1980

Stellar Winds, Supernovae, and the Origin of the H I A supershells

C. Bruhweilier
Catholic University of America

T. R. Gull
NASA, Goddard Space Flight Ctr

Menas Kafatos
Chapman University, kafatos@chapman.edu

S. Sofia
Univ Estadual Londrina

Recommended Citation

Bruhweiler, C., Gull, T.R., Kafatos, M., Sofia, S. (1980) Stellar Winds, Supernovae, and the Origin of the H I A supershells, *Astrophysical Journal*, 238: L27-L30. doi: 10.1086/183250

Stellar Winds, Supernovae, and the Origin of the H I A supershells

Comments
This article was originally published in *Astrophysical Journal*, volume 238, in 1980. DOI: 10.1086/183250

THE ASTROPHYSICAL JOURNAL, 238:L27–L30, 1980 May 15

STELLAR WINDS, SUPERNOVAE, AND THE ORIGIN OF THE H I SUPERSHELLS

FREDERICK C. BRUHWEILER,[1] THEODORE R. GULL, MINAS KAFATOS,[2] AND SABATINO SOFIA[1]
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, Maryland
Received 1979 June 11; accepted 1980 January 4

ABSTRACT

It is shown that the H I shells and supershells, recently reported by Heiles, are a natural by-product of the interaction of the stellar winds and supernovae, originating from stars in typical OB associations, with the surrounding interstellar medium. The validity of this model is supported by its ability to reproduce observed characteristics of the shells such as the shell sizes and shapes as a function of their distances from the galactic center. This process may also be responsible for injecting synthesized elements into the galactic halo.

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

I. INTRODUCTION

In a recent paper Heiles (1979) described the detection of large shells of neutral hydrogen located above and below the galactic plane. In discussing the origin of these shells, he pointed out that if a single explosive event were responsible for the larger shells (supershells with radii of a few kpc), the kinetic energy required ($E_K \geq 10^{53}$ ergs) exceeds that available in a supernova by at least a factor of 100. He suggested that a single explosive event (a hypothetical Type III supernova) might be responsible for their formation.

The shells cataloged by Heiles (1979) were detected by means of careful velocity mapping of the 21 cm H I line at low galactic latitudes. At least six of the smaller structures are found to be correlated with OB associations.

In this *Letter*, we propose to show that a shell of the type discussed by Heiles is a natural by-product of an evolving OB association interacting with the interstellar medium. The energetics of interstellar bubbles as modeled by Castor, McCray, and Weaver (1975), and by Weaver *et al.* (1977), can be combined with the energetics of supernovae (cf. Chevalier 1977) to describe the evolution of a shell surrounding an OB association. We find that such shells, located at different distances from the galactic center constitute very good models of the Heiles shells.

II. THE MODEL

We computed the evolution of the large bubble produced by collective stellar winds within an OB association. From Humphreys (1978) we find that the Sco OB1 association, containing 28 stars B0 and earlier with no apparent later-type evolved stars, could well represent a typical unevolved OB association. The average bolometric magnitude of these 28 stars is −8.8, corresponding to a main-sequence star of O6.

During the stellar wind phase of each of these stars we adopted for simplicity a mass-loss rate, $\dot{m} \sim 10^{-6}$ $M_\odot$ yr^{-1} with a terminal wind velocity $v \sim 2 \times 10^3$ km s^{-1} lasting for 3×10^6 years. These adopted values are in good agreement with averaged values derived in various studies (Cassinelli 1979; McCray and Snow 1979; Conti 1978; Barlow and Cohen 1977; Lamers and Morton 1976; and Hutchings 1976), and are similar to those used by Weaver *et al.* (1977).

Using the theory presented by Weaver *et al.* (1977), we give the radius and the expansion velocity of the shell composed of the swept-up interstellar material (in the snowplow phase of the bubble) as

$$R_B = 27 n^{-1/5} L_{36}{}^{1/5} t_6{}^{3/5}\ \mathrm{pc} \qquad (1)$$

and

$$v_B = 16 n^{-1/5} L_{36}{}^{1/5} t_6{}^{-2/5}\ \mathrm{km\ s^{-1}}\ , \qquad (2)$$

where $L_{36} = \frac{1}{2}\, M\, v^2\, 10^{-36}$ ergs s^{-1}, n is the ambient interstellar medium number density, v is the terminal velocity of the stellar wind, and t_6 is the time in units of 10^6 years.

We shall compute the evolution of the bubble in three galactic environments, representatives of the inner galactic disk ($R_{\mathrm{gal}} = 5$ kpc), the solar environment ($R_{\mathrm{gal}} = 10$ kpc), and the outer reaches of the galactic disk ($R_{\mathrm{gal}} = 20$ kpc), Other than the solar environment, the mean density and gas scale height for all these regions are not well determined.

We used the density scale height of the H I gas from Kerr (1969). These scale-heights, appropriate for an exponential distribution, are in agreement with the scale-heights computed by Celnik, Rohlfs, and Braunsfurth (1979) for a density distribution of the form $\mathrm{sech}^{0.7}\, z/z_0$. Closer to the plane the density distribution is more like a Gaussian (Falgarone and Lequeux 1973; Celnik, Rohlfs, and Braunsfurth 1979). It is, however, the large z form of the density distribution which is of more interest for the H I shells. Our model compensates for this by the assumption of a constant density during the interstellar bubble phase. For the density of the H I gas on the plane (in spiral arms) we used the values from Paul, Cassé, and Cesarsky (1976). The values of the gas parameters are shown in Table 1.

---

[1] NAS-NRC Fellow.

[2] Also, Department of Physics, George Mason University, Fairfax, VA.

TABLE 1

ASSUMED CHARACTERISTICS OF THE GALACTIC PLANE

$R_{\rm gal}$ (kpc)	n_0(cm^{-3})	h(pc)	$(Mv)_{\rm sw}$ (g cm s^{-1})	$R_{\rm crit}$(pc)	$k_z = 0$ (cm s^{-2}pc^{-1})
5.....	3	70	6.0×10^{44}	145	1.4×10^{-10}
10....	1	150	4.7×10^{44}	500	2.4×10^{-11}
20....	0.1	500	3.0×10^{44}	820	4.0×10^{-13}

NOTE.—$R_{\rm gal}$ ≡ distance from galactic center; n_0 ≡ number density in the plane; h ≡ scale height of the number density ($n = n_0 e^{-z/h}$); $(Mv)_{\rm sw}$ = momentum of the stellar wind; $(Mv)_{\rm sn1}$ = momentum of the first supernova phase = 1.3×10^{44} g cm s^{-1}; $(Mv)_{\rm sn2}$ = momentum of the second supernova phase = 9.0×10^{44} g cm s^{-1}; $k_{z=0}$ = gravitational constant in the z-direction at $z = 0$.

We realize that the uniform medium which we have assumed in our model is not always a realistic representation of the interstellar medium. Indeed, the interstellar medium may be very inhomogeneous (McKee and Ostriker 1977; and Jenkins 1978).

The uniform interstellar medium used in our model provides a realistic lower limit to the shell radius. In a two-component ISM, supernova ejecta propagate faster and substantially further through the hot, less dense component, leaving behind the cool, more dense clouds. However, we point out that the hot, dilute component of the ISM may have been a product of previous evolution of OB associations.

The bubble phase ends when the massive stars begin to become supernovae. We assume that momentum imparted by the supernova ejecta (5 $M_\odot$ at 5000 km s^{-1}) is conserved. Details of how the supernova evolves within an interstellar bubble have been discussed by Kafatos *et al.* (1980). The properties of the shells at this point are listed in Table 2 for the three galactic environments.

For simplicity in our calculations, we assume that all 28 massive stars become supernovae at once, at a time $t_1 = 3 \times 10^6$ yr. This assumption is not critical, and the same results would be obtained by individual explosions occurring in an interval about t_1. Prior to the supernova burst of the 28 massive stars, the shell is made up a cool H I–H$_2$ gas. Because of the large amount of material compressed in the shell, the individual supernovae are unable to raise the temperature to high values, and consequently, to a very good approximation, the subsequent evolution of the shell can still be described by the snowplow model for supernovae. For this case,

$$R_s(t) = \left[R_1^4 + \frac{3M_1v_1}{n\mu m_{\rm H}\pi}(t - t_1)\right]^{1/4} \tag{3}$$

and

$$v_s(R_s) = R_s^{-3}\left(\frac{3M_1v_1}{4\mu m_{\rm H}n\pi}\right), \tag{4}$$

where M_1, R_1, t_1, and v_1 are, respectively, the total mass of the swept-up ISM, and the radius, time, and velocity of the shell just after the supernova burst. It must be noted that equations (3) and (4) neglect gravitational effects, an approximation very acceptable for young shells, but which breaks down at late stages of the shell evolution.

Because the density distribution of the gas depends on z, the evolution of the shell is latitude-dependent. We shall specifically address here the extreme cases of

TABLE 2

EXPANSION OF SHELLS AT SELECTED DISTANCES FROM THE GALACTIC NUCLEUS, $R_{\rm gal}$, IN THE GALACTIC PLANE

		PARALLEL TO THE PLANE			PERPENDICULAR TO THE PLANE		
$R_{\rm gal}$(kpc)	v(km s^{-1})	t(10^{6}yr)[a]	R_s(pc)	$\bar{n}$(cm^{-3})	t(10^{6}yr)[a]	R_s(pc)	$\bar{n}$(cm^{-3})[c]
a) End of Bubble Phase							
5...........	17	3	85	3	3	85	3
10..........	21	3	106	1	3	105	1
20..........	33	3	168	0.1	3	168	0.1
b) End of First Supernova Burst Phase ($M \geq 15\ M_\odot$)							
5...........	5	8.6	137	3	9	170[b]	0.44
10..........	5	11	185	1	10	207	0.37
20..........	5	19	357	0.1	17	384	0.054
c) End of Second Supernova Burst Phase ($M \geq 8\ M_\odot$)							
5...........	...	4	179	3	...	170[b]	0.44
10..........	5	19	251	1	37	497	0.086
20..........	5	43	520	0.1	46	693	0.033

[a] t is the total characteristic time of the shell expansion through each phase.

[b] Expansion has exceeded $R_{\rm crit}$, and the shell size is now limited by gravitational deceleration (see text).

[c] $\bar{n}$ is the average of the region between the initial z and final z for each phase and is derived as $\bar{n} = (\pi n_0 \int_{z_2}^{z_1} z^2 e^{-z/h}\,dz)/[4/3\ \pi(z_2^3 - z_1^3)]$.

evolution parallel and perpendicular to the galactic plane, and all other cases will be bracketed between these.

There are stars with main-sequence spectral types later than B0 (intermediate-mass stars) which also produce supernova. Ostriker, Richstone, and Thuan (1974) take the mass of a B0 V to be 21 $M_\odot$. However, a compilation of eclipsing binary data by Heintze (1973) indicates 15 $M_\odot$ to be a more representative value. The lower mass limit of stars producing supernovae is controversial, although estimates vary between 4 and 8 $M_\odot$ (cf. Endal and Sparks 1975). By conservatively assuming the range of intermediate-mass stars to be between 8 and 15 $M_\odot$ and using the stellar mass function (Ostriker, Richstone, and Thuan 1974) with corrections for the mass of a B0 star, we find that 180 additional stars will become supernovae in the OB associations. Had we taken 4 $M_\odot$ as the lower limit, the sample would have increased by a factor of 4.

These intermediate-mass stars will begin contributing supernovae after 10^7 years. For simplicity, we assume that these supernova events deposit their momenta to the shell immediately after the shell has slowed to stall velocity from the first supernova phase. The evolution following the second supernova burst can be obtained from equations similar to (3) and (4) by substituting for the appropriate values of starting radius and time, and for the decreasing values of n in the direction perpendicular to the galactic plane.

Although we have so far ignored gravitational effects, the deceleration perpendicular to the galactic plane has an important impact upon the supernova remnant-bubble evolution. The deceleration ($\ddot{z}_{\rm grav}$) is only a function of z and of the distance from the galactic center $R_{\rm gal}$. In order to study this effect, we have corrected Schmidt's (1956) results for $\ddot{z}_{\rm grav}$ at different galactic radii with a solar distance of 10 kpc from the galactic center, and by renormalizing them to provide better agreement with Oort's (1969) results for $\ddot{z}_{\rm grav}$ for the region near the Sun.

Let us now include the effects of gravitation in studying the expansion of the shell. This effect, which operates only in the direction perpendicular to the galactic plane, can be approximately described by the equation $\ddot{z}_{\rm grav} = kz$ near the plane with a much flatter dependence at large z. The values of k near $z = 0$ and at $R_{\rm gal} = 5$, 10, and 20 kpc are given in Table 1. At the same time, the deceleration of the shell due to the snowplow mechanism found by differentiating equation (3) twice is

$$\ddot{z} = \frac{3}{16}\left(\frac{3Mv^2}{\mu n m_{\rm H}}\right) z^{-7} \,. \tag{5}$$

For small z the snowplow effect dominates, whereas for large z the gravitational effects take over. The crossover occurs in a narrow transition region which occurs at a z-distance that we denote as $R_{\rm crit}$ and list in Table 1. The results of the evolution of the shell, including the combined (snowplow plus gravitational) effects for the three cases $R_{\rm gal} = 5$, 10, and 20 kpc, are also shown in Table 2.

Naturally, $R_{\rm crit}$ is a function of the total momentum Mv, but most of the momentum in the shell is initially due to the stellar bubble, and subsequent SN explosions occurring in the first impulse phase (described in Table 2) will not substantially increase $R_{\rm crit}$. All SN events before the shell reaches $R_{\rm crit}$ can be treated collectively as a single explosive event. However, when the shell expands beyond $R_{\rm crit}$, the gravitational deceleration becomes dominant, and subsequent supernovae do not effectively contribute to shell expansion.

The final configuration of the shell is determined by the stall radius (i.e., the radius at which v_s equals the random velocity of the interstellar clouds, $v_s \approx 5$ km s^{-1}) in directions normal and parallel to the galactic plane. If $R_{\rm stall} < R_{\rm crit}$, gravitation has little effect on the evolution, and the shell is distorted only as a consequence of ambient density differences. If, however, $R_{\rm stall} > R_{\rm crit}$, the later stages of the shell's evolution are vastly different along these different directions, as the expansion along the galactic plane is unimpeded by gravitation while the expansion perpendicular to the galactic plane is strongly inhibited by gravity. Flattened shells would be the result.

Only in the case $R_{\rm gal} = 5$ kpc does $R_{\rm stall}$ exceed $R_{\rm crit}$. This occurs at $t = 8.9 \times 10^6$ years, before all of the massive stars have become supernovae. Our single-impulse assumption breaks down, and the subsequent supernova explosions will have the effect of preventing the shell from falling onto the galactic plane.

III. DISCUSSION AND CONCLUSIONS

On the basis of observed association star populations, conventional stellar wind and supernova parameters, and a conservative mass range for supernova progenitors, we have shown that the typical shells and supershells recently observed by Heiles are a natural byproduct of the evolution of an OB association immersed in an interstellar medium of conventional characteristics. We chose Sco OB1 as a typical association, and this led to the shell properties listed in Table 1. Comparison of these values with Heiles's observations shows general agreement. The larger or more energetic supershells require larger association star numbers and/or somewhat lower ambient densities, both of which are plausible.

A comparison between our model results and the observations by Heiles shows that R_b, the supershell radius perpendicular to the galactic plane, is the only relevant observable parameter useful in estimating the input momentum deposited into the supershell. Heiles uses $R_{\rm sh} = (R_l R_b)^{1/2}$, which can lead to overestimates of the input momentum. Heiles notes that several of the larger supershells are flattened with $R_l > R_b$, and at the same time recognizes that R_l can be affected by differential galactic rotation. In addition, Blaauw (1962) has pointed out that star formation progresses with time through a cloud in a direction parallel to the plane. Because of these two effects, it seems inappropriate to include R_l in estimating the input momentum. As an illustration, we take the most energetic supershell listed by Heiles: G139-03-69. We first note there is an error in computing $R_{\rm sh}$ which is actually 800 pc, not 2000 pc as quoted. Then, using the Heiles formula, E_K becomes 4.8×10^{53} ergs, not 6.3×10^{54} ergs. However, this shell has $R_l > R_b$, where R_b is 630 pc, which would again lead to a decrease in initial kinetic energy.

Rather than the total initial blast energy scaled by some arbitrary conversion factor, the input momentum is the best quantity to use in scaling our models to larger radii. Apart from the stellar wind phase and gravitational effects, conservation of momentum implies $R_b \propto n^{1/3}$ where n is the total number of supernovae each with an initial $E_K \sim 1 \times 10^{51}$ ergs. Therefore, larger shells can be produced by increasing the number of stars in an association or decreasing the lower mass limit for supernova progenitors.

Further examination of Table 2 shows additional details in agreement with observations which further strengthen the validity of our model. In what follows, we list the most salient of these:

1. At least six of the smaller bubbles are clearly related to OB associations. Because of stellar evolution, such a relationship would, of course, be more difficult to establish for larger, and thus older, supershells. For other smaller shells, the involved associations may not be detectable because of intervening extinction.

2. The radii of the shells increase with $R_{\rm gal}$. While the radius increases both along the plane and perpendicular to it, the parallel component may be changed by effects of galactic rotation. Moreover, the latitudinal radius is a more sensitive test, as it is affected by the gravitational field. Hence, we use the latitudinal radius $R_b = D \sin(\Delta b/2)$ (in the notation of Heiles 1979) and compare it to our model-predicted latitudinal radius. This is shown in Figure 1.

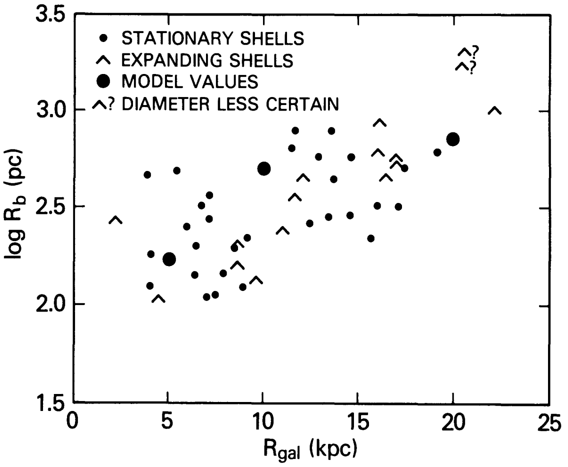

FIG. 1.—Predicted and actual latitudinal supershell radius vs. distance from the galactic center. The data are derived from the compilation of Heiles (1979). The model values are given for 5, 10, and 20 kpc as calculated for the physical conditions described in the text.

3. The large $\ddot{z}_{\rm grav}$ for small values of $R_{\rm gal}$ not only prevents the development of large shells, but it also begins to distort the shells when they are still relatively small. For example, shells are found at $R_{\rm gal} < 10$ kpc whose extent above the galactic plane (Δb) is smaller than their extent in the plane (Δl). Although the effect may result from differential galactic rotation (Heiles 1979), this process requires 5×10^7 years, and these shells may not live that long. This deformation however, is a direct consequence of $\ddot{z}_{\rm grav}$, and only requires 2×10^7 years to develop.

4. The smaller stationary shells (those having $-0.3 \leq \log \bar{n} \leq 0.3$ and $1.0 \leq \log R_S \leq 2.0$) can be explained by the stellar winds and the supernova contribution from only the massive stars ($M \geq 15\ M_\odot$). The associations within these smaller shells are more likely quite young, and the stars of intermediate masses have not yet become supernovae.

This mechanism also leads to consequences worthy of further examination. For example, when the shell reaches stall velocity, it will probably break up and begin falling toward the galactic plane as a consequence of $\ddot{z}_{\rm grav}$. This process may produce the high-velocity H I clouds observed falling into our Galaxy, and the dusty structures noted by Sandage (1976). In addition, these shells inject newly synthesized elements into the galactic halo. Moreover, the longer shells occurring at the largest $R_{\rm gal}$ may lead to mass loss from the Galaxy, and thus contribute to a galactic wind.

REFERENCES

Barlow, M. J., and Cohen, M. 1977, *Ap. J.*, **213**, 277.
Blaauw, A. 1962, *Ann. Rev. Astr. Ap.*, **2**, 49.
Cassinelli, J. P. 1979, *Ann. Rev. Astr. Ap.*, **17**, 275.
Castor, J., McCray, R., and Weaver, R. 1975, *Ap. J.* (*Letters*), **200**, L107.
Celnik, W., Rohlfs, K., and Braunsfurth, E. 1979, *Astr. Ap.*, **76**, 24.
Chevalier, R. A. 1977, *Ann. Rev. Astr. Ap.*, **15**, 175.
Conti, P. 1978, *Ann. Rev. Astr. Ap.*, **16**, 371.
Endal, A. S., and Sparks, W. M. 1975, *Ap. J.* (*Letters*), **200**, L77.
Falgarone, E., and Lequeux, J. 1973, *Astr. Ap.*, **25**, 253.
Heiles, C. 1979, *Ap. J.*, **229**, 533.
Heintze, J. R. W. 1973, *IAU Symposium No. 54, Problems of Calibration of Absolute Magnitudes and Temperatures of Stars*, ed. B. Hauck and B. E. Westerlund (Dordrecht: Reidel), p. 231.
Humphreys, R. M. 1978, *Ap. J. Suppl.*, **38**, 309.
Hutchings, J. B. 1976, *Ap. J.*, **203**, 438.
Jenkins, E. B. 1978, *Ap. J.*, **220**, 107.
Kafatos, M., Sofia, S., Bruhweiler, F., and Gull, T. 1980, *Ap. J.* submitted.
Kerr, F. J. 1969, *Ann. Rev. Astr. Ap.*, **7**, 39.
Lamers, H. J. G. L. M., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 715.
McCray, R. F., and Snow, T. P. 1979, *Ann. Rev. Astr. Ap.*, **17**, 213.
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.
Oort, J. H. 1969, *Bull. Astr. Inst. Netherlands*, **15**, 45.
Ostriker, J. P., Richstone, D. D., and Thuan, T. X. 1974, *Ap. J.* (*Letters*), **188**, L87.
Paul, J., Cassé, M., and Cesarsky, C. J. 1976, *Ap. J.*, **207**, 62.
Sandage, A. 1976, *A.J.*, **81**, 954.
Schmidt, M. 1956, *Bull. Astr. Inst. Netherlands*, **13**, 15.
Weaver, R., McCray, R., Castor, J., Shapiro, P., and Moore, R. 1977, *Ap. J.*, **218**, 377.