PSR J0538+2817 as the Remnant of the First Supernova Explosion in a Massive Binary

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Resume: The supernova remnant S147 harbors the pulsar PSR J0538+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 J0538+2817 could be the stellar remnant of the first supernova explosion in a massive binary system and therefore could be as old as indicated by its characteristic age. Our proposal implies that S147 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 S147. We use the existing observational data on the system to suggest that the progenitor of the supernova that formed S147 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.

1. 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.

- $P \simeq 0.143\,\mathrm{s}$, $\dot{P} \simeq 3.67\times10^{-15}\,\mathrm{s\,s^{-1}} \Rightarrow \tau = P/2\dot{P} \simeq 6.2\times10^5$ yr, $B \simeq 7.3\times10^{11}$ G, $|\dot{E}| \simeq 4.9\times10^{34}\,\mathrm{erg\,s^{-1}}$
- PSR J 0538+2817 is located $\simeq 40'$ northwest of the geometric center of S 147 (see Fig. 1)
- proper motion: $\mu = 67^{+48}_{-22}\,\mathrm{mas\,yr^{-1}}$; position angle: $311^{\circ +28^{\circ}}_{\ -56^{\circ}}$ (Kramer et al. 2003)

The position angle is consistent with the movement of PSR J 0538+2817 away from the geometric center of S 147. 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. SNR S 147

• S 147 (also G 180.0−1.7, Simeis 147, Shajn 147, etc) is a shell-type SNR with a diameter of $\sim 3°$ (see Fig. 1). The east and west edges of the SNR show signatures of blow-ups, that makes the SNR somewhat elongated in the east–west direction. 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 (see Fig. 1).
• Optical and ultraviolet observations of S 147 (e.g. Lozinskaya 1976; Kirshner & Arnold 1979) suggest that the expansion velocity of its shell is $\simeq 80-120\,\mathrm{km\,s^{-1}}$, that implies that the SNR has already entered the momentum-conserving stage of evolution. The same conclusion can be derived from the good positional agreement between several optical and radio filaments (e.g Sofue et al. 1980) and from the non-detection of X-ray emission from the SNR's shell (Souvageot et al. 1990).

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

• For a long time it was believed that S147 is one of the oldest evolved SNRs in the Galaxy. This belief was based on the age estimates derived with help of the Sedov-Taylor solution. It was further supported by the discovery of the associated pulsar PSR J0538+2817 of comparable characteristic age.
• The proper motion measurements 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 the system PSR J 0538+2817/SNR S 147 of $\sim 3\times10^4$ yr (Kramer et al. 2003). To reconcile the discrepancy between $t_{\rm kin}$ and τ, Kramer et al. (2003) suggested that the pulsar was born with a spin period close to the present one and therefore its true age is $\ll \tau$. They also admit the possibility that S 147 was formed by the supernova (SN) explosion in a low-density bubble blown-up by the SN progenitor's wind, i.e. the Sedov-Taylor solution cannot be used to estimate the age of the SNR.
• We agree that S 147 could be the result of a cavity SN explosion (see Sect. 5) and note that in this case the pulsar birthplace could be significantly offset from the geometric center of the SNR due to the proper motion of the SN progenitor star (e.g. Gvaramadze 2002; Bock & Gvaramadze 2002). Thus, the true age of the system could be either $\leq$ or $\geq$ than $t_{\rm kin}$. In the following we assume that the age of the system (or the age of S 147) is much smaller than τ and that τ is nearly equal to the true age of the pulsar.

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

• Numerous studies of absorption lines in spectra of stars located along the line-of-sight towards S 147 suggest that the distance, d, to this SNR ranges from 0.4 to 0.9 kpc (e.g. Phillips et al. 1981; Sallmen & Welsh 2004).
• The dispersion measure of PSR J 0538+2817 and the Cordes & Lazio (2002) model for the distribution of Galactic free electrons yield a distance to the pulsar of $\simeq 1.2$ kpc. This estimate could be reconciled with the distance to S 147 if one takes into account a possible contribution to the dispersion of the pulsar's signal from the material associated with the SNR's shell (Gvaramadze 2006).

5. S 147 as the result of SN explosion within a Wolf-Rayet bubble

The bilateral and elongated appearance of S 147 implies that the regular interstellar magnetic field is involved in shaping its shell. 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 stellar wind of SN progenitor stars. The relatively small size of S 147 and the low expansion velocity of its shell suggest that the pre-existing bubble was blown-up during the WR phase and that the bubble was surrounded by a massive shell. In the presence of the regular 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). 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.

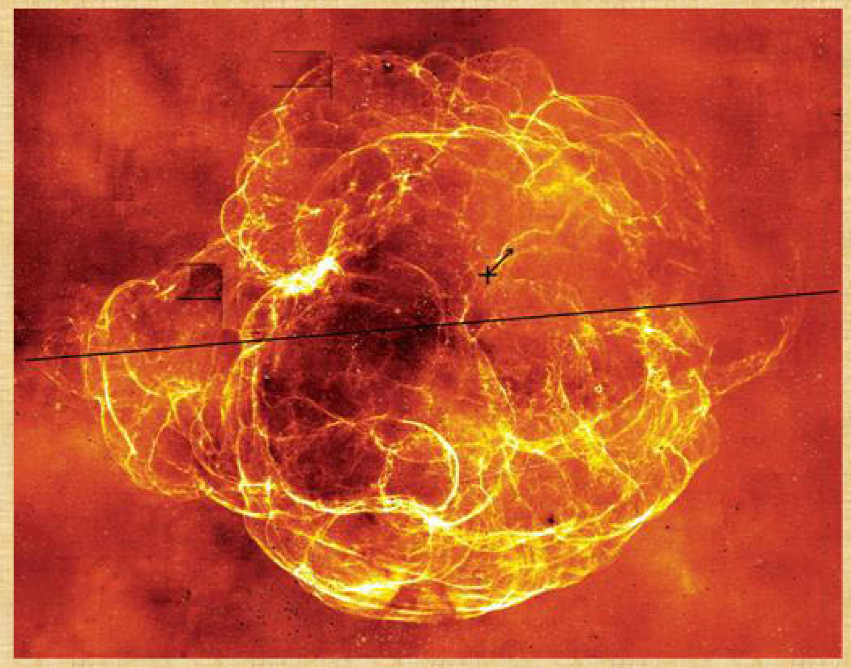

Figure 1. The H_α image of S 147 (Drew et al. 2005; reproduced with permission of the IPHAS collaboration). Position of PSR J 0538+2817 is indicated by a cross. The arrow shows the direction of the pulsar proper motion vector (Kramer et al. 2003). The line drawn in the east-west direction shows the bilateral symmetry axis (see Sect. 2 and Sect. 5). North is up, east at left.

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

6.1 Constraints on the parameters of the binary system

• In Sect. 5 we suggested that the progenitor of the SN that created S 147 was a WR star, i.e. a massive star with the initial mass $\geq 20\,M_\odot$. Let us assume that this SN explosion was the second one in a massive binary and that PSR J 0538+2817 is the remnant of the first SN explosion. The latter assumption implies that the initial mass of the first SN progenitor was $\leq 25-30\,M_\odot$ (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 initial masses of the binary components were nearly equal to each other, so that it is likely that the second SN explosion also forms a neutron star (NS).
• The spin characteristics (P and $\dot{P}$) and the (inferred) magnetic field of PSR J 0538+2817 (typical of non-recycled pulsars) suggest that the binary system was sufficiently wide so that the stellar wind of the companion star did not appreciably affected the evolution of the pulsar.
• One can envisage two possible situations at the moment of the first SN explosion: (1) the companion star was a red supergiant; (2) the companion star had already entered into the WR phase. Simple estimates show (Gvaramadze 2006) that the binary separation, a, should be $\geq 10^5\,R_\odot$ (first situation) or $\geq 35\,R_\odot$ (second one).

6.2 Origin of the pulsar peculiar velocity

• Proper motion measurement of PSR J 0538+2817 yields a pulsar transverse velocity $v_{\rm p} \simeq 130-290\,\mathrm{km\,s^{-1}}$ for $d = 0.4-0.9$ kpc. Using the estimates of a given in Sect. 6.1, one can check whether or not $v_{\rm p}$ is 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 $v_{\rm NS}^{\rm old} = (m^2-2m-2/m+1)^{1/2}\,(GM_{\rm p}/a)^{1/2}$, where $m = M/M_{\rm p}$, $M_{\rm p} = 1.4\,M_\odot$ is the mass of the pulsar and $M \leq 5-6M_\odot$ is the mass of the pre-SN star. One can see that $v_{\rm NS}^{\rm old}$ is inconsistent with $v_{\rm p}$ not only for $a \simeq 10^5\,R_\odot$, but also for $a \simeq 35\,R_\odot$.
• If the SN explosion was asymmetric (so that the young NS received a kick velocity, w, at birth), the new-born NS can impart some momentum to the old NS in the course of disintegration of the binary system (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. One can show (Gvaramadze 2006) that the momentum imparted to the old NS is maximum if $\theta \sim \theta_* \equiv \arccos(-v/w)$, where $v = [G(M+M_{\rm p})/a]^{1/2}$ is the relative orbital velocity, and provided that the kick 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.
• Fig. 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 $\theta \simeq \theta_* \simeq 118°$ (we assume that $w = 400\,\mathrm{km\,s^{-1}}$, $M = 5M_\odot$ and $a = 35\,R_\odot$, and that $\phi = 0°$) $v_{\rm NS}^{\rm old}$ is maximum, while $v_{\rm NS}^{\rm new}$ drops to a minimum value. It is also seen that for θ ranging from $\simeq 115°$ to $\simeq 135°$ $v_{\rm NS}^{\rm old}$ is larger than $v_{\rm p}$ at the upper distance 0.9 kpc, $v_{\rm p}^{\rm max} = 290\,\mathrm{km\,s^{-1}}$.
• Fig. 3 shows how $v_{\rm NS}^{\rm old,max}$ depends on ϕ; it is seen that $v_{\rm NS}^{\rm old,max} \geq v_{\rm p}^{\rm max}$ if $\phi \leq 10°$ (i.e. the kick should be restricted close to the orbital plane).

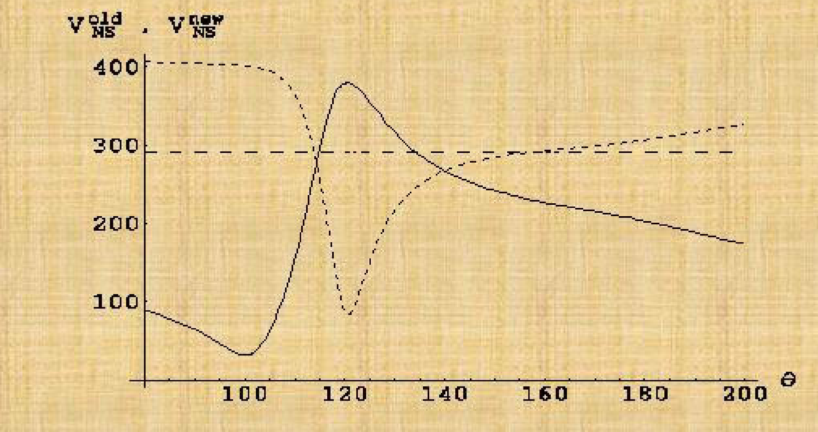

Figure 2. The dependence of the velocities of the old and new-born NSs (shown, respectively, by the solid and the short-dashed lines) on the angle between the kick vector and the direction of motion of the exploding star. The long-dashed line shows $v_{\rm p}^{\rm max}$. See Sect. 6.2 for details.

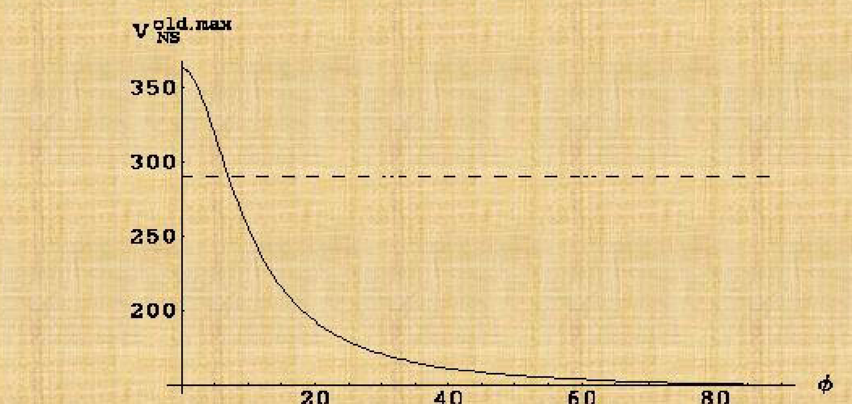

Figure 3. The dependence of the maximum value of the velocity of the old NS on the angle between the kick vector and the orbital plane.

• The above considerations show that $v_{\rm NS}^{\rm old}$ could be consistent with $v_{\rm p}$, but a must be as small as possible while avoiding pulsar recycling and the kick direction must be carefully tuned. For $d = 0.9$ kpc and $a \sim 35R_\odot$ the probability of a favourable kick orientation is $\sim 10^{-3}$ (for the isotropic kick distribution) or $\sim 10^{-2}$ (if the kick is restricted close to the orbital plane). Note also that the smaller d 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.

7. Second (young) NS

• 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.
• Fig. 4 shows how the angle, ψ, between the velocity vectors of the old and new-born NSs 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 $\theta \sim \theta_*$ 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 $\leq 70°$ 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 $v_{\rm NS}^{\rm new} < v_{\rm NS}^{\rm old}$. Remind that the SN blast center could be significantly offset from the geometric center of S 147 (see Sect. 3).

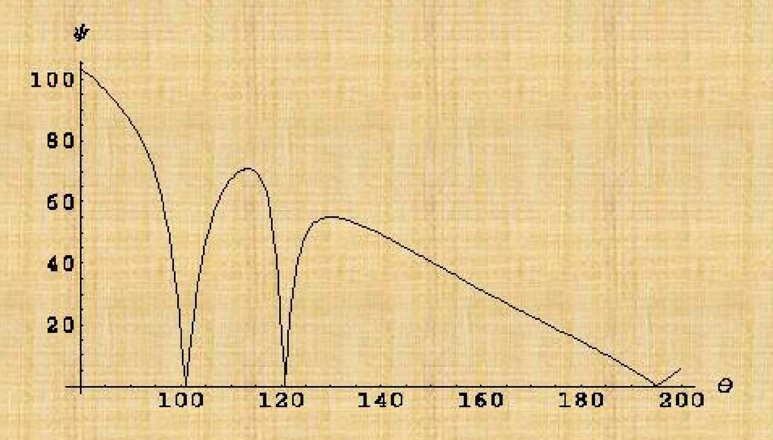

Figure 4. The angle between the velocity vectors of the old and new-born NSs as a function of the angle between the kick vector and the direction of motion of the exploding star.

• 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 shows five sources in the proper place. The count rates of these sources (ranging from $\simeq 0.014$ to $\simeq 0.039\,\mathrm{ct\,s^{-1}}$) should be compared with the count rate in the *ROSAT* pass band expected for a NS of age of $\simeq 3\times10^4$ 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 $\simeq 2.5-3\times10^{21}\,\mathrm{cm^{-2}}$ (e.g. McGowan et al. 2003; Romani & Ng 2003) and using PIMMS, one has $\simeq 0.017-0.022$ *ROSAT* PSPC $\mathrm{ct\,s^{-1}}$, 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 (Romani & Ng 2003). Deep radio or X-ray observations would allow us to verify the existence of such a nebula.
• 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 the pulsar belongs to a class of slowly cooling NSs (see Gvaramadze 2006).

For more details see:
*Gvaramadze, V.V., 2006, A&A, **454**, 239*