Young Neutron Stars and Their Environments
IAU Symposium, Vol. 218, 2004
F. Camilo and B. M. Gaensler, eds.

The Association of PSR B1757–24 and the SNR G5.4–1.2

V. V. Gvaramadze

Sternberg Astronomical Institute, Moscow State University,
Universitetskij Pr. 13, Moscow, 119992, Russia

E. K. Kharadze Abastumani Astrophysical Observatory, Georgian
Academy of Sciences, A. Kazbegi Ave. 2A, Tbilisi, 380060, Georgia

Abstract. The association of PSR B1757–24 and the supernova remnant (SNR) G5.4–1.2 was recently questioned by Thorsett et al. (2002) on the basis of proper motion measurements of the pulsar and the "incorrect" orientation of the vector of pulsar transverse velocity (inferred from the orientation of the cometary-shaped pulsar wind nebula). We show, however, that the association could be real if both objects are the remnants of an off-centered cavity supernova explosion.

1. Introduction

Recent proper motion measurements of PSR B1757–24 by Thorsett, Brisken & Goss (2002) put a 2σ upper limit on the pulsar transverse velocity, $v_{\rm p} \leq 160\,d_5\,{\rm km\,s^{-1}}$, where d_5 is the distance to the pulsar in units of 5 kpc. This upper limit is at least an order of magnitude less than the velocity estimate inferred from the angular displacement of PSR B1757–24 from the geometric center of G5.4–1.2 (Frail & Kulkarni 1991; Manchester et al. 1991). Thorsett et al. interpreted the discrepancy between the "measured" and inferred velocities as an indication of equally large discrepancy between the kinematic age of the system, $t_{\rm kin} = l/v_{\rm p}$, where l is the distance traveled by the pulsar from its birthplace, and the characteristic age of the pulsar, $\tau = P/(n-1)\dot{P}$. The latter discrepancy and the "incorrect" orientation of the inferred line of pulsar proper motion (the cometary-shaped pulsar wind nebula [PWN] does not point to the geometric center of G5.4–1.2; Frail, Kassim & Weiler 1994) constitute two arguments against the physical association of PSR B1757–24 and G5.4–1.2 proposed by Thorsett et al. (2002). In this paper we show, however, that the association could be real if both objects are the remnants of a supernova (SN) explosion within a bubble blown-up by the moving SN progenitor star during the Wolf-Rayet (WR) phase of its evolution.

2. SNR G5.4–1.2 and its Progenitor Star

Let us explain why we believe that the pre-SN was a WR star and that the SN exploded within the WR bubble, but not in the bubble created during the preceding main-sequence (MS) phase. In our reasoning we proceed from the fact that a young neutron star (born with a moderate kick velocity of appropriate orientation) can overrun the shell of the associated SNR only on condition that: (a) the SN exploded within a pre-existing bubble surrounded by a massive shell, (b) the SN explosion site was significantly offset from the center of the bubble (e.g. Gvaramadze 2002a, b). It is unlikely, however, that these conditions can be fulfilled for the MS bubbles. Indeed, simple estimates show that most of the massive stars explode outside their MS bubbles, while the bubbles stall and loose their shells well before the end of the MS phase (Brighenti & D'Ercole 1994). On the other hand, if a massive star ended its evolution as a WR star, the energetic WR wind could create a new large-scale bubble, whose supersonic expansion drives a shell of swept-up interstellar matter (ISM) during the whole relatively short WR phase. Besides, it is the short duration of the WR phase that results in even a runaway massive star being able to explode within its WR bubble.

We assume that the SN exploded near the western edge of the WR bubble (cf. Gvaramadze & Vikhlinin 2003) on the line defined by the cometary-shaped PWN, i.e. the SN exploded $\simeq 9\,d_5$ pc east of the current position of the pulsar (or about $3.5\,d_5$ pc behind the western edge of G5.4–1.2). In this case, $t_{\rm kin} (\simeq 5.4 \times 10^4$ yr) could be reconciled with τ if $n \leq 1.6$, i.e. for braking indices comparable with n measured for the Vela pulsar (cf. Thorsett et al. 2002).

The further evolution of the blast wave depends on the mass of the pre-existing shell, $M_{\rm sh} = (4\pi/3)R_{\rm sh}^3 \rho_{\rm ISM}$, where $R_{\rm sh}$ is the radius of the shell, $\rho_{\rm ISM} = 1.3 m_{\rm H} n_{\rm ISM}$, $m_{\rm H}$ is the mass of a hydrogen atom and $n_{\rm ISM}$ is the number density of the ambient ISM. The number density could be evaluated by comparing the observed minimum size of the PWN ahead of the moving pulsar, $R_{\rm n}$, with the theoretically predicted one, $\kappa R_0 = \kappa(\dot{E}/4\pi c \rho_{\rm ISM} v_{\rm p}^2)^{1/2}$, where $\kappa \simeq 1.26$ (Bucciantini 2002), R_0 is the stand-off distance, $\dot{E} \simeq 2.6 \times 10^{36}\,{\rm ergs\,s^{-1}}$ is the spin-down luminosity of the pulsar and c is the speed of light. For $R_{\rm n} = 3.6 \times 10^{-2} d_5$ pc (Gaensler & Frail 2000) and $v_{\rm p} = 160\,{\rm km\,s^{-1}}$, one has $n_{\rm ISM} \simeq 1.0\,{\rm cm^{-3}}$. Then assuming that $R_{\rm sh} = 20$ pc, one has $M_{\rm sh} \simeq 10^3\,{\rm M_\odot}$.

The numerical simulation of cavity SN explosions by Tenorio-Tagle et al. (1991) showed that the SN blast wave evolves into a momentum-conserving stage if the mass of the pre-existing shell was larger than $\simeq 50 M_{\rm ej}$, where $M_{\rm ej}$ is the mass of the SN ejecta. For any reasonable initial mass of the SN progenitor, one has that $M_{\rm sh} >> 50\,M_{\rm ej}$. Thus the SNR G5.4–1.2 is in the radiative stage (with the initial expansion velocity of $\simeq 100\,{\rm km\,s^{-1}}$), so that the pulsar can easily overrun the SNR.

3. G5.27–0.9

We now discuss the origin of the compact source G5.27–0.9 located between PSR B1757–24 and G5.4–1.2 (e.g. Frail & Kulkarni 1991). We suggest that G5.27–0.9 is a lobe of a low Mach number jet of gas outflowing from the interior of G5.4–1.2 through the hole bored in the SNR's shell by the escaping pulsar.

The gas velocity at the origin of the jet is $v_{\rm j} \simeq \sqrt{3}\,c_{\rm j}$, where $c_{\rm j}$ is the sound speed of the outflowing gas. The structure and the dynamics of supersonic jets propagating through the ambient medium are mainly determined by two parameters: the jet Mach number, $\mathcal{M}_{\rm j} = v_{\rm j}/c_{\rm j}$, and the jet-to-ambient-medium density ratio, $\rho_{\rm j}/\rho_{\rm ISM}$ (see Norman et al. 1982). In our case $\mathcal{M}_{\rm j} \simeq 1.7$ and $\rho_{\rm j}/\rho_{\rm ISM} << 1$. Numerical simulations conducted by Norman et al. (1982) showed that a low-density, Mach 1.5 jet ends itself in a gradually inflating and slowly-moving lobe. The morphological similarity of this lobe (see Fig. 10a of Norman et al. 1982) and G5.27–0.9 (see Fig. 1b of Frail & Kulkarni 1991) allows us to consider the existence of inner bright spots in G5.27–0.9 and the edge-darkened appearance of this source as indications that the jet has already reached its maximum spatial extent (see Norman et al. 1982). Therefore the pulsar moving along the jet axis was able to overrun the lobe and now it travels through the ISM.

4. PSR B1757–24 and its PWN

Is is clear that the proper motion of a neutron star born in an off-centered cavity SN explosion could be oriented arbitrarily with respect to the geometric center of the associated SNR (Gvaramadze 2002a, b). Therefore one should not worry why the cometary-shaped PWN does not point to the geometric center of G5.4–1.2. Let us briefly discuss some points related to the origin of this nebula.

The supersonic motion of PSR B1757–24 through the ISM results in the origin of an elongated structure, where the pulsar wind is swept back by the ram pressure. The region occupied by the wind is bounded by a contact discontinuity, which asymptotically becomes cylindrical with a characteristic radius $R \simeq 0.85\mathcal{M}_{\rm p}^{3/4}(1 - 0.85\mathcal{M}_{\rm p}^{-1/2})^{-1/4}R_0$, where $\mathcal{M}_{\rm p} = v_{\rm p}/c_{\rm ISM}$ and $c_{\rm ISM}$ is the sound speed of the ambient ISM (Bucciantini 2002). For the temperature of the ambient ISM of $\simeq 8000\,{\rm K}$, one has that $R(\simeq 7'' \, d_5^{-1})$ is few times larger than the half-width of the PWN, i.e. most of the pulsar wind is unobservable.

We suggest that the non-thermal X-ray emission of the cometary tail behind the pulsar (Kaspi et al. 2001) is due to the synchrotron losses of the relativistic pulsar wind shocked at the termination shock, which extends in the tail up to a distance of $L \simeq 1.29\,\mathcal{M}_{\rm p}R_0$ (see Bucciantini 2002 and Fig. 1 therein) and where the wind particles acquire non-zero pitch angles. An indirect support to this suggestion comes from the comparison of $L \simeq 19'' \, d_5^{-1}$ with the observed length of the X-ray tail of $\simeq 20''$.

We also suggest that the (non-thermal) radio emission of the PWN originates in the vicinity of the termination shock and in a much more extended narrow cylindrical region of subsonically moving shocked pulsar wind (cf. Bucciantini 2002). This suggestion implies that in the absence of the radio source G5.27–0.9 the radio tail would be much longer than its X-ray counterpart (perhaps as long as the tail of the "Mouse" radio nebula [G359.23–0.82; Yusef-Zadeh & Bally 1987] powered by the young pulsar PSR J1747–2958, whose spin characteristics are almost the same as those of PSR B1757–24; Camilo et al. 2002).

5. Concluding Remark

To conclude, we note that the idea of off-centered cavity SN explosions could be used not only to assess the reliability of proposed neutron star/SNR associations

(Gvaramadze 2002a; Bock & Gvaramadze 2002), but also to explain the diverse morphologies of the known SNRs (Gvaramadze 2002b, 2003; Gvaramadze & Vikhlinin 2003) and to search for new stellar remnants associated with SNRs (Gvaramadze & Vikhlinin 2003).

Acknowledgments. I am grateful to R. N. Manchester, M. Orine and H. Rickman, whose support allowed me to attend the symposium.

References

Bock, D. C.-J., & Gvaramadze, V. V. 2002, A&A, 394, 533

Brighenti, F., & D'Ercole, A. 1994, MNRAS, 270, 65

Bucciantini, N. 2002, A&A, 387, 1066

Camilo, F., Manchester, R. N., Gaensler, B. M., & Lorimer, D. R. 2002, ApJ, 579, L25

Frail, D. A., & Kulkarni, S. R. 1991, Nature, 352, 785

Frail, D. A., Kassim, N. E., & Weiler, K. W. 1994, AJ, 107, 1120

Gaensler, B. M., & Frail, D. A. 2000, Nature, 406, 158

Gvaramadze, V. V. 2002a, in ASP Conf. Ser., Vol. 271, Neutron Stars in Supernova Remnants, eds. P. O. Slane, & B. M. Gaensler (San Francisco: ASP), p. 23

— 2002b, astro-ph/0208028

— 2003, in IAU Symp. 214, High Energy Processes and Phenomena in Astrophysics, eds. X. Li, V. Trimble, & Z. R. Wang, (San Francisco: ASP), p. 141

Gvaramadze, V. V., & Vikhlinin, A. A. 2003, A&A, 401, 625

Kaspi, V. M., Gotthelf, E. V., Gaensler, B. M., & Lyutikov, M. 2001, ApJ, 562, L163

Manchester, R. N., Johnston, S., Kaspi, V. M., Lyne, A. G., & D'Amico, N. 1991, MNRAS, 253, 7P

Norman, M. L., Winkler, K.-H. A., Smarr, L., & Smith, M. D. 1982, A&A, 113, 285

Tenorio-Tagle, G., Różyczka, M., Franco, J., & Bodenheimer, P. 1991, MNRAS, 251, 318

Thorsett, S. E., Brisken, W. F., & Goss, W. M. 2002, ApJ, 573, L111

Yusef-Zadeh, F., & Bally, J. 1987, Nature, 330, 455