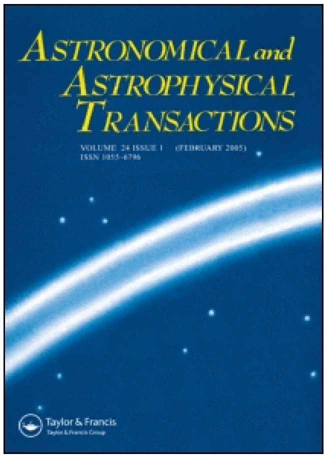

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TWO-COMPONENT KINEMATICS OF THE INTERSTELLAR MEDIUM AROUND RICH OB ASSOCIATIONS AND TRIGGERING STAR FORMATION

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Observations of the multi-shell complexes around stellar associations Cyg OB1, Cyg OB3 (Lozinskaya *et al.*, 1998) and its comparison to complexes around Ori OB1/λ Ori; Car OB1, Car OB2; and Sco OB1 suggest a new approach to the problem of triggering star formation on the space scale of 100–500 pc. The data indicate that a rich OB association can produce a set of expanding shells: a massive slow-expanding one swept-up by stellar winds of MS stars and several fast inner shells produced by the activity of WR stars and, later, by supernova explosions. We argue that the dynamical structures of this type provide favorable conditions for triggering star formation. Under these conditions, two basic physical mechanisms of star formation – gravitational fragmentation and shock compression – can act together in the most effective combination, enhancing each other.

Keywords: Stars; Formation – ISM; Supershells

1 INTRODUCTION

The idea that activity of stars can initiate formation of other stars in the surrounding interstellar medium dates back to the work by Öpik (1953) who had in mind supernova explosions as a key mechanism of the process. Blaauw (1964) presented strong observational evidence that this way star formation may propagate like a wave in the galaxies rich in gas. A physical model of the process, which was called the triggering model of star formation, was introduced by Elmegreen and Lada (1977) (see also Lada *et al.*, 1979). In this model, gas that is collected into a compressed ridge by a moving shock front produced by multiple supernova explosions becomes gravitationally unstable because of its high density, and due to this, high density gas cores appear, in which stars form.

The first analytic work on gravitational instability in expanding shells was by Ostriker and Cowie (1981) and Vishniac (1983). The formation of giant molecular clouds in expanding shells was studied by Tenorio-Tagle (1981) and Elmegreen (1982a,b). A detailed analytical treatment of shell expansion and collapse was carried out by McCray and Kafatos (1987). The first work on gravitational instability in expanding rings was Elmegreen (1985).

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This type of triggering star formation is assumed by Efremov *et al.* (1998) and Efremov and Elmegreen (1998) to be responsible for the formation of the giant arcs of stars in the Large Magellanic Cloud, both in shell and ring geometry; gamma-ray burst explosions are considered the energy sources for this process.

Another prominent triggering mechanism assumes pre-existing clouds that are compressed by a shock front directly. This model was suggested by Dibai (1958), Dyson (1968), Bychkov and Pikelner (1975), Sgro (1975) and developed in recent works by Lefloch and Lazareff (1994), Boss (1995) and others. It is applied to star forming regions (Constellation III in the Large Magellanic Cloud by Dopita *et al.* (1985). A comparative review of the triggering mechanisms is given by Elmegreen (1998).

Multiple SN explosions have been considered as the major agent of propagating star formation in all the works we mentioned.

In this paper, we will argue that both mechanisms of star formation mentioned above can work together in effective combination, one enhancing the other, with stellar winds playing an important role, in the vicinity of rich OB associations in the dense ISM. We are basing on recent observational data on complex multishell structures around associations. The data are presented in Sec. 2 and discussed in Sec. 3; gravitational fragmentation of a massive slow shell is analyzed in Sec. 4; shock compression in shell–shell collisions is considered in Sec. 5; and the results are summarized in Sec. 6.

2 OBSERVATIONS: TWO-COMPONENT KINEMATICS OF ISM AROUND OB ASSOCIATIONS

The focus of our discussion here is on the shells around OB associations. The phenomenon of "two-component kinematics" of the interstellar medium around the association was first discussed in detail by Lozinskaya (1998, 1999) basing on a study of kinematics of the multishell complex related to Cyg OB1, OB3.

However, actually first indications on the two-component kinematics of the ISM around OB associations have appeared from UV spectra of early type stars that demonstrated two sets of interstellar absorption lines: strong low-velocity ones and also weak features at high negative velocities. Covie *et al.* (1981) detected high-velocity absorptions in UV spectra of early type stars of Ori OB1, Car OB1/OB2 and Sco OB1 associations. Phillips *et al.* (1984); St-Louis and Smith (1992) and Nikhols-Bohlin and Fesen (1993) detected high-velocity absorptions towards most of investigated WR and O stars of the Cyg OB1, OB3. Since the very beginning an expanding supershell created by OB association has been considering as the most reasonable explanation of the high velocity absorptions. However, as long as the major data were based on stellar spectra of WR stars formally one couldn't rule out a local to each star fenomenon.

A systematic search for high-velocity absorptions in spectra WR stars by Nichols-Bohlin and Fesen (1994) gave some indications that high-velocity absorptions cannot be attributed to individual WR stars. According to the paper, 12 of the 16 WRs with high-velocity absorptions belong to OB associations. Where the high-velocity motions were detected, they are observed in a large region around the WR star and are interpreted as the manifestation of supershells. (We note, that four remaining WRs are all located far from the Galactic plane, *i.e.*, in a medium of a very low density. An extended shell around them can be produced by their main-sequence progenitors.) High-velocity features of absorption lines in WR stars that do not belong to the associations are normally not observed (no high-velocity features were detected in 82% of the "isolated" WR stars).

The complex of multiple shells around Cyg OB1 and Cyg OB3 is the first object where the stellar absorption data are confirmed by a study of radial velocities of the ionised gas all over the multiple shells as large as about 5 deg. with a space resolution as high as 10–15 arcsec and velocity resolution corresponding to 10–15 km/s.

The complex has been studied in details and may be considered as a typical example.

Its structure is revealed by the ionized gas in optical lines and in radio continuum (Brand and Zealy, 1975; Wendker, 1984; Lozinskaya and Sitnik, 1988), by the infrared emission (Lozinskaya and Repin, 1991; Saken *et al.*, 1992), and by neutral hydrogen (Heyles, 1979; Dewdney and Lozinskaya, 1994; Gosachinskij and Lozinskaya, 1997).

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.*, 1998 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 (Lozinskaya *et al.*, 1998; Losinskaya, 1998).

No definite signs of the general expansion of the supershell are detected, as indicated by the bright H_α features, an upper limit of the expansion velocity is about 5–10 km/s.

To summarize the observational material, following Lozinskaya *et al.*, 1998; 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 while faint features correspond to fast motions.

The two-component kinematics of the multi-shell complex around Cyg OB1 and Cyg OB3 is not unique. Complexes of this type have been found around Car OB1 and Car OB2, Ori OB1/λ Ori, and the Sco OB1 region. Their main parameters are presented in Table I.

The kinematic age is defined in Table I from the size of a shell and the velocity of slow or fast features correspondingly (its physical meaning see in the next section).

Note that the Table represents "model/simplifying/main" kinematical parameters of the objects. All the supershells display really complex multishell structure and dynamics as observed in different energy ranges.

The ISM around the Ori OB1 show a HI and IRAS cavity filled by hot ionized gas, seen in X-ray (see *Brown et al.*, 1995; review by Heiles, 1999; and references herein).

An expansion velocity of the Orion-Eridanus Bubble is of about 15 km/s as measured by Reynolds, Ogden (1979) from H_α emission of ionized gas; that of associated HI shell – of about 40 km/s (Braun *et al.*, 1995).

TABLE I Supershells with Two-Component Kinematics.

		Slow features		*Fast features*		
Supershell	*Size, pc*	*V km/s*	*Kinematic age Myr*	*V km/s*	*Kinematic age Myr*	*Reference*
Cyg OB1, Cyg OB3	80–100	≤10	≥3	−85 −55	0.4	1,10
Car OB1, Car OB2	200	10	6	100	0.6	2–6
Ori OB1, λ Ori	280	15–25	4	100–120	0.3	2,7–9

References: 1 – Lozinskaya *et al.* (1998); 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 and Ogden (1979); 9 – Cowie *et al.* (1979); 10 – Lozinskaya, 1998.

The initial number density from HI mass is 0.9 cm^{-3}; gas density of CO emitting regions is in the range of 2×10^2, to 3×10^3 cm^{-3} (Sakamoto *et al.*, 1994). An active star formation process is ongoing in the area.

Nevertheless, to summarize the observational material, we can say that the major properties of the shells complexes around rich OB associations are rather similar: (1) they have similar sizes of about 100–300 pc, (2) the shells reveal a two-component kinematics; (3) the characteristic velocities are 5–30 km/s for the bright components and 90–120 km/s for the weak ones. (4) they all are related to dense molecular complexes.

Therefore the phenomenon of two-component kinematics seems to be fairly common for the shells and supershells related to rich OB associations in dense molecular complexes.

3 THE NATURE OF TWO-COMPONENT KINEMATICS

The supershells with its two-component kinematics is the most interesting structure in the ISM around associations, – from the point of view of induced star formation. An interpretation of the phenomenon suggested by Lozinskaya (1998, 1999) assumes that two sets of velocities observed in the complexes of Table I are due to two different shells formed by the same association. One shell is massive and expanding slowly, while the other (or several others), inside the first one, is less massive and expanding with relatively high velocity. The shells are formed at two different stages of the evolution of the association and under different physical conditions. The slow supershell is formed at the initial stage, before the most massive stars of the association leave the main sequence. The shells responsible for the weak fast features are formed at the later stage due to strong winds from WR stars and, perhaps, energy output in supernova explosions.

The key point here is that the shells are formed in a totally different ambient gas. The first shell is formed in the relatively dense parent gas which is distributed more or less uniformly in the region of the systems. On the contrary, the second shell is formed in the tenuous gas of the cavity and, because of this, the second shell may have a high velocity at the same size as the first one.

Let us discuss this conjecture in some more details using the best studied multi-shell complex related to Cyg OB1 as an example.

In terms of the standard theory of a wind-blown bubble (Castor *et al.*, 1975; Weaver *et al.*, 1977), one can show that a shell of about 200 pc in size (300–100 pc for the densities 1–100 cm^{-3}) with a low expansion velocity of about 10 km/s (7–16 km/s for the same densities) could be formed by OB stars of Cyg OB1 in about 5 Myr. The initial density in the Cyg OB1 area is most probably $n_o \simeq 1$–$10\ cm^{-3}$ (Lozinskaya, Repin, 1991; Saken *et al.*, 1992; Nichols-Bohlin, Fesen, 1993).

The times scales obtained this way are in agreement with kinematic ages of about 4–6 Myr found for the slow shells (Tab. I).

The shell expands with decreasing velocity, and finally the velocity drops to the isothermal sound speed in the ambient gas (see, for instance, Oey and Massey 1994) which is in its turn near the chaotic velocities of interstellar clouds $\simeq 5$–10 km/s.

The strong short-lived winds from WR stars and maybe supernova explosions are responsible for high-velocity motions in the inner cavity and for the formation of rapidly expanding inner shells. In terms of the standard theory, shells around WR stars in the central low-density cavity ($n_b \simeq 0.1$–1 cm^{-1}) reach 80–120 pc in size and expand at a velocity of 40–70 km/s, at this stage. The sizes are comparable to the size of the supershell around Cyg OB1, OB3 and to the mean separations between WR stars in the area. The later means, that complete merging

TABLE II Cooling and Stalling of a Classical Wind-Blown Bubble.

$n_o cm^{-3}$	1	10	50
t(cool), 10^6 yrs	13–16	2.5–3	0.8–0.9
R(cool), pc	270–350	63–80	22–30
v(cool), km/s	12.5–13	15–16	17–20
t(stall), 10^6 yrs	23–32	7–10	3–5
R(stall), pc	380–530	116–166	50–80

of individual fast shells (see Sec. 5) and/or formation of weak fast inner shells of an hierarchical system are possible in the region.

In terms of energetics, even the wind of one WR star in the inner cavity is enough to drive a weak high-velocity shell, with size like that of the supershell around Cyg OB1 and with velocity like faint fast features of H_α line in the area. Supernova energy input is possible, generally, but not necessarily for this supershell.

The duration of WR stage corresponds to the kinematic ages $\simeq 5 \times 10^5$ yrs determined by the fast features in the Table I.

To conclude, the coexistence of the old and young shells at about the same sizes around rich OB associations gives rise to the observed phenomenon of two-component kinematics, as we believe.

It is important to note that a fast inner shell around WR star forms only after cooling of the hot interior of the supercavity. Otherwise the wind of a WR star just adds energy to the hot-wind layer of the supershell in terms of the classical model.

Table II shows a characteristic parameters for a typical wind blown bubble at the stage of cooling and at the final stage of “stalling” or fossilization (as such a final state is characterized by Meaburn 1980; V(stall) = u = 10 km/s) for a solar metallicity and for Lw = (0.5–1)10^{38} erg/s.

As can be seen from the Table II in a reasonable ambient density of about several atoms per cm^{-3} cooling time is shorter than the Main Sequence lifetime for the massive progenitors of WR. It means that strong winds of the WR stage turns on in the cooled inner gas providing the condition for fast inner shells formation.

The fast inner shells appear close to the stage of “stalling” of massive shell.

4 GRAVITATIONAL INSTABILITY IN THE SLOW SHELL

This interpretation of the phenomenon of two-component kinematics enables us to argue that enhanced star formation can occur in the massive shells around rich associations. The process is controlled by a combine action of gravitational fragmentation in the slow shells and subsequent shock compression of the fragments by the fast shells.

Consider, first, the dynamical state of the slow massive supershells and clarify the physical conditions under which gravitational instability develops in them. The expansion velocities of these shells (Tab. I) are rather low and comparable with the typical velocity of gas clouds in the ambient medium. Most probably, the shells are observed at the isothermal momentum driven stage approaching fossilization state. To see whether gravitational instability can develop in the shells before their fossilization, we compare the growth rate of this instability with the ages of the shells.

The criterion for the onset of gravitational instability in an expanding shell may be formulated in terms of its surface density σ_s, expansion velocity V_s, and the isothermal sound velocity u in the material of the shell (Ostriker and Cowie, 1981; McCray and Kafatos 1987; Palouš J. *et al.*, 1990; Elmegreen, 1994; Vishniac, 1994; Ehlerová *et al.*, 1997): $\sigma_s > (V_s u)/(2GR_s)$, where G is the gravitational constant. One can see from this relation that gravitational instability begins in the shell before its fossilization, if $t_s > t_g \simeq \alpha u/(2G\sigma_s) = 3\alpha u/(2G\rho_o R_s)$, where $t_s = \alpha R_s/V_s$ is the age of the shell, t_g is the time scale of gravitational instability, $\rho_o = mn_o$ is the initial mass density of the medium in which the slow shell forms and $m = 1.3m_H$ is the mean mass of the particles of the medium, m_H is hydrogen atom mass. The dimensionless factor $\alpha = \alpha_s = 1/4$, for a momentum driven outer shock of the shell (Kaplan, 1966).

The onset of instability is sensitive to the initial density of the medium and the sound speed in the shell. The density is most probably within the range $n_o = 1$–$100\,\mathrm{cm}^{-3}$ (see Sec. 4). As for the sound speed, it decreases during the shell isothermal expansion from about 10 km/s to about 1 km/s in the H I layer (temperature ≈ 100 K) of the shell or to 0.3 km/s (temperature ≈ 20 K) in its H_2 layer due to rapid radiative cooling (cf. McCray and Kafatos, 1987). If interstellar magnetic fields are taken into account, u is considered as the magnetosonic speed, and its value may depend on the field orientation relative to the expansion velocity of the shell. Even at zero temperature, $u \simeq 2$ km/s, if the field has a strength 1 G in the medium with the density $n_o \simeq 1\,\mathrm{cm}^{-3}$. On the other hand, the dynamic pressure of the shock front in the shell, $P_s = \rho_o V_s^2$, puts an upper limit on the pressure (magnetic pressure including) in the material of the shell behind the shock: $p_s < P_s$. Because of this, $u < (P_s/\rho_s)^{1/2}$, where ρ_s is the mass density of the shell. Since $\rho_s > 4\rho_o$ in the isothermal shell, $u < u_{up} = V_s/2$. For the shell near the state of fossilization, V_s tends to the isothermal sound speed in the ambient medium $u_o \sim 6$–10 km/s (Oey and Massey, 1994). If so, $u_{up} \simeq 3$–5 km/s, at this state of the shell.

With the use of $u \simeq u_{up}$, the criterion above can be re-written in a form: $n_o > n_{crit} \simeq (20$–$40) V_{10} R_{100}{}^2$, where $V_{10} = V_s/(10\,\mathrm{km/s})$, $R_{100} = R_s/(100\,\mathrm{pc})$.

For the complex around Cyg OB1 and Cyg OB3 ($R_s = 80$–100 pc and $V_s \leq 5$–10 km/s), the criterion indicates that the slow shell is stable against gravitational instability during its expansion, if the initial density in the area $n_o \simeq 1$–$10\,\mathrm{cm}^{-3}$ (see Sec. 3). In two other complexes of Table I, the slow shells are unstable and their fragmentation can begin before fossilization, if $n_o > 5$–$10\,\mathrm{cm}^{-3}$ in the area of Carina and $n_o > 2$–$3\,\mathrm{cm}^{-3}$ in the Orion area.

Generally, gravitational instability develops most effectively, when a rich association forms its massive shell in a dense molecular cloud with $n_o \sim 10$–$100\,\mathrm{cm}^{-3} \geq n_{crit}$. Under these conditions, the Jeans length $L_J = ut_g \simeq 3u^2/(4Gmn_o) \simeq 0.03R_s \sim 6$ pc and the Jeans mass $M_J = 4\pi/3\rho_s(L_J/2)^3 \simeq 500M_\odot$, where it was taken that $R_s = 200$ pc, $V_s = 10$ km/s, $n_o = 30\,\mathrm{cm}^{-3}$, $u = 10$ km/s.

If a shell is stable against gravitational instability during its expansion, fragmentation may occur at the state of fossilization. In this case, the Jeans time scale can be estimated in the standard way: $t_J = (4\pi Gmn_s)^{-1/2}$, where n_s is the density of the shell. One can see that $t_J < 3$–10 Myr for $n_o = 1$–$10\,\mathrm{cm}^{-3}$. If this time scale is less than the age of the association at the moment of the formation of the last fast shell, the massive shell will fragment out before the collision with the fast one.

Note that, as usually, the accuracy of the estimates is actually not better than within a factor 2 or so, in application to the observed shells – because of their non-spherical geometry, the non-uniformity of the ambient medium, etc. Nevertheless it is clear that the efficiency of gravitational instability in the massive shell depends mainly on the initial density n_o in the area of the OB association that produces the shell. The way in which the process develops depends – under other equal conditions – on this density: fragmentation of the shells occurs before (or after) its fossilization, before (or after) most massive stars leave the MS, if the density is relatively high (low).

In both cases, however, there is a range of physical conditions, under which the fast shell will collide with the fragmented, cloudy material of the slow massive one. The fast shell may also collide with the slow shell as a whole initiating this way gravitational fragmentation in the latter, as we will show in the next section.

5 SHELL–SHELL COLLISION AND SHOCK COMPRESSION

The fast shell of two-component structures we discuss expands in the adiabatic regime in the rarefied gas of the cavity inside the slow shell. As we mentioned in Sec. 3, the fast shell in complex around Cyg OB1 and Cyg OB3 may be due to the activity of one or a few WR stars, and perhaps SN explosions. Since the observed size of the shell is comparable with the mean separation between the stars (Sec. 3), it forms perhaps as a result of merging of individual expanding shells, produced by each of the stars.

The process of merging of adiabatic shells was studied by Voinovich and Chernin (1995). From the point of view of the present discussion, it is important that (1) the merger shell forms on the same hydrodynamical time scale as the expansion of the individual shells proceeds; (2) the merger shell acquires rapidly a nearly spherical shape. Because of this, the merger fast shell can be treated with the use of the standard relations (as it was done in Secs. 3,4) soon after its formation.

The fast shell may reach the slow one before or after the fragmentation of the slow shell. If the slow shell is stable against gravitational instability (like perhaps the slow shell around Cyg OB1, Cyg OB3 – see Sec. 4), the collision can initiate its compression and fragmentation. This may be due to two physical mechanisms. One of them is related to the momentum of the fast shell and the other to its dynamic pressure.

The momentum of the fast shell is transferred to the slow one almost completely in their collision. As a result, the slow shell gains an additional velocity Δ which can be estimated as: $\Delta \simeq V_f(\rho_b/\rho_o)$, where n_b is the density in the bubble where the fast shell expands. As we see, the velocity of the massive shell changes little, if the ratio of densities is less than, say, 0.01. If the ratio is, say 0.1, the additional velocity is about 10 km/s (for the velocity $V_f = 90$ km/s). In this latter case, the shell will expand due to the additional momentum, and come to the new state of fossilization with the velocity $V_0 \approx u$ and a new radius $R_{s1} = R_s((V_s + \Delta)/V_0)^{1/3}$. According to the criterion of gravitational instability (Sec. 4), the critical density will be now less by the factor $(R_{s1}/R_s)^2 = ((V_s + \Delta)/V_0)^{1/3}$. This, however, does not mean necessarily that the criterion will be met now.

More essential effect can be produced by the dynamic pressure of the fast shell. This gives rise to compression of the slow shell in isothermal regime: $\rho_{sf}/\rho_s \simeq (V_f/u)^2(n_b/n_o)$, where ρ_s and ρ_{sf} are the densities of the slow shell material before and after the collision. If the ratio of densities n_b/n_o is 0.1–0.01, and $V_f = 90$ km/s (see Table I), $u = u_{up}$, the density of the material after collision will be 30–3 times larger than before it. The shock compression proves to be considerable indeed, and obviously it can really initiate and accelerate gravitational fragmentation of the slow shell. The time scale for gravitational instability decreases 2–5 times under these conditions, which gives a clear quantitative measure of the effect.

If the slow shell fragments before the collision with the fast one, the latter interacts not with the shell as a whole, but rather with individual gaseous fragments, or clouds. The physics of shock-cloud collisions is rich in gasdynamical effects. In the simplest case, when the cloud can be considered as a weak perturbation in the up-flow, the planar shock oblates the cloud and compresses it; the density increases 4 times, in the adiabatic regime, and the density contrast in the medium remains the same. A nontrivial feature of this process is the formation of a vorticity torus around the cloud (Chernin, 1993). In general case, a number of other important effects appears: destruction and evaporation of a cloud by a strong high velocity shock (McKee and Cowie, 1975; Cowie and McKee, 1977; Cowie *et al.*, 1981), compression and acceleration of a cloud by a moderately strong shock (Sgro, 1975; Woodward, 1976; McKee *et al.*, 1987; Bedogni and Woodward, 1990; Klein *et al.*, 1994; Boss, 1995), development of the Kelvin-Helmholtz and Rayleigh-Taylor instabilities in the cloud material (Woodward, 1976), formation of a converging conical shock and cumulative compression of a dense cloud (Tenorio-Tagle and Rozyczka, 1984).

Here we will make simple gasdynamical estimates for the physical condition in the shell complexes of Table I, using the basic physics of cloud-shock interaction and not going into much detail.

When a cloud is struck by the outer shock of the fast shell, it is subjected to a large increase in pressure which can drive the shock front into the cloud. Then the fast shock overtakes the cloud, it compresses the cloud in the process which is similar to hydrodynamical implosion. If the overpressure is strong and $\rho_f V_f^2 \gg \rho_c u_c^2$ (here ρ_c and u_c are the mean mass density of a cloud and the isothermal sound speed in its material), the process induces formation of a compression wave which propagates into the cloud, a rarefaction wave propagating in the hot gas of the fast shell, etc. The net effect can be estimated in a way similar to that above. The mean density of a cloud, n_c, increases in the isothermal process as $n_{cf} \simeq n_b (V_f/u_c)^2$. If $n_b = 1$–$0.1\,\mathrm{cm}^{-3}$, $V_f = 100\,\mathrm{km/s}$ and $u = 5\,\mathrm{km/s}$, the density of the compressed cloud is $n_{cf} \simeq (4$–$0.4) \times 10^3\,\mathrm{cm}^{-3}$, which is comparable to the observed density of molecular clouds in the interstellar medium.

The time scale of shock compression is $t_{shock} \simeq R_c/V_{shock}$, where R_c is the radius of the cloud, $V_{shock} \simeq V_f(\rho_f/\rho_c)^{1/2}$ is the velocity of the compression wave. If the ratio of the densities here is 0.1–0.01, then $V_{shock} \simeq 30$–$10\,\mathrm{km/s}$, and $t_{shock} \simeq 0.2$–$0.6\,\mathrm{Myr}$ for a fragment with the (Jeans) size $L_J = 6\,\mathrm{pc}$ (see Sec. 4). This time is considerably less than the free-fall gravitational time $t_{ff} = (4\pi G\rho_c)^{-1/2}$ for the same cloud with $n_c \sim 10$–$100\,\mathrm{cm}^{-3}$ and the (Jeans) mass $M_J = 500 M_\odot$. So shock compression of the cloud develops faster than the gravitational collapse.

In the compressed state, the size of the same cloud is $R_{shock} \simeq 1$–$2\,\mathrm{pc}$, and the particle column density in it is $\Sigma = M/(4\pi R^3_{shock}) \simeq (1 - 0.2) \times 10^{22}\,\mathrm{cm}^{-2}$. It can be compared with the critical figure, $\Sigma_{mol} = 5 \times 10^{20} (Z_\odot/Z)\,\mathrm{cm}^{-2}$, found by Franco and Cox (1986) as a threshold density for molecularization (here Z is the metallicity measured in the solar unit $Z_\odot$). If the column density surpasses Σ_{mol}, the gas is shielded against the ionizing interstellar radiation, and it can become molecular in the core of the cloud. As we see, this condition is met, and $\Sigma_{shock}/\Sigma_{mol} = (20$–$4)(Z_\odot/Z)^{-1} > 1$, in the typical cloud which is formed by gravitational instability in the slow shell and then compressed by the fast shell (for any reasonable value of the metallicity). This means that the combine action of gravitational instability and shock compression can indeed lead to formation of molecular clouds, and this way it triggeres effective star formation around rich associations.

A similar estimate can also be made for a typical cloud which is formed in the process of gravitational fragmentation of the shocked slow shell (if the shell is gravitationally stable before this – see above). The Jeans length in the shocked material of the shell is $L_J \simeq u_c (u_c/V_f)(16\pi G\rho_b)^{-1/2}$, and the particle column density in the cloud of this size with the density ρ_{sf} (estimated above) is $\Sigma_{sf} = 1/3\ (\rho_{sf}/m) L_J \simeq 0.2 u_c (V_s/u_c)(G\rho_b)^{-1/2}$. One can see that with $n_b \geq 3 \times 10^{-3}\,\mathrm{cm}^{-3}$, $V_s = 100\,\mathrm{km/s}$, and $u_c = 5\,\mathrm{km/s}$, this column density satisfies the condition for moleculazation: $\Sigma_{sf} > \Sigma_{mol}$ for any reasonable metallicities.

6 CONCLUSIONS

The most important feature of the supershell around Cyg OB1, Cyg OB3 in the Gygnus complex is its two-component kinematics, which was described briefly in Sec. 2 on the basis of the considerable observational material (Lozinskaya *et al.*, 1998). Following the physical interpretation of the phenomenon (Sec. 3), suggested by Lozinskaya (1998, 1999), we consider the supershell as a complex gasdynamical structure which includes a massive slow shell and a fast shell which are produced by the rich OB association at two different stages of its evolution. Treated this way, the phenomenon may lead to better understanding of the physics of propagating star formation on the space scale of 100–500 pc.

We argued that gasdynamical interaction between two components of these structures can give rise to the physical conditions that are fairly favorable for effective fragmentation and compression of the gaseous material. We discussed two possible sequences of the events. In one of the scenarios, (1) the slow shell is near the state of fossilization with the expansion velocity which is about the isothermal sound speed in its material; (2) this shell seems to be stable against gravitational fragmentation during all its expansion time and also stable or marginally unstable near the stage of fossilization (Sec. 4); (3) the fast shell expands within the slow one and reaches it having a considerably higher (5–10 times) velocity; (4) then the shells come into the contract collision with each other; (5) this collision is able to compress the material of the slow shell, initiating the onset or/and acceleration of gravitational instability in it; (6) the typical parameters of the fragments formed via this instability are favorable for molecularization in their cores (Sec. 5).

In the other scenario, (1) the slow shell keeps expanding with a velocity which is 2–3 times the isothermal sound speed in its material; (2) this shell is larger than one in the Cygnus area, and because of this it may undergo gravitational fragmentation before its fossilization (Sec. 4); (3) the fast shell has a somewhat higher velocity, than that in the Cygnus, when it reaches the slow shell; (4) the sizes of the slow and fast shells are almost the same, and it means that the shells are near the contact collision with each other; (5) in this collision, the fast shell will interact not with the slow shell as a whole, but rather with individual fragments formed by gravitational instability, and it is able to compress these clouds and accelerate their gravitational collapse; (6) the typical parameters of the clouds shocked by the fast shell are favorable for molecularization in their cores, in this case too (Sec. 5).

Thus, rich OB associations are able to produce suitable physical conditions for the formation of the next generation stars in the surrounding interstellar medium. In both scenarios of this process, which we outlined, two major mechanisms of triggering star formation – gravitational fragmentation and shock compression – work in different, but equally effective combinations, enhancing each other. This enables us to expect that the net result of their combine action may be much significant than that in other cases, when they may act separately. Rich OB associations seem, therefore, to be most active and effective agents of triggering star formation – at least on the space scales of 100–500 pc. (It is interesting to compare our considerations here with what was said by Ambartsumian (1995) about the cosmogonic role of associations many years ago.)

Finally, a few brief remarks in conclusion.

1. The fact, that the interstellar medium around rich OB associations reveals two-component kinematics, does not mean that there might be two and only two episodes of shell formation in the evolutionary history of each of these systems. While a massive slow shell may be the only one in a system, there must be rather a few fast shells produced at various stages of the system's evolution. The slow shell may undergo multiple interactions with the fast shells, and it may occur both in the whole body of the shell or in its separate segments, depending on the sizes and shapes of the fast shells. The observed two-component state of the supershell is most probably a result of multiple interactions of this type, and if it is so, the treatment of the origin and dynamics of the slow shell needs a more elaborated theory than the standard relations used in Sec. 3. Nevertheless, the net result of the

shell–shell interaction (which is important for star formation) depends mostly on the instant state of the shells rather than on their prehistory, as one may expect.

2. The vicinity of a rich OB association is obviously not the only area where multiple shell dynamics is observed. There are known also examples of much more complex structures that include multiple slow and fast shells. Irr galaxies open up the best opportunity to learn about the large-scale and long-term interrelation between stellar groupings, shells and supershells and triggered star formation. An extraordinary complex of interstellar environment is revealed in 30 Doradus giant H II region in the LMC, where a large number of expanding structures are observed (see especially Chu and Kennicutt, 1994), ranging in size from one to a hundred pc and expansion velocities of 20–200 km/s.

As a fine example of the process discussed in the paper we are presenting here shortly some results of our recent study of IC1613 (for more details see Lozinskaya, 2002b and references herein). Figure 1 shows a high-resolution VLA HI map of a large sector of the galaxy superimposed on the deep Hα image according to Lozinskaya *et al.* (2001).

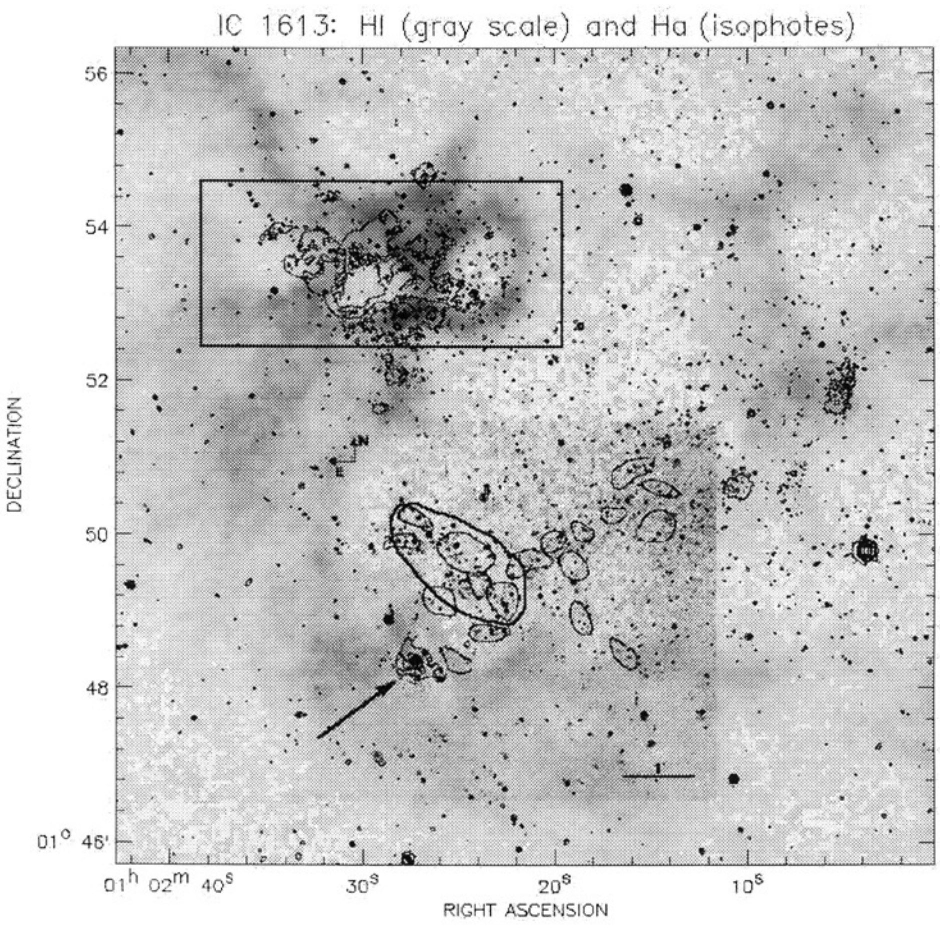

FIGURE 1 The HI map of the large sector of the galaxy IC 1613 (shown in shades tones) superimposed on the deep Hα image (shown by isophotes). The large box at NE indicates location of the only resent starformation complex known in the galaxy; the arrow at SE indicates on the WO star and its nebula. Position of the Hodge No9 association is indicated as a large elliptical area; smaller curves show the new boundaries of the stellar associations outlined by Borissova and collaborators (as cited in Rosado *et al.*, 2001).

North-east part of the Figure demonstrates the only recent star-forming region known in the galaxy: the huge complex of colliding ionized shells and the neutral shells that surround them. The complex includes about 20 OB associations with ages ranging from 5 to 20 mln yrs (Georgiev *et al.*, 1999). Shells in the complex have sizes ranging from 100 to 300 pc; the expansion velocities of ionized shells are about 30–50 km/s (Meaburn *et al.*, 1988; Valdes-Guttieres *et al.*, 2001) and those of HI shells, about 15–20 km/s (Lozinskaya *et al.*, 2003). Star formation is still going on in the region (Lozinskaya *et al.*, 2002).

Interactions of the shells (in various versions of their geometry and dynamics – see, for instance, Chernin *et al.*, 1995) are obviously probable in such regions. Their role in the general dynamics of the ISM and ongoing star formation may be as essential there, as in the vicinity of an "isolated" rich OB association.

The object of most interest for the subject of the paper is the supercavity surrounded by a dense HI shell. The size of the supercavity is about 1–1.5 kpc, the thickness of the surrounding neutral ring is 200–350 pc. This large-scale structure is apparently formed as the result of a burst of star formation in the region.

The surrounding giant HI ring is probably a toroidal structure, because the size of the ring is larger than the scale-height of the disk of the galaxy leading to the break-out of the wind-blown supercavity. The HI ring displays a characteristic filamentary structure. The filamentary system making up the HI ring bifurcates at its southeastern end. A system of arclike filaments with characteristic lengths of 1–1.5 arc-min, or 200–300 pc, is also apparent. A typical column density of the brightest filaments is about $(5\text{–}10) \times 10^{20}\,\mathrm{cm}^{-2}$. If the filaments represent curved sheets seen edge on and their sizes along the line of sight is comparable to their lengths in the plane of the sky this yields a characteristic density of $n_{[H\ I} \simeq 1\text{–}10\,\mathrm{cm}^{-3}$. If they have the cylindrical space structure then the characteristic density is about 10 times higher.

This filamentary pattern undoubtedly testifies to the action of dynamically active processes that are responsible for the formation of the supercavity surrounded by the dense ring and probably suggest the mechanism for triggering star formation we are discussing in the paper.

It appears that we already see fingerprints of star-formation within the HI ring triggered by a collision from inside (Lozinskaya, 2002a,b). There is a star of a very rare class WO in the wall of the supercavity. WO stars occur within a very short final stage of the evolution of massive stars – that of a nearly naked CO core – immediately preceding the SN explosion. Progenitors of WO stars are very massive objects, $M(\mathrm{init}) \geq 40\text{–}50\,M_{\odot}$, see i.e. Dopita *et al.*, 1990. Such a massive star cannot live for more than 10^7 yrs, which is shorter than the lifetime of the ring.

Therefore the WO star, being among the most massive and short-lived stars, might present a case of star-formation triggered by a collision of the dense ring with a fast shock from inside. There is a source of energy capable of initiating a fast shock to push the HI ring: the Hodge No9 association, which is adjacent to and inside the supercavity (Hodge, 1978; Rosado *et al.*, 2001). This association is the largest one and the richest in the galaxy.

3. The formation of clouds and their subsequent compression by a large-scale shock is the basic mechanism that triggers star formation in spiral galaxies like the Milky Way (Roberts, 1969; Shu *et al.*, 1972; 1973). The clouds form and undergo coalescence in the gravitational potential wells of the spiral arms, and then they are compressed by the spiral shocks. One may see an analogy (and also a difference) with the combine action of gravitation and shocks in the massive shells around rich associations, as discussed in this paper. Both observational and theoretical aspects of this analogy will be considered in a separate work.

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