STELLAR WIND IN THE ISM

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ABSTRACT. After a brief review of the modern understanding of stellar wind's action on the ISM we consider two aspects of its "global" collective effect from observational viewpoint. First, stellar winds from OB associations do provide favorable conditions for triggering star formation. Second, the entire history of an active star-forming complex does regulate the nature of a wind-blown bubble or a SNR.

Key words: ISM: SNR, wind-blown bubbles; stars: WR, OB-associations, star formation

1. Introduction

Stellar wind's and SNe' collective action are the dominant factors regulating the structure and dynamics of the ISM. Deep high-resolution images of nearest galaxies in $H\alpha$ and 21-cm lines look just like "layers of foam" of neutral and ionized shells and supershells that are believed to be created by stellar winds and SNe.

The wind from early-type Main Sequence stars was discovered in 1967; and since then we know that all OB stars (earlier than B2) are characterized by powerfull winds.

The physics of wind's action on the ambient gas has been understood immediately. According to the classical theory (Pikelner, 1968; Avedisova, 1971; Steigman et al., 1975; Castor at al., 1975; Weaver et al., 1977) strong stellar wind in the homogeneous ambient gas creats a multilayer system, so called "wind-blown bubble". Starting from inside it consists of the cental cavity filled with a freely expanding wind; the geometrically thick layer of hot wind material, heated by the reflected shock, and mixed with evaporated interstellar gas; and the outermost dense shell of the interstellar gas that is swept-up and heated by the shock wave.

The general concepts of the classical theory have remained unchanged for three decades. Modern theory has added radiative losses and instabilities, outflow changes over the lifetime of stars, inhomogeneities of the ISM (large-scale density gradients and cloudy structure) and, finally, clumpy structure of stellar winds.

The idea has recently been put forward that the standard "wind-blown bubble model" is not consistent with observations: kinematic ages of wind-swept shells appear to be lower than ages of related stellar populations or expansion velocities are higher than the model predicts (see Oey, Massey 1994; Oey 1996, and references therein).

I would say that it is not completely clear so far. In many cases we may have been oversimplifying the nature of real shells. Actually, pure, "constant density wind-blown bubbles" just do not exist. In terms of modern understanding of massive stars evolution three types of shells must exist around each WR star: 1 – wind-blown bubbles, 2 – stellar ejecta and 3 – shell-like HII regions. In some cases, indeed, they are clearly seen together. Two best studied examples are the following (Lozinskaya, 1992 contains the images and further references to the literature). The Of star HD148937 and its bright ejected shell NGC6164-5 are surrounded by very faint filaments of a wind-blown bubble and both are located at the center of an extended shell-like HII region and the outermost shell of dust.

The prototype of a wind-blown bubble: the nebula NGC6888 around WR WR has been shown to represent the stellar ejecta material, perhaps shocked by stellar wind, while surrounding system of very faint [OIII] filaments is swept-up by the wind of WR star. Both are located in the center of an extended IR shell, probably created by the wind at MS stage (Marston, 1995; Lozinskaya et al., 1997), or alternatively by SN-explosion of a close companion star (Nichols-Bohlin, Fesen, 1993). And all the system, in its turn, belongs to the multishell complex around OB association Cyg OB1.

What is more important: if there is no ring nebula around a WR star with strong wind we do understand why not. Because of evacuation of surrounding gas by common winds of the parent OB-association, we observe a rind nebula around a WR provided that there is an ejected material, and as long as its emission is detectable.

The general approach to the problem of the wind action on the ISM has been changing. Today we do understand that the nature of an "individual" wind-blown bubble (or a SNR) strongly depends on the entire history of the interaction of stars and the ISM in an active star-forming complex. In terms of the new approach each giant molecular complex must be considered as an ecosystem. Collective winds and SNe create expanding supershells around rich stellar groups, and that triggers a new wave of star formation.

I'll illustrate two aspects of the new approach basing on recent results of our investigations:

First, stellar winds from OB associations do indeed provide favorable conditions for triggering star formation.

Second, the entire history of an active star-forming complex does indeed regulate the nature of a wind-blown bubble or a SNR.

2. Star formation triggered in supershells around OB associations

One of the best studied multishell complex in the Galaxy is that related to the Cyg OB1 association (see Lozinskaya, Sitnik, 1988; Lozinskaya *et al.* 1998a; Lozinskaya, 1998 and references herein). The shell-like structure of this region is revealed by optical lines and by radio continuum, by the infrared emission and by neutral hydrogen.

Lozinskaya and Sitnik (1988) identify here an extended elongated shell (we will refer to it as *the supershell*) and several inner shells of different sizes. The kinematics of the multi-shell complex has been studied in a long lasting set of H_α Fabry-Perot observations (Lozinskaya *et al.* 1998a and references herein).

It has been found that the dominant kinematic structure of the shell as a whole exhibits bright emission at low velocities 2-20 km/s and also weaker emission at both high negative up to -100– -90 km/s, and positive, up to +60–+80 km/s, velocities.

To summarize the observational material, following Lozinskaya *et al.* 1998a; Lozinskaya, 1998, 1999, we can conclude the following.

1 – The multishell system appears to be formed by a rich OB association in a dense molecular complex.

2 – It clearly exhibits a hyerarchical structure and "two-component" kinematics: the bulk of the gas is unaccelerated (the supershell's expansion velocity ≤ 10 km/s) while faint features correspond to fast motions.

The two-component kinematics of this supershell is not unique. Complexes of this type have been distinguished around Car OB1/OB2, Ori OB1/λ Ori, and Sco OB1, see Table. Note, that two sets of velocities in these supershells have been detected from interstellar absorption lines in spectra of WR and O stars. Our detailed observations of the Cyg OB1 supershell confirm, that faint high-velocity features are not local to the stars with strong stellar winds. They really characterize a supershell as a whole.

The major properties of the supershells are rather similar: they have similar sizes of about 100-300 pc, the shells reveal a two-component kinematics; the characteristic velocities are 5-25 km/s for the bright line components and around 100 km/s for the weak ones. (Kinematic age of the slow shells is $\approx 5 \times 10^6$ yrs, that of fast features is $\approx 5 \times 10^5$ yrs.) And, finally, they all are related to dense molecular complexes.

Therefore the phenomenon of two-component kinematics seems to be fairly common for supershells around rich OB associations in the dense ISM.

A possible scenario for the formation of two-component kinematics suggest a new insight to the problem of triggered star formation. An interpretation of the phenomenon assumes that two-component kinematics is entirely consistent with the classical theory of the interaction of the winds from OB associations with the interstellar gas (Lozinskaya (1998, 1999). Two different shells are formed by the winds of an OB association: one is massive and expanding slowly, while the other (or several others), inside the first one, are less massive and expanding with relatively high velocity. The key point here is that the shells develop in a totally different ambient gas: the massive slow one is created before the most massive stars leave the MS in the dense quasy-homogeneous parent gas; the fast shells are formed by strong winds from WR stars and, perhaps, by SNe in the tenuous cavity surrounded by dense walls. According to Lozinskaya, Chernin (in preparation) dynamical structures of this type provide very favorable conditions for triggering star formation.

The idea that activity of OB associations can trigger star formation in the surrounding interstellar medium is not a new one, see for example a detailed analytical treatment by McCray and Kafatos (1987); a review by Elmegreen (1998) and references therein. Multiple SN explosions have been considered as the major agent of propagating star formation.

Lozinskaya and Chernin argue that multiple collisions of the fast inner shells with the massive slow one trigger the process of star formation regulated by a combine action of gravitational fragmentation in the slow shells and shock compression of the fragments by the fast shells. Stellar wind plays an important role in the vicinity of rich OB associations in the dense ISM.

The way in which the process develops depends on the ambient density: fragmentation of the shells occurs before (or after) its termination, before (or after) WR stars appear if the density is relatively high (low).

Two sequences of the events are possible. (1) It may be that the slow shell is near the state of termination with the expansion velocity about its isothermal sound speed; and this shell remains stable against gravitational fragmentation. Then first impacts by the fast inner shells are able to compress the gas of the slow shell, initiating the onset of instability.

(2) In the dense ISM the slow shell may come to the state of gravitational fragmentation before its termination and before WR stars appear. In that case the fast shells collide with individual fragments and it's able

Table 1: Supershells with two-component kinematics.

supershell	size, pc	slow shell		fast features		reference
		V(exp) km/s	kinematic age, yrs	V km/s	kinematic age, yrs	
Cyg OB1, Cyg OB3	80 – 100	$\leq$ 10	$\geq 3 \cdot 10^6$	-85 -55	$4 \cdot 10^5$	1
Car OB1, Car OB2	200	10	$6 \cdot 10^6$	100	$6 \cdot 10^5$	2 – 6
Ori OB1, λ Ori	280	15 – 25	$4 \cdot 10^6$	100 – 120	$3 \cdot 10^5$	2, 7 – 9

REFERENCES:
1 - Lozinskaya et al. (1998a);
2 - Lozinskaya, 1992 and references therein
3 - Cowie et al. (1981); 4 - Walborn and Hesser (1981)
5 - Walborn et al. (1984); 6 - Seward, Chlebowski (1982)
7 - Goudis (1982); 8 - Reynolds, Ogden (1979)
9 - Cowie et al. (1979)

to compress these clouds and accelerate their gravitational collapse.

In both cases the typical parameters of the massive shell's fragments are favorable for molecularization in their cores.

The result of the combine action of two major mechanisms of triggering star formation – gravitational fragmentation and shock compression – may be much more significant, than in other cases, when they act separately. In this sense, rich OB associations seem to be most effective agents of induced star formation, at least on the 500 pc scale dimensions.

3. The origins of an "individual" wind-blown bubble (or a SNR) strongly depends on the entire history of an active star-forming complex

Our recent observations of the galaxy IC1613 clearly illustrate this approach (Lozinskaya et al., 1998b; Afanasiev, Lozinskaya, Moiseev, Blanton (in press). This irregular dwarf galaxy represents a relatively clean case: we know of only one WR star (and that one of a rare subclass WO), only one SNR, and only one recent star-forming region.

Six WO stars have been identified in the Local Group galaxies (compared to about 600 WRs): three are in our Galaxy, two are in the Magellanic Clouds and one is in IC1613. WOs occur in the very short final stage in the massive stars evolution, the stage of a nearly naked CO core, immediately preceding the supernova explosion. These stars are characterized by a very powerful wind, the wind's mechanical luminosity 10 times higher than that for usual WRs; and they are extremely hot, $T_{eff} \simeq 100,000$ K.

Figure 1(a) shows a deep monochromatic H_α image of the neighborhood of the WO star in IC1613 we obtained with the Interferometer Fabry=Perot at 6-m telescope SAO RAN (Afanasiev et al., in press). The WO star is in the center of the previously known bright nebula S3 – an HII region $29 \times 9''$ in size, with strong HeII 4686 emission near the star (Hodge et al. 1990; Hunter et al. 1993; Garnett et al. 1991). Two extended, weak, shell-like formations 100 and 300 pc in size are clearly seen both sides of the bright elongated core. I have already declared several times that there is a huge bipolar structure related to the WO star (see Lozinskaya, 1997) but it was at the level of my suspicion.

Our measurements indicate on the expansion of both shells: the lower limit of expansion velocity is around 50 km/s for the brighter lobe and at least 70 km/s for the faint one (Afanasiev et al., in press).

A possible explanation of the structure is that these two shells are formed by the powerful wind on either sides of a dense layer of gas. The origin of the layer may be related to a previous stellar activity in the area. The large-scale neutral gas distribution in IC1613 seems to confirm the suggestion.

The image of the galaxy in the 21 cm line obtained by Lake, Skillman (1989) displays two most prominent features: a "supercavity" and a brightest spot – a dense giant complex of the neutral gas. The sizes of both features are about 700 pc.

Deep H_α images of the dense giant cloud's area displays an extended complex of interlocked ionized shells and supershells (see Meaburn et al., 1988; Lozinskaya et al., 1998b) around a group of young stellar associations. The sizes of the shells are 100–300 pc, expansion velocities of 30-50 km/s according to Meaburn at al.,

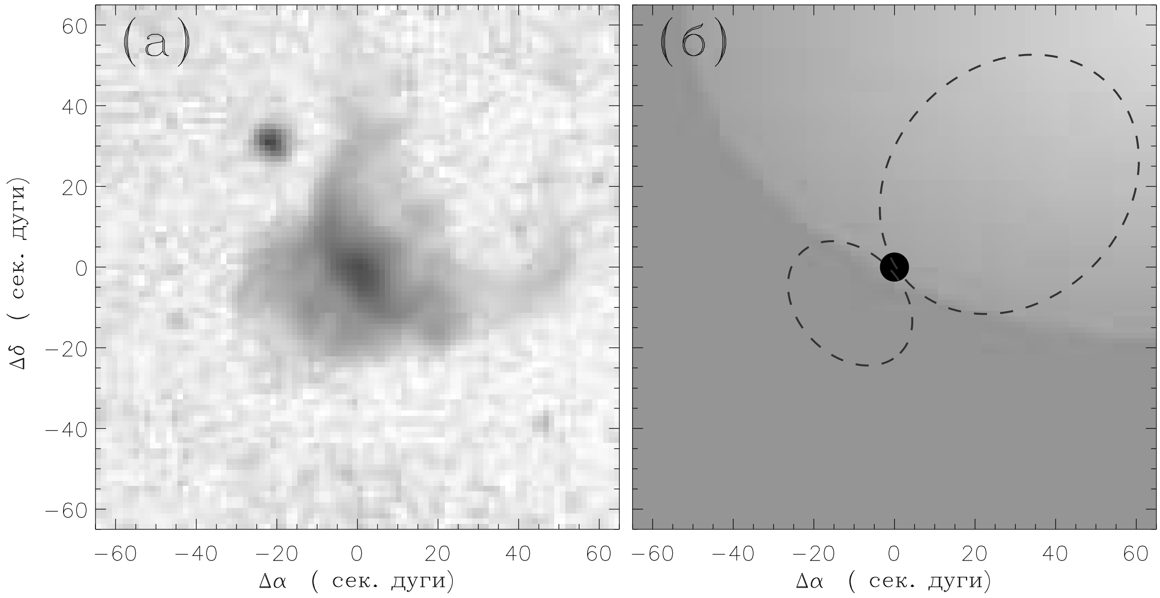

Figure 1: (a): Deep monochromatic H_α image of the bipolar shell related to the WO star in IC1613 obtained with the Interferometer Fabry=Perot at 6-m telescope SAO RAN (Afanasiev et al., in press). The brightness is in the logarithmic scale. (b): The scheme of the bipolar structure superimposed on the one-quarter sector of the "supecavity" in the neutral gas distribution from 21 cm line observations by Lake, Skillman, 1989.

1988. This is the only recent star-forming region in the galaxy.

It is interesting to note that the single known SNR in IC1613 is located in this star-forming complex. We proposed for ROSAT observations, and we identified the brightest X-ray source in the galaxy IC1613 with its single known SNR (Lozinskaya et al., 1998b) This SNR appears to be peculiar. It is one of the brightest nebulae in the galaxy. At the same time, this is one of the most luminous X-ray SNR in the Local Group, including Milky Way – like Crab Nebula and Cass A. To explain the coexistence of the hot X-ray plasma and cool, dense optical gas we proposed that the supernova explosion took place inside a cavity surrounded by a dense shell. And the SNR is just at the stage of encountering the dense wall of the cavity. The cavity's origin is most probably related to the previous activity of the parent OB-association.

Now, let us return to the WO star and its bipolar shells. What is an expected future of a star-forming complex like one just mentioned? In about 10^8 yrs we'll find here a supercavity surrounded by a dense neutral shell, similar to the above mentioned superhole.

Therefore, the two most prominent large-scale structures in IC1613: the superhole in 21 cm distribution and the giant complex of star formation appear to represent two stages of evolution of a giant molecular cloud.

The bipolar shell's location at the edge of the supercavity, and orientation of the larger and fainter lobe in the direction of the low-density interior of the cavity, and the shapes of the large lobes (see Fig. 1b) - all seem to be in agreement with the scenario of the WO star in the dense core of a layer of the interstellar gas with large-scale density gradient, proposed by Lozinskaya, 1997. The cavity and the wall seems to be created by a previous burst of star formation in the galaxy, similar to previously mentioned one.

Therefore our observations of the two peculiar objects in IC1613: the bipolar shell around WO star and the SNR provide a clear demonstration of the statement that the entire history of an active star-forming complex dictates the nature of each individual SNR or wind-swept shell.

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