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Supernova remnant S 147 and its associated neutron star(s)

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ABSTRACT

The supernova remnant S 147 harbors the pulsar PSR J 0538+2817 whose characteristic age is more than an order of magnitude greater than the kinematic age of the system (inferred from the angular offset of the pulsar from the geometric center of the supernova remnant and the pulsar proper motion). To reconcile this discrepancy we propose that PSR J 0538+2817 could be the stellar remnant of the first supernova explosion in a massive binary system and therefore could be as old as its characteristic age. Our proposal implies that S 147 is the diffuse remnant of the second supernova explosion (that disrupted the binary system) and that a much younger second neutron star (not necessarily manifesting itself as a radio pulsar) should be associated with S 147. We use the existing observational data on the system to suggest that the progenitor of the supernova that formed S 147 was a Wolf-Rayet star (so that the supernova explosion occurred within a wind bubble surrounded by a massive shell) and to constrain the parameters of the binary system. We also restrict the magnitude and direction of the kick velocity received by the young neutron star at birth and find that the kick vector should not strongly deviate from the orbital plane of the binary system.

Key words. stars: pulsars: individual: PSR J 0538+2817 – ISM: bubbles – ISM: individual objects: S 147 – ISM: individual objects: G 180.0−1.7 – ISM: supernova remnants – stars: binaries: general

1. Introduction

It is generally accepted that the supernova remnant (SNR) S 147 is associated with the radio pulsar PSR J 0538+2817. The only solid argument in support of this association is the positional coincidence of both objects: the pulsar is located (at least in projection) well within the extended shell of the SNR (Anderson et al. 1996). The numerous estimates of the distance to the SNR are, in general, not inconsistent with the dispersion measure distance to the pulsar. The basic problem for the association is the obvious discrepancy (Kramer et al. 2003) between the kinematic age of the system of $\sim 3 \times 10^4$ yr (estimated from the angular offset of the pulsar from the geometric center of the SNR and the pulsar proper motion) and the characteristic (spin-down) age of the pulsar of $\sim 6 \times 10^5$ yr. To reconcile these ages one can assume that the pulsar was born with a spin period close to the present one (Kramer et al. 2003; see also Romani & Ng 2003). This assumption is often exploited to explain the similar age discrepancy inherent to several other neutron star (NS)/SNR associations (e.g. Migliazzo et al. 2002).

In this paper, we propose an alternative explanation of the age discrepancy because PSR J 0538+2817 could be the stellar remnant of the first supernova (SN) explosion in a massive binary system and therefore could be as old as indicated by its characteristic age (cf. Morris et al. 1978). Our proposal implies that S 147 is the diffuse remnant of the second SN explosion (that disrupted the binary system) and that a much younger second NS (not necessarily manifesting itself as a radio pulsar) should be associated with S 147. In Sect. 2 we review the existing observational data on the system PSR J 0538+2817/SNR S 147. In Sect. 3 we suggest that the progenitor of the SN that formed S 147 was a Wolf-Rayet (WR) star and that the SN explosion occurred within a wind bubble surrounded by a massive shell. In Sect. 4 we consider the possibility that PSR J 0538+2817 is the remnant of the first SN explosion in a massive binary. Section 5 deals with some issues related to the content of the paper.

2. The SNR S 147 and PSR J 0538+2817: observational data

2.1. General structure of S 147

S 147 (also G 180.0−1.7, Simeis 147, Shajn 147, etc) is a shell-type SNR with a diameter of ∼3°. The optical image of S 147 presented by van den Bergh et al. (1973) shows a filamentary shell with a sharp circular boundary to the south. The north boundary of the shell is less regular: it consists of a long arc stretched in the east-west direction and two lobes protruding beyond the arc in the northeast and northwest directions for about one third of the characteristic radius of the SNR. There are some indications that the northern half of S 147 expands somewhat faster than the southern one (see Fig. 2 of Lozinskaya 1976). The east and west edges of the SNR show signatures of blow-ups (more obvious to the east), that makes the SNR somewhat elongated in the east-west direction. The blow-ups are seen more prominently in the recent excellent H_α image of S 147 presented

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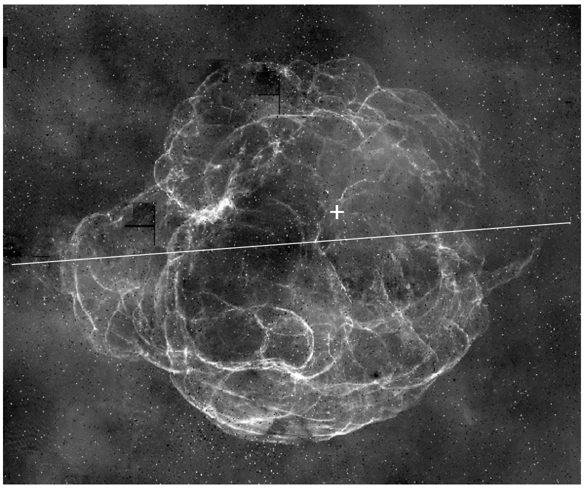

Fig. 1. The H_α image of the supernova remnant S 147 (Drew et al. 2005; reproduced with permission of the IPHAS collaboration). Position of the pulsar PSR J 0538+2817 is indicated by a cross. The line drawn in the east-west direction shows the bilateral symmetry axis (see text for details). North is up, east at left.

by Drew et al. (2005; see Fig. 1)[1]. The 1.6 GHz image of S 147 by Kundu et al. (1980) shows a break between the south and north halves of the SNR, typical of SNRs with bilateral symmetry. The bilateral axis of S 147, defined by the radio brightness distribution, is parallel to the east-west elongation of the SNR's shell.

Optical and ultraviolet observations of S 147 (e.g. Lozinskaya 1976; Kirshner & Arnold 1979; Phillips et al. 1981) suggest that the expansion velocity of its shell is $\simeq 80-120$ km s^{-1}, that implies that the SNR has already entered the final (momentum-conserving) stage of evolution (see, however, Sect. 3). The same conclusion can be derived from the good positional agreement between several optical and radio filaments (Sofue et al. 1980; see also Fürst & Reich 1986) and from the non-detection of X-ray emission from the SNR's shell (Souvageot et al. 1990).

2.2. PSR J 0538+2817

PSR J 0538+2817 was discovered in the untargeted pulsar survey conducted with the Arecibo radio telescope (Anderson et al. 1996), which covered a 1° strip in the north half of S 147. The pulsar is located $\simeq 40'$ northwest of the geometric center of the SNR. The spin period $P \simeq 0.143$ s and the period derivative $\dot{P} \simeq 3.67 \times 10^{-15}$ s s^{-1} of the pulsar (Anderson et al. 1996) yield the characteristic age $\tau = P/2\dot{P} \simeq 6.2 \times 10^5$ yr, the magnetic field strength $B = 3.2 \times 10^{19} \, (P\dot{P})^{1/2} \simeq 7.3 \times 10^{11}$ G and the spin-down luminosity $|\dot{E}| = 4\pi^2 I P^{-3} \dot{P} \simeq 4.9 \times 10^{34}$ erg s^{-1}, where $I \simeq 10^{45}$ g cm^{-2} is the moment of inertia of the pulsar.

The *Chandra X-ray Observatory* revealed a compact nebula surrounding PSR J 0538+2817 (Romani & Ng 2003). Romani & Ng (2003) interpreted the nebula as an equatorial torus produced by the relativistic pulsar wind, similar to those observed around several other rotation-powered pulsars located in the high pressure interiors of their associated SNRs (e.g. Ng & Romani 2004). Ng & Romani (2004) found that the symmetry axes of the toroidal nebulae (it is believed that they coincide with the pulsar spin axes) show a trend (most prominent in the case of the Crab and Vela pulsars) toward alignment with the proper motion vectors of the pulsars. Based on this trend, Romani & Ng (2003) predicted the direction of the proper motion of PSR J 0538+2817 at a position angle of $\simeq 334°$ (measured north through east), which is consistent with the direction from the geometric center of S 147 to the present position of the pulsar (see, however, Sect. 5).

Kramer et al. (2003) used timing observations of PSR J 0538+2817 to measure its proper motion in the ecliptic coordinates, $\mu_\lambda = -41 \pm 3$ mas yr^{-1} and $\mu_\beta = 47 \pm 57$ mas yr^{-1}, with a median value $\mu = 67^{+48}_{-22}$ mas yr^{-1} and a position angle of $311°^{+28°}_{-56°}$. The position angle is consistent with the movement of PSR J 0538+2817 away from the geometric center of S 147. Kramer et al. (2003) consider this result as strong evidence that the pulsar is associated with the SNR (cf. Sect. 2.3). The large error in the proper motion measurement in the latitudinal direction, however, allows the possibility that the pulsar trajectory is significantly offset (up to $\simeq 0.5°$) from the geometric center of S 147.

2.3. Age of the system PSR J 0538+2817/SNR S 147

For a long time it was believed that S 147 is one of the oldest evolved SNRs in the Galaxy. This belief was based on the age estimates of $1-2 \times 10^5$ yr derived with help of the Sedov-Taylor solution or relationships for radiative blast waves (e.g. Sofue et al. 1980; Kundu et al. 1980). It was further supported by the discovery of the associated pulsar PSR J 0538+2817 of comparable (characteristic) age (Anderson et al. 1996).

The subsequent studies of the pulsar, however, lead to a substantial reduction of the age of the system PSR J 0538+2817/SNR S 147. The proper motion measurement of PSR J 0538+2817 combined with its angular offset from the geometric center of S 147 yields the kinematic age, $t_{\rm kin}$, of only $\sim 3 \times 10^4$ yr (Kramer et al. 2003). Kramer et al. (2003) pointed out that "since SNRs typically fade away after 100 000 yr, pulsars genuinely associated with SNRs are necessarily young". To reconcile the discrepancy between $t_{\rm kin}$ and τ, they suggested that the pulsar was born with a spin period, $P_0 \simeq 0.139$ s, close to the present one (cf. Romani & Ng 2003)[2] and therefore its true age is $\ll \tau$. They also admit the possibility that S 147 was formed by the SN explosion in a low-density bubble blown-up by the SN progenitor's wind (cf. Reich et al. 2003), i.e. the Sedov-Taylor solution cannot be used to estimate the parameters of the SN blast wave, and particularly the age of the SNR (see Sect. 3).

We agree that S 147 could be the result of a cavity SN explosion (see Sect. 3) and note that in this case (*i*) the pulsar birthplace could be significantly offset from the geometric center of the SNR due to the proper motion of the SN progenitor star; and therefore (*ii*) the proper motion vector should not necessarily point away from this center (e.g. Gvaramadze 2002; Bock & Gvaramadze 2002; Gvaramadze 2004). Thus; (*i*) the true age of the system PSR J 0538+2817/SNR S 147, $t_{\rm sys}$, could be either $\leq$ or $\geq$ than $t_{\rm kin}$; and (*ii*) the association between PSR J 0538+2817 and S 147 could be genuine even if more accurate proper motion measurements will not prove that the pulsar is moving away from the geometric center of the SNR.

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[1] For other recent images of S 147 see `http://www.skyfactory.org/simeis147/simeis147.htm`

[2] Another possible way to reduce the age of the pulsar is to assume that the pulsar's magnetic field grows exponentially with a characteristic time-scale of $\sim 4\tau/(n-\tilde{n}) \simeq 2 \times 10^4$ yr, where $n = 3$, $\tilde{n} = \ddot{\nu}\nu/\dot{\nu}^2$, and ν, $\dot{\nu}$ and $\ddot{\nu}$ are, respectively, the pulsar spin frequency and its two first time derivatives (measured by Kramer et al. 2003).

Note also that the actual age of the system PSR J 0538+2817/SNR S 147 is not fundamental for the further content of the paper (see, however, Sect. 5). The only thing we will assume in the following is that $t_{\rm sys}$ (or the age of S 147) is much smaller than τ and that τ is nearly equal to the true age of the pulsar. Even in the case of maximum possible offset of the SN blast center from the geometric center of S 147 and the current position of PSR J 0538+2817, $t_{\rm sys} \lesssim 10^5$ yr.

Now we discuss whether or not the spectral characteristics of the X-ray emission observed from PSR J 0538+2817 are at variance with our assumption that this pulsar is as old as indicated by its characteristic age. Thus one should check whether or not the effective temperature of the pulsar derived from model fits of its X-ray spectrum agree with the theoretical expectations.

It is believed that the X-ray emission of middle-aged ($\sim 10^5$ yr) rotation-powered pulsars is predominantly of thermal origin and consists of two components. The first one, the hard thermal component, presumably originates from the hot polar caps heated due to the pulsar activity, and the second one, the soft thermal component, emerges from the rest of the surface of the pulsar. For older ($\sim 10^6$ yr) pulsars, the stellar surface could be too cold to be observable in X-rays, so that the X-ray emission of these NSs comes mainly from the polar caps.

The blackbody fits to the X-ray spectra of PSR J 0538+2817 obtained with the *Chandra X-Ray Observatory* (Romani & Ng 2003) and the *XMM-Newton* (McGowan et al. 2003) give the effective temperature $T_{\rm eff} \simeq 2.0{-}2.5 \times 10^6$ K and the effective radius $R_{\rm eff} \simeq 1{-}3$ km of the spherical emitter. The inferred temperature is too high to be consistent with the temperatures predicted by the standard cooling models for NSs of age $\sim \tau$ (e.g. Yakovlev & Pethick 2004), while small $R_{\rm eff}$ suggests that the X-ray emission is associated with regions much smaller than the entire surface of the NS. A possible interpretation of these fits is that PSR J 0538+2817 is a transition object between the middle-aged pulsars and the older ones, and that the observed X-ray emission is produced by the polar caps heated by the bombardment of relativistic particles streaming down from the pulsar acceleration zones (McGowan et al. 2003).

Alternatively, the above temperature inconsistency could be considered as an indication that the surface of PSR J 0538+2817 is not a perfect blackbody emitter and therefore its X-ray spectrum should be treated in the framework of a NS atmosphere model (with or without a magnetic field). McGowan et al. (2003) fitted the *XMM-Newton* spectrum of PSR J 0538+2817 with a nonmagnetic hydrogen atmosphere model. They fixed the effective radius at values typical of NSs and found $T_{\rm eff} \simeq 0.6{-}0.7 \times 10^6$ K and $d \simeq 0.3{-}0.4$ kpc, where d is the distance to the pulsar. Romani & Ng (2003) used the *Chandra* data to fit the spectrum of the pulsar with a magnetic hydrogen atmosphere model and derived about the same effective temperature, $T_{\rm eff} \simeq 0.65 \times 10^6$ K; they also found $R_{\rm eff} = 13$ km for d fixed at 1.2 kpc (the figure based on the dispersion measure of PSR J 0538+2817; see Sect. 2.4). Although the temperatures derived in both models better agree with the standard cooling curves, they are still somewhat higher than the predicted ones. McGowan et al. (2003) suggested that their fit should be ruled out since it implies a much lower distance to the pulsar than the generally accepted value of 1.2 kpc (see, however, Sect. 2.4).

Another possibility is that the pulsar PSR J 0538+2817 belongs to a class of very slowly cooling low-mass NSs with strong proton superfluidity in their cores, whose cooling curves lie above the basic standard cooling curve (see Yakovlev & Pethick 2004, and references therein).

Thus we conclude that the existing X-ray data do not contradict the possibility that the true age of PSR J 0538+2817 is $\simeq \tau$.

2.4. Distance to the system PSR J 0538+2817/SNR S 147

Most of the existing distance estimates for S 147 are based on the highly unreliable empirical relationships between surface brightness and linear diameter for SNRs. These estimates, ranging from $d \simeq 0.7$ kpc (Milne 1970) to $\simeq 1.6$ kpc (Sofue et al. 1980), cannot be restricted from H I absorption measurements since S 147 lies towards the Galactic anticenter. A possible way to constrain the distance to S 147 comes from the study of absorption lines in spectra of stars located along the line-of-sight towards this extended SNR. Numerous observations (e.g. Phillips et al. 1981; Phillips & Gondhalekar 1983; see also Sallmen & Welsh 2004) have revealed the existence of high-velocity gas (associated with the SNR's shell) towards two stars, HD 36 665 and HD 37 318, located, respectively, at $\simeq 0.9$ and $\simeq 1.4$ kpc (these figures were derived on the basis of spectral types, visual magnitudes and color excesses of the stars). Thus the distance to S 147 is $\lesssim 0.9$ kpc, that is consistent with the distance of $\simeq 0.8$ kpc derived by Fesen et al. (1985) from the interstellar reddening to the SNR. Note that the latter two estimates should be somewhat reduced if the reddening to S 147 and the background stars is enhanced by the dust associated with the SNR's shell (cf. Gondhalekar & Phillips 1980). There are also several stars in the direction of S 147 with parallaxes measured with *Hipparcos*. The most distant of them, HD 37 367, is located at $0.36^{+0.15}_{-0.09}$ kpc. The absorption spectrum of this star does not show high-velocity lines (Sallmen & Welsh 2004), that suggests that HD 37 367 is a foreground star and puts a lower limit on the distance to S 147 of ~ 0.4 kpc.

An indirect estimate of the distance to S 147 comes from its association with PSR J 0538+2817. The dispersion measure of the pulsar, DM $\simeq 40$ pc cm^{-3} (Anderson et al. 1996), and the Cordes & Lazio (2002)[3] model for the distribution of Galactic free electrons yield a distance to the system of $\simeq 1.2 \pm 0.2$ kpc, that is somewhat greater than the upper limit on the distance to S 147 of $\simeq 0.9$ kpc. Note that the Cordes & Lazio model does not take into account a possible contribution to the dispersion of the pulsar's signal from the ionized material associated with the shell of S 147. If the excess dispersion measure due to the SNR's shell $\Delta DM \gtrsim 10$ pc cm^{-3} (see Sect. 3), than the distance to the pulsar is $\lesssim 0.9 \pm 0.2$ kpc (Cordes & Lazio 2002).

In the following we allow d to vary in a wide interval from 0.4 to 0.9 kpc, and sometimes use the figure of 1.2 kpc (accepted in the majority of recent papers devoted to PSR J 0538+2817 and S 147) to compare our results with those of other authors. The uncertainty in the distance, however, does not affect the main results of the paper.

3. S 147 as the result of SN explosion within a WR bubble

Let us now show that the small (kinematic) age of S 147 and the low expansion velocity of its shell cannot be reconciled with each other if one assumes that the SN blast wave evolves in a homogeneous, uniform medium, i.e. if one describes the evolution of S 147 in the framework of the standard Sedov-Taylor model or models for radiative blast waves.

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[3] See also
`http://rsd-www.nrl.navy.mil/7213/lazio/ne_model/`

According to the Sedov-Taylor model, the expansion velocity of the SN blast wave is given by $v_{\rm S\text{-}T} = 0.4R_{\rm SNR}/t_{\rm SNR}$, where $R_{\rm SNR}$ and $t_{\rm SNR}$ are, respectively, the radius and the age of the SNR. The use of this model implies that the SN blast center coincides with the center of the SNR, and therefore $t_{\rm SNR} = t_{\rm kin}$. For the angular radius of S 147 of $\simeq 1\overset{\circ}{.}5$ and $t_{\rm SNR} \simeq 3 \times 10^4$ yr, one has $v_{\rm S\text{-}T} \simeq 340\, d_1$ km s^{-1}, where d_1 is the distance to the SNR in units of 1 kpc. This estimate agrees with the observed expansion velocity $v_{\rm SNR} \simeq 80-120$ km s^{-1} if $d_1 = 0.24-0.35$, that is for distances smaller than the lower limit given in Sect. 2.4. Moreover, the Sedov-Taylor solution implies the following estimate of the number density of the ambient interstellar medium: $n_{\rm ISM} \simeq 0.24\, d_1^{-5}$ cm^{-3}, i.e. $\simeq 300$ cm^{-3} for $d_1 = 0.24$ or $\simeq 50$ cm^{-3} for $d_1 = 0.35$. Both values of $n_{\rm ISM}$ are inconsistent with the fundamental assumption of the Sedov-Taylor model that the SN blast wave is adiabatic.

The use of radiative models (e.g. Cioffi et al. 1988; Blondin et al. 1998) does not improve the situation. For example, using the relationships given in Cioffi et al. (1988; see their Eqs. (3.32)–(3.33)), one has that $v_{\rm SNR}$ could be consistent with the theoretical value if $n_{\rm ISM} \simeq 10$ cm^{-3} (for $v_{\rm SNR} \simeq 120$ km s^{-1}) or $n_{\rm ISM} \simeq 30$ cm^{-3} (for $v_{\rm SNR} \simeq 80$ km s^{-1}). In turn, these density estimates imply the distance to the SNR of, respectively, $\simeq 0.41$ and $\simeq 0.32$ kpc.

An alternative to these models is the possibility that S 147 is the remnant of a SN which exploded within a low-density bubble surrounded by a shell (created by the stellar wind of the SN progenitor). In this case, the expansion velocity of the SN blast wave could be small even for young SNRs (see below). We believe that S 147 is the result of a SN explosion within the bubble blown-up during the WR phase of evolution of the SN progenitor star. Our belief is based on the interpretation of the general structure of S 147, whose shell is characterized by bilateral symmetry and is elongated along the symmetry axis.

The bilateral and elongated appearance of some SNRs implies that the regular interstellar magnetic field is involved in shaping their shells. However, it was recognized long ago that the tension associated with the interstellar magnetic field cannot directly affect the shape of a typical SN blast wave to cause it to be elongated (e.g. Manchester 1987). On the other hand, the regular magnetic field could affect the symmetry of large-scale structures created in the interstellar medium by virtue of the ionizing emission and stellar wind of massive stars – the progenitors of most of SNe. For example, the elongated bilateral SNRs could originate if the SN blast waves in these SNRs take on the shape of the wind bubbles blown-up by the SN progenitor stars during the main-sequence phase and distorted by the surrounding regular magnetic field (Arnal 1992; Gaensler 1998). But the relatively small size of S 147 argues against a SN explosion within the main-sequence bubble and suggests that the pre-existing bubble was rather blown-up during the (much shorter) WR phase. Additional support for this suggestion comes from the low expansion velocity of the SNR's shell, which could be naturally explained if the wind bubble was surrounded by a massive shell – the distinctive feature of WR bubbles (see Gvaramadze 2004). In the presence of the regular interstellar magnetic field the structure of the WR shell is modified in such a way that the density distribution over the shell acquires an axial symmetry with the minimum column density at the magnetic poles (see Gvaramadze 2004 and references therein). A good example of a bilateral WR shell is the nebula S 308 around the WR star HD 50896 (see, e.g., Fig. 1c of van Buren & McCray 1988). The subsequent interaction of the SN blast wave with the magnetized WR shell results in the origin of a bilateral SNR with two blow-ups along its symmetry axis.

The low expansion velocity of the SNR's shell could be treated as an indication that the pre-existing (WR) shell was massive enough. Numerical simulations by Tenorio-Tagle et al. (1991) showed that the SN blast wave merges with the wind-driven shell and the resulting SNR enters into the momentum-conserving stage (i.e. $v_{\rm SNR} \sim 100$ km s^{-1}) if the mass of the shell is $\gtrsim 50\, M_{\rm ej}$, where $M_{\rm ej}$ is the mass of the SN ejecta. Assuming that the radius of the WR shell $R_{\rm WR} \simeq 20$ pc ($d = 0.9$ kpc) and $M_{\rm ej} \simeq 4\, M_\odot$ (see Sect. 4), one has the number density of the ambient interstellar medium $n_{\rm ISM} \geq 0.2$ cm^{-3}. This estimate could be further constrained if one uses the result by Tenorio-Tagle et al. (1991) that the reaccelerated wind-driven shell (now the shell of the SNR) acquires $\sim 10\%$ of the initial SN energy $E_0 = 10^{51}$ erg, i.e. $v_{\rm SNR} \simeq (0.2E_0/M_{\rm shell})^{1/2}$, where $M_{\rm shell} = (4\pi/3)R_{\rm WR}^3\rho_{\rm ISM}$, $\rho_{\rm ISM} = 1.4m_{\rm H}n_{\rm ISM}$, and $m_{\rm H}$ is the mass of the hydrogen atom. For $v_{\rm SNR} = 100$ km s^{-1}, one has $n_{\rm ISM} \simeq 1.0$ cm^{-3}. The latter figure could be used to estimate the excess dispersion measure caused by the SNR's shell, $\Delta DM \simeq R_{\rm SNR}n_{\rm ISM}/3 \simeq 8\, (d/0.9\ {\rm kpc})^{-2}$ pc cm^{-3}, where $R_{\rm SNR} \simeq 23\, (d/0.9$ kpc) pc is the characteristic radius of the SNR (cf. Sect. 2.4). This excess could be much larger if a large-scale deformation of the SNR's shell (caused by the development of the Richtmaier-Meshkov and Rayleigh-Taylor instabilities in the reaccelerated wind-driven shell; see Gvaramadze 1999) increases the line-of-sight extent of the ionized gas against the pulsar (cf. Gvaramadze 2001).

The north-south asymmetry of S 147 could be understood if the WR shell was swept up from the medium with the density growing to the south (i.e. perpendicular to the orientation of the local regular magnetic field, implied by the bilateral symmetry of the SNR's shell). In this case, the SN blast wave merges with the south (more massive) half of the WR shell and this part of the SNR repeats the circular shape of the pre-existing shell. In the north direction the blast wave merges only with the equatorial part of the WR shell (where the column density is enhanced due to the magnetic effect mentioned above) and overruns the less massive segments of the shell in the northeast and northwest directions, thereby producing two lobes in the north half of S 147. Our interpretation of the north-south asymmetry is testable. It would be interesting to measure (e.g. with a Fabry-Pérot interferometer; see Lozinskaya 1976) the expansion velocity of the northeast and northwest segments of S 147 to check whether or not it exceeds the characteristic expansion velocity of the SNR's shell of ~ 100 km s^{-1}.

Note that the above arguments in favour of cavity SN explosion should be relevant independent of whether S147 is the result of the SN explosion of a single (WR) star or of the (second) SN explosion in a massive binary system.

4. PSR J 0538+2817 as the remnant of the first SN explosion in a massive binary

4.1. Constraints on the parameters of the binary system

In Sect. 3 we suggested that the progenitor of the SN that created S 147 was a WR star, i.e. a massive star with the zero-age main-sequence (ZAMS) mass $\gtrsim 20\, M_\odot$ (e.g. Vanbeveren et al. 1998). Let us assume that this SN explosion was the second one in a massive binary and that the pulsar PSR J 0538+2817 is the remnant of the first SN explosion. The latter assumption implies that the ZAMS mass of the first SN progenitor was $\lesssim 25-30\, M_\odot$ (more massive progenitors produce black holes). We assume also that PSR J 0538+2817 is as old as indicated by its characteristic age, i.e. the SN explosions were separated by a time scale of $\sim\tau$. From this it follows that the ZAMS masses of the binary components were nearly equal to each other (cf. Bethe & Brown 1998; Vlemmings et al. 2004), so that it is likely that the second SN explosion also forms a NS.

The spin characteristics (P and $\dot{P}$) and the (inferred) magnetic field of PSR J 0538+2817 are typical of non-recycled pulsars. One can conclude therefore that the binary system was sufficiently wide so that the stellar wind of the massive companion star did not appreciably affect the evolution of the pulsar, i.e. the standoff radius of the pulsar wind, $r_{\rm s}$, was larger than the accretion radius, $r_{\rm a}$ (cf. Illarionov & Sunyaev 1985):

$$r_{\rm s}(t) \equiv (|\dot{E}(t)|/4\pi\rho_{\rm w}cv_{\rm w}^2)^{1/2} > r_{\rm a} \equiv 2GM_{\rm p}/v_{\rm w}^2, \qquad (1)$$

where c is the speed of light, $\rho_{\rm w} = \dot{M}_{\rm w}/4\pi a^2 v_{\rm w}$, $\dot{M}_{\rm w}$ and $v_{\rm w}$ are, respectively, the mass-loss rate and wind velocity of the companion star, a is the binary separation, G is the gravitational constant, and $M_{\rm p} = 1.4\ M_\odot$ is the mass of the pulsar. From Eq. (1) one has that a should be larger than some critical value given by the following relationship:

$$a_{\rm cr} = \frac{2GM_{\rm p}}{v_{\rm w}^2}\left(\frac{\dot{M}_{\rm w}v_{\rm w}c}{|\dot{E}_\star|}\right)^{1/2}, \qquad (2)$$

where $|\dot{E}_\star| = 32\pi^4\mu^2/3c^3P_\star^4$ and $P_\star = (P^2 - 16\pi^2\mu^2 t_{\rm sys}/3c^3 I)^{1/2}$ are the spin-down luminosity and the spin period of the pulsar at the moment of the second SN explosion, $\mu = BR^3$ is the magnetic moment of the pulsar (we assume that μ = const.), $R = 10$ km is the radius of the pulsar, and $t_{\rm sys} \simeq 3\times10^4$ yr.

One can envisage two possible situations at the moment of the first SN explosion. First, the companion star was a red supergiant and its extended envelope survived the passage of the SN blast wave. Second, the convective envelope of the companion red supergiant star was blown up by the SN ejecta to leave a bare He core (i.e. a WR star) or the companion star had already entered into the WR phase. In the first situation, $\dot{M}_{\rm w} \equiv \dot{M}_{\rm w}^{\rm RSG} \simeq 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ and $v_{\rm w} \equiv v_{\rm w}^{\rm RSG} \simeq 10\ {\rm km\,s}^{-1}$, so that one has from Eq. (2) that $a_{\rm cr} \simeq 10^5\ R_\odot$. In such a wide system the stripping and ablation of the red supergiant envelope can be neglected. In the second situation, $\dot{M}_{\rm w} \equiv \dot{M}_{\rm w}^{\rm WR} \simeq 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ and $v_{\rm w} \equiv v_{\rm w}^{\rm WR} \simeq 2000\ {\rm km\,s}^{-1}$, so that one has $a_{\rm cr} \simeq 35\ R_\odot$. Thus if $a \geq a_{\rm cr}$, the pulsar was active during the whole period between the two SN explosions and its spin characteristics were not appreciably affected by the wind of the companion star; the latter implies that the true age of the pulsar is equal to τ (provided that $P_0 \ll P$).

4.2. Origin of the pulsar peculiar velocity

Proper motion measurement of PSR J 0538+2817 by Kramer et al. (2003) yields a pulsar transverse velocity of $v_{{\rm p},\lambda} = 194 \pm 14\ d_1\ {\rm km\,s}^{-1}$, if one uses the proper motion in the ecliptic longitude only, or $v_{\rm p} = 318^{+230}_{-100}\ d_1\ {\rm km\,s}^{-1}$ for the composite proper motion. For $d_1 = 0.4$–0.9, one has $v_{{\rm p},\lambda} \simeq 80$–$170\ {\rm km\,s}^{-1}$ and $v_{\rm p} \simeq 130$–$290\ {\rm km\,s}^{-1}$. Using the estimates of $a_{\rm cr}$ derived in Sect. 4.1, one can check whether or not $v_{{\rm p},\lambda}$ and $v_{\rm p}$ are consistent with the velocity, $v_{\rm NS}^{\rm old}$, of the old NS released from orbit by the second SN explosion.

In the case of a symmetric SN explosion and a circular binary orbit one has

$$v_{\rm NS}^{\rm old} = \left(\frac{m^2-2m-2}{m+1}\right)^{1/2}\left(\frac{GM_{\rm p}}{a}\right)^{1/2}, \qquad (3)$$

where $m = M/M_{\rm p}$ and $M \lesssim 5$–$6\ M_\odot$ (e.g. Vanbeveren et al. 1998) is the mass of the pre-SN star. It is clear that $v_{\rm NS}^{\rm old}$ is inconsistent with both $v_{{\rm p},\lambda}$ and $v_{\rm p}$ if the second SN exploded after the red supergiant phase (i.e. $a \geq 10^5\ R_\odot$). In the second situation (i.e. $a \geq 35\ R_\odot$), one has from Eq. (3) that $v_{\rm NS}^{\rm old} \leq 80$–$110\ {\rm km\,s}^{-1}$. This estimate shows that $v_{\rm NS}^{\rm old}$ is inconsistent with $v_{\rm p}$, but could be equal to $v_{{\rm p},\lambda}$ if one adopts the smallest values of a and d_1 and the largest one of M, and provided that the radial component of the pulsar velocity is small.

One can, however, assume that the SN explosion was asymmetric so that the young NS received a kick velocity, w, at birth. In this case, the new-born NS can impart some momentum to the old NS in the course of disintegration of the binary system (see Tauris & Takens 1998). The magnitude of the momentum depends on the angle, θ, between the kick vector and the direction of motion of the exploding star, and the angle, ϕ, between the kick vector and the orbital plane (see Fig. 1 of Tauris & Takens 1998)[4]. An analysis of Eqs. (44)–(47) and (51)–(56) given in Tauris & Takens (1998) shows that the momentum imparted to the old NS is maximum if

$$\theta \sim \theta_* \equiv \arccos(-v/w), \qquad (4)$$

where $v = [G(M+M_{\rm p})/a]^{1/2}$ is the relative orbital velocity, and provided that the vector of the kick velocity does not strongly deviate from the orbital plane of the binary system; i.e. than the kick received by the second-born NS is directed almost towards the old NS. Figure 2 illustrates how the direction of the kick affects the velocities of the old and new-born NSs released from the disrupted binary. One can see that for $\theta \simeq \theta_* = 118°$ (we assume that $w = 400\ {\rm km\,s}^{-1}$, $M = 5\ M_\odot$ and $a = 35\ R_\odot$, and that $\phi = 0°$) $v_{\rm NS}^{\rm old}$ is maximum ($\sim w$), while $v_{\rm NS}^{\rm new}$ drops to a minimum value of $\simeq 0.25w$. It is also seen that for θ ranging from $\simeq 115°$ to $\simeq 135°$ $v_{\rm NS}^{\rm old}$ is larger than the best-fit transverse velocity at the upper distance 0.9 kpc. Note that the maximum value of $v_{\rm NS}^{\rm old}$ is almost independent of a (or v): $v_{\rm NS}^{\rm old,max}$ tends to w with increasing a[5], while $v_{\rm NS}^{\rm new}$ drops to 0. Figure 3 shows how $v_{\rm NS}^{\rm old,max}$ depends on ϕ; it is seen that $v_{\rm NS}^{\rm old,max} \gtrsim v_{\rm p}^{\rm max}$ if $\phi \lesssim 10°$. The above considerations show that $v_{\rm NS}^{\rm old}$ could be consistent with $v_{\rm p}$, but the binary separation must be as small as possible while avoiding pulsar recycling and the kick direction must be carefully tuned. For $d_1 = 0.9$ and $a \sim 35\ R_\odot$ the probability of a favourable kick orientation is $\sim 10^{-3}$ (for the isotropic kick distribution) or $\sim 10^{-2}$ (if kicks produced by SN explosions in binary systems are restricted close to the orbital plane; see Sect. 5). Note also that the smaller d_1 the wider the range of angles for which $v_{\rm NS}^{\rm old} > v_{\rm p}$ and the larger the probability that the second-born NS will receive an appropriately oriented kick.

5. Discussion

In Sect. 4.2 we considered two possible explanations for the origin of the peculiar velocity of PSR J 0538+2817 based on the idea that the pulsar could be the remnant of the first SN explosion in a massive binary. Proceeding from this we found that although the pulsar motion in the ecliptic longitude taken separately (cf. Hobbs et al. 2005; Lewandowski et al. 2004) could be

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[4] For $\phi = 0°$ and $0° \leq \theta \leq 180°$, the kick vector lies in the orbital plane and points to the half-sphere occupied by the old NS.

[5] Vlemmings et al. (2004) draw an erroneous conclusion that in a wide binary disrupted after the second (asymmetric) SN explosion the old NS could be accelerated to a velocity $\sim w$, while the second-born NS to a velocity several times exceeding w.

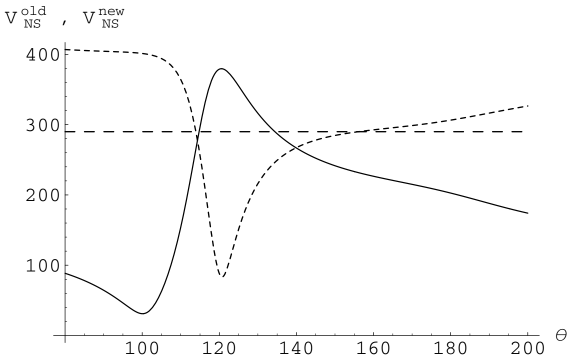

Fig. 2. The dependence of the velocities of the old and new-born neutron stars (shown, respectively, by the solid and the short-dashed lines) on the angle between the kick vector and the direction of motion of the exploding star. The long-dashed line shows the best-fit transverse velocity at the upper distance 0.9 kpc. See text for details.

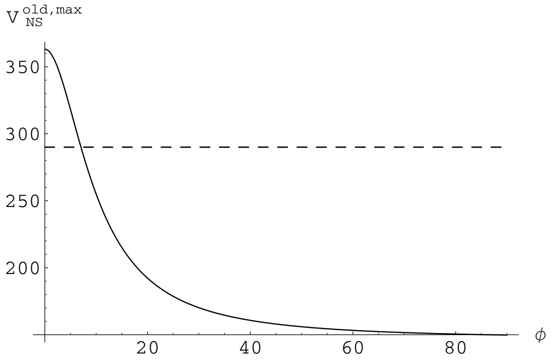

Fig. 3. The dependence of the maximum value of the velocity of the old neutron star on the angle between the kick vector and the orbital plane.

consistent with the possibility that the binary was disrupted by a symmetric SN explosion, the large composite proper motion measured by Kramer et al. (2003; if confirmed by more accurate measurements) makes the case of an asymmetric SN explosion more plausible. In this case, we expect that the kick velocity received by the second-born NS is restricted close to the orbital plane (i.e. $\phi \lesssim 10°$; cf. Wex et al. 2000). Figure 4 shows the angle, χ, between $v_{\rm NS}^{\rm old}$ [for θ given by Eq. (4)] and the pre-SN orbital plane as a function of ϕ: χ grows from 0° (for $\phi = 0°$) to $\simeq 40°$ (for $\phi \simeq 10°$) and than gradually decrease to $\simeq 10°$ for $\phi = 90°$. Thus if our explanation of the age discrepancy is correct, we do not expect any alignment between the pulsar spin axis and proper motion, although one cannot exclude that they are perpendicular to each other if the second SN explosion was symmetric about the orbital plane (i.e. $\phi \simeq 0°$; cf. Cordes & Wasserman 1984; Colpi & Wasserman 2002; Vlemmings et al. 2004) and provided that the spin axis of PSR J 0538+2817 was perpendicular to this plane. To check whether this possibility was realized one must know the precise position angles of the pulsar proper motion and the symmetry axis of the X-ray nebula surrounding the pulsar. However, the large error in latitudinal direction makes the position angle of the pulsar proper motion very uncertain (see Sect. 2.2), while the low photon statistics of the *Chandra* data does not allow us to infer the symmetry axis of the pulsar wind nebula unambiguously. We will discuss this point in more detail.

The existing *Chandra* data on PSR J 0538+2817 show that the nebula around the pulsar consists of a core and a dim halo (Romani & Ng 2003). These substructures could be fitted with ellipses with the semi-major axes of $2\farcs5$ and $9''$, at the position angles of $\sim 130°$ and $\sim 60°$. Romani & Ng (2003) suggested that the halo "has a scale comparable to the expected wind shock radius for a confinement pressure appropriate to the interior of S 147" and used the geometry of the halo to infer the pulsar spin axis at a position angle of $334\fdg0 \pm 5\fdg5$ (that is consistent with the position angle of the pulsar composite proper motion). Their calculations of the shock radius were carried out in the framework of the Sedov-Taylor model and under the assumption of a spherically-symmetric pulsar wind.

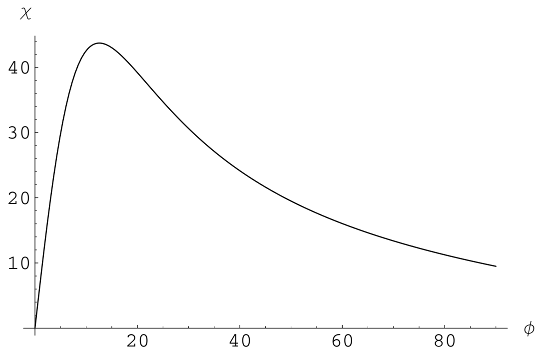

Fig. 4. The angle between the velocity vector of the old neutron star and the orbital plane as a function of the angle between the kick vector and the orbital plane.

The angular radius of the toroidal shock can be expressed as

$$\Theta \simeq (|\dot{E}|/4\pi\alpha c d^2 P_{\rm in})^{1/2}, \tag{5}$$

where $\alpha \leq 1$ is a factor characterizing the anisotropy of the energy flux of the pulsar wind (for $\alpha \ll 1$ most of the pulsar wind is confined to the equatorial plane, while $\alpha = 1$ corresponds to the spherically-symmetric wind),

$$P_{\rm in} = \frac{(\gamma - 1)E_{\rm th}}{V}, \tag{6}$$

is the mean gas pressure inside the SNR, γ is the specific heat ratio, $E_{\rm th} = \delta E_0$ is the thermal energy of the SN blast wave, $\delta < 1$, and $V = (4\pi/3)R_{\rm SNR}^3$ is the volume of the SNR. For adiabatic gas ($\gamma = 5/3$) and an angular radius of the SNR of $\sim 1\fdg5$, one has from Eqs. (5) and (6) that

$$\Theta \simeq 1\farcs4\,(\alpha\delta)^{-1/2}\, d_1^{1/2}. \tag{7}$$

For a Sedov-Taylor blast wave (i.e. $\delta \simeq 0.72$) and assuming $\alpha = 1$ and $d_1 = 1.2$ (Romani & Ng 2003), one has $\Theta = 1\farcs8$, that is consistent with the angular radius of the core of the nebula rather than with the scale of the more extended halo. Moreover, in Sect. 3 we showed that the Sedov-Taylor model cannot reconcile the small expansion velocity of S 147 with its low kinematic age and suggested that this SNR is the result of a SN explosion within a pre-existing bubble surrounded by a massive wind-driven shell. In this case, the evolution of the SN blast wave completely differs from that of the Sedov-Taylor one. The presence of the massive shell strongly increases the radiative cooling of the SN blast wave, that results in a rapid decrease of the thermal content of the SNR as compared with the Sedov-Taylor one. Numerical simulations by Tenorio-Tagle et al. (1991; see their Fig. 3) show that $\delta \simeq 0.4$ at $t_{\rm SNR} = 3 \times 10^4$ yr and further decreases to $\simeq 0.1$ at $t_{\rm SNR} = 10^5$ yr. Thus assuming that $t_{\rm SNR} = t_{\rm kin} = 3 \times 10^4$ yr, one has from Eq. (7) that $\Theta \leq 2\farcs1$ if the distance to S 147 is ≤ 0.9 kpc, or $\simeq 2\farcs4$ if $d_1 = 1.2$. These estimates also suggest that the toroidal shock could be associated with the core of the pulsar wind nebula. However, in the case of a cavity SN explosion $t_{\rm kin}$ could be as large as $\sim 10^5$ yr (see Sect. 2.3); in this case $\delta \sim 0.1$ and $\Theta \simeq 3''.6-4''.7$ (for d_1 ranging from 0.9 to 1.2), that better agrees with the scale of the halo (cf. Romani & Ng 2003). The agreement could also be achieved when the anisotropy of the pulsar wind is taken into account. Assuming that $\alpha = 0.1$, one has from Eq. (7) that $\Theta \leq 6''.6$ and $7''.6$ for $d_1 = 0.9$ and 1.2, respectively.

If the core indeed corresponds to the equatorial torus of the pulsar wind nebula (this could be checked with forthcoming deep *Chandra* observations[6] or high-resolution radio imaging), than the position angle of the symmetry axis of the torus is exactly perpendicular to the direction of the pulsar composite proper motion (interferometric measurements of PSR J 0538+2817 would be highly valuable for further restricting the position angle of the pulsar proper motion), i.e. just what is expected if the pulsar obtained its peculiar velocity by the disintegration of the binary system (with aligned angular momenta) by symmetric SN explosion or by SN explosion symmetric about the orbital plane (see above). Note, however, that the same spin-kick orientation could be produced by the SN explosion of a solitary massive star if the spin and the peculiar velocity of the pulsar are due to a single off-center kick (Spruit & Phinney 1998).

Now we discuss the problem of the second (young) NS possibly associated with S 147. The detection of such a NS would allow us not only to distinguish the case of a SN explosion in a binary system from that of a solitary SN explosion, but also would lend strong support to our explanation of the age discrepancy and would have a strong impact on our understanding of the kick physics.

In the case of a symmetric SN explosion the angle, ψ, between the velocity vectors of the old and new-born NSs depends only on the mass of the SN ejecta and is given by (Gott et al. 1970; see also Iben & Tutukov 1996)

$$\psi = \arccos\left[4\left(\frac{M_{\rm ej}}{2M_{\rm p}}\right)^2 - 3\right]^{-1/2}, \qquad (8)$$

where $M_{\rm ej} = M - M_{\rm p}$. It follows from Eq. (8) that ψ is always smaller than 90°; e.g. $\psi \sim 60°$ for the parameters adopted above. In the case of an asymmetric SN explosion ψ could be larger than 90°. Figure 5 shows how ψ depends on the direction of the kick vector (we assume here that $\phi = 0°$). It is seen that ψ is very sensitive to θ. For θ ranging from 115° to 135° (i.e. when $v_{\rm NS}^{\rm old} > v_{\rm p}^{\rm max}$) $\psi = 0°$ for $\theta \sim \theta_*$ (see Eq. (4)) and grows to $\simeq 60°-70°$ at the bounds of the range. Thus we expect that the young NS should be located in a cone with a half-opening angle $\lesssim 70°$ with the cone axis oriented along the proper motion of PSR J 0538+2817. We also expect that the young NS should be situated closer to the vertex of the cone (i.e. to the SN blast center) than PSR J 0538+2817 since $v_{\rm NS}^{\rm new} < v_{\rm NS}^{\rm old}$ (the same is true for the case of a symmetric SN explosion). Remind that the SN blast center could be significantly offset from the geometric center of S 147 (see Sect. 2.3).

The most optimistic supposition is that the young NS is an ordinary (rotation-powered) pulsar with a favourably oriented radio beam. The youth of the pulsar implies that it should be more energetic than PSR J 0538+2817, and therefore could be easily detected somewhere to the south of the 1° strip covered by the Arecibo survey (most likely in the west half of the SNR). Another possibility is that the young NS is an off-beam radio pulsar or that it belongs to a class of radio-quiet NSs. In both cases one can expect that the young NS should be a sufficiently bright soft X-ray source to be detected with the *ROSAT* All-Sky Survey (RASS). Indeed, the RASS Faint Source Catalog[7] shows five sources in the proper place. The count rates of these sources (ranging from $\simeq 0.014$ to $\simeq 0.039$ ct s^{-1}) should be compared with the count rate in the *ROSAT* pass band expected for a NS of age of $\simeq 3 \times 10^4$ yr. Let us assume that the new-born NS is a spherical blackbody emitter of radius of 10 km and temperature of $\simeq 10^6$ K (predicted by standard cooling models). Then assuming an interstellar absorption column density of $\simeq 2.5-3 \times 10^{21}$ cm^{-2} (e.g. McGowan et al. 2003; Romani & Ng 2003) and using PIMMS[8], one has $\simeq 0.017-0.022$ *ROSAT* PSPC ct s^{-1}, that is, the figures comparable with the above count rates. Thus one cannot exclude that one of the five RASS sources is a young NS associated with S 147. If this NS is a rotation-powered pulsar, its position should be marked by a pulsar wind nebula with a characteristic scale of at least an order of magnitude larger than that of the nebula around PSR J 0538+2817. Deep radio or X-ray observations would allow us to verify the existence of such a nebula.

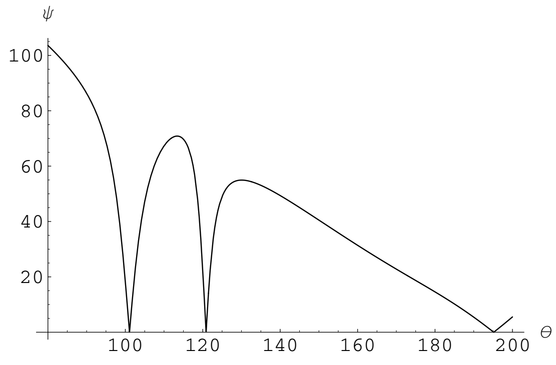

Fig. 5. The angle between the velocity vectors of the old and new-born neutron stars as a function of the angle between the kick vector and the direction of motion of the exploding star.

Note that the RASS sources are about 1.5–4 times fainter than the pulsar PSR J 0538+2817 (also detected by the RASS; e.g. Sun et al. 1996), while the opposite situation is expected if PSR J 0538+2817 is as old as indicated by its spin-down age and if its cooling follows the standard cooling curves. The contradiction, however, could be removed if (as discussed in Sect. 2.3) the pulsar belongs to a class of slowly cooling NSs.

One cannot exclude that the young stellar remnant collapsed into a black hole. In this case, the chances of finding this object are small.

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[6] See, `http://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3table.pl`

[7] `http://www.xray.mpe.mpg.de/rosat/survey/rass-fsc/`

[8] `http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html`

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