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SUPERSHELLS AND PROPAGATING STAR FORMATION

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ABSTRACT

Stellar winds and repeated supernovae from an OB association will create a cavity of coronal gas in the interstellar medium, with radius greater than 100 pc, surrounded by a dense, expanding shell of cool interstellar gas. If the association has a typical initial mass function, its supernovae explosions will inject energy into the supershell at a nearly constant rate for about 5×10^7 yr. The supershell loses its interior pressure and enters the snowplow phase when radiative cooling becomes important or when the shell bursts through the gas disk of a galaxy, typically after a few times 10^7 yr and with a radius ~100–300 pc. At approximately the same time, the supershell becomes gravitationally unstable, forming giant molecular clouds which are sites for new star formation. There is widespread evidence for supershells in the Milky Way and other spiral and irregular galaxies from 21 cm emission-line surveys, optical emission-line surveys, and studies of supernova remnants. The gravitational instability of the supershells provides a physical mechanism for induced star formation and may account for bursts of star formation, especially in irregular galaxies.

Subject headings: interstellar: matter — stars: formation — stars: supernovae

I. INTRODUCTION

A supernova explosion in the galactic disk creates a hot ($T \gtrsim 10^6$ K) cavity of low-density ($n \lesssim 10^{-2}$ cm^{-3}) coronal gas that may persist for $\gtrsim 10^6$ yr, much longer than the time scale $\sim 3 \times 10^4$ yr for which the radio or optical remnant is visible. Cox and Smith (1974) recognized that these cavities would persist for times more than about 10^6 yr and therefore might occupy a significant fraction of the disk volume, an idea that was developed by McKee and Ostriker (1977) into a quantitative theory for a "three-phase" interstellar medium (ISM), in which cool ($T \lesssim 10^2$ K), dense ($n \sim 10^2$ cm^{-3}) "clouds" surrounded by warm ($T \sim 10^4$ K) intercloud medium are embedded in the coronal gas. A fundamental assumption of this theory is that the supernovae occur at random in the disk.

However, as McCray and Snow (1979) pointed out, the structure of the disk gas might differ significantly from that predicted by McKee and Ostriker if the supernovae in the disk are highly correlated in space and time. That should be the case, because the (Type II) supernovae that are confined to the disk probably result from the collapse of fairly massive ($\gtrsim 7$ $M_\odot$) Population I stars, which are typically formed in associations of tens or hundreds. (It is true that many supernovae, the Type I supernovae from Population II stars and the Type II supernovae from runaway stars, are not highly correlated. However, in the Milky Way these supernovae are distributed with a galactic scale height considerably greater than that of the galactic H I, so that their impact on this gas is diminished.)

McCray and Snow noted that repeated supernovae from a stellar association would produce a huge (radius $\gtrsim 100$ pc) expanding shell in the disk gas and mentioned a variety of observations that might be interpreted as evidence for such shells. That idea has been developed by Bruhweiler *et al.* (1980), Tomisaka, Habe, and Ikeuchi (1980), and Cowie and Jeffrey (1983). Meanwhile, the evidence for such shells in the Milky Way and in other galaxies has continued to accumulate. In this paper we develop this idea further and explore its consequences in the context of an idealized model in which the interstellar H I is assumed to have fairly uniform density. In § II we discuss the energy input to the ISM by young stellar associations. In § III we present an idealized model for the dynamics and evolution of a supershell caused by such an association. In § IV we consider the criterion for the onset of gravitational instability in the expanding shell and show that supershells can trigger bursts of star formation. Finally, in § V, we review the observational evidence for supershells and propagating star formation in the Milky Way and other galaxies, and we discuss the limitations of the present model. In a subsequent paper (MacLow and McCray 1987, hereafter Paper II) we shall consider in more detail the development of supershells in an inhomogeneous and stratified ISM.

II. EVOLUTION OF OB ASSOCIATIONS

The mechanical power imparted to the ISM via ionizing photons, stellar winds, and supernovae explosions is dominated by OB stars (Abbott 1982). The ionizing radiation is provided almost entirely by the O stars, with masses greater than ~ 30 $M_\odot$ and lifetimes less than $\sim 10^7$ yr. In a time less than $\sim 5 \times 10^6$ yr, during its main-sequence or a subsequent Wolf-Rayet phase, a massive ($\gtrsim$30–40 $M_\odot$) star will lose a substantial fraction of its mass in a strong stellar wind with terminal velocity ~ 2500 km s^{-1}, imparting a net mechanical energy $\sim 10^{51}$ ergs, comparable to the thermal energy of its H II region (Abbott 1982). An initially less massive star may also have a significant stellar wind, but its energy input to the ISM is probably dominated by that of its terminal supernova explosion, which we estimate to be $E_{\rm SN} \sim 10^{51}$ ergs. The least massive star that is expected to terminate as a Type II supernova has initial mass ~ 7 $M_\odot$ (Trimble 1982), corresponding to main-sequence spectral type B3. The main-sequence lifetimes of massive stars are given approximately by $t_{\rm MS} \sim 3 \times 10^7$ yr

$(M_*/[10\ M_\odot])^{-\alpha}$, where $\alpha \approx 1.6$ for $7 \lesssim M_* \lesssim 30\ M_\odot$ (Stothers 1972) and by $t_{\rm MS} \sim 9 \times 10^6$ yr $(M_*/[10\ M_\odot])^{-0.5}$ for $30 \lesssim M_* \lesssim 80\ M_\odot$ (Chiosi, Nasi, and Sreenivasan 1978).

We presume that most OB stars are formed in clusters or associations (cf. Miller and Scalo 1978). OB associations typically contain ~20–40 stars with spectral type earlier than B3 in a region of diameter less than ~100 pc (Blaauw 1964; Humphreys 1978; Garmany, Conti, and Chiosi 1982; Heiles 1987), and there are several large OB associations within 3 kpc of the Sun that contain tens of O stars and hundreds of B0–B3 stars. In fact, newborn associations may be even more condensed, because the stars are unbound and may drift apart with velocities ~5 km s^{-1}. The initial mass function of such stars can be written $dN_*/d(\log M_*) \sim M_*^{-\beta}$, where $\beta \sim 1.0$–1.7 (Garmany, Conti, and Chiosi 1982). Adopting $\beta = 1.6$ for simplicity (our results are not very sensitive to this choice), we estimate that an OB association should produce roughly 9 times as many stars with masses in the range 7–30 $M_\odot$ (main-sequence spectral type B3–B0) as stars with masses greater than 30 $M_\odot$ (MS type O).

Consider the energy delivered to the ISM by a typical modest OB association formed with, say, 20 type B0–B3 stars and three type O stars. Initially, the power is dominated by the ionizing radiation and stellar wind of the most massive star, say, a 35 $M_\odot$ type O7 V star. Such a star will produce ionizing photons at a rate $S_i \sim 7 \times 10^{48}$ s^{-1} (Panagia 1973) and stellar wind power $L_W = \dot{M}_W V_W^2/2 \sim 6 \times 10^{35}$ ergs s^{-1} (Abbott 1982), giving a total wind energy $E_W \sim 10^{50}$ ergs during its main-sequence lifetime, $t_{\rm MS} \sim 5 \times 10^6$ yr. The star may release another few times 10^{50} ergs in a strong stellar wind during a subsequent Wolf-Rayet phase before it terminates as a supernova or black hole. The ionizing radiation and stellar wind power from the association then decrease rapidly, vanishing by $t \sim 5 \times 10^6$ yr, the lifetime of the last O star.

By this time, a few supernova explosions have occurred; they will continue until $t \sim 5 \times 10^7$ yr, the lifetime of the least massive (~7 $M_\odot$) star that can explode. According to our expressions for the main-sequence lifetimes and initial mass function of the 7–30 $M_\odot$ stars (which dominate the supernova energy input), the rate of supernova explosions will remain approximately constant: $r_{\rm SN} \sim t^\gamma$, where $\gamma = ([\alpha/\beta] - 1) \approx 0$. Thus, if each supernova explosion produces an energy $E_{\rm SN} = 10^{51} E_{51}$ ergs, we may write an expression for the mean power delivered by supernova explosions from an OB association as

$$P_{\rm SN} \approx 6.3 \times 10^{35}\ {\rm ergs\ s^{-1}}\ (N_* E_{51})\ , \tag{1}$$

where N_* is the number of stars formed in the association with mass greater than 7 $M_\odot$. Note that only ~20% of the total energy available from the association is delivered during the first 10^7 yr of its lifetime; most of the energy is delivered after the ionizing O stars have perished. By that time, the association may be hard to recognize because the B stars are fainter and they may have migrated ~50 pc from their original sites.

III. EVOLUTION OF SUPERSHELLS

In order to discuss the dynamics of a supershell caused by stellar winds and supernovae, we first consider a model in which the ambient ISM consists of gas of uniform atomic density, n_0. As we discussed in § II, for the first few million years of an OB association's lifetime, the mechanical energy imparted to the ISM is dominated by stellar winds if the association contains stars with mass greater than 30 $M_\odot$ (i.e., if $N_* \gtrsim 10$). If so, the combined action of the winds will create a supershell with radius given by equation (21) of Weaver *et al.* (1977), which may be written

$$R_S = 269\ {\rm pc}\ (L_{38}/n_0)^{1/5} t_7^{3/5}\ , \tag{2}$$

where $L_{38} = L_W/(10^{38}\ {\rm ergs\ s^{-1}})$, L_W is the combined mechanical luminosity of all the stellar winds in the association, and $t_7 = t/(10^7\ {\rm yr})$. Thus, for such an association the stellar winds alone can create a supershell of large radius even before the first supernova has occurred. For example, Abbott, Bieging, and Churchwell (1981) have argued that the Cygnus supershell, with $R_S = 225$ pc (Cash *et al.* 1980), could have been created in a time scale $t_7 = 0.2$ (for $n_0 = 0.35$ cm^{-3}) by the stellar winds from Cyg OB2, an unusually rich association with $N_* \sim 200$ and $L_{38} = 5.3$.

However, for most OB associations, which are not so rich, the radius of the shell at the end of the wind-driven phase will be less than ~100 pc. In that case, the main growth of the supershell will be caused by supernova explosions, which continue to hammer at the shell until $t_7 \approx 5$, long after the O stars have vanished. Then, if the energy of the hot interior (45% of the net supernova energy) is conserved, the radius and velocity of the outer shell follow from equation (2) with the replacement $L_W = P_{\rm SN}$, where $P_{\rm SN}$ is given by equation (1). The results are

$$R_S = 97\ {\rm pc}\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}\ , \tag{3}$$

and

$$V_S = 5.7\ {\rm km\ s^{-1}}\ (N_* E_{51}/n_0)^{1/5} t_7^{-2/5}\ . \tag{4}$$

Note that the shell expands more rapidly than the stars of the association drift apart (at ~5 km s^{-1}), so that the supernovae will continue to occur inside the supershell for $t_7 \lesssim 5(N_* E_{51}/n_0)^{1/2}$. The density in the shell is given by $n_S = n_0(V_S/a_S)^2$, or

$$n_S = 32\ {\rm cm^{-3}}\ (N_* E_{51})^{2/5} n_0^{3/5} a_S^{-2} t_7^{-4/5}\ , \tag{5}$$

where $a_S = (kT_S/\mu + B_S^2/4\pi\rho_S)^{1/2}$ is the magnetosonic speed (km s^{-1}) in the shell. The kinetic energy, E_S, of the shell is equal to 20% of the net supernova energy (Weaver *et al.* 1977):

$$E_S = 4.0 \times 10^{49}\ {\rm ergs}\ (N_* E_{51}) t_7\ . \tag{6}$$

Note that the radius, velocity, and kinetic energy of the supershell exceed substantially the values that follow from equations (3) and (4) of Bruhweiler *et al.* (1980). Those authors underestimated the size of the supershell in the repeated supernova phase because they neglected the pressure of the hot interior. However, our expressions agree fairly well with the results of hydrodynamical simulations by Tomisaka, Habe, and Ikeuchi (1981).

According to the theory of Weaver *et al.* (1977), the time-averaged interior atomic density and temperature resulting from thermal evaporation from the shell are given approximately by (hereafter, exponents are rounded off to the nearest tenth):

$$n_i \sim 1.5 \times 10^{-3}\ {\rm cm^{-3}}\ (N_* E_{51})^{0.2} n_0^{0.5} t_7^{-0.6} (1 - r/R_S)^{-0.4}\ , \tag{7}$$

and

$$T_i \sim 1.1 \times 10^6\ {\rm K}\ (N_* E_{51})^{0.2} n_0^{0.1} t_7^{-0.2} (1 - r/R_S)^{0.4}\ . \tag{8}$$

However, n_i and T_i fluctuate considerably as blast waves propagate through the interior.

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When a supernova (with energy $E_{\rm SN}$) explodes inside a supershell, its ejecta expand freely, for $t \sim 10^4$ yr, until a few solar masses of hot interior gas are encountered at $r \sim 30$ pc. Then an adiabatic blast wave is established, which at first expands according to the Sedov law, $r \propto t^{2/5}$, but then decelerates more rapidly when it encounters the higher density gas near the supershell. The blast wave than merges with the shell, losing its remaining kinetic energy ($\sim 0.28\ E_{\rm SN}$) to radiation (Kafatos *et al.* 1980). We estimate that before it strikes the shell the blast wave will have velocity

$$V \sim 240 \text{ km s}^{-1}\ N_*^{-0.4} E_{51}^{0.1} t_7^{-0.6} , \qquad (9)$$

or $V \sim 44$ km s^{-1} for a "typical" supershell, with $N_* = 20$, $E_{51} = 1$, $t_7 = 2.5$, and $n_0 = 1$. The time scale for the blast wave to reach the shell is given by $\Delta t \sim 0.4\ R_S/V_S$, and the (very uncertain) probability for catching one or more such blast waves within a supershell is given by

$$P(r < R_S) = 1 - \exp\,(-r_{\rm SN}\,\Delta t) ,$$

or

$$P(r < R_S) \sim 1 - \exp\,(-4 \times 10^{-3} N_*^{1.6} E_{51}^{0.1} n_0^{-0.2} t_7^{1.2}) , \qquad (10)$$

i.e., $P(r < R_S) \sim 0.7$ for a typical supershell.

The adiabatic phase of the supershell persists until radiative cooling becomes important in the hot interior, at a time

$$t_c \sim 4 \times 10^6 \text{ yr } \zeta^{-1.5} (N_* E_{51})^{0.3} n_0^{-0.7} , \qquad (11)$$

and radius

$$R_c \sim 50 \text{ pc } \zeta^{-0.9} (N_* E_{51})^{0.4} n_0^{-0.6} , \qquad (12)$$

where ζ is the metallicity ($\zeta = 1$ for solar system abundances). (In order to derive eqs. [11] and [12], we have used the radiative cooling function $\Lambda[T]$ given by Gaetz and Salpeter 1983—cf. Paper II.) Thereafter, the shell expands according to the zero-pressure snowplow law,

$$R(t) \sim R_c (t/t_c)^{1/4} . \qquad (13)$$

When the radius of the supershell becomes comparable to the density scale height, z_0, of the galactic H I layer, the shell becomes distorted and equation (3) is no longer valid. If, at this time, the shell is expanding rapidly (compared with ~ 10 km s^{-1}, the typical RMS velocity of the disk gas), the vertical expansion will begin to accelerate. If it is expanding slowly, the gravity of the galactic disk will decelerate the vertical expansion (Bruhweiler *et al.* 1980). In either case the polar caps of the supershells will become Rayleigh-Taylor unstable, causing the supershell to "burst" through the H I layer and discharge its internal pressure into the galactic corona (Tomisaka and Ikeuchi 1986; Paper II). Thereafter, the radius in the plane should increase according to equation (13).

We find that the supershell is likely to develop a molecular (H_2 and CO) layer very early during its evolution. Using the theory of Jura (1975) and Hollenbach, Chu, and McCray (1976) for the formation of H_2 on grains and its photodissociation by starlight, we estimate that such a layer is likely to develop within $t \sim 10^6$ yr. Of course, the supershell will always contain a layer of H I and, as long as the ionizing stars persist, an inner skin of H II as well. However, most of the swept-up mass in the shell will probably be molecular.

IV. GRAVITATIONAL INSTABILITY

The idea that supernovae might initiate star formation has been suggested before, notably by Öpik (1953), Elmegreen and Lada (1977), and Herbst and Assousa (1979). Here we show how multiple supernovae from an OB association can induce or accelerate star formation as a result of a supershell fragmenting into gravitationally bound interstellar clouds.

An approximate analytic model for this instability was provided by Ostriker and Cowie (1981) in their theory for propagating galaxy formation in the early universe. Consider a small circular disk, with radius $r \ll R_S(t)$, on the surface of an expanding spherical shell of radius $R_S(t)$ and expansion velocity $V_S(t)$. The disk subtends a cone half-angle $\theta = r/R_S$ and solid angle $\pi\theta^2$ and has mass $m(R_S, \theta) = \pi R_S^3 \rho_0 \theta^2/3$, where $\rho_0 = 1.3 n_0 m_{\rm H}$ is the density of the ISM outside the shell. The disk expands due to the divergence of the flow, with kinetic energy of expansion $E_K = \pi R^3 \rho_0 V_S^2 \theta^4/12$. It has gravitational binding energy $E_B = -0.86 G R_S^5 \rho_0^2 \theta^3$ and thermal energy $E_T = \pi R^3 \rho_0 a_S^2 \theta^2/2$. The criterion for the onset of gravitational instability is approximately $E_K + E_T + E_B < 0$. Accordingly, an unstable mode first appears when

$$0.67 G \rho_0 R_S^2/(V_S a_S) \gtrsim 1 . \qquad (14)$$

Thereafter, the most rapidly growing unstable fragments have

$$\theta_r \approx 9 a_S^2/(4 G \rho_0 R_S^2) \qquad (15)$$

and growth *e*-folding time scale

$$t_g \approx 3 a_S/(\pi G \rho_0 R_S) . \qquad (16)$$

If $R_S(t)$ is given by equation (3), the instability begins at

$$t_1 \approx 3.2 \times 10^7 \text{ yr } (N_* E_{51})^{-1.8} n_0^{-1/2} a_S^{5/8} \qquad (17)$$

and

$$R_1 \approx 200 \text{ pc } (N_* E_{51})^{1/8} n_0^{-1/2} a_S^{3/8} , \qquad (18)$$

where a_S is in units (km s^{-1}). At first, the fragmentation proceeds slowly, with gravitational collapse time $t_g \sim t_1$, but the process accelerates as the shell continues to expand and progressively smaller fragments become unstable. The most rapidly growing unstable fragments have

$$\theta_r \approx 0.44 (N_* E_{51})^{-1/4} a_S^{5/4} (t/t_1)^{-6/5} , \qquad (19)$$

$$M_r \approx 5 \times 10^4\ M_\odot\ (N_* E_{51})^{-1/8} n_0^{-1/2} a_S^{29/8} (t/t_1)^{-3/5} , \qquad (20)$$

and

$$t_g \approx t_1 (t/t_1)^{-3/5} . \qquad (21)$$

The supershell may lose its interior pressure and enter the snowplow phase before gravitational instability sets in, as a result of radiative cooling or breaking through the galactic disk. If so, $R_S(t)$ is given by equation (13) instead of equation (3), and one should replace equations (17)–(21) by

$$t_1 \approx 1.2 \times 10^7 \text{ yr } (N_* E_{51})^{-1/15} n_0^{-11/15} a_S^{4/5} R_{100}^{-7/15} , \qquad (22)$$

$$R_1 \approx 100 \text{ pc } (N_* E_{51})^{1/15} n_0^{-4/15} a_S^{1/5} R_{100}^{7/15} , \qquad (23)$$

$$\theta_r \approx 1.7 (N_* E_{51})^{-2/15} n_0^{-7/15} a_S^{8/5} R_{100}^{-14/15} (t/t_1)^{-1/2} , \qquad (24)$$

$$M_r \approx 9 \times 10^4\ M_\odot (N_* E_{51})^{-1/15} \times n_0^{-11/15} a_S^{19/5} R_{100}^{-7/15} (t/t_1)^{-1/4} , \qquad (25)$$

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and

$$t_g \approx 2.5 t_1 (t/t_1)^{-1/4} , \tag{26}$$

where $R_{100} = R_c/(100 \text{ pc})$, the radius at which the transition from equation (3) to equation (13) occurs. We see that in either case t_1 and M_r have similar values. Note that equations (22)–(25) depend on metallicity implicitly through equation (12) in the case that radiative cooling is important.

To see whether thin-shell formation can actually accelerate gravitational instability, we compare t_1 to the growth time, $t_0 = (4\pi G \rho_0)^{-1/2} \approx 2.3 \times 10^7 \text{ yr } n_0^{-1/2}$, of gravitational instabilities in the undisturbed ISM. For $R_S \propto t^\alpha$ the condition that $t_1 < t_0$ may be written

$$V_S(t_1)/a_S \gtrsim 19\alpha^2 . \tag{27}$$

For example, if V_S is given by equation (4), the shell will become gravitationally unstable in a time less than t_0 if $(N_* E_{51}) \gtrsim 13 a_S{}^5$ (independent of n_0). The ratio of M_r to the Jeans mass, $M_0 = (\pi a^2/G\rho_0)^{3/2}\rho_0$, in the undisturbed ambient medium may be written

$$M_r/M_0 \approx 0.8(a_S/a_0)^3 (a_S/V_S)^{1/2} (t_1/t) . \tag{28}$$

Elmegreen and Lada (1977) derived a criterion $\sigma \gtrsim 2.3(P_1/\pi G)^{1/2}$ for gravitational instability of a thin sheet of column density σ confined by a pressure P_1. According to that criterion, a pressure-driven shell could not accelerate gravitational instability. However, that criterion results from a choice of boundary conditions that precludes the interesting mode and is too restrictive. Criterion (14), which is less restrictive, also follows from a detailed analysis by Vishniac (1983).

Note that the onset of gravitational instability is sensitive to the value of a_S, the magnetosonic speed in the shell. If magnetic pressure can be neglected, it is likely that a_S will decrease from $a_0 \sim 10 \text{ km s}^{-1}$ to, say, $\sim 0.8 \text{ km s}^{-1}$ in its H I layer ($T \sim 100$ K, $\mu \approx 1.3 m_{\rm H}$) to $\sim 0.3 \text{ km s}^{-1}$ in its outer $\rm H_2$ layer ($T \sim 20$ K, $\mu \approx 2.1 m_{\rm H}$) as a result of enhanced radiative cooling in the dense shell.

Magnetic pressure may be the main obstacle to the onset of gravitational collapse. Suppose, for example, that the ambient interstellar magnetic field is fairly uniform on scales greater than $\sim R_S$ and has a strength $B_0 \sim 1\ \mu\text{G}\ (n_0/1 \text{ cm}^{-3})^{1/2}$ (cf. Troland and Heiles 1986). Then the magnetosonic speed in the ambient gas is given by $a_0 \sim 1.9 \text{ km s}^{-1}$, even for zero temperature. By assuming flux conservation in a thin spherical shell and equating the magnetic pressure in the shell to $\rho_0 V_S{}^2$, we obtain:

$$a_S = \left(\frac{3\pi}{2} V_S a_0 \sin\theta\right)^{1/2} , \tag{29}$$

where $\sin\theta$ is the colatitude of the shell measured from the direction of $\boldsymbol{B}_0$. Thus, except for the region of the polar cap with $\sin\theta \lesssim V_S{}^{-1}$, a "typical" interstellar magnetic field strength may be sufficient to delay the onset of gravitational instability [cf. eq. (17)]. Ambipolar diffusion will permit the magnetic field to leak out of the shell in a time scale $< t_0$ if the gas in the shell becomes molecular with ionized fraction $n_e/n_S \lesssim 5 \times 10^{-7}$ (cf. Spitzer 1978).

V. DISCUSSION

a) *Supershells*

There is abundant evidence for giant shells in the Milky Way and other spiral and irregular galaxies in the Local Group. Heiles (1979, 1984) and Colomb, Poppel, and Heiles (1980) have discussed evidence from 21 cm emission maps for giant H I shells in the Milky Way. These shells have radii ranging from ~ 100 pc to more than ~ 1 kpc and kinetic energies ranging from $\sim 10^{50}$ ergs to more than $\sim 10^{53}$ ergs. In some cases the observed radial expansion velocities of the shells exceed 10–20 km s^{-1}. A small fraction, $\sim 10\%$, of the shells seems to contain OB associations (these may be chance coincidences), but most do not. The expanding H I shells have kinematic ages, $t \approx 0.6\ R_S/V_S$, ranging from 5×10^6 yr to 8×10^7 yr. Although there are a few beautiful examples of full circular arcs, most of the shells are only partial arcs. The complete shells and the largest shells are preferentially found beyond the solar circle, while many fragments of shells, called "worms" by Heiles (1984), are found in the inner Milky Way. Recently, Brinks and Bajaja (1986) (cf. Brinks and Shane 1984) have discovered similar structures in velocity-resolved 21 cm emission-line maps of M31, including a large (diameter ~ 400 pc) hole surrounding the OB association responsible for NGC 206 (Brinks 1981). They list 141 giant holes in the H I disk, concentrated at a galactocentric radius ~ 10 kpc like the bright H II regions. The radii of the holes are typically ~ 125 pc but in several cases more than ~ 300 pc, and their expansion velocities range from ~ 6 to 20 km s^{-1}. Similar H I holes have been found in M101 (Allen *et al.* 1978). We have no doubt that these H I supershells will be found to be common features in all spiral and irregular galaxies when high-resolution maps are available.

Somewhat smaller H II shells are also seen in optical emission-line surveys, both in the Milky Way (e.g., Brand and Zealey 1975; Bochkarëv 1985) and in galaxies of the Local Group (e.g., Courtès 1977; Courtès, Boulesteix, and Sivan 1981). They contain clusters or associations of OB stars, and they tend to be kinematically younger ($<10^7$ yr) than the supergiant H I shells. As with the H I shells, the larger H II shells are preferentially found in the outer parts of the galaxies. Many giant ($R_S \sim 50$–150 pc) and several supergiant ($R_S \sim 300$–600 pc) emission-line shells have been seen in the Magellanic Clouds (Westerlund and Mathewson 1966; Davies, Elliott, and Meaburn 1976; Meaburn 1980; Caulet *et al.* 1982; Georgelin *et al.* 1983; Braunsfurth and Feitzinger 1983). Giant shells, OB clusters, and supernova remnants are often found along the rims of the supergiant shells.

These observations of giant shells, supershells, and H I holes are all consistent with the theory presented in § III. As discussed there, the early ($t < 3 \times 10^6$ yr) dynamics of the shell can be dominated by the stellar winds. For $t_7 \lesssim 1$ the OB association within the shell will produce enough ionizing radiation to make a visible inner rim of H II on the shell that we see as a giant H II shell. For $1 \lesssim t_7 \lesssim 5$ the ionizing radiation will have vanished along with the bright O stars, but the H I shell will continue to grow according to equation (3) as a result of the supernova explosions of the B stars. Thus, we may estimate that roughly 20% of the H I shells should contain ionizing O stars and have an associated H II shell, and that these younger systems should be somewhat smaller and more rapidly expanding than the older systems. The radii, ages, and kinetic energies of the expanding H I shells are consistent with the theory if they are created by OB associations with $10 \lesssim N_* \lesssim 1000$. The older supershells would be less likely to contain a recognizable cluster, because the remaining B stars are fainter and would have dispersed significantly.

The observation of H I holes in other galaxies without obvious shells surrounding them could be explained if the shells were predominantly H_2; this hypothesis would imply that expanding rings of CO emission should be seen around these holes. Note also that the kinetic energies of the supershells inferred from their H I masses and expansion velocities could be substantial underestimates if most of the mass of the shell is H_2.

Heiles (1984) has asserted that the supershells cannot be produced by multiple supernovae because the energies ($\gtrsim 10^{53}$ ergs) required to produce the larger expanding shells are too great. We disagree with that argument, because it is based on the theoretical model of Bruhweiler *et al.* (1980) in which the pressure of the hot interior of the supershell is neglected. If a supershell is the pressure-driven phase [eq. (3)], its kinetic energy is equal to 20% of the net supernova energy. Therefore, the more energetic shells found by Heiles could be produced by clusters with $N_* \sim 10^3$. We note that the multiple supernova interpretation of the H I supershells requires that the shells contain their internal pressure for $t_7 > 1$. This interpretation seems to require that the supershells are developing in a fairly homogeneous ambient ISM, in order that they remain coherent until they reach radii $R_S \gtrsim 100$ pc.

Bruhweiler *et al.* (1980) explained why the radii of the supershells in spiral galaxies tend to increase with galactocentric radius. As discussed in § III, the pressure-driven phase [eq. (3)] of the supershells ends when the shell radius becomes comparable to the scale height of the galactic H I layer. Typically, this scale height increases with galactocentric radius owing to the decreasing surface density of the stellar disk. For example, in the Milky Way the H I scale height, z_0, increases from ~ 70 pc in the inner disk (Bruhweiler *et al.* 1980) to ~ 190 pc in the solar vicinity (Shull and Van Steenberg 1985) to ~ 530 pc at 20 kpc (Kulkarni, Blitz, and Heiles 1982). Thus, one would expect that most of the supershells in the inner parts of spiral galaxies would have burst through the disk, leaving "holes" with radius comparable with the disk thickness. Therefore, we might interpret the H I "worms" seen by Heiles (1984) in the inner Milky Way as the limb-brightened rims of supershells that have burst through the disk. The larger supershells and the complete shells should be found mostly in the outer parts of spiral galaxies, as observed (Kafatos *et al.* 1980). The partial arcs might be interpreted as supershells that have burst through only one side of the galactic disk.

Another effect that favors the development of larger shells in the outer parts of spiral galaxies is the dependence of the radiative cooling on metallicity, ζ, and ambient density, n_0. As indicated by equation (11), the radius, R_c, at which radiative cooling removes the interior pressure increases with decreasing ζ and n_0. In spiral galaxies both ζ (Pagel *et al.* 1979) and n_0 decrease with increasing galactocentric radius.

All of these effects conspire to favor the development of supershells in irregular galaxies. The interstellar gas in an irregular galaxy has large scale height and low density as a result of the low mass of the galaxy, and possibly also because the gas layer has been disturbed by tidal interactions with neighboring galaxies. The irregular galaxies tend to have lower metallicity than the giant spirals. Thus, for example, for the LMC, with $\zeta \sim 0.3$ (Dufour 1984) and $n_0 \sim 0.35$ cm^{-3} (Hindman 1967), equation (12) gives $R_c \sim 2.5$ kpc $(N_* E_{51}/200)^{0.4}$ for the radius at which radiative losses become important. We believe that these factors may explain why the Magellanic Clouds contain so many spectacular supershells.

b) Structure of the Interstellar Medium

In the model presented above, we have assumed that the supershells develop in an ISM of fairly uniform density. Our model is certainly not realistic if the ISM has the structure envisioned by McKee and Ostriker (1977), in which cool clouds with warm H I mantles are embedded in a substrate of low-density coronal gas. In that case, the supershell would propagate very rapidly through the coronal gas, overtaking and entraining clouds as it does. In such a medium, even the blast wave from a single supernova explosion could propagate right out of the disk before it becomes radiative, and coherent supershells would be hard to produce. On the other hand, blast waves cannot easily circumvent the warm H I if it is distributed primarily in large-scale sheetlike rather then cloudlike structures.

Recent observations indicate that the warm H I is more pervasive and smooth than predicted by the McKee-Ostriker model (Liszt 1983; Lockman, Hobbs, and Shull 1986; Kulkarni and Heiles 1987; Cowie 1987; Shull 1987), suggesting that the model requires some qualitative revision. There are several possibilities, not necessarily exclusive. First, if the supernova rate in the galactic disk is dominated by Type II supernovae, which come in clusters, then most of the coronal gas in the disk should be found in the interiors of supershells. Moreover, the supershells in the inner parts of spiral galaxies should burst through the thin H I disk fairly early in their evolution and vent most of their energy into the galactic corona (cf. Cowie 1987). Thus the volume fraction of coronal gas in the disk might be substantially less than that estimated by McKee and Ostriker (1977) on the assumption that the supernovae are randomly distributed in space and time.

However, the low apparent porosity of the ISM is a puzzle in any case. Even allowing for the venting of supershells into the galactic corona, Heiles (1987) has estimated that the covering factor of holes from supershells should be more than $\sim 90\%$ in the solar neighborhood, much greater than indicated by observations. Furthermore, not all supernovae are clustered. The Type I supernovae from Population II stars, which should be randomly distributed, will make an additional contribution to the porosity of the ISM which may be substantial. The question of the relative impact of the Type I and Type II supernovae on the ISM is knotty and still unresolved, however (cf. Heiles 1987). The Type I supernovae from Population II stars probably have a substantially larger scale height than the galactic H I disk, so that many of them will discharge their energy directly into the galactic corona and have relatively little impact on the disk gas. Furthermore, many Type I supernovae may actually be "Type Ib" supernovae from Population I stars (Branch 1986). Finally, supernova rates and energy inputs are still very uncertain and may have been overestimated (cf. Shull 1987).

Cowie and Jeffrey (1983) have pointed out that a coherent giant shell can form in a three-phase ISM as a result of "homogenization" of the ISM around a young OB association by photoevaporation of clouds (Elmergreen 1976; McKee, Van Buren, and Lazareff 1984).

c) Missing Supernova Remnants

If, as we assume, most supernovae in the disk come from associations, only the first supernova from the association might encounter relatively high-density ($n_0 \sim 1$ cm^{-3}), ambient interstellar gas within less than ~ 50 pc. All subsequent supernovae (and even the first one, if the association has very massive stars with strong stellar winds) will occur in a large cavity of low-density coronal gas, as discussed in § III. Thus, if all Type II supernovae are formed in associations with typically, say, $N_* \sim 20$, one would expect only $\sim 5\%$ of Type II supernovae to create well-formed supernova shells with radius less than 50 pc. The blast waves created by Type II supernovae within supershells may have very low surface brightness and escape detection by optical or radio surveys (Kafatos *et al.* 1980; Tomisaka, Habe, and Ikeuchi 1981). This phenomenon may help to explain why the formation rate of pulsars in the Milky Way seems to exceed the formation rate of supernova remnants containing pulsars (Helfand and Becker 1984). Perhaps most of the Type II supernovae that produce pulsars have "missing" supernova remnants.

d) *Propagating Star Formation*

Evidence for propagating star formation on local (<50 pc) scales has been discussed by Blauw (1964), Elmegreen and Lada (1977), Lada, Blitz, and Elmegreen (1979), and others: It seems clear that OB stars can drive a wave of star formation into an existing molecular cloud complex. Elmegreen (1982, 1985*a*, *b*; 1986) has discussed a variety of evidence for propagating star formation on larger ($\gtrsim 100$ pc) scales.

Following Mueller and Arnett (1976), Gerola and Seiden (1978—see also Seiden and Gerola 1982) have made computer simulations of propagating star formation in disk galaxies, in which they simply assumed that stars at one location can, with some probability, induce the formation of stars at some characteristic length, L_*, after some time t_*. These simulations produced model galaxies with morphologies remarkably similar to some "feathery" spiral galaxies—e.g., NGC 2841. In order to produce the right angles for the spiral arms, Gerola and Seiden chose a propagation length $L_* \sim 200$ pc and time $t_* \sim 10^7$ yr, implying a propagation velocity ~ 20 km s^{-1}. We see that these values are consistent with the theory presented in § IV: for example, if $(N_* E_{51}) = 20$, $n_0 = 1$ cm^{-3}, and $a_S = 1$ km s^{-1}, equations (17) and (18) give $t_1 \sim 2.2 \times 10^7$ yr and $R_1 \sim 290$ pc for the time and radius at which a supershell becomes gravitationally unstable. However, as far as we can tell, the mechanism we propose here can induce only a single generation of star formation in a disk galaxy, because most of the supernova energy from the secondary star clusters will escape into the galactic corona through the hole in the H I disk that was made by the original supershell.

Clearly, the ISM in spiral galaxies must have reached a state of marginal stability, so that any dynamical mechanism that can compress the gas by a modest factor will trigger star formation. Indeed, rotation and shear in a disk galaxy will suppress gravitational instability of low-density ($n_0 < n_{\rm cr}$) gas. For example, Spitzer (1978) estimates $n_{\rm cr} \sim 2$ cm^{-3} in the solar neighborhood. Therefore, we see that supershells (or some other kind of shock, such as a spiral-arm density wave) may be necessary to trigger gravitational instability in a homogeneous ($n_0 \sim 1$ cm^{-3}) ISM. It is clear that the density waves are the main trigger of star formation in spiral galaxies (Lin and Shu 1964; Roberts 1969), although supershell-induced star formation may occur as a secondary mechanism in some instances.

In contrast, the mechanism for propagating star formation that we have described in § IV is likely to dominate in irregular galaxies. Since the Magellanic irregulars (Gallagher and Hunter 1984) often rotate nearly as rigid bodies and do not have well-formed spiral arms, the spiral density wave mechanism is not available to trigger star formation. Yet in these galaxies the star-formation rate per unit gas mass is comparable, and in some cases far greater, than that in the Milky Way. We have already pointed out (§ V*a*) that Magellanic irregular galaxies provide particularly favorable sites for the development of very large supershells, owing to their low metallicities and extended gas distributions.

Indeed, the supershells in the Magellanic Clouds show evidence for second-generation star formation around their peripheries, where OB associations, giant shells, and supernova remnants abound. Many of the stellar associations in the Magellanic Clouds are organized into large-scale systems (Shapley's "constellations") that are suggestive of propagating star formation (Braunsfurth and Feitzinger 1983; Isserstedt 1984; Dopita 1986; Feitzinger 1986). The most spectacular of these is constellation III (Westerlund and Mathewson 1966), a great arc of bright blue stars stretching some 600 pc.

For example, the largest supershell in the LMC, loop IV, which surrounds constellation III and a large H I hole (Rohlfs *et al.* 1984; Dopita, Mathewson, and Ford 1985), has a radius ~ 750 pc. It contains ~ 700 bright ($M_V \lesssim -4$) OB stars in ~ 20 young ($t_7 \lesssim 1.3$) associations (Lucke 1974; Braunsfurth and Feitzinger 1983; Isserstedt 1984), implying $N_* \sim 6000$ for an IMF with $\beta = 1.6$. Thus each association typically has $N_* \sim 300$. We believe that these associations could be the result of gravitational instability of a supershell, of which loop IV is the residue. To illustrate that this is possible, assume that the supershell was created by an association with $N_* \sim 300$, and that $n_0 = 0.1$ cm^{-3}. (Constellation III itself cannot be the culprit; with age $\sim 3 \times 10^6$ yr, it is too young.) Then, from equation (3), we see that a supershell with $R_S \sim 750$ pc could be created in a time $t \sim 2 \times 10^7$ yr, and from equation (17) we see that such a shell would first become gravitationally unstable at about the same time if $a_S \approx 0.4$ km s^{-1}.

Another good example of supershell-induced star formation in Magellanic irregulars is the spectacular ring (diameter ~ 500 pc) of OB stars in NGC 4449 pointed out by Bothun (1986).

According to Gallagher and Hunter (1984), the star-formation history in most Magellanic irregulars may be fairly steady when averaged over long times. However, there is clear evidence that large bursts of star formation have occurred in local (~ 1 kpc) regions of these galaxies. Furthermore, in some Magellanic irregulars the current star-formation rate must be substantially (factor >10) greater than the long-term average; otherwise the metallicity of the gas would exceed the observed values. This inference is also true for some compact blue dwarf galaxies, e.g., I Zw 18 and II Zw 40 (Sargent and Searle 1970; Searle and Sargent 1972). The star-formation rates in these systems seem much greater than one might expect from normal statistical excursions and suggest that some infectious mechanism is at work (cf. Gerola, Seiden, and Schulman 1980). Not surprisingly, the bursts of star formation are associated with supersonic (~ 15–50 km s^{-1}) velocities in the H II regions.

Clearly, the idealized theory outlined here is at best a crude approximation to the actual evolution of supershells in spiral and irregular galaxies. In order to assess the actual importance of supershells and their role in star formation, we must also consider theoretical models for supershells in an inhomogeneous ("cloudy") ISM. Perhaps more important, we need much more detailed and systematic observations of the spatial structure and relationship of stars and gas in nearby galaxies. We believe that when such observations are made, the case for supershell-induced star formation will become compelling.

Finally, we remark that the conditions that favor propagating star formation according to the theory presented here—low metallicity and an extended distribution of fairly homogeneous gas—must have been much more common when the first generations of stars (" Population III ") were formed in protogalaxies. Therefore, studies of starbursts in irregular galaxies and galactic nuclei may provide clues to the dynamics of galaxy formation.

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