SUPERBUBBLES

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ABSTRACT

Individual massive stars with $M_{bol} < -6$ have huge stellar winds that create interstellar bubbles. Stars with masses greater than $8M_\odot$ ($4M_\odot$?) are considered supernova progenitors. These massive stars are numerous in OB associations where few supernova remnants are detected. Model calculations describing the evolution of an association show: 1) that large, hot cavities are formed by pushing the ambient gas into neutral shells; 2) that the shell radii change with galactocentric radius, 3) that only thirty percent of the interstellar medium is in the form of supercavities and 4) that a consequence is that only a small fraction of supernovae form supernova remnants. These results have strong bearing on interpretation of interstellar studies being done by IUE and by HEAO-B.

INTRODUCTION

The previous talk (ref. 1) described the observable interstellar bubble being driven by an O star, HD148937. Other talks (ref. 2,3) discussed IUE observations of supernova remnants which presumably had massive stars as progenitors. We know that O and B stars form as associations throughout the galactic plane. If individual stars can dramatically alter the interstellar medium, we are led to wonder what an OB association would do. The model calculations discussed here described the bulk properties of how the surrounding interstellar medium is changed as an OB association evolved. The resultant structure of the interstellar medium can be studied by IUE and HEAO-B and indeed such studies are underway at present.

THE BASIS FOR CONSIDERING SUPERBUBBLES

Our interest in the structure of the interstellar medium has been whetted by a recent emission line survey of the Milky Way (ref. 4). It presents a photographic record of nearby dust clouds and ionized hydrogen regions with a rough excitation classification being possible by singly-ionized sulfur imagery and by doubly-ionized oxygen imagery. Several new supernova remnants (ref. 5, 6) were discovered from this data. Many interstellar bubbles in the form of bowshocks (ref. 7), arcs and shells (ref. 8 and 9) were newly detected. However, ionization structure around OB associations varied considerably. We were led to ask how a supernova remnant, formed within an OB association, would be detected. The answer proved non-trivial, but opened up the realization that OB associations play a major role in determining structure of the interstellar medium.

Supernova remnants within our galaxy present an enigma: there do not seem to be enough. Based upon statistics of supernova events within similar galaxies, we should expect one every thirty years (ref. 10). If we assume that pulsars are stellar remnants left over from supernova events, then pulsar statistics imply a supernova every ten years (ref. 11). We might expect that for every supernova there should exist, for a finite time, a supernova remnant generated by the ejecta propagating through the interstellar medium. Yet the supernova rate derived from statistics of supernova remnants is about one every eighty years (ref. 12).

Related to this puzzle is the apparent lack of supernova remnants within OB associations. There simply is a lack of non-thermal radio emission plus associated filamentary optical shells within OB associations.

An intriguing clue comes from 21-cm studies (ref. 13), that large shells of neutral hydrogen having 100 to 2000 pc radii were scattered throughout the galactic plane. Because the associated kinetic energies exceeded the available energy of a supernova by a factor of 100, Heiles (ref. 13) postulated a type III supernova event. We find a more reasonable explanation is available based upon evolutionary products of an OB association.

AN EVOLUTIONARY MODEL OF OB ASSOCIATIONS

A simple model was devised based upon the kinematic properties of stellar winds plus supernovae in an OB association (ref. 14). The model could be divided into three phases: A. Bubble Phase, B. First Supernova Phase, and C. Late Supernova Phase. The bubble phase lasts for about 3×10^6 years during which the approximately thirty stars with $M_{bol} < -6$ push the interstellar medium away with the combined stellar winds. For a typical OB association these most massive stars have the following averaged properties: $\overline{M}_{bol} = -8.8$, $\dot{M} \sim 10^{-6} M_\odot \text{ yr}^{-1}$, $v_t \sim 2000 \text{ km s}^{-1}$, where M_{bol} is the bolometric magnitude, $\dot{M}$ is the mass loss rate in solar masses, $M_\odot$, per year, and v_t is the terminal wind velocity. For an individual star an interstellar bubble is driven outward by the stellar wind. The bubble radius is (ref. 15):

$$R_B = 27\, n^{-1/5}\, L_{36}^{1/5}\, t_6^{3/5} \text{ pc} \tag{1}$$

with outward moving velocity of

$$V_B = 16\, n^{-1/5}\, L_{36}^{1/5}\, t_6^{-2/5} \text{ km s}^{-1} \tag{2}$$

where

$$L_{36} = \frac{1}{2} \dot{M}\, v_t\, 10^{36} \text{ ergs s}^{-1} \tag{3}$$

(n = ambient interstellar medium number density and t_6 = time in 10^6years).

The first supernova phase begins at about $3x10^6$ years when the 30 most massive stars ($M \geq 15M_{\odot}$) become supernovae. The ejecta initially has little interstellar gas to shock until it has expanded to the shell radius ($\gtrsim$85 pc). Because the shell is mostly HI and H_2 gas and because the ejecta is very dilute when it shocks the shell, the temperature is not very high and the shell evolution is well described by the snowplow model for supernovae. The shell expands with time as:

$$R_S(t) = R_1^{\ 4} + 3 \frac{M_1V_1}{n\mu_H m_H \pi} (t-t_1)^{1/4} \tag{4}$$

with

$$V_S(R_S) = R_S^{\ -3} \frac{3M_1V_1}{4\mu m_H n\pi}$$

This phase lasts until the shell stalls or until the second wave of supernovae occur.

The second supernova phase commences as stars down to $8M_{\odot}$ become supernovae. This occurs at $t \sim 10^7$ years and serves to maintain and/or enlarge the shell. Approximately 180 stars exceed $8M_{\odot}$ and contribute to the second phase. The shell radius becomes 170 to 700 pc before stalling. We note that <u>if</u> stars as low as $4M_{\odot}$ become supernovae, then the shell will continue to expand and be maintained longer.

The model calculations included number densities with scale heights and gravitational restoring forces depending upon the z-distance and for three galactocentric radii: 5 kpc, 10 kpc and 20 kpc. As the gravitational force only affects the bubble in the z-direction, bubble radii, etc. were calculated for parallel to the plane and perpendicular to the plane (Table 1). The radii perpendicular to the plane, being least affected by galactic rotation, are felt more reliable. We find that the bubble radius changes with galactocentric radius as calculated by our model (Figure 1).

Of about 50 hydrogen shells, we find only six to be associable with OB associations. This is not surprising as the larger bubbles would surround very evolved associations with remaining spectral types trending towards A. Moreover, interstellar extinction prevents detecting the more distant associations. Approximately thirty percent, not ninety percent, of the interstellar medium is superbubble interiors. This indeed will produce only arcs, or partial shells as shells break into adjacent shells, setting up hot, ionized tunnels.

MODELLING THE SUPERNOVA REMNANT OCCURRENCES

We realized that supernovae occurring within an interstellar bubble or superbubble would not create the classically detectable supernova remnants. Basically, a supernova remnant is the product of ejecta interacting with the ambient interstellar gas (ref. 16). Until the supernova ejecta ($\sim 5M_{\odot}$) has swept an equivalent amount of material, the ejecta is in free expansion.

By the time the supernova ejecta has expanded to encounter the shell boundary it is too diffuse and only a brief flash (like Barnard's Loop) is detected. Studies of detected supernova remnants both in the Milky Way and the Magellanic Clouds suggest supernova remnants are detectable only if the ambient density exceeds 0.1 cm^{-3}.

A compensating factor includes the knowledge that many runaway stars occur and some B stars diffuse from the association beyond the hot cavity into the neutral shell. About two-thirds of all stars are in binary systems. In a massive binary system, the more massive star explodes and tends to fling the less massive star away. The lower-massed star then becomes a runaway star. (Twenty percent of all OB stars appear to be runaways (ref. 17)). Those runaway OB stars that escape the hot cavity create the detectable supernova remnants.

Only a small fraction escape the supercavities. Since the shell radii are much smaller at 5 kpc, more escape the hot cavity than at 10 kpc. No OB stars escape the hot cavity at 20 kpc. Hence, the model demonstrates a very galactocentric distribution of supernova remnants. We also note that the OB stars that escape are on the lower mass portion of the OB star mass function. There indeed may be a narrow mass range of OB stars that produce detectable supernova remnants. Based upon thirty percent of the interstellar medium being supercavities, the following percentages of supernovae create detectable supernova remnants:

R gal = 5 kpc 15 percent to 30 percent
= 10 kpc 9 percent to 23 percent
= 20 kpc 0 percent

The distribution of supernova remnants is maximum near the galactic center and zero beyond 20 parsecs. Radio observations bear this out.

CLOSING COMMENTS

The superbubbles, along with hot supercavities around OB associations provide a model for comparing interstellar column densities, velocity components and degree of ionization. Perhaps the most important test regions are young OB associations, like Orion OB 1, where the first supernova events should have occurred. Very highly ionized gases should be interior, with rapidly expanding HII, HI and H_2 shell components.

We note that a Crab-like supernova remnant, namely ejecta still interacting with the expelled magnetic fields, will be detectable for several thousand years. With a 50,000 year interval between supernovae within a specific OB association, about six percent of the OB associations would have a detectable supernova remnant at any given time. However, very hot interiors with isothermal X-ray emission should occur for much longer times. We point out that the Carina Nebula has a diffuse component seen by HEAO-B (ref. 18) and suggest more detailed studies be done to check our models. We are already investigating several superbubbles in our galaxy using IUE and HEAO-B, and we are studying shell structures in the Magellanic Clouds using HEAO-B.

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TABLE . EXPANSION OF SHELLS AT SELECTED DISTANCES FROM THE GALACTIC NUCLEUS, R_{GAL}, IN THE GALACTIC PLANE

R_{gal} (kpc)	v(km s^{-1})	Parallel to the Plane			Perpendicular to the Plane		
		t(10^6yr)*	R_s(pc)	$\bar{n}$(cm^{-3})	t(10^6yr)*	R_s(pc)	$\bar{n}$(cm^{-3})§
		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 ($M \geq 15M_\odot$)					
5	5	8.6	137	3	9	170+	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 ($M \geq 8M_\odot$)					
5	-	14	179	3	-	170+	0.44
10	5	19	251	1	37	497	0.086
20	5	43	520	0.1	46	693	0.033

* t is the total characteristic time of the shell expansion through each phase.

\+ Expansion has exceeded R_{crit} and the shell size is now limited by gravitational deceleration (see text).

§ $\bar{n}$ is the average of the region between the initial z and final z for each phase and is derived as:

$$\bar{n} = \frac{\pi n_o \int^{z_2} z^2 e^{-z/h}\, dz}{4/3\pi(z^3 - z\ ^3)}$$

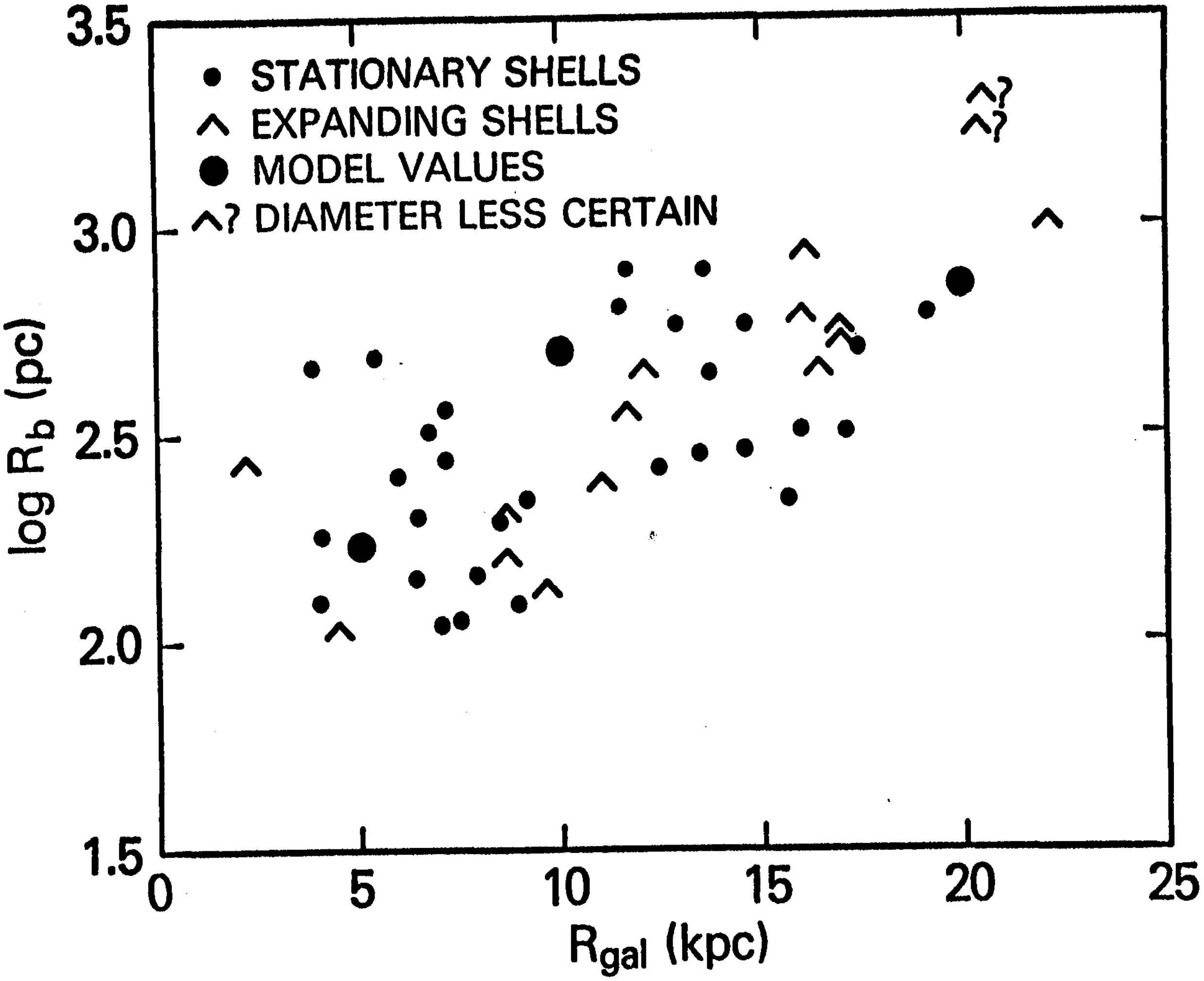
3.5
3.0
2.5
2.0
1.5
log R_b (pc)
0
5
10
15
20
25
R_{gal} (kpc)
● STATIONARY SHELLS
^ EXPANDING SHELLS
● MODEL VALUES
^? DIAMETER LESS CERTAIN
^?
^?

Figure 1