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An unresolved X-ray source inside the supernova remnant RCW 86

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Abstract. We report on the discovery of an unresolved X-ray source inside the supernova remnant G315.4-2.3 (RCW 86). The source is located $7'$ to the Southwest of the geometrical centre and may be close to the actual explosion centre of the supernova, which makes this a candidate for the stellar remnant associated with RCW 86. However, the presence of a possible optical counterpart with $V \sim 14$ at $3''$ from the X-ray position and evidence for long term variability means that the source is probably an active star. A better X-ray position and better X-ray spectroscopy along with an identification of the optical source are needed to exclude the X-ray source as a neutron star candidate.

Key words: Stars: flare – Stars: neutron – ISM: individual objects: RCW 86 – ISM: supernova remnants – X-rays: Stars

1. Introduction

In recent years it has become clear that young neutron stars do not necessarily manifest themselves as radio pulsars. Instead a large variety of unresolved objects associated with supernova remnants are thought to be the stellar remnants of the explosion (see Helfand 1998 for a review). Examples are the point-like sources recently discovered in Cas A (Tananbaum 1999) and Puppis A (Petre et al. 1996), the enigmatic variable source in RCW 103 (Gotthelf et al. 1999), and a handful of relatively slow rotating X-ray pulsars called "anomalous X-ray pulsars" or AXPs (see Mereghetti 1998 for a review).

Here we report on our analysis of an unresolved X-ray source in the supernova remnant RCW 86 (G315.4-2.3, MSH 14-6*3*). We discovered it during our work on the X-ray properties of the remnant (Vink et al. 1997, Bocchino et al. 2000). The source qualifies as the possible stellar remnant associated with RCW 86, but the presence of a possible optical counterpart and long term source variability make this identification, as we will show, uncertain.

RCW 86 is the candidate remnant of the supernova AD 185 (Clark & Stephenson 1977, Strom 1994), but the interpretation of the Chinese records is ambiguous (Chin & Huang 1994). The large extent of the remnant ($40'$) can only be reconciled with an explosion as recent as AD 185, if its distance does not exceed 1 kpc too much. However, Rosado et al. (1996) have pointed out that the kinematic distance towards RCW 86 seems to be higher, namely 2.8 ± 0.4 kpc. In that case RCW 86 may be physically associated with an OB association (Westerlund 1969). The presence of a stellar remnant in RCW 86 would establish the nature of the supernova as a core collapse supernova (Type II or Ib/c), and therefore a connection with the OB association would be more likely.

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Table 1. A summary of ROSAT and Einstein observations which cover the point source. Dates refer to the start date of the observation.

Date d/m/y	ID	Target	Instrument	Exposure s
4/2/1980	h1437s62	SW	Einstein HRI	8756
4/9/1992	rp500078n00	NE	ROSAT PSPC	3212
2/2/1993	rp500079n00	SW	ROSAT PSPC	4567
3/2/1993	rp500078a01	NE	ROSAT PSPC	2224
18/8/1993	rp500078a02	NE	ROSAT PSPC	4509
2/9/1994	rh500077a01	SW	ROSAT HRI	2447
4/8/1995	rh500077a02	SW	ROSAT HRI	6034

2. Data analysis

Our analysis is based on archival ROSAT PSPC and HRI data and on an observation of RCW86 by the Einstein HRI. Both HRI instruments have a similar spatial resolution of $4''$ FWHM, but the ROSAT HRI is more sensitive. The PSPC has a resolution of only $30''$ FWHM, is more sensitive than the HRI and has better spectral capabilities covering the energy range of 0.1 to 2.4 keV with a spectral resolution $\Delta E/E = 0.4$ at 1 keV. The data used for our analysis are summarised in Table 1. The starting point of the analysis are the basic screened event lists. Further processing, like photon extraction and barycentric correction, was done with NASA's *ftools* v4.2 package.

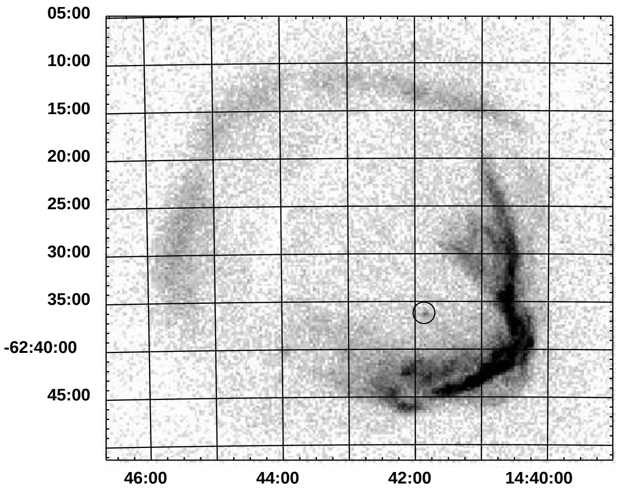

Fig. 1. RCW 86 as observed by the PSPC (SW pointing). The circle indicates the position of the point source.

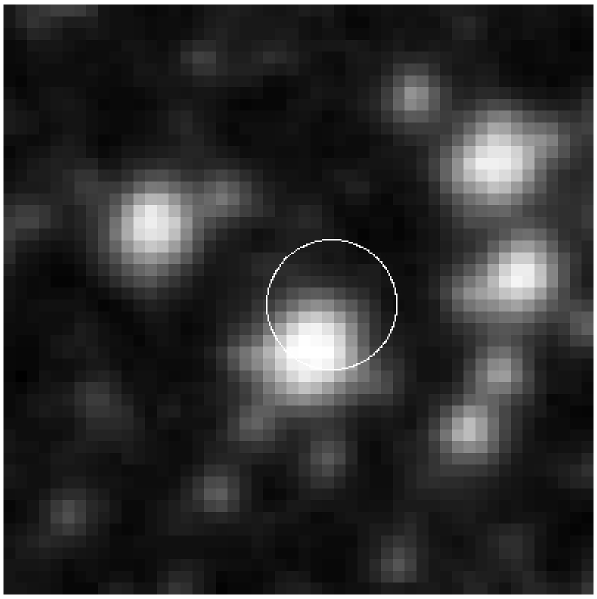

Fig. 2. A $50'' \times 50''$ field image taken from the Digital Sky Survey 2. Overplotted is a circle with a radius of $5''$ centered on the point source and roughly corresponding to a 95% confidence region.

Table 2. Best fit positions and count rates of the point source. The first three rows list the result of maximum likelihood fits to the ROSAT and Einstein HRI data. The statistic $-2\ln\lambda$ has a χ^2 distribution with three degrees of freedom. Position errors do not include systematic errors and correspond $\Delta(-2\ln\lambda) = 4.6$ (90% confidence regions). The PSPC positions and count rates were estimated with a wavelet analysis method (Damiani et al. 1997) using the energy channels 20-200 ($\sim 0.2 - 2$ keV).

ID	RA (J2000) h m s	DEC (J000) $\circ$ $'$ $''$	error $''$	count rate 10^{-3}cnts/s	$-2\ln\lambda$
h1437s62	14 41 51.52	-62 36 13.1	2.6	1.2 ± 0.4	28.6
rh500077a01	14 41 51.64	-62 36 11.9	3.5	2.1 ± 1.1	12.4
rh500077a02	14 41 51.11	-62 36 13.2	1.9	3.4 ± 0.8	55.3
rp500078n00	14 41 53.3	-62 36 37	65	10.9 ± 3.9	
rp500079n00	14 41 51.4	-62 36 8	15	17.9 ± 2.7	
rp500078a01	14 41 49.0	-62 35 52	59	19.4 ± 6.5	
rp500078a02	14 41 48.9	-62 36 22	39	26.8 ± 6.8	

2.1. Position of the source

In order to find an accurate position for the unresolved source we used the HRI data and fitted the point spread function to the source using the very sensitive maximum likelihood fits (Cash 1979 and e.g. Hasinger et al. 1994). We used a field of $80''\times 80''$ roughly centred on the source. The normalisation was coupled to the background level using $N_{total} = N_{bgd} + N_{src}$, N_{total} being the observed number of photons and N_{bgd}, N_{src} the fitted background and source normalisations. The results of these maximum likelihood fits are listed in Table 2, which also lists the source parameters for the PSPC data as found with a wavelet analysis (Damiani et al. 1997). One of the HRI detections has a significance level of 2.7σ, not good enough to claim a detection by itself, but combined with the other detections the source parameters can be regarded as meaningful.

Unfortunately, positions based on ROSAT sometimes suffer from errors in the attitude calculations which are typically $6''$ (Hasinger et al. 1994 and private communication). The observed scatter in the positions based on the Einstein and ROSAT HRI images, as compared to the statistical position errors, suggests that also our results are affected by systematic errors. Einstein HRI observations are less affected by systematic position errors, the typical systematic position error being $\sim 2''$ (Van Speybroeck et al. 1979). Adding statistical and systematic errors in quadrature the weighted average of the positions based on HRI images is $\alpha =$14h 41m 51.42s and $\delta = -62°36'12.9''$ (J2000) with a 1σ position error of approximately $3''$. For a two dimensional gaussian this translates into a 95% confidence radius of $5''$. Note that a very bright, unresolved, radio source inside the remnant with coordinates $\alpha = 14^h41^m44.5^s$ and $\delta = -62°34'47''$ (J2000) is clearly not associated with the unresolved X-ray source (Dickel et al. 2000).

2.2. Spectral analysis

For the spectral analysis of the PSPC data of the unresolved source we extracted photons using a circular area with a radius of $32''$ for the SW (on-axis) pointing and $44''$ for the other pointings. We estimate that with such radii we cover roughly 90% of the photons coming from the unresolved source (c.f. Hasinger et al. 1992). Background spectra, extracted from an annulus around the source, were appropriately scaled and subtracted from the source spectra. The combined spectrum consists of 177 net source counts. The spectrum was rebinned in order to have at least 15 counts per bin.

For our spectral analysis we used he spectral fitting program SPEX[1] (Kaastra et al. 1996). Since we want to know whether the source qualifies as the potential stellar remnant associated with RCW 86, we fitted the spectrum with several

[1] The black body model in SPEX v1.10 contains a small bug which we fixed for this analysis. The thin thermal plasma or CIE (collisional ionization equilibration) model is similar to the *mekal* model in xspec.

Table 3. Results of the spectral fits to the PSPC data. The luminosities are normalised to a distance of 1 kpc. For each model the spectrum was fitted with $N_{\rm H} = 1.7\ 10^{21}$ cm^{-2} and with $N_{\rm H}$ as a free parameter. Error ranges correspond to $\Delta\chi^2 = 2.7$, or 90% confidence limits.

Model	Parameter	Normalization	$N_{\rm H}$ 10^{21} cm^{-2}	$L_X\,(0.2-2.5\,{\rm keV})$ 10^{31} erg/s	χ^2/d.o.f.
Blackbody	k$T = 0.17 \pm 0.04$ keV	$(4.6^{+16.8}_{-3.5})\ 10^{10}$ cm^2	1.7	3.6	8.4/9
	k$T = 0.23 \pm 0.06$ keV	$(0.59^{+1.9}_{-0.35})\ 10^{10}$ cm^2	$0.12^{+4.0}_{-0.2}$	1.6	1.1/8
Power Law	$\Gamma = 3.9^{+0.12}_{-0.9}$	$(9.7 \pm 2.7)\ 10^{39}$ ph/s/keV @ 1 keV	1.7	16.9	4.1/9
	$\Gamma = 2.9 \pm 1.0$	$(7.5 \pm 2.9)\ 10^{39}$ ph/s/keV @ 1 keV	0.84 ± 0.47	5.1	1.7/8
hot thin plasma	k$T = 0.68 \pm 0.41$ keV	$(6.8 \pm 2.4)\ 10^{53}$ cm^{-3}	1.7	1.9	14.7/9
(mekal)	k$T = 1.12^{+7.1}_{-0.57}$ keV	$(6.6^{+1.4}_{-0.3})\ 10^{53}$ cm^{-3}	< 0.3	1.3	4.3/8
idem,$Z = 0.1$	k$T = 0.63 \pm 0.35$ keV	$(4.4^{+4.1}_{-1.2})\ 10^{54}$ cm^{-3}	1.7	3.0	10.5/9
	k$T = 0.87^{+0.96}_{-0.33}$ keV	$(2.6 \pm 0.7)\ 10^{54}$ cm^{-3}	0.3 ± 0.2	1.9	1.0/8

emission models both with the interstellar absorption value fixed at $N_{\rm H} = 1.7\,10^{-21}$ cm^{-2}, the typical absorption value for the X-ray emission of the supernova remnant (Vink et al. 1997), and with $N_{\rm H}$ as an additional free parameter. The results are listed in Table 3. The best fit values of $N_{\rm H}$ for all models seem to be in favor of a low absorption column towards the source, but also models with fixed $N_{\rm H}$ give acceptable reduced χ^2 values. The fact that models with three parameters result in very low reduced χ^2 values (i.e. far from the χ^2 expectation value), suggests that the statistics of the data is not really good enough to fit models with three or more parameters. All models provide reasonable fits to the data with only the thin plasma model with solar abundances and fixed $N_{\rm H}$ having a reduced χ^2 substantially larger than 1. The spectrum appears to be rather soft as indicated by the steep power law index, Γ, and the low black body temperature.

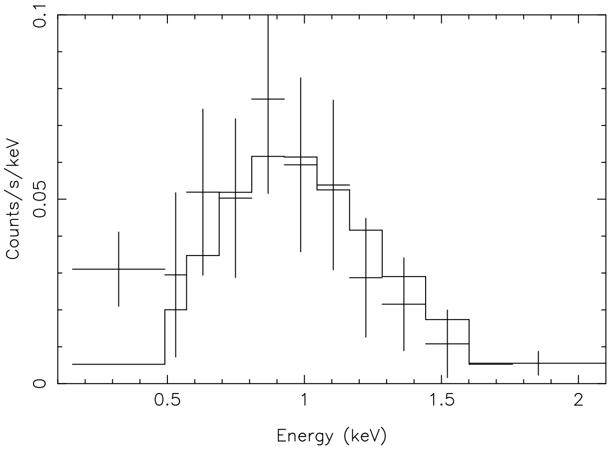

Fig. 3. The PSPC spectrum of the unresolved source in RCW 86. It consists of a combination of 4 individual observations. The solid line shows the best fit black body model with $N_{\rm H}$ fixed to a value of $1.7\ 10^{21}$ cm^{-2}.

2.3. Timing analysis

We searched the four PSPC observations for possible pulsations using the Rayleigh method (Buccheri et al. 1983). This method is one of the most sensitive methods and it does not involve any binning of the data. A sensitive method is needed as the longest PSPC observations yielded only 101 events. We searched in each set for pulsations in the period range 0.02 to 300 s, sampling the frequency range with step of $1/T_{obs}$ with T_{obs} the total length of the observation. We compared the periodograms to look for peaks showing up in two or more periodograms at or near the same period. Such correlations were, however, not found. The peak values of the Rayleigh statistic, $Z_1^2 \sim 28$, imply an upper limit to the pulsed fraction of $\sim$20%.

As for the variability on the timescales of month, at first sight there is little evidence for variability as all measured PSPC count rates are consistent with a count rate of $(17.0 \pm 2.8)\ 10^{-3}$ cnts/s. However, if we convert the Einstein and ROSAT HRI count rates to PSPC count rates using the best fit power law model in Table 3 (the conversion factors are 4.9 and 2.7, respectively) we get the following PSPC count rates (in the same order as in Table 2): $(5.8 \pm 1.9)\ 10^{-3}$ cnts/s, $(5.7 \pm 2.7)\ 10^{-3}$ cnts/s, and $(9.0 \pm 2.1)\ 10^{-3}$ cnts/s. The dependence of the ROSAT HRI/PSPC conversion factor on the chosen model is small (9%), but the conversion factor for the Einstein HRI count rates is more model dependent, varying from 4.6 to 8.0. Even taking into account the model uncertainties it is clear that the observations are not consistent with a constant source count rate, although it is a strange coincidence that low count rates were only observed by the HRI instruments. Source contamination with the PSPC instrument seems unlikely, as no other unresolved sources are seen with the HRI instruments near the point source. Therefore, the X-ray source is very likely variable on a time scale of months to years.

3. Discussion

So, could this X-ray source be the stellar remnant associated with RCW 86? The radius of the star, as inferred from the black body fit, is 1.7 km at a distance of 2.8 kpc. This is too small for a neutron star, but the spectrum may not be a black body. The X-ray luminosity is lower than the luminosity of typical AXPs, but it is consistent with the surface luminosity of young neutron stars in case pion cooling is important (Umeda et al. 2000). Also emission from a black hole accreting supernova fall back material should be considered as an alternative model (Umeda et al. 2000, Chakrabarty et al. 2000). The softness of the X-ray spectrum is a property shared with the unresolved sources in Puppis A, G296.5+10.0 and AXPs (Mereghetti et al. 1996). Its long term variability is more in line with the behaviour of an active star, but a well established neutron star candidate like the point source in RCW 103 is also variable on similar time scales (Gotthelf et al. 1999).

The position of the X-ray source is roughly at an angular distance of $7'$ from the geometrical center of the supernova remnant. This corresponds to a transverse velocity $\lesssim 1200$ km/s, if the supernova remnant is at a distance of 2.5 kpc and 5000 yr old, or if the distance is 1 kpc and an age of 1800 yr. Such a kick velocity is rather high, but still consistent with observations of other neutron stars (Lyne & Lorimer 1994). Note, however, that the remnant is far from circularly symmetric, and the contrast in emission between the Northeast and Southwest of the remnant (see e.g. Vink et al. 1997, Bocchino et al. 2000) suggests that in the Southwest the shock wave is encountering a denser medium, which could mean that the actual explosion center was more to the Southwest of the geometrical center and closer to the unresolved source. Interestingly, the remnant is quite symmetric in the Northeast/Southwest direction and the X-ray source is roughly located on the axis of symmetry. The position of the point source is one of its salient properties. The wavelet detection code has also detected another significant point source inside the remnant, $7'$ from the Northern shell with coordinates $\alpha =$14h 43m 47.0s and $\delta =$ -62°19$'$29$''$. The source seems embedded in a small $1'$ size extended structure. However, spectral analysis of this source rules out models with non-thermal or black-body radiation and the spectrum is consistent with thermal X-ray emission, characteristic for the North rim as reported by Bocchino et al. (2000). This suggests that this a small fragment of the shell seen in projection.

It seems unlikely that the unresolved X-ray source is much further away than RCW 86, as the X-ray absorption column is too low for a distant source near the galactic plane. This means that it is unlikely that it is either an AGN or an X-ray binary. For the source to be a typical X-ray binary with a luminosity of $10^{36} - 10^{38}$ erg/s, it should be at a distance of 300 kpc. This is incompatible with both the X-ray absorption and with the size of our galaxy.

The main argument against an unambiguous identification of the source with a stellar remnant is the presence of a candidate optical counterpart. The USNO-A2.0 catalogue (Monet et al. 1998) contains one source at an angular distance of $3''$ to the unresolved X-ray source (see Fig. 2). The star has magnitudes $r = 13.6$ and $b = 15.9$, which suggest a K-star, although the magnitude errors and the unknown extinction make a late type G-star or a early type M star also possible (Zombeck 1990). The typical V magnitude of this star would be $V \sim 14$, which, for a main sequence star, implies a distance of ~ 250 pc. For this distance the X-ray luminosity of the X-ray source is $L_X \gtrsim 6\ 10^{29}$. This is consistent with the X-ray luminosity of a bright active star (see e.g. Zombeck 1990 p. 88, Agrawal et al. 1986). The possibility that this is just a chance alignment can be estimated using the USNO-A2.0 catalogue. There are about 0.0015 stars per square arcsec with $M_R \leq 16$ in the field around the X-ray source, which means that the chance to find a bright star within the 95% error circle (see Fig. 2) is $\sim$11%.

The evidence for long term variability and the presence of a late type star close to the X-ray position favour the identification of the X-ray source with an active star, rather than with the stellar remnant associated with RCW 86. However, to firmly establish this identification, optical spectroscopy of the possible optical counterpart and X-ray observations with a better positional accuracy of the source are needed. Improved X-ray spectroscopic data can also be used to distinguish between the typical optically thin thermal spectrum of an active star and the featureless spectrum of a neutron star.

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