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Is RX J1856.5-3754 an old neutron star?

S. Campana[1,2], **S. Mereghetti**[3], **and L. Sidoli**[3]

[1] Osservatorio Astronomico di Brera, Via Bianchi 46, I-22055 Merate (Lc), Italy (campana@merate.mi.astro.it)
[2] Affiliated to I.C.R.A.
[3] Istituto di Fisica Cosmica del C.N.R., Via Bassini 15, I-20133 Milano, Italy ((sandro, sidoli)@ifctr.mi.cnr.it)

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Abstract. An unusual X-ray source, RX J1856.5-3754, has recently been discovered with ROSAT: its spectrum resembles that of supersoft sources, but the very high X-ray to optical flux ratio excludes the presence of a companion star, pointing to an isolated compact object. It has been proposed that RX J1856.5-3754 is an old, isolated neutron star accreting from the interstellar medium. Here we present a reanalysis of the ROSAT data. The HRI observation reveals an attitude reconstruction problem, resulting in a larger error box than previously reported. Deeper optical observations allow us to reveal a few optical counterparts inside the new error box, but the X-ray to optical flux ratio is still very high ($\gtrsim 20$) and none of the candidates has peculiar colors.

Key words: stars: individual: RX J1856.5-3754 – accretion – X-rays: stars – stars: neutron

1. Introduction

Though only about 700 radio pulsars are presently known, the Galaxy contains a large population of old neutron stars (ONSs). Estimates of the neutron star birth rate, integrated over the Galaxy lifetime, predict that there are about $10^8 - 10^9$ ONSs. These elusive objects could be discovered through the detection of radiation powered by accretion from the interstellar medium (Ostriker, Rees & Silk 1970). Since this emission is expected to peak in the UV and soft X-ray range, the advent of the ROSAT satellite stimulated much theoretical work on the subject (Treves & Colpi 1991; Blaes & Madau 1993; Colpi, Campana & Treves 1993), as well as observational searches which recently led to the proposal of a few candidate ONSs (Belloni, Zampieri & Campana 1996; Stocke et al. 1995; Walter, Wolk & Neuhäuser 1996).

A large number of isolated neutron stars still active as radio pulsars are presently undiscovered simply due to beaming effects. The few pulsars seen above 100 MeV indicate that the $\gamma-$ray beam is probably larger than the radio one and, as clearly shown by Geminga, radio-quiet pulsars are now a reality (Bignami & Caraveo 1996). On the other hand, the thermal X-ray emission from these objects is practically visible over $4\,\pi$, as can be inferred from the small pulsed fractions of the ROSAT light curves and from the spectra consistent with emission from the whole (or a very large fraction of the) neutron star surface (Ögelman 1995). Thus it is not surprising that other "radio-quiet" neutron star candidates have recently been found with ROSAT (Mereghetti, Bignami & Caraveo 1996; Petre, Becker & Winkler 1996). In the lack of a detectable periodicity, the main arguments supporting their neutron star nature are the location at the center of supernova remnants and their high X-ray to optical flux ratio (F_X/F_{opt}), which rules out other known classes of X-ray sources.

Walter et al. (1996) have recently reported the discovery of an unusual source, RX J1856.5-3754, which they interpreted as a nearby ONS powered by accretion from the interstellar medium. This source is the brightest ONS candidate reported so far. Its main properties (very high F_X/F_{opt}, ultra soft spectrum with blackbody temperature, lack of variability) have already been reported by Walter et al. (1996). However, the importance of this source prompted us to present here a more detailed analysis of the X-ray data and a more critical interpretation of the results.

2. The position of RX J1856.5-3754

A ROSAT Position Sensitive Proportional Counter (PSPC) observation of RX J1856.5-3754 was carried out during a survey of the RCrA molecular cloud, on October 11-16, 1992 followed by a deeper ROSAT High Resolution Imager (HRI) pointing performed on October 7-8, 1994.

In the 6332 s PSPC observation, RX J1856.5-3754 was detected at an off-axis angle of $14.5'$, still in the central region within the window support rib. Due to the large number of counts detected from RX J1856.5-3754, the error on its position is dominated by possible systematic uncertainties, rather than counting statistics. To evaluate this uncertainty we applied a maximum likelihood detection algorithm provided with the MIDAS/EXSAS software to the inner ($40'$ diameter) PSPC im-

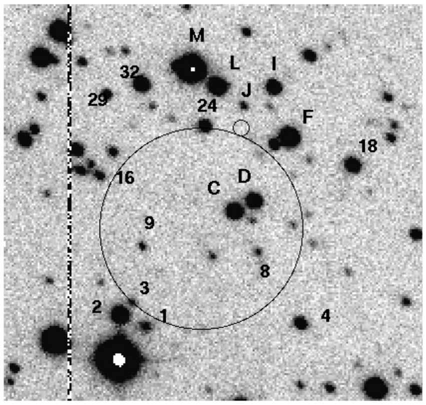

Fig. 1. Image of $1.4' \times 1.4'$ RX J1856.5-3754 field (i band). The center of the larger error box is the PSPC position after the boresight correction. The smaller circle represents the error circle derived by Walter et al. (1996). North is to the top and East to the left.

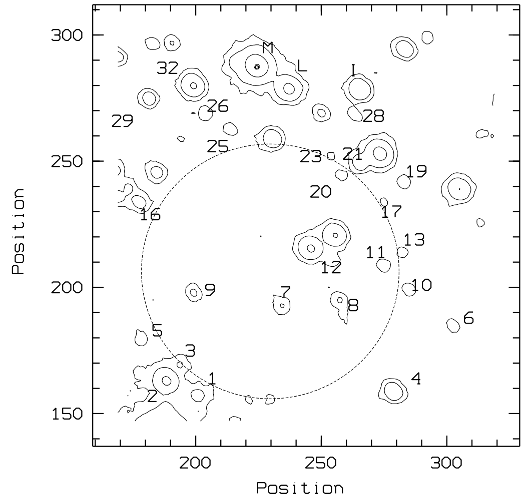

Fig. 2. Contour plot of the central region of Fig. 1. Many faint sources can be observed in this figure inside the error box.

age corresponding to the 0.4-2.4 keV energy range. Ten sources were detected above a threshold corresponding to a chance occurrence probability of 5×10^{-5}. Due to the crowding of this low galactic latitude field, their identification with objects visible on the digitized sky plates is quite problematic. Seven of these sources have relatively bright (V $\gtrsim$ 15) stars of the HST Guide Star Catalogue (GSC) within their error boxes. Based on the resulting F_X/F_{opt}, we considered these stars as plausible identifications, and used them to calibrate, with a least square fit, the X-ray reference frame. This resulted in the best fit position 18h 56m 36s, $-37°54'52''$ indicated by the error circle in Fig. 1. The radius of $20''$ corresponds to the average residuals of the fit.

Walter et al. (1996) derived a much smaller error circle based on the 17800 s HRI pointed observation. However, a careful analysis of the radial and azimuthal distribution of the source counts in the HRI shows that some problems in the satellite attitude reconstruction affected this observation. The source appears elongated in a way inconsistent with the expected Point Spread Function (PSF). We note that this elongation ($\sim 20''$, approximately in the north-south direction) is much greater than that occasionally reported for other HRI sources (David et al. 1992). Clear displacements in the source position can be seen by inspecting the images corresponding to the individual time intervals which compose the observation. We corrected the HRI image by dividing it in very short time intervals (20 s) and applying appropriate shifts to a reference position, in a way similar to that described by Mereghetti et al. (1995). In the resulting image the source profile is consistent with that of the instrument PSF and the statistical significance of the weaker sources in the field has increased. However, the derived absolute coordinates are clearly affected by a systematic uncertainty of at least $20''$, since we had to arbitrarily choose the reference position. A boresight correction for the HRI data similar to that done for the PSPC data is presently unfeasible, due to the ambiguos identification of the HRI sources. We note that the GSC star used by Walter et al. (1996) is at an off-axis angle of $21'$, where the uncertainties in the HRI PSF largely affect the source location accuracy.

3. Optical observations

Optical images of the RX J1856.5-3754 field were taken on 18-19 October 1995 with the Danish 1.54 m telescope of the European Southern Obervatory (ESO) on La Silla. The telescope was equipped with the LORAL 2052×2052 pixels CCD, with a pixel size of $0.39''$. Three exposures of 5 minutes each were obtained in the g, r (18 Oct.) and i (19 Oct.) Gunn filters.

Using the MIDAS/ROMAFOT photometric package, we have derived the r and g magnitudes of several objects in the $\sim 1' \times 1'$ field around the source position (see Table 1). No possible counterparts with particularly unusual colours were found.

The deepest view through interstellar absorption was obtained in the i filter image (Fig. 1), which however suffered from some uncertainty in the absolute flux calibration. Several faint objects not visible in the V band image of Walter et al. (1996) are clearly detected inside the error circle. These sources are more clearly visible in the contour plot shown in Fig. 2. For instance, the star number 23 is detected at a statistical significance of $\sim 4\,\sigma$ in both the i and r band. We are therefore confident that they are real objects and not background fluctuations.

4. Spectral analysis

Source photons in the PSPC instrument were extracted from a circle of radius $3'$ and the background from an annulus centered on the source position of inner and outer radii of $3'$ and $6'$, respectively. Due to the very high count rate of 3.55 ± 0.03 c s^{-1}, the fit results do not depend significantly on the particular region used for the background determination. The source is extremely soft, with very few counts above $\sim$ 1 keV. We therefore rebinned

Table 1. Photometry of the stars in the field of Fig. 1.

Star	g	$g-r$
1	21.77	0.27
2	18.30	0.63
3	21.50	0.58
4	19.40	0.45
5	21.80	0.39
6	>22.7	>0.6
7	21.80	0.81
8	21.13	0.54
9	21.92	0.96
10	>22.7	>1.15
11	>22.7	>0.6
12	21.81	0.77
13	22.00	0.04
14 (C)	18.27	-0.03
15 (D)	18.83	0.33
16	20.15	0.24
17	>22.7	>0.02
18	19.26	0.99
19	22.50	1.08
20	>22.7	>0.83
21	21.50	1.32
22 (F)	17.54	-0.06
23	>22.7	>-0.12
24	20.89	1.33
25	22.12	0.17
26	21.64	0.64
27 (J)	21.39	0.85
28	21.85	0.63
29	20.20	0.40
30 (I)	19.09	0.82
31 (L)	17.82	-0.18
32	18.80	0.90
33 (M)	15.72	0.44

the counts in the hard channels in order to achieve a signal to noise ratio larger than 7 in each energy bin.

Using XSPEC 9.0 software, we explored different single component models. The best fit is obtained by a blackbody with a temperature $T_{\rm bb}$ = $57.5^{+1.1}_{-2.7}$ eV and an absorbing column density N_H = $(1.4^{+0.4}_{-0.2}) \times 10^{20}$ cm^{-2}. The unabsorbed 0.1-2.4 flux is to 3.8×10^{-11} erg s^{-1} cm^{-2}. The 0.1-2.4 keV luminosity derived from the black body model is $1.3 \times 10^{32}\, R_6^2$ erg s^{-1} (where R_6 is the neutron star radius in units of 10 km), implying a distance of about $170\, R_6$ pc. The relatively poor value of the reduced χ^2 = 1.8 (42 d.o.f., probability $\sim 10^{-3}$) likely derives from calibration uncertainties in the response matrix. These small uncertainties, which are particulary evident in the region between 0.4 and 0.5 keV, are usually irrelevant in the case of weaker sources, but dominate the fit residuals for such a strong and soft X-ray source. By adding to the data a 5% relative error to account for this effect, the best fit χ^2 drops to an acceptable value of 1.1 (this additional systematic error is included in all the following fit results). The best fit values of other simple models are summarized in Table 2.

A detailed numerical analysis of the spectral properties of unmagnetized neutron stars accreting well below the Eddington limit has been presented by Zampieri et al. (1995). The emergent spectrum turns out to be significantly harder than a blackbody at the star effective temperature. Using this model, we obtained a reduced χ^2=1.2 (42 d.o.f.; see Table 2), corresponding to a total luminosity released by the neutron star of $(4.3^{+4.0}_{-0.8}) \times 10^{29}$ erg s^{-1} and a column density of N_H = $(2.4^{+0.3}_{-0.3}) \times 10^{20}$ cm^{-2}. The low luminosity implies a very small distance of $\sim$ 10 pc, inconsistent with the high column density. These problems might also indicate that, contrary to the Zampieri et al. assumptions, a non-negligible magnetic field be present. Nelson et al. (1995) have suggested that if ONSs have remained strongly magnetized ($\sim 10^{12}$ G) there should be a cyclotron emission feature in the hard X-ray band at $\sim$ 10 keV on top of the soft X-ray continuum, releasing up to 10% of the total X-ray luminosity. Observations at energies higher than the PSPC range can help investigating this topic.

5. Timing analysis

The PSPC observation is sufficiently long to allow a periodicity search. We take the same PSPC counts used for the spectral analysis, after correcting their arrival times to the solar system barycenter. No periodicities were found. Assuming a sinusoidal light curve, we can put a $3\,\sigma$ upper limit of $\sim$ 15% on the amplitude of the X-ray modulation in the range 0.1-10 s.

We extracted about 9700 counts from a circle of 80$''$ radius around the source position in the HRI observation. No periodicities were found; we can put a $3\,\sigma$ upper limit of $\sim$ 25% in the range 0.04-100 s.

6. Discussion

We have shown that several optical objects are positionally compatible with the revised error region of RX J1856.5-3754. These possible counterparts should be investigated in more details before looking for fainter objects. In any case, also assuming a conservative error budget on the source position, counterparts are limited to objects fainter than $g \sim 18$ (F star in Fig. 1). The X-ray to optical flux ratio of RX J1856.5-3754 is therefore $\gtrsim 20$, ruling out most classes of known X-ray emitters.

RX J1856.5-3754 lies in the direction of the molecular cloud RCrA, whose distance was estimated as $\sim$ 130 pc (Dame et al. 1987). On the basis of the low N_H value derived from the PSPC fit, Walter et al. (1996) concluded that RX J1856.5-3754 is probably closer than the cloud. However, RX J1856.5-3754 does not coincide with the dense core of RCrA, but it lies on the boundary of the cloud, in a region of much lower extinction. Rossano (1978) derived an optical absorption $A_V \sim 0.7$ mag in the direction of RX J1856.5-3754, compared with $A_V \gtrsim 3$ mag at the cloud core. Also OH and HI maps lead to a similar conclusion (Cappa de Nicolau & Poppel 1991). So it is not

Table 2. Summary of spectral fits for RX J1856.5-3754 (errors are 90%).

Model	Column density	Parameter	Red. χ^2
Black body	$1.4^{+0.4}_{-0.2} \times 10^{20}$ cm^{-2}	$T_{\rm bb} = 57.7^{+2.5}_{-6.5}$ eV	1.1
Bremsstrahlung	$2.3^{+0.4}_{-0.3} \times 10^{20}$ cm^{-2}	$T_{\rm br} = 94.8^{+8.2}_{-6.2}$ eV	1.2
Power law	$4.1^{+0.5}_{-0.5} \times 10^{20}$ cm^{-2}	$\alpha = 6.6^{+0.3}_{-0.3}$	1.9
Raymond-Smith	$5.5^{+0.5}_{-1.0} \times 10^{20}$ cm^{-2}	$T_{\rm RS} = 53.2^{+3.9}_{-6.3}$ eV	1.7
Zampieri	$2.4^{+0.3}_{-0.3} \times 10^{20}$ cm^{-2}	$\log L/L_{Edd} = -8.47^{+0.29}_{-0.08}$	1.2

obvious that the source lies in front on the cloud, based only on absorption considerations.

This is in agreement with the distance estimated from the black body spectrum (170 R_6 pc) which places the neutron star beyond the molecular cloud. At this distance the interstellar medium density is about 1 cm^{-3}, so that the neutron star velocity should be of $\sim$ 5 km s^{-1} in order to produce the observed luminosity. Taking the ONS velocity distribution of Blaes & Madau (1993), we expect 0.15 % neutron stars at such low velocities (1% are slower than 10 km s^{-1}). Assuming a spatial density of 10^{-3} ONS pc^{-3} we expect about 14 such slow objects within 170 pc (90 with $v < 10$ km s^{-1}). Therefore, even if different mechanisms conspire against low velocity ONSs (Blaes, Warren & Madau 1995), the derived numbers are large enough to retain the case of an ONS accreting directly from the interstellar medium.

A different possibility is that RX J1856.5-3754 is a young object still dissipating its internal heat or emitting by some non-thermal processes. In this respect, we note that different young "radio quiet" neutron stars are characterized by very soft spectra such as Geminga, and a few other X-ray emitting neutron stars have recently been found associated to supernova remnants.

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