1. Introduction

Usually the evaluation of reliability of claimed NS/SNR associations is based on the use of several criteria formulated by Kaspi (1996), which lead to the following questions:

1. Do independent distance estimates agree?
2. Do independent age estimates agree?
3. Is the implied transverse velocity reasonable?
4. Is there evidence for any interaction between the NS and SNR?
5. Does the proper motion vector of the NS point away from the SNR center?

The last question is considered the most important one since a proper motion measurement has the potential to disprove an association regardless of the answers to the other questions (Kaspi 1996).

Some even as a claimed NS/SNR association is considered as false on the basis of statistical studies of associations (e.g., Gaensler & Johnston 1999, Lorimer et al. 1998). For example, one of the arguments against the association of PSR B 1706-44 with the SNR G 343.1-2.3 (Kaspi et al. 1998) is based on the suggestion by Gaensler & Johnston (1995) that young (< 25,000 yr) NSs cannot over pump their parent SNR shells.

However, these approaches neglect two very important effects: the modification of the ambient medium by the ionizing emission and stellar wind of massive stars (the progenitors of most of SN), and the proper motion of SN progenitor stars. The first effect is important since it is the subsequent interaction of SN blast waves with their processed ambient medium (a system of cavities and shells) that results in the observed SNRs; their structure and evolution are already known to deviate significantly from those derived from standard models of SNRs based on the Sedov-Taylor solution (e.g., Shull et al. 1985, Lott & D'Ercole 1989, Chevalier & Liang 1989, Franco et al. 1994). The stellar proper motion should be considered since it could result (Varamadze 2000, 2002 and references therein) in a considerable set of the SNR explosion site from the center of the wind-driven bubble (i.e., from the geometric center of the future SNR).

Taking into account these two effects could significantly affect the results of previous studies of NS/SNR associations, and allow us to enlarge the circle of possible NS/SNR associations and to search for new associations.

2. Reliability of NS/SNR associations

We now discuss the criteria for evaluating the reliability of NS/SNR associations proposed by Kaspi (1996). It is obvious that the first two criteria should be undoubtedly fulfilled for any proposed association. But the application of the third and fifth ones for evaluating proposed associations is not so straightforward, since they are based on the assumption that the SN explosion site coincides with the geometric center of the SNR. This assumption, however, could be erroneous in the case of density-stratified interstellar medium (e.g., Gullbrand 1974) or in the case of an off-centered cavity SN explosion (Varamadze 2000, 2002 and references therein). In both cases...
the velocity estimates implied by angular displacements of NSs from the geometric centers of associated SNRs could be significant in error, while the associations rejected on the basis of high implied transverse velocities of NSs (e.g. SGR 0525-66/SNR N 49, Kasparyan et al. 2000, or PSR B 1706-44/SNR G 343.1-2.3, Nicastro et al. 1996) could be genuine.

It is clear that the proper motion vector of a NS born in an o- centered cavity SN explosion could be oriented arbitrarily with respect to the geometric center of the associated SNR. Therefore one can naturally explain why the tails behind a number of NSs (e.g. PSR B 1757-24 Frail et al. 1994; see also Sect. 3.2) or a compact X-ray source in the SNR IC 433 (Oberst et al. 2001)) do not point towards the centers of their parent shells. In principle, the proper motion vector of a NS even could be directed to the center of the SNR (just this situation takes place in the case of PSR B 0565+14, which is located within the SNR Monogem Ring; see Thompson & Cordova 1994). Therefore it is not impossible that a NS born far from the center of the remnant wind-driven bubble (now the center of the SNR) will reach it after a while (a possible example: the 24,000 yr old PSR J1811-1925 located close to the center of the nearly circular SNR G 11.2-0.3; see Coriat et al. 1997). From this follows that the age of a NS inferred from the NS displacement can be very large from the geometric center of the associated SNR could be considerably underestimated (cf. Kasper et al. 2001 and Mignazzo et al. 2002).

The fourth criterion should be applied for those claimed associations, where the NS is located not far (at least in projection) from the SNR’s shell, e.g. in the case of PSR B 1706-44, which is superposed on the arc-like “shell” of the SNR G 343.1-2.0. However, the two objects against the association between these objects is any signs of any interaction between the pulsar and the SNR’s shell (e.g. Nicastro et al. 1996). But the apparent location of a NS on the edge of SNR’s shell simply could be due to the effect of projection in nonspherically-symmetric SNRs (Bock & Gvaramadze 2002a,b).

3. Some examples

3.1. PSR B 1610-50/SNR Kes 32

Some times the high implied transverse velocities of NSs are used to discard the possible NS/SNR associations. For example, Stappers et al. (1999) suggested (cf. Polvarez et al. 2000) that the lack of a pulsar wind nebula around PSR B 1610-50 means that the maximum space velocity of this pulsar is 450 km s$^{-1}$, where $d$ is the distance to the pulsar in units of kpc, and therefore it could not be associated with the nearby SNR Kes 32 since this association implies the transverse velocity of the pulsar of 2000 km s$^{-1}$ (Caraveo 1993). The implied velocity, however, could be reduced two times simply due to the possible o- centered cavity SN explosion, and once again two or even more times if the braking index of the pulsar is similar, respectively, to that of PSR B 0540-69 (n = 1.2) or the Vela pulsar (n = 1.6).

3.2. PSR B 1757-24/SNR G 5.4-1.2

The high transverse velocity also was inferred for PSR B 1757-24, which lies well outside the shell of the SNR G 5.4-1.2 (e.g. Cassel et al. 1997). The physical association of these two objects was firmly established after the discovery (e.g. Frail & Kulkarni 1991) of a tail of radio emission connecting the pulsar with the SNR. However, the pulsar PSR B 1757-24 is more interesting in that its proper motion vector does not point away from the geometric center of the SNR (Frail et al. 1994). We suggest that the SNR G 5.4-1.2 is the result of an o- centered SN explosion in the preexisting wind-driven bubble surrounded by a massive shell. The mass of the shell is a very important parameter since it determines the evolution of the SN: if the mass of the shell is 50 times the mass of the SN ejecta, the SN blast wave merges with the shell (e.g. Cassel et al. 1998) and evolves into a m on entum-conserving stage (i.e. propagates with a velocity < 200 km s$^{-1}$). In this case, even a young NS moving with a moderate velocity (200 km s$^{-1}$) is able to over-run the SNR’s shell (e.g. Cassel & Johnston 1999), provided that the NS was born not far from the edge of the wind-driven bubble. Our suggestion allows to reduce considerably the transverse velocity of the pulsar and naturally explains why the tail behind the pulsar does not point back to the center of the SNR.

3.3. PSR B 1706-44/SNR G 343.1-2.3

The reader is referred to Bock & Gvaramadze 2002a,b who provide some arguments in support of this association in details.

4. Peculiar SNRs

A concept of an o- centered cavity SN explosion could be used to explain the peculiar structure of a number of SNRs and thereby to infer the “true” SN explosion sites in these SNRs. The later, in its turn, could be used for searches for stellar remnants possible associated with these SNRs.

4.1. RCW 86

We suggest that the SNR RCW 86 is the result of a cavity SN explosion of a moving massive star (cf. Vink et al. 1999), which ends its evolution just near the edge of the main-sequence (MS) bubble. We also suggest that the

1. An indirect support to this suggestion comes from the recent observations of the radio nebula surrounding PSR B 1757-24 (Cassel et al. 2000), which showed that the proper motion velocity of this pulsar should be much less than the implied one.
bright protrusion in the southwest half of the SNR is the recently shocked dense material of a bow shock-like structure generated by the moving SN progenitor star during the red supergiant (RSG) phase. We interpret a clumpy optical arc of radius of’ 15d_{2,8} pc located interior to the X-ray and radio outlines of the protrusion (see, e.g., Fig. 2 of Rosado et al. 1996) as the remnant of this structure, while the remnant of the SN is due to the interaction of the SN blast wave with the wall of the adjacent MS bubble. For the SNR’s age of few times 10^3 yr (i.e., the time required for the SN blast wave to cross the MS bubble of diameter of’ 35 pc) and provided that the NS was born with the velocity of 200 km s^{-1}, one can propose that the stellar remnant should still be within the region bounded by the optical arc. To check this proposal we analysed archival ROSAT data, but the limited photon statistics and the moderate spatial resolution of the ROSAT PSPC did not allow the detection of a possible compact X-ray source against the bright background emission of the SNR’s shell. The analysis of the Chandra data (which shortly will be publicly available) would be highly desirable.

4.2.1E 0102.2-7219

A massive star moving with a sufficiently large velocity (> 2000 km s^{-1}) crosses the MS bubble and during the RSG phase moves mainly through the unperturbed interstellar medium. The slow, dense wind losing during the RSG phase assum the form of an elongated tail-stretched behind the moving star. This asymmetric and massive (‘10 M⊙) circumstellar structure could survive the passage of the SNR blast wave and will appear as a ‘spoke’ of aX-ray emission joining the SN explosion site to the circular shell of the young (few times 10^3 yr) SN. We suggest that just this situation takes place in the case of the SNR 1E 0102.2-7219 and interpret a prominent curl on the south end of the ‘spoke’ (see Fig. 1 of Gaetz et al. 2000) as the recently shocked wall of the ‘hollow’ tail produced by the moving SN progenitor star.

In the above two examples we assumed that the SN explodes just after the RSG phase, that is, at the zero age MS mass of the SN progenitor star was 20 M⊙ (e.g., Vanbeveren et al. 1998). If, however, the progenitor star is more massive, then after the RSG phase evolves through the Wolf-Rayet (WR) phase. The existence of this additional evolutionary phase could have some important consequences. One of them is discussed below.

5. Mixed-morphology SNRs

We propose that the SN explosion sites in some mixed-aged (shell-like) SNRs could be marked by nebulae of the aX-ray emission and that this emission could be responsible for the centrally-peaked X-ray appearance of some (so-called mixed-morphology; Hiro & Petruk 1998) SNRs. Our proposal is based on the following simple arguments (see also Varvadoula 2000, 2002).

A massive star, before it explodes as a SN, loses during the RSG phase a considerable fraction (2-3) of its initial mass in the form of a slow, dense wind, which occupies a region of radius a few pc. The subsequent interaction of the fast WR wind with the slow RSG wind results in the origin of dense clumps, radially moving with velocities of 100 km s^{-1} (see Varvadoula 2000) and references therein). A fast the SN explodes, the slow wind produces through the tenuous interstellar medium, leaving behind the dense clumps in the hot shocked interstellar gas. The gradual evaporation of the material of radially moving clumps results in the origin of an expanding nebula of the aX-ray emission, which is centered on the SN explosion site.

Let us consider two mixed-morphology SNRs.

5.1. 3C 400.2

The SNR 3C 400.2 consists of two circular radio shells with the centrally-liked them alX-ray emission peaked on the region where the radio shells overlap each other (Dubner et al. 1994; see also Yoshida et al. 2001). We suggest that this SNR is the result of a SN explosion inside the large-scale WR bubble adjacent to the MS bubble (cf. Dubner et al. 1994; Velazquez et al. 2001). We also suggest that the them alX-ray emission comes from the hot gas evaporated from the dense circumstellar clump (see above) and that the X-ray peak coincides with the SN explosion site. Note that the mass of X-ray emitting material is < 10 M⊙ (Yoshida et al. 2001), where d_{2,8} is the distance to the SNR in units of 2.3 kpc (Levan et al. 1998), whereas the expected mass of circumstellar gas (i.e., the mass lost during the RSG phase) is > 15 M⊙.

5.2. G 290.1-0.8

The SNR G 290.1-0.8 consists of an elongated radio shell and a central nebula of them alX-ray emission. The unabsorbed 0.5-10.0 keV ux from the SNR is 1.8 × 10^{34} erg cm^{-2} s^{-1} (Slane et al. 2002), that at a distance of 7 kpc corresponds to a luminosity L = 10^{35} erg cm^{-2} s^{-1}. We suggest that the SN escapes far from the MS bubble, but inside the large-scale WR bubble (surrounded by a massive shell; see below). To estimate the mass of X-ray emission,...

2 The centrally-liked X-ray appearance of some SNRs could be connected with the development of large-scale Rayleigh-Taylor deformations of the preexisting wind-driven shell (induced by the impact of the SN blast wave), which results in the increase of the effective "thicknes" of the SNR’s shell. For example, this effect could be responsible for the absence of the limb-brightening in the northwest and southeast quadrants of the Vela SNR (Varvadoula 1999a). For details of view on the origin of them mixed-morphology SNRs see: Hines & Long (1991) and Petruk (2001).
ting gas, $M_X$, we assume that most of the observed X-ray flux comes from the bright central nebula of radius $R = 4 \, d_{10}$ pc. Then assuming that the gas is homogeneously distributed over the whole volume of the nebula, one has $M_X = \left(4 \pi^{\frac{3}{2}} R^3 \frac{2}{3} \right) \times m_H$, where $= 62 \, 10^{19}T^{0.6} \, \text{erg cm}^{-2}$ is the cooling function for temperatures between $10^5$ K and $4 \times 10^5$ K (e.g., Cowie et al. 1981), and $m_H$ is the mass of a hydrogen atom. For $T \gtrsim 72 \, 10^6$ K, $\text{F showed},$ one has $M_X \approx 100 \, M_\odot$, that is a quite reasonable value if the initial mass of the SN progenitor star was 20 $M_\odot$ (in this case the progenitor star ends its evolution as a WR star).

We note that the size and the general appearance of the SNR G 290.1-0.8 elongated shell, roughly parallel to the galactic plane, bright optical emission on either side from the major axis of the SNR (e.g., Elliot & Martin 1979) suggest that the SN explosion occurs inside a cavity surrounded by a massive (barrel-like) shell swept-up by the fast WR wind. The large-scale interstellar magnetic field (at low latitudes parallel to the plane of the Galaxy) accumulated in the wind-driven shell reduces the column density near the magnetic poles of the shell (Ferriere et al. 1997), that leads to the elongated shape of the resulting SNR and could be responsible for the bilateral distribution of the optical emission along the SNR's shell (the SN blast wave becomes radiative primarily near the magnetic equator, where the column density is maximum; cf. Gvamadze 1999b).

Acknowledgements

I am grateful to W. Brinkmann for his support during my stay at the Max-Planck-Institut für extraterrestrische Physik (Garching), where this work was partially carried out. I am also grateful to R. Petroff for his interest to the paper and to the LOC for financial support. This work was partly supported by the Deutscher Akademischer Austauschdienst (DAAD).

References

Bock D. C. J., Gvamadze V. V., 2002a, in Slane P. D., Gaensler B. M., eds, Neutron Stars in Supernova Remnants. ASP Conf. Ser., in press [astro-ph/0111430]

Bock D. C. J., Gvamadze V. V., 2002b, submitted to A&A

Caraveo P. A., 1993, ApJ, 415, L111

Caswell J. L., Kesteven M. J., Kom esko M. M., et al., 1987, MNRAS, 229, 325

Chevalier R. A., Liang E. P., 1989, ApJ, 344, 332

Chtáli L., De Vico A., 1989, A&A, 215, 347

Cowie L. L., Mckeel C. F., Ostriker J. P., 1981, ApJ, 247, 908

Dubner G. M., García E. B., Gottlieb M. et al., 1994, AJ, 108, 207

Elliot K. H., alain D. F., 1979, MNRAS, 186, 45p

Ferriere K. M., Mc Low M. M., Zweibel E. G., 1991, ApJ, 375, 239

Filippenko A. V., Kulkarni S. R., 1991, Nat, 352, 785

Filippenko A. V., Gottlieb M. W., Hinzkaz J. B. Z., 1994, ApJ, 437, 781

Franco J., Tercio-Tagle G., Bodenheimer P. et al., 1991, PASP, 103, 803

Frisch P. C., 2001, astro-ph/0109300

Gaensler B. M., Frail D. A., 2000, Nat, 406, 158

Gaensler B. M., Johnston S., 1995, Proc. A. stron. Soc. Aust., 12, 76

Gaitatzes J., Butt Y. M., Edgar R. J. et al., 2000, ApJ, 534, L47

Giacani E. B., Dubner G., Cappa C. et al., 1998, A&A, 333, 61

Gulliford P., 1974, Ap&SS, 31, 241

Gvamadze V. V., 1999a, A&A, 357, 712

Gvamadze V. V., 1999b, O desm Astron. Publ., 12, 117 astro-ph/9912512

Gvamadze V. V., 2000, astro-ph/0005572

Gvamadze V. V., 2001, A&A, 374, 259

Gvamadze V. V., 2002, in Slane P. D., Gaensler B. M., eds, Neutron Stars in Supernova Remnants. ASP Conf. Ser., in press

Kasi V. M., 1996, in Johnston S., Walker M. A., Balas M. V., eds, Pulsars: Problems and Progress. ASP, San Francisco, p. 375

Kasi V. M., 2000, in Kramar M., Wex N., Wielebinski R., eds, Pulsar Astronomy (2000 and Beyond). ASP, San Francisco, p. 485

Kasi V. M., Roberts M. E., Vasishth G. et al., 2001, ApJ, 560, 371

Lorimer D. R., Lyne A. G., Camilo F., 1998, A&A, 331, 1002

Migliazzio J. M., Gaensler B. M., Backer D. C. et al., 2002, ApJ, in press [astro-ph/0202063]

Nastro L., Johnston S., Korbelaik B., 1996, A&A, 306, 49

O'Dell C. M., Clear ekl C. R., Williams S. E. et al., 2001, ApJ, 554, L205

Petitko O., 2001, A&A, 371, 267

Pirovano M. J., Kasi V. M., Gotthelf E. V., 2000, ApJ, 528, 436

Rosado M., Ambrocio-Cruz P., Le Coarer E. et al., 1996, A&A, 315, 243

Rho J., Petroff R., 1998, ApJ, 503, L167

Shull J., Davison J. E., Kahn F. D. et al., 1985, MNRAS, 212, 799

Slane P. S., Smith R. K., Hughes J. P. et al., 2002, ApJ, 564, 284

Stappers B. W., Gaensler B. M., Johnston S., 1999, MNRAS, 308, 609

Thompson R. J., Cordova F., 1994, ApJ, 421, L13

Tori K., Taunem H., Dotani T. et al., 1997, ApJ, 489, L145

Vanbeveren D., De Loore C., Van Rensbergen W., 1998, A&A, 9, 63

Velazquez P. F., de la Fuente E., Rosado M. et al., 2001, A&A, 377, 1136

Vink J. S., Kastner J. S., Blaeker J. A. M., 1997, A&A, 328, 628

Vink J. S., Long J. S., 1991, ApJ, 373, 543

Yoshida K., Toriumi H., Miyata E. et al., 2001, PASJ, 53, 98