INTERACTION OF SUPERNOVA BLAST WAVES WITH WIND-DRIVEN SHELLS: FORMATION OF "JETS", "BULLETS", "EARS", ETC

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ABSTRACT. Most of middle-aged supernova remnants (SNRs) have a distorted and complicated appearance which cannot be explained in the framework of the Sedov-Taylor model. We consider three typical examples of such SNRs (Vela SNR, MSH 15-52, G 309.2-00.6) and show that their structure could be explained as a result of interaction of a supernova (SN) blast wave with the ambient medium preprocessed by the action of the SN progenitor's wind and ionized emission.

Key words: ISM: bubbles; ISM: supernova remnants.

1. Introduction

Most of middle-aged SNRs have a distorted and complicated appearance which cannot be explained in the framework of the standard Sedov-Taylor model. Three possibilities are usually considered to describe the general structure of such remnants:

– the SN blast wave interacts with the inhomogeneous (density stratified and/or clumpy) interstellar medium;
– the SN ejecta is anisotropic and/or clumpy;
– the stellar remnant (e.g. a pulsar) is a source of the relativistic wind and/or collimated outflows (jets) which power the central synchrotron nebula (plerion) and/or interact with the SNR's shell.

For example, all above possibilities were considered to explain the structure of the Vela SNR. Namely, the general asymmetry of this remnant (the northeast half of the Vela SNR faced towards the Galactic plane has a nearly circular boundary, whereas the opposite half is very distorted) as well as its patchy appearance in soft X-rays were attributed to the expansion of the SN blast wave in the inhomogeneous (large-scale cloud + a multitude of cloudlets) interstellar medium (e.g. Kahn et al. 1985, Bocchino et al. 1997). One of consequences of this suggestion is the proposal that the origin of optical filaments constituting the shell of the remnant is due to the slowing and cooling of parts of the SN blast wave propagating into dense clumps of matter (cloudlets). A number of radial structures (most prominent in soft X-rays) protruding far outside the main body of the remnant was interpreted as bow shocks produced by fragments of the exploded SN star ("bullets") supersonically moving through the interstellar medium (Aschenbach et al. 1995). An elongated X-ray structure stretched from the Vela pulsar position to the center of the brightest radio component of the Vela SNR (known as Vela X) was interpreted as a one-sided jet emanating from the Vela pulsar and transferring the pulsar's slow-down energy to the Vela X (e.g. Markwardt & Ögelman 1995). This interpretation supports the proposal of Weiler & Panagia (1980) that the Vela X is a plerion. A nebula of hard X-ray (2.5-10 keV) emission stretched nearly symmetrically for about 1° on either side of the pulsar in the northeast-southwest direction was also interpreted as a plerion (Willmore et al. 1992).

The first and third possibilities were considered in connection with the SNR MSH 15-52 (G 320.4-01.2). The radio map of this remnant given by Caswell et al. (1981) shows the elongated shell consisting of two bright components stretched parallel to the Galactic plane and separated by a gap of weak emission. The brightest X-ray emission of this remnant comes from two components, one of which centres on the position of the pulsar PSR B1509-58 (located close to the geometrical center of the MSH 1509-58), while the second one coincides with the maximum of emission of the brightest (closer to the Galactic plane) radio component and with the bright optical nebula (known as RCW 89). It was suggested that the central X-ray component of the MSH 15-52 is a plerion (e.g. Seward et al. 1984) and that the general structure of this remnant is affected by one (Tamura et al. 1996, Brazier & Becker 1997) or two (Manchester 1987, Gaensler et al. 1999) jets emanating from the pulsar.

And the third example is the SNR G 309.2-00.6, which consists (at radio wavelengths) of a nearly circular shell and two "ears" – arclike filamentary structures protruding from the shell in the opposite directions (nearly parallel to the Galactic plane). It was suggested, by analogy with the well-known system SS433/W50, that the distorted appearance of the G 309.2-00.6 is due to the interaction between a pair of jets produced by the central (unvisible) stellar remnant and the originally spherical shell of the SNR (Gaensler et al. 1998). It was also suggested that one of linear filaments in the northeast "ear" represents one of the proposed jets.

The goal of this paper is to show that the structure of at least three above-mentioned SNRs could be explained as a result of interaction of a SN blast wave with the ambient medium preprocessed by the action of the SN progenitor's wind and ionized emission.

2. Interaction of SN blast waves with wind-driven shells

It is known that progenitors of most of SN stars are massive ones (e.g. van den Bergh & Tammann 1991). Such stars are sources of intense stellar winds and ionizing emission which strongly modify the ambient interstellar medium. The ionizing radiation of the progenitor star creates an H II region, the inner, homogenized part of which gradually expands due to the continuous photoevaporation of density inhomogeneities in stellar environs (McKee et al. 1984). If the mechanical luminosity of the stellar wind L is much smaller than some characteristic wind luminosity, $L^* \simeq 10^{34}(S_{46}^2/n)^{1/3}$ ergs s^{-1}, where S_{46} is the stellar ionizing flux in units of 10^{46} photons s^{-1} and n is the mean density the ambient medium would have if were homogenized, the stellar wind flows through a homogeneous medium and creates a bubble of radius (e.g. Weaver et al. 1977) $R(t) = 11 L_{34}^{1/5} n^{-1/5} t_6^{3/5}$ pc, where $L_{34} = L/(10^{34}\,\mathrm{ergs\,s^{-1}})$, $t_6 = t/(10^6\mathrm{years})$. Initially the expanding bubble is surrounded by a thin, dense shell of swept-up interstellar gas, but eventually the gas pressure in the bubble becomes comparable to that of the ambient medium, and the bubble stalls, while the shell disappears. The radius of the stalled bubble is $R_\mathrm{s} = 5.5 L_{34}^{1/2} n^{-1/2}$ pc. Since the star continues to supply the energy in the bubble, the radius of the bubble continues to grow, $\propto t^{1/3}$, until the radiative losses in the bubble interior becomes comparable to L. Then the bubble recedes to some stable radius R_r, at which radiative losses exactly balance L (D'Ercole 1992): $R_\mathrm{r} = 2.2\, L_{34}^{6/13}\, n^{-7/13}$ pc. Before a massive star exploded as a supernova it becomes for a relatively short time, $t_\mathrm{RSG} \simeq 10^6$ years, a red supergiant (RSG). The ionized gas outside the bubble rapidly cools off because the central star cannot keep it hot. At the same time the rarefied interior of the bubble remains hot as the radiative losses there are negligible on time-scales of t_RSG. As a result, the bubble supersonically reexpands in the external cold medium and creates a new dense shell (D'Ercole 1992; cf. Shull et al. 1985). Two main factors could significantly affect the structure of the shell. The first one is the regular interstellar magnetic field (generally it is parallel to the Galactic plane). This factor leads to the matter redistribution over the shell and to its concentration near the magnetic equator: the column density at the equator is increased about ten times (Ferrière et al. 1991). The second factor is the large-scale density gradient. It is known (Landecker et al. 1989, Gosachinskij & Morozova 1999) that molecular clouds tend to be stretched along the Galactic plane, therefore one might expect that due to the interaction with a nearby cloud one of two sides of the shell (not necessary the nearest to the Galactic plane) could be more massive than the opposite one. These two factors naturally define two symmetry axes (parallel and perpendicular to the Galactic plane) of the future SNR.

During the RSG stage a massive star lost most of its mass (e.g. a $20M_\odot$ star loses about two thirds of its mass) in the form of slow, dense wind. This material expands in the interior of the reexpanded main-sequence (MS) bubble and occupies a compact region surrounded by a dense shell. The size of this region is determined by the counter-pressure of the external hot gas and is equal to about few parsecs (e.g. Chevalier & Emmering 1989, D'Ercole 1992). Most probably that this region is far from the spherical symmetry (it is believed that the wind of a RSG is concentrated close to the stellar equatorial plane).

After the SN exploded, the blast wave interacts with the dense RSG wind. This interaction continues few hundreds years and determines the appearance of young SNRs (e.g. Cas A, see Borkowski et al. 1996). Then the blast wave propagates through the low-density interior of the MS bubble until it catches up the dense shell. During this period (lasting about one thousand years) the blast wave is unobservable. The subsequent evolution of the blast wave (i.e. the SNR) depends on the mass of the shell. If the mass of the shell is smaller than about 50 times the mass of the SN ejecta the blast wave overruns the shell and continues to expand adiabatically as a Sedov-Taylor shock wave. For more massive ones, the blast wave merges with the shell, and the reaccelerated shell evolves into a momentum-conserving stage (e.g. Franco et al. 1991). The impact of the blast wave with the shell causes the Rayleigh-Taylor and other dynamical instabilities. The inhomogeneous mass distribution over the shell affects the development of instabilities and results in the asymmetry of the resulting SNR. The more massive half of a shell created in the density-stratified medium is less sensitive to the impact of the SN blast wave, while the opposite (less massive) one becomes strongly deformed and sometimes even disrupted. The effect of the regular magnetic field is twofold: first, it leads to the bilateral appearance of SNRs (cf. Ferrière et al. 1991, Gaensler 1998), second, it results in the elongated form of remnants (because of reduced inertia of shells at the magnetic poles).

3. Three examples

Let us consider the SNRs mentioned in Sect. 1.

3.1. Vela SNR

We suggest that the Vela SNR is a result of type II SN explosion in a cavity created by the wind of a 15-20 $M_\odot$ star and propose that the general structure of the remnant is determined by the interaction of the SN blast wave with the massive shell created around the reexpanded MS bubble (see Sect. 2; for details see Gvaramadze (1999a)). The impact of the blast wave with the shell causes the development of Rayleigh-Taylor deformations of the shell ("blisters"), which appear as arclike and looplike filaments when our line of sight is tangential to their surfaces. The optical emission is expected to come from the outer layers of the shell, where the transmitted SN blast wave slows to become radiative, while the soft X-ray emission represents the inner layers of the shell heated by the blast wave up to X-ray temperatures. The origin of some radial protrusions (labelled by Aschenbach et al. (1995) as "bullets" A,B,C, and D/D') could be connected with the shell deformations, while the "bullets" E and F could be interpreted as outflows of a hot gas escaping through the breaks in the SNR's shell (Gvaramadze 1998a, Bock & Gvaramadze 1999). As to the X-ray "jet" discovered by Markwardt & Ögelman (1995), an analysis of the radio, optical, and X-ray data suggested that it is a dense filament in the Vela SNR's shell (projected by chance near the line of sight to the Vela pulsar), and that its origin is connected with the nonlinear interaction of the shell deformations (see Gvaramadze 1999a). The nature of the radio source Vela X is considered in the paper by Gvaramadze (1998b), where it is shown that the Vela X is also a part of the shell of the Vela SNR, but not a plerion. In conclusion one should be noted that the slow, dense RSG wind lost by the progenitor star and subsequently reheated and reaccelerated by the passage of the SN blast wave could be responsible for the origin of a hard X-ray nebula discovered by Willmore et al. (1992) (Willmore et al. mentioned that their data do not allow to discern the thermal and nonthermal forms of the spectrum of this nebula).

3.2. SNR MSH 15-52

The SNR MSH 15-52, associated with the pulsar PSR B1509-58, is usually classified as a composite SNR. This is because of it consists of an extended nonthermal radio shell (at the distance of $\simeq 5$ pc (e.g. Gaensler et al. 1999) the diameter of the remnant ≥ 40 pc) and a central elongated X-ray nebula ($\simeq 7$ pc $\times 12$ pc) which is thought to be a synchrotron pulsar-powered nebula (a plerion). The spin-down age of the pulsar is $\simeq 1700$ years (i.e. nearly the same as that of the Crab pulsar), while the size and general appearance of the MSH 15-52 suggest that this system should be much older (few times 10^4 years). To reconcile the ages of the pulsar and remnant, Seward et al. (1983) considered two possibilities: 1) MSH 15-52 is a young SNR, and 2) PSR B1509-58 is an old pulsar. The first one implies (in the framework of the Sedov-Taylor model) that the SN explosion was very energetic and occured in a tenuous medium (see also Bhattacharya 1990). This point of view is generally accepted (e.g. Gaensler et al. 1999). The second possibility was reexaminated by Blandford & Romani (1988), who suggested that the pulsar spin-down torque grew within the last $\simeq 10^3$ years (due to the growth of the pulsar's magnetic field) and therefore the true age of the pulsar could be as large as it follows from the age estimates for the SNR. We propose an alternative explanation (Gvaramadze 1999b) and suggest that the high spin-down rate of the pulsar is inherent only for a relatively short period of the present spin history and that the enhanced braking torque is connected with the interaction of the pulsar's magnetosphere with a dense clump of circumstellar matter (whose origin is connected with the late evolutionary stages of the progenitor star). This suggestion implies that the central X-ray nebula could be interpreted as a dense material lost by the progenitor star during the RSG stage and reheated to high temperatures by the SN blast wave. The existance of a hot plasma (of mass of about few $M_\odot$) around the pulsar follows from the IR observations of the MSH 15-52 by Arendt (1991), who discovered an IR source near the position of the pulsar. We believe that the thermal emission of this plasma is contaminated by the hard nonthermal emission from a (much smaller) compact nebula powered by the pulsar (similar to the $1^{'}(\simeq 4 \times 10^{17}$ cm) nebula discovered by Harnden et al. (1985; see also de Jager et al. 1996) around the Vela pulsar), and that this is the reason why the spectrum of the whole central nebula is usually described by a nonthermal model (e.g. Greiveldinger et al. 1995, Tamura et al. 1996).

The shell of the MSH 15-52 remainds that of the Vela SNR (cf. Fig.8 of Gaensler 1998 and Fig.1 of Gvaramadze 1999a). In both remnants the halves faced towards the Galactic plane are brighter and more regular than the opposite ones. We suggest that the MSH 15-52 is a result of interaction of the SN blast wave with the wind-driven shell created in the inhomogeneous interstellar medium: the northwest half of the shell interacts with the region of enhanced density (that results in the origin of bright radio, optical and X-ray emission), and therefore is less affected (distorted) by the impact of the SN blast wave than the southeast half. The bilateral and elongated appearance of the shell could be connected with the effect of the large-scale interstellar magnetic field (cf. Gaensler 1998, Gaensler et al. 1999).

3.3. SNR G 309.2-00.6

We suggest that the "ears" of this SNR were blown up in the polar regions of the (former) wind-driven shell created in the interstellar medium with regular magnetic field (oriented nearly parallel to the Galactic plane). The origin of the "jet" and other filamentary structures visible in the remnant (see Fig.2 of Gaensler et al. 1998) we connect with projection effects in the Rayleigh-Taylor unstable shell. We suggest also that the SN explosion site[1] should be marked by a hard X-ray nebula and predict that the angular size of the nebula (for the distance to the remnant of 5-14 kpc (Gaensler et al. 1998)) is about $1.5^{'} - 2^{'}$.

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[1]Note that it could be shifted from the geometrical centre of the SNR due to the proper motion of the SN progenitor star.