SUPERSHELLS

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ABSTRACT: Repeated supernovae from an OB association will, in a few $\times 10^7$ yr, create a cavity of coronal gas in the interstellar medium, with radius > 100 pc, surrounded by a dense expanding shell of cool interstellar gas. Such a cavity will likely burst through the gas layer of a disk galaxy. Such holes and "supershells" have been observed in optical and H I radio emission maps of the Milky Way and other nearby galaxies. The gas swept up in the supershell is likely to become gravitationally unstable, providing a mechanism for propagating star formation that may be particularly effective in irregular galaxies.

1 INTRODUCTION

Cox and Smith (1974) were the first to recognize that the hot interiors of old supernova shells should persist in the interstellar medium (ISM) for timescales $\gtrsim 10^6$ yr, long enough that the hot interiors might interconnect to form a "tunnel" system of coronal ($T \gtrsim 10^6$ K) gas in the ISM with a morphology resembling Swiss cheese. This idea was developed further by McKee and Ostriker (1977), who argued that the supernova rate in the Milky Way is high enough that the porosity of the coronal gas should approach unity. In their model the Swiss cheese falls apart: the substrate is the coronal gas and the H I is found in isolated clouds with dense cores surrounded by warm H I envelopes.

Here I shall describe a model for the interaction of supernova remnants with the ISM that may add an important new ingredient to the McKee-Ostriker model. I depart from their model by assuming that the morphology of the hot gas in the disk of the Milky Way is dominated by clustered type II supernovae from massive Population I stars rather than by randomly distributed type I supernovae from Population II stars. This assumption makes a qualitative difference in the resulting morphology of the hot gas. A cluster of massive stars should, over a few $\times 10^7$ yr, produce many supernova explosions that act in concert to pack the ambient interstellar gas into a giant (radius $R_S \gtrsim 100$ pc) expanding shell called a "supershell." The

supershell will likely blast a hole right through the thin H I layer of a disk galaxy, venting a substantial fraction of the supernova energy into the galactic halo. As a result, the porosity of the coronal gas should be less than it would be if the supernovae occurred at random in the disk.

Finally, I shall discuss a most exciting possibility, namely, that supershells may become gravitationally unstable, providing a mechanism for propagating star formation. Although gravitational instability of supershells may provide only a secondary mechanism for star formation in disk galaxies, where spiral density waves dominate, it may be the dominant mechanism in irregular galaxies.

The ideas presented here are discussed and referenced in more detail in papers by Heiles (1987), McCray and Kafatos (1987), and MacLow and McCray (1988).

2 SUPERSHELL DYNAMICS

Consider first the energy delivered to the ISM by a cluster of OB stars. The lifetimes of massive stars are given approximately by $t_{MS} \sim 3 \times 10^7$ yr$[M_*/(10M_\odot)]^{-1.6}$. In a cluster with a "typical" initial mass function, $dN_*/d(logM_*) \sim M_*^{-1.6}$, the increasing numbers of low mass stars fortuitously compensates for the increasing stellar lifetimes so that the mean supernova rate from the cluster should be nearly constant until $t \approx 5 \times 10^7$ yr, the lifetime of the least massive star ($\sim 7M_\odot$, corresponding to spectral type B3) that can explode. A typical newborn OB cluster may have $N_* \sim 20$ stars with $M_* > 7M_\odot$. At first ($t \lesssim 5 \times 10^6$ yr), the ionizing radiation and stellar winds from the most massive O stars will dominate the energy imparted by the cluster to the surrounding ISM; but thereafter, the supernova explosions will dominate, ultimately providing a net energy input ~ 20 times greater.

As a first approximation, we model the impulsive supernova energy input to the ISM by a steady source, with power $P_{SN} \approx 6.3 \times 10^{35}[N_*E_{51}]$ ergs s^{-1}, where N_* is the number of stars in the newborn association with mass $> 7M_\odot$ and E_{51} is the energy of a supernova explosion in units of 10^{51} ergs. Then, if we assume that the ambient medium has uniform atomic density n_0, the supershell expands according to the theory for a stellar wind-driven bubble (Weaver *et al.* 1977):

$$R_S = 97 \text{ pc } [N_*E_{51}/n_0]^{1/5}t_7^{3/5}, \tag{1}$$

where $t_7 = t/(10^7 \text{ yr})$. Numerical experiments (MacLow and McCray 1988), in which the supernova energy is injected in random impulses, show that equation (1) provides a good approximation to the actual evolution of

the supershell after a few supernovae have occurred.

Thus, a "typical" supershell, with, say, $N_* E_{51} = 20$ and $n_0 \approx 1$ cm^{-3} will grow to a radius $R_S \approx 180$ pc within $\sim 10^7$ yr as a result of $\sim$ four supernova events. At that time, the supershell consists of $\sim 7 \times 10^5 M_\odot$ of interstellar gas expanding with velocity $V_S \approx 10$ km s^{-1} and kinetic energy $\approx 10^{51}$ ergs (20% of the net supernova energy). The atomic density of the shell is given by $n_S = n_0 (V_S / a_S)^2$, where a_S, the magnetosonic speed in the shell, has a typical value $\sim 1 - 2$ km s^{-1}. Because of its elevated pressure, the gas in the supershell will radiate efficiently and most of its mass will be in the form of cool ($T \lesssim 100$ K) H I or H_2. The younger supershells, with $t \lesssim 5 \times 10^6$ yr, may have enough O stars in the cluster to create a thin skin of H II on the inner surface of the supershell that may be visible as a giant optical loop. However, most supershells will be older and larger, so that the O stars will have vanished; these older shells will be visible through H I or CO radio line emission, or perhaps as infrared dust shells.

During the early stages of the evolution of a supershell, approximately 45% of the net supernova energy resides in its interior, providing pressure to drive the expansion. The gas in the interior, which comes from conductive evaporation from the inner surface of the shell, has mass

$$M_i \sim 500 M_\odot [N_* E_{51}]^{0.8} n_0^{-0.06} t_7^{1.2} \tag{2}$$

and temperature $\sim 10^6$ K. However, after a time

$$t_c \sim 4 \times 10^6 \text{ yr } \zeta^{-1.5} [N_* E_{51}]^{0.3} n_0^{-0.7}, \tag{3}$$

where ζ is the metallicity in solar system units, the interior radiates at a rate comparable to the average supernova energy input rate, robbing the system of its driving pressure. This pressure never becomes negligible, however: numerical calculations (MacLow and McCray 1988) show that $R_S \propto t^{0.5}$ for $t > t_c$.

A more realistic model for supershell evolution would allow for expansion into an inhomogeneous ISM containing dense clouds embedded in a smoother intercloud medium. In that case the supershell will overtake and entrain clouds as it propagates through the intercloud medium. Clouds punch holes in the shell as the shell overtakes them, but the shell "heals" after it passes the clouds. The main effect of the entrained clouds on the dynamics of the shell is to enhance the radiative cooling of the interior, reducing the value of t_c.

After the first few supernovae, the interior mass of a supershell is sufficient to slow subsequent blast waves to subsonic ($\lesssim 250$ km s^{-1}) velocities before they reach the shell. Thus, our steady-power approximation for the global dynamics of the supershell is reasonable, because these blast

waves do not substantially change the interior density profile. In a mature ($t \gtrsim 10^7$ yr) supershell there is a substantial chance of catching one or more supernova blast waves within the interior. If $t \gtrsim t_c$ these blast waves may have entered the radiative phase, and so might be observed as high velocity UV absorption line systems.

It is likely that a supershell will blast a hole through the gas layer of a disk galaxy. The scale height of the H I disk in the Milky Way increases from $z_0 \sim 80$ pc in its inner regions to $z_0 \sim 200$ pc in the solar neighborhood and $z_0 > 500$ pc in its outer reaches. Thus, the radius of a typical supershell in the solar neighborhood becomes comparable to z_0 at a time $t \sim 10^7$ yr.

To understand what happens after this time, MacLow and McCray (1988) have constructed numerical models for the development of supershells in a stratified medium. [Tomisaka and Ikeuchi (1986) have also calculated such models.] In their numerical scheme, MacLow and McCray employ the approximation by Kompaneets (1960, cf. Zeldovich and Raizer 1968) for the dynamics of a thin shell. This approximation, which should be excellent for the problem at hand, consists of assuming that the interior is isobaric and that the surface moves in the direction of its local normal.

Typical results are shown in Figures 1a,b for a model in which the disk gas is assumed to have a density profile $n(z) = n_0(0.8\exp[-(z/z_0)^2] + 0.2\exp[-z/3.7z_0])$ (cf. Lockman, Hobbs and Shull 1986). The dimensions of the systems are expressed in units z_0 and times are expressed in units of t_1, the time at which a spherical shell would reach a radius z_0 in a medium of uniform density n_0 (cf. equation 1). Figure 1a shows what happens if the star cluster is located on the midplane of the galaxy, so that the supershell expands symmetrically about this plane. As one would expect, the shell becomes noticeably prolate in the vertical direction for $z \gtrsim z_0$. The shell becomes quite distended and would appear as a ring for $t \gtrsim 5t_1$, at which time $z \approx 3z_0$ and $r \approx 2r_0$. After this time, the expansion in the plane decelerates rapidly, so that the terminal radius of the hole in the plane becomes a measure of the scale height of the gas disk.

Figure 1b shows what happens when the cluster is located at a height $\Delta z = 0.6z_0$ above the midplane. The resulting supershell blows out through only one side of the gas disk. The result should appear as a partial arc.

The most interesting aspect of supershell hydrodynamics is the development of instabilities. There are three instabilities that we should be concerned about: (1) the dynamical instability of a cold decelerating shell discovered by Vishniac (1983); (2) the Rayleigh-Taylor instability that occurs when the shell begins to accelerate; and (3) gravitational instability. In order to investigate the non-linear development of these instabilities, we have begun to model the development of supershells with a supercomputer hydrodynamics code (MacLow, Norman and McCray 1987). Our results do

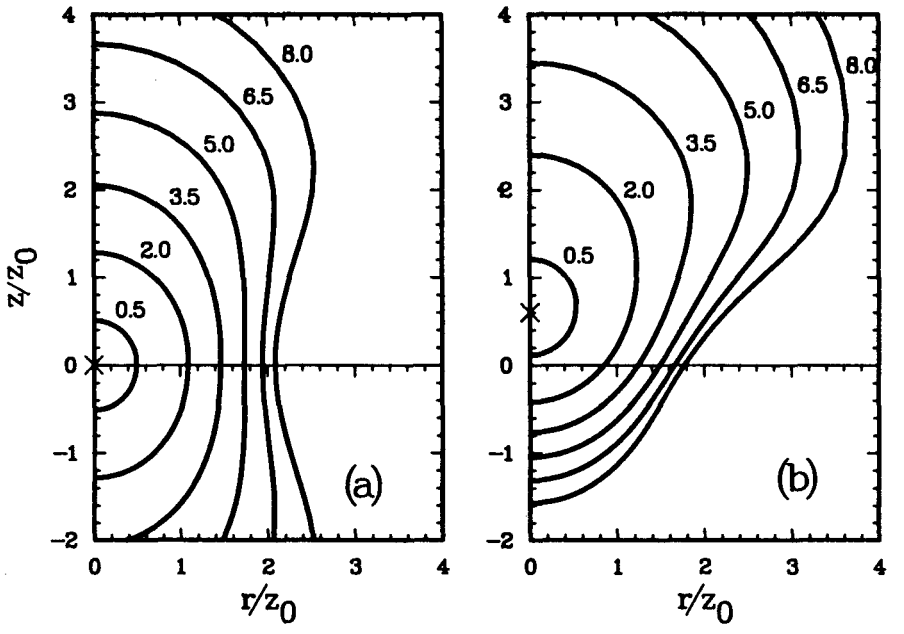


Figure 1: Development of a Supershell in a Stratified Gas Layer. a) Star cluster (marked by cross) located at the galactic midplane; b) Cluster located at a height $0.6z_0$ above the midplane. Curves are labeled by time in units t_1.

show a hint of the Vishniac instability, as do very similar calculations by Ròżyczka (1985), but a detailed comparison of the numerical investigations with the linear theory is still lacking (*cf.* Bertschinger 1986). Our results for the nonlinear development of the Rayleigh-Taylor instability in a stratified disk are very similar to the results of simulations by Ròżyczka and Tenorio-Tagle (1985).

3 OBSERVATIONS OF SUPERSHELLS

Supershells in the Milky Way and other nearby galaxies have been seen through H I 21-cm and H II optical emission line surveys. Heiles (1979, 1984) and Colomb, Poppel, and Heiles (1980) have discussed evidence for giant H I shells in the Milky Way, with radii ranging from $\sim$ 100 pc to $\gtrsim$ 1 kpc and kinetic energies ranging from $\sim 10^{50}$ to $\gtrsim 10^{53}$ ergs. The expanding shells have kinematic ages $\sim 10^7 - 10^8$ 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 most often 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 Shane (1984) have discovered $\sim$ 140 holes in velocity-resolved 21-cm emission line maps of M31, with radii $\sim 125 - 300$ pc. Similar H I holes have been found in the Large Magellanic Cloud (Rohlfs *et al.* 1984; Dopita, Mathewson and Ford 1985), and M101 (Allen *et al.* 1978). X-ray emission has been observed from the supershell in Cygnus (Cash 1980) and from the region of Shapley's Constellation III in the LMC (Singh *et al.* 1987; Helfand, Wu, and Wang 1987).

The most prominent optical supershell in the Milky Way is the Gum Nebula, a giant $R \sim 400$ pc H II emission loop in the direction of the Vela supernova remnant (Maran, Brandt, and Stecher 1973). Many similar giant ($R \sim 100 - 200$ pc) and supergiant ($R \gtrsim 200$ pc) H II emission line shells containing clusters of OB stars are seen in the Milky Way (Brand and Zealey 1975; Bochkarev 1985; Fich 1986), 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), and in galaxies of the local group (e.g., Courtès 1977; Courtès, *et al.* 1987).

These observations of giant shells, supershells, and H I holes are all consistent with the theory described above. For $t_7 \lesssim 1$ the ionizing radiation from the OB association will create an H II emission line region on the inner rim of the supershell. For $1 \lesssim t_7 \lesssim 5$ the H II emission will have vanished along with the bright O stars, but the H I shell will continue to grow according to equation (1) as a result of the supernova explosions of the B stars. Thus, roughly 20% of the H I shells should have an associated H II shell, and 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.

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 ISM, in order that they remain coherent until they reach radii $R_S \gtrsim 100$

pc. If the intercloud medium is low density ($n_0 \lesssim 10^{-2}$ cm^{-3}) coronal gas, as in the McKee-Ostriker (1977) model, the blast wave from even a single supernova explosion will propagate right out of the galactic disk, and coherent supershells will not form.

The radii of the supershells in spiral galaxies tend to increase with galactocentric radius for two reasons. First, since the interstellar gas density is lower in the outer parts of galaxies, a given net supernova energy can produce a larger shell. Second, as we have shown, a shell will burst through the galactic disk when $R_S \gtrsim 1.3 z_0$, and z_0 increases with galactocentric radius. In the inner parts of spiral galaxies the supershells will burst through the disk, leaving "holes" with radius comparable to the disk thickness. The H I "worms" seen by Heiles (1984) in the inner Milky Way are probably the limb-brightened rims of supershells that have burst through the disk. The partial arcs might be fragments of supershells that have burst through only one side of the galactic disk.

Although supershells are seen in disk galaxies, the most spectacular examples are found in the Large Magellanic Cloud. There are two reasons why irregular galaxies are especially favorable environments for supershell formation. First, 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. Second, irregular galaxies tend to have lower metallicity than the giant spirals, so that radiative cooling is less important (cf. equation 3). Thus, supershells can grow to larger radii in irregular galaxies before they lose their interior pressure as a result of "blowout" or radiative cooling.

A major theme of this conference has been the growing recognition that many supernova remnants are not propagating into any kind of "standard" ISM, which may be fairly represented by uniform gas. Indeed, very interesting evidence has been presented that in many cases the ISM has been drastically modified before the supernova occurred, either by the progenitor star (*cf.* Lozinskaya 1987; Braun 1987), or by previous supernovae. In the latter case supernova remnants would be hard to detect because of their rapid expansion and low surface brightness, but this is now becoming possible (Chu and Kennicutt 1987). The supernovae that give rise to pulsars come from massive stars that usually occur in clusters, so most of these supernovae would occur within a supershell and expand to large radius without becoming radiative. Therefore, it is not surprising that many of the Crab-like SNR's are "Crabs without shells" (Becker and Helfand 1987).

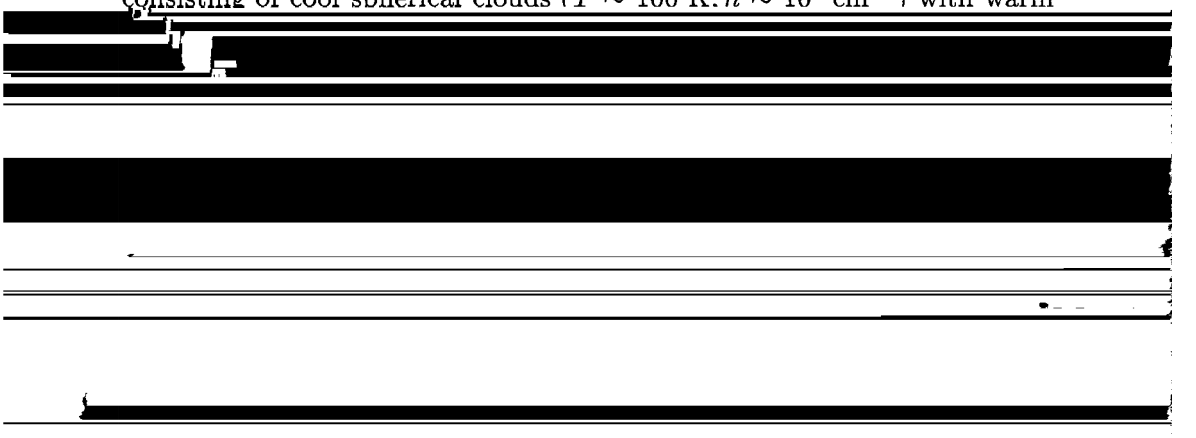
4 POROSITY OF THE INTERSTELLAR MEDIUM

It is clear that coronal gas is a major component of the ISM. Ultraviolet absorption line studies (Frisch and York 1983) and soft X-ray emission maps (McCammon *et al.* 1983) show that the solar system itself is located in a hot bubble, and observations of O VI $\lambda\lambda 1032 - 1037$ interstellar absorption lines in the spectra of more distant stars can be interpreted as the conductive interfaces between interstellar clouds and more distant bubbles of coronal gas (Cowie *et al.* 1979). Two major questions remain: 1) What is the porosity of the coronal gas; and 2) what is the morphology of the cool clouds? The answers to these questions are intimately related to the interaction of supernova remnants with the ISM.

In their theory for the ISM, McKee and Ostriker (1977) begin with an estimate of the porosity of coronal gas created by supernova remnants, given by

$$Q = (\frac{r_{SN}}{A_{disk} H_{SN}})(\frac{4\pi}{3} R_{SNR}^3)(\frac{R_{SNR}}{v_{rms}}), \qquad (4)$$

where r_{SN} is the galactic rate of supernova explosions, A_{disk} is the area of the galactic disk, H_{SN} is the thickness of the supernova distribution, R_{SNR} is the radius of a supernova shell after it stops growing, and R_{SNR}/v_{rms} is the time for interstellar gas moving at random velocity v_{rms} to fill in a supernova shell. With reasonable estimates of the galactic supernova rate, McKee and Ostriker find that $Q \sim 1$ if the supernovae are uncorrelated in space and time and the ISM is initially uniform. They construct a model consisting of cool spherical clouds ($T \sim 100$ K, $n \sim 10^2$ cm^{-3}) with warm



the porosity of a disk galaxy. In reality, all the parameters must be nctions of galactocentric radius, and the rates and scale heights of type I id type II supernovae are different functions. If we knew these functions, would be straightforward to construct more detailed versions of equations) and (5), but, given our present ignorance, such an exercise may not be arranted.

Direct observations of the H I distribution in the Milky Way and other earby galaxies may be a more fruitful approach to understanding the fac- rs determining the porosity of the gas. Observations of the Milky Way

round. (The clouds should tend to become round only when self-gravity becomes important.) Indeed, the 21-cm emission maps of the Milky Way (Colomb, Poppel and Heiles 1980) and the *IRAS* images of infrared cirrus (Low *et al.* 1984) certainly give one the impression that the clouds have sheet-like geometry — *cirrus*, not *cumulus*! If so, blast waves cannot easily circumvent and entrain the clouds.

5 PROPAGATING STAR FORMATION

Since multiple supernovae can pack some $10^6 M_\odot$ of interstellar gas into a supershell, it is natural to ask whether such an expanding shell might become gravitationally unstable. The relevant instability criterion was first derived from a simple energy principle by Ostriker and Cowie (1981) and was verified by Vishniac (1983) with a linear perturbation analysis. When applied to a supershell (cf. equation 1) this criterion gives

$$t_1 \approx 3.2 \times 10^7 \text{ yr } [N_* E_{51}]^{-1/8} n_0^{-1/2} a_S^{5/8} \tag{7}$$

and

$$R_1 \approx 200 \text{ pc } [N_* E_{51}]^{1/8} n_0^{-1/2} a_S^{3/8}, \tag{8}$$

for time and the radius at which gravitational instability first ensues, where a_S is the magnetosonic speed (in km s^{-1}) in the supershell. The typical mass of a gravitationally unstable fragment is given by

$$M_1 \approx 5 \times 10^4 M_\odot [N_* E_{51}]^{-1/8} n_0^{-1/2} a_S^{29/8}. \tag{9}$$

Thus, we see that if $a_S \sim 1$ km s^{-1}, a supershell is likely to break up into gravitationally bound fragments with masses comparable to giant molecular clouds at about the same time that it bursts through the galactic disk.

The main uncertainty in the theory comes from the interstellar magnetic field, which may inhibit gravitational collapse. If the field is negligible, the sound speed in the cool H I or H_2 shell will have a value $a_S < 1$ km s^{-1}. On the other hand, if the ambient interstellar magnetic field has a typical value $B_0 \sim 1 \mu\text{G}(n_0/1 \text{ cm}^{-3})^{1/2}$ (cf. Troland and Heiles 1986), the pressure in the shell will be dominated by the compressed interstellar magnetic field and the magnetosonic speed in the shell will have the typical value $a_S \sim (V_S V_A)^{1/2}$, where $V_A = (B_0^2/4\pi\rho_0)^{1/2} \sim 2$ km s^{-1} is the Alfven speed in the ambient ISM. Thus, it appears that the typical magnetic field in the Milky Way will suppress propagating star formation induced by supershells.

In disk galaxies, supershells may induce secondary star formation in some instances, but it is clear that the dominant mechanism is provided by

the spiral density waves. However, gravitational instability of supershells may be the dominant mechanism for star formation in irregular galaxies. There are three possible reasons. First, as mentioned in §3, supershells can and do grow to greater size in irregulars because of their thicker gas distribution and lower metallicity. Second, because irregular galaxies lack well-organized spiral arms, interstellar gas will continue to accumulate in them until some other mechanism triggers gravitational instability. Indeed, Magellanic irregulars do tend to have higher (~ 1) gas/stellar mass ratios than spirals (~ 0.1). Finally, one may speculate that Magellanic Irregulars do not have an effective interstellar dynamo, and so magnetic suppression of star formation might be less effective.

There is fragmentary evidence that supershell-induced star formation is occurring in the Milky Way and other nearby galaxies (cf. Elmegreen 1985a,b). The most obvious example is Shapley's Constellation III in the LMC, a great arc of bright blue stars stretching some 600 pc (Westerlund and Mathewson 1966). Another example is the distribution of OB associations around the periphery of the Loop IV supershell in the LMC (Dopita, Mathewson, and Ford 1985). The most spectacular example that I have seen is the giant (diameter $\sim$ 500 pc) ring of OB stars pointed out by Bothun (1986) in the Magellanic Irregular NGC 4449.

Finally, under propitious circumstances, supershell-induced star formation might continue for more than one generation, causing a huge excursion in the star formation rate of an irregular galaxy (cf. Gerola, Seiden, and Schulman 1980). Thus, supershells may provide a mechanism for "starburst" activity in galaxies.

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