mag, and $\pm$0.5 for the faintest objects. Reddening correction with A_V = 0.144 mag known from the X-ray spectral fit (WWN96).

Designation	V [a]	$B-V$ [a]	$V-R$ [b]	g [c]	$g-i$ [c]
WWN-C	18.21	0.45	0.63	18.27	-0.03
WWN-D	18.72	0.68	0.81	18.83	0.33
WWN-F	17.45	0.52	0.69	17.54	-0.06
WWN-I	18.92	0.69	0.79	19.09	0.82
WWN-J	21.18	0.85	0.64	21.39	0.85
WWN-L	17.75	0.43	0.65	17.82	-0.18
WWN-M	15.69	0.34	0.38 [d]	15.72	0.44
CMS-17	24.52		1.63		
CMS-19	22.40	1.19	0.84	22.50	1.08
CMS-20	23.92		1.23		
CMS-21	21.54	1.96	0.94	21.50	1.32
CMS-23	24.41		0.17		
CMS-24	20.85	1.82	1.19	20.89	1.33
CMS-25	22.24	1.49	0.90	22.12	0.17
CMS-26	21.84	1.23	0.84	21.64	0.64
CMS-28	22.05	1.00	0.76	21.85	0.63
object u	23.88				
object v	20.88				
object w	detected in combined $B+V+R$ image only				

Remarks: a. All V data (and B data for WWN objects) from ESO, B data for other objects from Keck. Color-correction for objects detected in B via $V = V_{ncc} + 0.059 \cdot (B_{ncc} - V_{ncc})$ and $B = B_{ncc} + 0.229 \cdot (B_{ncc} - V_{ncc}) - 0.035 \cdot (B_{ncc} - V_{ncc}) \cdot a$ with V_{ncc} and B_{ncc} for 'not-color-corrected' and airmass a. Magnitudes and colors given in WWN96 are not color-corrected and suffer from a slightly incorrect zero point.
b. All R data from Keck (except for WWN-M).
c. All g and i data from CMS96 (ESO - Danish 1.54 m).
d. R magnitude from WWN96 as saturated in Keck image.

There are several relatively bright objects (C, D, F, J, L, 21, and 24) within $\sim 10''$ of our X-ray position, which could be the optical counterpart to RXJ1856.5-3754 given the X-ray to optical flux ratio, e.g. any of them could be a CV with a magnetic white dwarf. However, as neither the X-ray flux of RXJ1856.5-3754 not the optical fluxes and colors of these objects are variable (neither within our 37 ESO V and B band exposures nor compared to the images taken on Keck and those by WWN96), we can eliminate these objects as true optical counterparts with very high probability. Also, none of them is blue, while almost all known NS and CVs are blue.

There are two stars (23 and w) within our error circle, and two more stars (20 and 24) just outside of it (figure 3). Objects no. 20 and 23 have magnitudes consistent with an old NS with H atmosphere and $B \sim 10^{12}$ G according to PZTN96. Although neither of them was detected in our B images, this does not argue against being a NS, since their expected magnitudes ($B \approx 24$ mag) are very close to our detection limit, even if they were blue NS. The colors of objects no. 20 and 23 are determined with low precision only, because they are close to our detection limit, so that we can only conclude that they are neither inconsistent with blue NS models nor with colors observed for Geminga and PSR0656+14. We note that present-day model atmospheres are somewhat unreliable as they cannot reproduce all the observed NS spectra.

With $V \sim 24$ mag or fainter, we obtain an X-ray to optical flux ratio of $\geq 10^4$ for the central X-ray source, which may well be an isolated (i.e. not in a binary system) NS. If the object is moving through the CrA (or some other) cloud, the complete picture would be consistent with the X-ray source being an old NS accreting from the cloud material. If the source is not within a cloud, but still a NS, then it may well be a middle-aged NS with emission from a cooling surface. Since old NS do not appear to be blue, one should not rely on the color when identifying this source as an old NS. Instead, one will rely on a precise measurement of its parallax and/or proper motion.

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