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THE FORMATION OF STELLAR SYSTEMS BY GRAVITATIONAL INSTABILITY IN THE CYGNUS SUPERBUBBLE

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ABSTRACT

We have developed an analytical model of the onset of gravitational instabilities in the dense shell surrounding an expanding superbubble, in order to account for the origin of Cygnus OB1-OB9 and the anomalous motion of the stars in that region as reported in a previous paper. Expressions for the masses, sizes, and ages for the resulting unstable complexes are derived, the observed peculiar velocity in Cygnus OB1-OB9 being used as an input parameter. It is shown that the mechanical luminosity injected into the Cygnus Superbubble by stellar winds in the active association Cygnus OB2 is consistent with the observational characteristics of Cygnus OB1-OB9, if Cygnus OB2 was originally immersed in an ISM dominated by giant molecular complexes.

Subject headings: instabilities — ISM: bubbles —
open clusters and associations: individual (Cygnus OB1, Cygnus OB9)

1. INTRODUCTION

Large-scale expanding structures have been extensively observed in the disk of ours and other galaxies (Heiles 1979, 1984; Tenorio-Tagle & Bodenheimer 1988; Dickey & Lockman 1990) and probably play a major role in the disk-halo interaction (Norman & Ikeuchi 1989; Cioffi & Shull 1991). Their importance in shaping the galactic interstellar medium (ISM) has been widely recognized in recent years (McKee & Ostriker 1977; McCray & Snow 1979; Ikeuchi, Habe, & Tanaka 1984; Franco et al. 1988; Comerón & Torra 1992). Such bubble-like structures are expected to appear around sites of intense star-forming activity in the arms of spiral galaxies, as a consequence of continuous (winds of O and B stars) or explosive (Type II supernovae) mass outflows from very massive stars (Bruhweiler et al. 1980).

In a previous paper (Comerón et al. 1993, hereafter Paper I) we reported the existence of anomalous proper motions of stars belonging to the associations Cygnus OB1 and Cygnus OB9, indicative of a group motion with a velocity of 30–40 km s^{-1} with respect to the local standard of rest. Interestingly, these associations lie near the boundaries of an arc-shaped structure observed in X-rays by Cash et al. (1980), known as the Cygnus Superbubble, and the motion is directed radially opposite to the compact, very active association Cygnus OB2, which lies near the center of the Superbubble. The real existence of the Superbubble was questioned by Bochkarev & Sitnik (1985), who favored an interpretation in terms of a casual arrangement of small, unrelated sources along the line of sight. However, the spatial arrangement of Cygnus OB2, the Superbubble, and Cygnus OB1-OB9, together with the newly reported kinematical peculiarity of the latter associations, give strong support to the view of a physical and genetical relationship among them. Such a relationship gives new observational evidence for the importance of processes of propagating star formation in galactic disks (Elmegreen 1985; McCray & Kafatos 1987).

Structures presumably related to the injection of energy in small volumes of the interstellar medium have been detected in the disk of M31 (Brinks 1981; Brinks & Bajaja 1986). A good candidate to an expanding superbubble with characteristics similar to those of the Cygnus Superbubble is the one reported by Kamphuis, Sancisi, & van der Hulst (1991) in the disk of M51. Palous (1991) has investigated the possible relationship between expanding shells and sites of recent star formation in the disk of M33. Detailed observations have been presented by Vallenari, Bomans, & de Boer (1992) of star formation around giant shells in the Large Magellanic Cloud, and evidence for sequential star formation in that same galaxy has been discussed by Parker et al. (1992). In our Galaxy, Junkes & Fürst (1992) have reported an excess of *IRAS* sources in the direction of the supernova remnant G54.4−0.3, where CO emission from a shell expanding at a velocity of 40 km s^{-1} has been detected. This is possibly a younger, smaller example of the same kind of structure we discuss here.

In this paper, we present an analytical treatment of the onset of gravitational instabilities in a shell expanding into the ISM to account for star-forming activity in it. We derive relationships for the most relevant parameters which can be directly compared to the observations and show that the required conditions are not incompatible with the proposed scenario of the formation of Cygnus OB1-OB9 taking place in the early phases of the development of a Superbubble originated by the combined action of Type II supernovae and stellar winds from Cygnus OB2.

2. BASICS ABOUT EXPANDING SUPERBUBBLES

The expanding hot cavity created by the combined action of supernovae and winds from OB stars in the early evolutionary stages of an OB association drives a spherical shock front into the surrounding ISM, leaving a hot cavity or bubble inside it. Three distinct phases can be considered in the life of a bubble, which have been described in more detail by Chevalier (1977). A first, free expansion phase is followed by the adiabatic phase (Sedov phase). When the dynamical timescale of the expanding bubble becomes of the order of the cooling time of the material entering the front shock, a cold, dense shell starts to form at the edge of the bubble. The transition up to this third stage takes place at times of characteristically $\sim 10^4$ yr; this is a very young age for the purposes of this paper, so we will consider only this phase in the evolution of our studied Superbubble.

The dynamics of the expanding shell is dominated by its inertia, the accretion rate onto it from the outer ISM, and the pressure difference between the hot cavity inside the shell and the material outside it. In the absence of a continuous source of energy inside the shell, the interior pressure would rapidly fall toward values similar to those of the outer ISM, and it is then easy to show, from momentum-conserving considerations, that the radius r of the shell should then grow with time as $r \propto t^{1/4}$. However, the existence of a continued energy input inside the cavity causes the shell to expand faster. Weaver et al. (1977) showed that a source of mechanical luminosity L inside a superbubble surrounded by an ISM with a density ρ_0 gives the following time dependence for the radius of the shell:

$$r = 0.76\left(\frac{Lt^3}{\rho_0}\right)^{1/5} . \tag{1}$$

The consequent expansion velocity v is

$$v = 0.46\left(\frac{L}{\rho_0 t^2}\right)^{1/5} . \tag{2}$$

Hydrodynamic considerations given by Mac Low & McCray (1988) show that if the energy is not injected in a continuous way, but rather in pulses, as in the case of supernova explosions, the energy is buffered in the hot interior so that the pressure on the shell remains constant and the expressions (1) and (2) are still valid, L now being the mechanical energy released by a supernova divided by the mean time interval between supernova explosions inside the bubble.

As the bubble expands into the ISM, the swept-up material is mostly accreted onto the shell. The surface density of the shell is

$$\sigma = \frac{\rho_0 r}{3} . \tag{3}$$

In writing equation (3), we neglect the evaporation of the shell into the cavity. This can be justified by the fact, pointed out by Ferrière, Mac Low, & Zweibel (1991), that even a low-intensity magnetic field parallel to the shell is able to suppress the evaporation by eliminating thermal conduction into the hot cavity. Derivation of equations (1) and (2) assumes a spherically symmetrical shell expanding in a uniform medium and neglects a number of effects which cause deviations from the described behavior. The sphericity is distorted, among other causes, by the density structure of the ISM and by the shearing effect of the galactic rotation. Olano (1982) and Tenorio-Tagle & Palous (1987) have studied the evolution of an expanding shell in a galactic rotation field. The distortion caused by shearing is independent of the expansion parameters and begins to be noticeable at times comparable to

$$t_1 \sim A^{-1} , \tag{4}$$

where Oort's constant $A = 15$ km s^{-1} kpc^{-1}; that is, after a few 10^7 yr.

Other effects neglected in equations (1) and (2) become important with time. One of them is due to the decrease of the surrounding density ρ_0 as the shell moves away from the galactic plane, and its characteristic timescale can be evaluated from

$$t_2 \sim 1.4\left(\frac{\rho_0}{L}\right)^{1/3} H^{5/3} , \tag{5}$$

which results from equaling equation (1) to the scale height H of the gaseous galactic layer using an averaged value of the ambient density between the galactic plane and H. Careful studies of the expansion of a superbubble in a stratified galactic disk published by Mac Low & McCray (1988) and Tenorio-Tagle, Różyczka, & Bodenheimer (1990) show that R-T instabilities appear when the shell reaches the rarefied regions distant from the galactic plane after a time of the order given by equation (5). Another effect is self-gravity of the dense shell, which progressively decreases its expansion rate. The age of a bubble at which the effects of self-gravity start to be important can be obtained by comparing the acceleration of the shell in the absence of self-gravity, given by the time derivative of equation (2), and the gravitational acceleration on a shell because of its own mass. The associated timescale is then given by

$$t_3 \sim 0.24 \frac{1}{\sqrt{G\rho_0}} . \tag{6}$$

Similarly, we can obtain an estimate of the time at which the gravitational force perpendicular to the galactic plane starts to be important at slowing down the vertical motions in the expanding bubble. Assuming that in the proximities of the galactic plane the vertical acceleration can be approximated by

$$g_z = -K_z z , \tag{7}$$

the characteristic timescale is given by

$$t_4 \sim 0.5 \frac{1}{\sqrt{K_z}} , \tag{8}$$

which is obtained by equaling the decreasing acceleration of a region of the shocked layer assuming the validity of equations (1) and (2) with the gravitational acceleration (eq. [7]). This timescale is independent of the characteristics of both the bubble and the surrounding ISM, and for the usually accepted value of K_z it gives $t_4 \sim 6 \times 10^6$ yr.

Obviously, a realistic model of an expanding bubble including the mentioned distorting effects and other, unconsidered ones such as ISM clumpiness or galactic magnetic fields, demands complex numerical simulations which have been partially carried out by the quoted authors and some others. Nevertheless, the timescales t_1, t_2, t_3, and t_4 are still useful for a critical evaluation of the validity of the analytical approach that we propose in this paper.

3. GRAVITATIONAL INSTABILITY OF THE EXPANDING SHELL

We assume a thin shell having at a given time a surface density σ. The shell expands according to the law (eq. [1]) with a radial velocity v given by equation (2). The apparition of dynamic and gravitational instabilities in expanding shells has been extensively studied by Vishniac (1983), and further discussion in connection with superbubble expansion in the galactic ISM has been made by McCray & Kafatos (1987). Here we will use a treatment similar to that developed by Elmegreen (1992a); let us study the evolution in the surface of the shell of wavelike perturbations such that the lines of equal phase are parallel strips. The prolongation of these strips across the surface of the bubble would define a system of meridians, the perturbed region lying at the equator. In this way, we set up a reference system in spherical coordinates where all perturbations take place in the azimuthal direction ϕ. At the equator, the perturbed equations of continuity and motion in spherical coordinates take the form

$$r^2 \frac{\partial \sigma'}{\partial t} + 2rv\sigma' + r\sigma \frac{\partial v'}{\partial \phi} = 0 , \tag{9}$$

$$\sigma \frac{\partial v'}{\partial t} + \sigma \frac{vv'}{r} + \frac{s}{r} \frac{\partial p'}{\partial \phi} - \sigma g' = 0 , \tag{10}$$

where σ' is the perturbation in the surface density of the shell, v' is the perturbation in velocity, p' is the pressure perturbation, s is the shell thickness (across which we consider p' to be constant), and g' is the perturbation in the gravitational field. We now assume the perturbed quantities to vary with time and position as

$$A' = A'_0 \exp(\omega t - ik\phi) , \tag{11}$$

where A' is any of the perturbed quantities, the imaginary part of ω is the angular frequency of the oscillating perturbation, and k is the angular wavenumber. Furthermore, we can approach the perturbed component of the gravitational field by that resulting from the wavelike perturbations in a flat, infinite layer as long as $k \gg (2\pi)^{-1}$. A general solution has been given by Elmegreen (1987) for the case of an exponentially stratified layer; here we shall use the limit for an infinitely thin layer, which reduces to

$$g' = -2\pi i G\sigma' . \tag{12}$$

Further simplification is introduced if we consider the perturbations to be isothermal, i.e., $p' = c^2\sigma' s^{-1}$, where c is the velocity dispersion in the shell medium. With these assumptions, the perturbed equations become

$$r^2\omega\sigma' + 2rv\sigma' - r\sigma i k v' = 0 , \tag{13}$$

$$\sigma\omega v' + \sigma v \frac{1}{r} v' - ik \frac{c^2}{r} \sigma' + 2\pi i G\sigma\sigma' = 0 . \tag{14}$$

The dispersion equation is

$$2\pi r G\sigma k - k^2c^2 - (r\omega + v)(r\omega + 2v) = 0 , \tag{15}$$

which has positive solutions for ω when

$$\frac{\pi G r\sigma}{c^2}\left(1 - \sqrt{1 - \frac{2v^2c^2}{\pi^2 r^2 G^2 \sigma^2}}\right) < k < \frac{\pi G r\sigma}{c^2}\left(1 + \sqrt{1 - \frac{2v^2c^2}{\pi^2 r^2 G^2 \sigma^2}}\right) . \tag{16}$$

That is, for real k within the interval defined by equation (16), the perturbations (eq. [11]) become gravitationally unstable. For very early stages when $vr^{-1}\sigma^{-1}$ is large, no real solutions exist for k, which means that the expansion velocity is too large and the accreted density too low for any gravitational perturbations to grow. It is easy to find the time at which real solutions of equation (16) are possible: from equations (1), (2), and (3), the condition

$$\frac{2v^2c^2}{\pi^2 r^2 G^2 \sigma^2} < 1 \tag{17}$$

can be expressed as a function of t, L, c, and ρ_0. The result is

$$t > 1.04\left(\frac{c}{G}\right)^{5/8} L^{-1/8} \rho_0^{-1/2} . \tag{18}$$

This result is analogous to that used by McCray & Kafatos (1987) by using criteria based on the energetic balance of regions of an expanding bubble as derived by Ostriker & Cowie (1981). The fastest growing mode, given by $d\omega/dk = 0$, has

$$k_{\rm fg} = \frac{\pi G r\sigma}{c^2} , \tag{19}$$

which is analogous to the result found for a uniform, infinite sheet (Larson 1985). It is useful to use the relationship between k and the wavelength λ of unstable perturbations:

$$k = \frac{2\pi r}{\lambda} . \tag{20}$$

Thus, using equation (3),

$$\lambda_{\rm fg} = \frac{6c^2}{G\rho_0 r} . \tag{21}$$

By replacing the fastest growing wavenumber $k_{\rm fg}$ in equation (15), we find that the characteristic time of growth at the age of the bubble given by equation (18) is

$$t_{\rm fg} = 5.5\left(\frac{c}{G}\right)^{5/8} L^{-1/8} \rho_0^{-1/2} , \tag{22}$$

that is, roughly 5 times the age of the bubble at the onset of the instability.

Obviously, any realistic unstable perturbation should have a wavelength not exceeding the characteristic dimensions of the shell. We can use this to impose an additional limit for gravitational instability:

$$\lambda_{\rm fg} < r , \tag{23}$$

which, using equation (1), can be written as a condition on the age of the bubble for gravitational instabilities to appear:

$$t > 7.0\left(\frac{c^2}{G}\right)^{5/6} \rho_0^{-1/2} L^{-1/3} . \tag{24}$$

Gravitational instability of the shell requires the simultaneous fulfilling of equations (18) and (24). As can be seen by comparing both expressions, the dominant condition depends only on the mechanical luminosity L injected into the bubble, allowing us to define a critical luminosity L_1 given by

$$L_1 = 9.3 \times 10^3 \frac{c^5}{G} . \tag{25}$$

For luminosities higher than L_1, equation (18) is a stronger constraint than equation (24), while equation (24) dominates for lower luminosities.

An additional term has been used by Elmegreen (1992a) in equation (10) to account for an extra transverse acceleration which appears due to the decrease of the expansion velocity of the bubble with time. The ratio η of the acceleration to the acceleration by self-gravity of the perturbations in the shell can be expressed as

$$\eta = 0.106\left(\frac{GL}{c^5}\right)^{1/4}\frac{1}{k}\,. \tag{26}$$

For a luminosity $L = L_1$, this is simply $\eta = 1.04k^{-1}$, and thus η is well below unity from the condition (23). For higher luminosities, the corresponding increase in k for the fastest growing mode makes η even smaller. This justifies the fact that we have omitted this additional acceleration term in the current treatment.

The mass enclosed in a fastest growing unstable region can be estimated as

$$M \simeq \sigma\lambda_{fg}^2\,, \tag{27}$$

where σ and λ_{fg}^2 to be employed in equation (27) are the values of these quantities at the onset of the gravitational instability. By using equations (1), (18), and (21), we find for the mass formed in the case of $L > L_1$:

$$M \simeq 15.4\left(\frac{c^{29/8}}{G^{13/8}}\right)L^{-1/8}\rho_0^{-1/2}\,, \tag{28}$$

while for the case of condition (24) dominating,

$$M \simeq 4.9\left(\frac{c^2}{G}\right)^{3/2}\rho_0^{-1/2}\,. \tag{29}$$

4. OBSERVATIONAL DETERMINATION OF THE EXPANSION PARAMETERS

When gravitational instability appears in a region, the density increase associated with contraction reduces the contact surface between the contracting region and the ISM it encounters, thus reducing the drag force. We may thus consider that after the onset of the gravitational instability, the unstable region detaches from the shell and starts to follow a ballistic path with constant velocity. We will now use the available kinematic information to obtain an estimate of the most relevant quantities involved in our model. We will consider the currently observed velocity as a probe of the expansion velocity of the shell at the time of the apparition of the gravitational instability. If $L > L_1$, then setting t equal to the right-hand side of equation (18) and using equation (2) we find

$$L = 24\,\frac{cv^4}{G}\,, \tag{30}$$

while, if equation (24) dominates,

$$L = 107\,\frac{c^2v^3}{G}\,. \tag{31}$$

By comparing equations (29) and (30) to the luminosity distinguishing between the two cases of equations (18) or (24) dominating, we can find the division between them as a function of the expansion velocity. The value v_d separating both cases is

$$v_d = 4.8c\,. \tag{32}$$

The observed velocities in Cygnus OB1-OB9 being around 30 km s^{-1}, $v > v_d$ unless the velocity dispersion in the shocked shell is of several kilometers per second. This is rather unlikely in the high-density conditions of the shocked medium, where energy dissipation by inelastic collisions is expected to take place within a short characteristic timescale. We will return to this point in § 5.1. The condition (18) should therefore be dominating over condition (24), and the expressions (28) and (30) are relevant to our study instead of expressions (29) and (31).

The mass of the stellar groups formed by gravitational instabilities can be expressed as a function of the observed velocity by eliminating L from equation (28) by means of equation (30):

$$M \simeq 10.3\sqrt{\frac{c^7}{G^3 v\rho_0}}\,. \tag{33}$$

Unlike the luminosity required to reproduce the observed velocities, M now depends on the mean density of the unperturbed ISM; moreover, this value is very sensitive to the velocity dispersion c.

The wavelength of the unstable region, which gives the approximate size of the so-formed stellar systems, is

$$\lambda \simeq 5.2\sqrt{\frac{c^3}{G\rho_0 v}}\,. \tag{34}$$

Other important quantities are the age and the radius of the bubble at which the instabilities appear, derived from equations (18) and (30):

$$t_0 \simeq 0.7\sqrt{\frac{c}{G\rho_0 v}}\,, \tag{35}$$

$$r = 1.2\sqrt{\frac{cv}{G\rho_0}}\,. \tag{36}$$

The comparison of this time with the timescales of the neglected effects t_1, t_2, t_3, and t_4 will be a check for the validity of some of our simplifying assumptions.

5. RESULTS AND DISCUSSION

5.1. *Masses, Dimensions, and Ages*

The growth timescale (eq. [22]) and a rough estimate of the current age of the Cygnus Superbubble of order 10^7 yr point toward a rather high density of the ambient medium where the expansion began. We will assume hereafter that the expansion took place, at least until the apparition of the gravitational instabilities, in a dense gas, with physical conditions closer to those of giant molecular clouds than to those of the diffuse intercloud medium. The collisional energy dissipation rate in the shocked gas in such conditions can be expected to be short (Elmegreen 1992b), taking place in a timescale less than 10^4 yr. The final velocity dispersion in the shocked shell should then be accordingly low. A velocity dispersion of $\simeq 1$ km s^{-1}, which is within the range of the observed values for dark cloud complexes (Myers 1987) will therefore be assumed along the forthcoming discussion.

TABLE 1

RELEVANT QUANTITIES OF THE GRAVITATIONAL INSTABILITIES FOR DIFFERENT VALUES OF THE ISM DENSITY

n_H (cm^{-3})	M ($M_\odot$)	λ_{fg} (pc)	r (pc)	t_0 (yr)	t_{fg} (yr)	t_1 (yr)	t_2 (yr)	t_3 (yr)	t_4 (yr)
0.1	75×10^3	210	1600	29×10^6	160×10^6	65×10^6	0.22×10^6	74×10^6	60×10^6
1	24×10^3	62	490	9.3×10^6	51×10^6	65×10^6	0.48×10^6	23×10^6	60×10^6
10	7.5×10^3	21	160	2.9×10^6	16×10^6	65×10^6	1.0×10^6	7.4×10^6	60×10^6
100	2.4×10^3	6.2	49	0.9×10^6	5.1×10^6	65×10^6	2.2×10^6	2.3×10^6	60×10^6
1000	0.75×10^3	2.1	16	0.3×10^6	5.1×10^6	65×10^6	4.8×10^6	0.74×10^6	60×10^6

In Table 1, we list the masses, lengths, and timescales, whose expressions are given in § 4, for different values of the ambient number density n_H. In addition, the timescales t_1, t_2, t_3, t_4 are calculated. The densities listed in Table 1 are characteristic of very different environments, the lowest densities being representative of the warm intercloud medium and the highest being representative of the cores of molecular clouds.

Superbubble expansion in densities below $n_H \simeq 10$ cm^{-3} are clearly difficult to reconcile with observations. The shell around the Superbubble would become gravitationally unstable only after having expanded to a radius of the order of several hundred parsecs, perhaps larger than the currently observed radius of the Superbubble, and after having blown out of the galactic disk. On the other hand, very high densities ($n_H > 10^3$ cm^{-3}) would form the first unstable complexes only a few 10^5 yr after the formation of the Superbubble, giving small and not very massive clumps when the shell radius is still small. Such a shell would rapidly decelerate its expansion under its own gravity, and its current radius would be much smaller than observed. In a medium with $n_H = 10^4$ cm^{-3}, the Superbubble would stop its expansion after 10^7 yr, reaching a maximum radius of 50 pc.

The most interesting results are obtained using $n_H \simeq 10$–100 cm^{-3}. Such a density would make the shell become unstable after a few 10^6 yr, forming instabilities with masses of order several thousand solar masses (with a high uncertainty due to the strong dependence on the assumed velocity dispersion), with dimensions of a few parsecs, which may evolve into stars or stellar systems. The region which is nowadays identified as Cygnus OB1-OB9 is thus possibly a portion of the shell where one or several unstable regions have developed earlier in the life of the Cygnus Superbubble. Moreover, the age of the Superbubble at the apparition of the instabilities is of order or below the timescales t_1, t_2, t_3, t_4 which constrain the validity of our assumptions.

As discussed in Paper I, the H-R diagrams of the clusters presumably belonging to the anomalously moving associations indicate a young age of about 10^7 yr. This is in a rough agreement with the expansion age derived by dividing the projected distance on the sky between Cygnus OB1-OB9 and Cygnus OB2 by the projected peculiar velocity, which gives 5×10^6 yr. Torres-Dodgen, Tapia, & Carroll (1991) have found a minimum age of 3×10^6 yr for Cygnus OB2, although it is difficult to fit the H-R diagrams presented by these authors by a single isochrone, perhaps as a consequence of sequential and time-dependent star formation (Elmegreen & Lada 1977; Doom, De Greve, & de Loore 1985; Blaauw 1991). The coexistence of evolved B stars together with early O-type stars confirms a continued process of star formation in Cygnus OB2 (Massey & Thompson 1991). Within the uncertainties arising both from theory and observations, we can conclude that the implied evolutionary timescales are not inconsistent with our model.

The density required for the ISM to form unstable structures leading to star formation with the detected expansion velocity is much higher than the mean density of the H I in the galactic disk (Dickey & Lockman 1990), which was the value used by Abbott, Bieging, & Churchwell (1981) in their modeling of the Cygnus Superbubble. This high density may be more realistic in the modeling of the initial stages of the expansion of superbubbles, taking into account that the OB associations giving rise to them form from large molecular complexes. A rough lower estimate for the mass and size of the parental molecular complex is obtained by assuming that its initial size had at least the diameter of the shell at the onset of the gravitational instabilities. Using a mean density $n_H = 100$ cm^{-3}, this gives a mass of 2.5×10^6 $M_\odot$ within a diameter of 100 pc, roughly corresponding to the mass and size of the largest molecular complexes (Goldsmith 1987). This mass, spread across a spherical surface with the radius that the Superbubble currently has (150 pc), should produce an extinction $A_V \simeq 0.5$ near its center for objects located inside it (where we have used the hydrogen column density to color excess ratio of Bohlin, Savage, & Drake 1978).

The three-dimensional structure of the gas in the vicinity of the Cygnus Superbubble is difficult to map, owing to the blending of individual contributions along the line of sight. Radial velocities due to galactic rotation are only a poor distance indicator in that direction of the sky, merely allowing for a segregation of sources belonging to the Orion-Cygnus spiral arm from those associated to the Perseus arm. Nevertheless, radio observations clearly indicate the existence of large concentrations of molecular gas in that region (see review by Bochkarev & Sitnik 1985). High extinctions are measured toward optical sources in Cygnus OB2 and other neighboring directions (Dickel & Wendker 1978; Torres-Dodgen et al. 1991), which confirm the existence of large column densities of absorbing material. The boundaries of the Cygnus Superbubble are outlined by an ensemble of Hα-emitting filaments (Brand & Zealey 1975), but no H I shell is observed at that position (GS 081 −05 −37, described by Heiles 1979, has an excessively negative velocity and most probably belongs to the Perseus spiral arm). The observation of a slowly expanding shell in that region is made very difficult, on the other hand, given the bright H I background in the range of velocities of the Orion-Cygnus arm objects.

A potentially important effect we have neglected in our model is the existence of a magnetic field in the medium where the bubble expands. The expansion of a bubble in a uniform magnetic field has been studied by Ferrière et al. (1991), who find that the overall expanding law is not greatly changed by its presence. The main consequences of it are a thickening of the shell and a circulation of material across it because of the induced Lorentz forces. Defining the magnetic poles of a bubble as the intersection of its surface and the diameter which is parallel to the magnetic field lines, the circulation of material tends to deplete the surface density at the poles, driving the material toward the magnetic equator, which modifies the surface density with respect to equation (3), introducing regional dependences. Moreover, the frozen-in magnetic field introduces an additional pressure which opposes gravitational collapse in the directions of the magnetic parallels of the so-defined magnetic reference frame of the surface of the bubble. We may thus expect the formation of gravitational instabilities to take place preferentially in structures elongated perpendicularly to the frozen-in field lines on the surface of the bubble.

The fact that the magnetic pressure at the poles vanishes is compensated, for gravitational instability purposes, by the depletion by about one order of magnitude of the surface density at those regions. We may thus expect the unstable complexes to appear near the magnetic equator. If the magnetic field lines in the region now occupied by the Superbubble initially followed the general pattern of the large-scale magnetic field, being perpendicular to the galactocentric direction (Kulkarni & Heiles 1988), then the galactic longitude of Cygnus implies that we are seeing the Superbubble nearly pole-on, the magnetic equatorial plane being perpendicular to the line of sight. This is consistent with the astrometric results, described in Paper I, which suggest that the anomalous motions of these stars lie on a line close to the plane of the sky.

5.2. *Luminosity Input*

A critical test for the plausibility of our model comes from the energetic requirements of the expansion, to be ultimately compared to equation (30). The mechanical luminosity injected into the cavity has its source in the mass outflow from massive stars in different phases of their evolution and in their final explosion as supernovae. Observational derivations of mass loss by massive stars, including some stars belonging to Cygnus OB2, can be found, among others, in Abbott et al. (1981), Leitherer et al. (1982), Lundstrom & Stenholm (1984), Bieging, Abbot, & Churchwell (1989), Howarth & Prinja (1989), and Vilkovskij & Tambovtseva (1992). These observations have been reviewed by Leitherer, Robert, & Drissen (1992), who have combined them with population synthesis models in order to derive the total mechanical input in the interstellar medium by young stellar groups. Their results show that for an ensemble of coeval stars, winds from OB stars are the dominating contribution at the beginning of the life of the group. Between 2×10^6 yr and 8×10^6 yr since the birth of the stellar group, massive outflows from Wolf-Rayet stars become a primary source of energy injection, together with the ejecta from the explosion as supernova of the most massive stars of the group. Afterward, OB stellar winds and supernova ejecta dominate. The contributions from luminous blue variables and red supergiants are always of a secondary importance in the energetic budget.

During the early phases of the stellar group, Leitherer et al. (1992) find that the mechanical energy output of the OB stars keeps roughly constant at around 2×10^{34} ergs s^{-1} per unit of the total mass of the stellar group locked in stars with $M > 1$ $M_\odot$. Since no stars with mass above 120 $M_\odot$ seem to exist, and the lifetime of a solar metallicity 120 $M_\odot$ star is around 3.5×10^6 yr (Maeder 1990), no supernovae are expected at this stage, and the OB stars are the only important source of energy at the beginning of the life of the cavity. The apparition of the gravitational instability in the Cygnus Superbubble took place in this early phase, according to our previous discussion; thus, only the effects of OB stars need to be considered in evaluating the energetic requirements imposed on Cygnus OB2 by the observed fast-moving stars. If $\mathscr{M}_0$ is the total initial mass of Cygnus OB2 in stars with masses between 1 $M_\odot$ and 120 $M_\odot$, then

$$L_{\rm OB} = 2 \times 10^{34} \text{ erg s}^{-1}\, M_\odot^{-1}\, \mathscr{M}_0 \tag{37}$$

implies $\mathscr{M}_0 = 1.3 \times 10^5$ $M_\odot$. The number of stars which contribute to this is approximately

$$N = \int_{M=1M_\odot}^{120M_\odot} A M^{-2.35}\, dM\,, \tag{38}$$

where the Salpeter exponent of the initial mass function, -2.35, has been chosen for consistency with the calculations of Leitherer et al. (1992). The proportionality constant A is given by the condition that the integral of the mass multiplied by the initial mass function be $\mathscr{M}_0$:

$$A = 0.43\, \mathscr{M}_0\,. \tag{39}$$

The high obscuration and foreground contamination in the direction of Cygnus OB2 makes it difficult to estimate the total contents of OB members of the association. Nevertheless, it has been clear since the early surveys that Cygnus OB2 is an outstandingly rich association, with a population well in excess of the typical contents of the better studied OB associations near the Sun (see reviews of early work on Cygnus OB2 in Torres-Dodgen et al. 1991 and Massey & Thompson 1991) that has been evaluated in as many as 400 members. Taking into account that the most massive members should have already exploded as supernovae, we can assume as a crude estimate that the Superbubble was powered by about 500 OB stars in its early stages, by taking main-sequence lifetimes from Maeder (1990). Using a value of 9 $M_\odot$ for the mass of the latest OB stars (corresponding to spectral type B2; see Schmidt-Kaler 1982), we obtain $\mathscr{M}_0 \simeq 3.1 \times 10^4$ $M_\odot$. When replaced in equations (37) and (30), we obtain a predicted expansion velocity at the onset of the gravitational instability somewhat in excess of 20 km s^{-1}. This can be considered to be in a reasonable agreement with the observations, in view of their accuracy and the crude approximations that we have needed to introduce in our calculations. Another important source of uncertainty concerns the input parameters of the model as they can be derived from observations of Cygnus OB2, regarding its stellar content, star formation history, and initial mass function.

6. CONCLUSIONS

Our study has shown the consistency of an explanation for the origin of Cygnus OB1-OB9 as gravitationally unstable perturbations in the early stages of the Cygnus Superbubble. An energetic expansion taking place in an ISM with a density of the order of that of a molecular complex would form a cold, dense shell which would become unstable after a few 10^6 yr, the instabilities then undergoing further collapse and giving origin to the currently observed stellar systems. By comparing the derived time of the apparition of the instabilities to the characteristic timescales limiting the validity of our analytical approach, we have found that our set of parameters which best fit the observations give rise to the instabilities before the distorting effects begin to be important.

Finally, we have investigated the energetic requirements of the model and have found that the expected action of winds from OB stars in Cygnus OB2 is in a reasonable agreement with the mechanical luminosity required by the Superbubble in order to have formed Cygnus OB1-OB9 with their currently observed high peculiar motions. We conclude that the observed anomaly in the proper motions of the stars in Cygnus OB1-OB9 can be interpreted as a new evidence for the mechanisms of propagating star formation in the galactic disk.

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REFERENCES

Abbott, D. C., Bieging, J. H., & Churchwell, E. 1981, ApJ, 250, 645
Bieging, J. H., Abbott, D. C., & Churchwell, E. 1989, ApJ, 340, 518
Blaauw, A. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 125
Bochkarev, N. G., & Sitnik, T. G. 1985, Ap&SS, 108, 237
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Brand, P. W., & Zealey, W. J. 1975, A&A, 38, 363
Brinks, E. E. 1981, A&A, 95, L1
Brinks, E. E., & Bajaja, E. 1986, A&A, 169, 14
Bruhweiler, F. C., Gull, T. R., Kafatos, M., & Sofia, S. 1980, ApJ, 238, L27
Cash, W., Charles, P., Bowyer, S., Walter, F., Garmire, G., & Riegler, G. 1980, ApJ, 238, L71
Chevalier, R. A. 1977, ARA&A, 15, 175
Cioffi, D. F., & Shull, J. M. 1991, ApJ, 367, 96
Comerón, F., & Torra, J. 1992, A&A, 261, 94
Comerón, F., Torra, J., Jordi, C., & Gómez, A. E. 1993, A&AS, 101, 37 (Paper I)
Dickel, H. R., & Wendker, H. J. 1978, A&A, 66, 289
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Doom, C., De Greve, J. P., & de Loore, C. 1985, ApJ, 290, 185
Elmegreen, B. G. 1985, in Birth and Infancy of Stars, ed. R. Lucas, A. Omont, & R. Stora (Amsterdam: Elsevier), 215
———. 1987, ApJ, 312, 626
———. 1992a, in Star Formation in Stellar Systems, ed. G. Tenorio-Tagle, M. Prieto, & F. Sánchez (Cambridge: Cambridge Univ. Press), 381
———. 1992b, in The Galactic Interstellar Medium, ed. D. Pfenniger & P. Bartholdi (Berlin: Springer-Verlag), 157
Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725
Ferrière, K. M., Mac Low, M.-M., & Zweibel, E. G. 1991, ApJ, 375, 239
Franco, J., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, M., & Mirabel, I. F. 1988, ApJ, 333, 826
Goldsmith, P. F. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson (Dordrecht: Reidel), 51
Heiles, C. 1979, ApJ, 229, 533
———. 1984, ApJS, 55, 585
Howarth, I. D., & Prinja, R. K. 1989, ApJS, 69, 527
Ikeuchi, S., Habe, A., & Tanaka, Y. D. 1984, MNRAS, 207, 909
Junkes, N., & Fürst, E. 1992, in Evolution of Interstellar Matter and Dynamics of Galaxies, ed. J. Palous, W. B. Burton, & P. O. Lindblad (Cambridge: Cambridge Univ. Press), 95
Kamphuis, J., Sancisi, R., & van der Hulst, T. 1991, A&A, 244, L29
Kulkarni, S. R., & Heiles, C. 1988, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur & K. I. Kellermann (Berlin: Springer-Verlag), 95
Leitherer, C., Hefele, H., Stahl, O., & Wolf, B. 1982, A&A, 108, 102
Leitherer, C., Robert, C., & Drissen, L. 1992, ApJ, 401, 596
Larson, R. B. 1985, MNRAS, 214, 379
Lundstrom, I., & Stenholm, B. 1984, A&AS, 58, 163
Mac Low, M.-M., & McCray, R. 1988, ApJ, 324, 776
Maeder, A. 1990, A&AS, 84, 139
Massey, P., & Thompson, A. B. 1991, AJ, 101, 1408
McCray, R., & Kafatos, M. 1987, ApJ, 317, 190
McCray, R., & Snow, T. P. 1979, ARA&A, 17, 213
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 211, 135
Myers, P. C. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson (Dordrecht: Reidel), 71
Norman, C. A., & Ikeuchi, S. 1989, ApJ, 345, 372
Olano, C. A. 1982, A&A, 112, 195
Ostriker, J. P., & Cowie, L. L. 1981, ApJ, 243, L127
Palous, J. 1991, Mem. Soc. Astron. Ital., 62, 969
Parker, J. W., Garmany, C. D., Massey, P., & Walborn, N. R. 1992, ApJ, 103, 1205
Schmidt-Kaler, Th. 1982, in Landolt-Börnstein, Vol. 2b, ed. K. Schaifers & H. H. Voigt (Berlin: Springer-Verlag), 30
Tenorio-Tagle, G., & Bodenheimer, P. 1988, ARA&A, 26, 145
Tenorio-Tagle, G., & Palous, J. 1987, A&A, 237, 207
Tenorio-Tagle, G., Różyczka, M., & Bodenheimer, P. 1990, A&A, 237, 207
Torres-Dodgen, A. V., Tapia, M., & Carroll, M. 1991, MNRAS, 249, 1
Vallenari, A., Bomans, D. J., & de Boer, K. 1992, in Star Forming Galaxies and Their Interstellar Medium, ed. J. Franco et al. (Cambridge: Cambridge Univ. Press), in press
Vilkoviskij, E. Ya., & Tambovtseva, L. V. 1992, A&AS, 94, 109
Vishniac, E. T. 1983, ApJ, 274, 152
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377