Part VII

Gas in Superbubbles and in the Galactic Halo

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Where's the Local Bubble? Here ...

... or there? Everywhere!

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Evolution of Evolution of Superbubbles

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Abstract. In the first place, I will summarize the evolution of our picture of the ISM over the past several decades in order to see the importance of superbubbles for ISM structure. In accordance with the progress of observations, the picture of the ISM has dramatically changed from the 1960s. Then, I will review the evolution of theoretical models of superbubbles including the idea of chimney structures of the ISM.

1 Evolution of ISM Pictures

Until the 1960s, the picture of the interstellar medium (ISM) was very simple and static. The ISM is composed of Cold Clouds (CNM) confined by ambient Warm Ionized Medium (WIM), originally proposed by L.Spitzer (1956) and formulated by Field, Goldsmith & Habing (1969). These two components of the ISM were thought to be in pressure equilibrium, so this model is called the Static Two-Phase Model. At that time, since only optical lines and the HI 21 cm radio line were available to observe the ISM, the observable ranges of temperature and density of the ISM were limited to $T = 10^2 \sim 10^4$ K and $n = 0.1 \sim 10^2 \mathrm{cm}^{-3}$ as is shown in Figure 1.

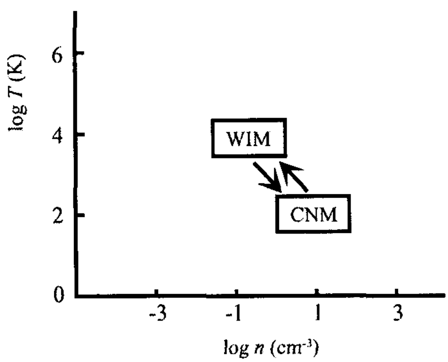

Fig. 1. Static Two - Phase Model

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In the 1970s, many new phases of the ISM were discovered, such as highly ionized gas seen in OVI by the COPERNICUS satellite and the hot gas seen in soft X-ray emission by sounding rockets. At the same epoch, giant molecular clouds (GMCs) were discovered by CO observations. These discoveries made a strong impact on studies of ISM structure and star formation. The dynamically exchanging picture of the ISM composed of Hot Ionized Medium (HIM), WIM and CNM were proposed by Cox & Smith (1974), who have firstly indicated the importance of hot phase formed by multiple supernova remnants, and Shapiro & Field (1976) who have discussed the possibility of disk-halo connection through an individual supernova remnant, galactic fountain. Finally, McKee & Ostriker (1977) have formulated the Three-Phase Model. I remember that Professor Hayakawa (1979) proposed the Local Hot Bubble picture by indicating the anticorrelation of the intensity of soft X-ray background and that of HI 21 cm. As is seen in Figure 2, the hot gas phase is thermally unstable and its cooling time is shorter than 1 Myr. Therefore, the three-components of the gas must be mutually interchanging. The driving force for this interchange seems to be energy input by supernova explosions. The analogy of worms and fountains was suggested for the cold gas component and the hot ambient gas.

In the 1980s, this dynamical picture of the ISM was established by discoveries

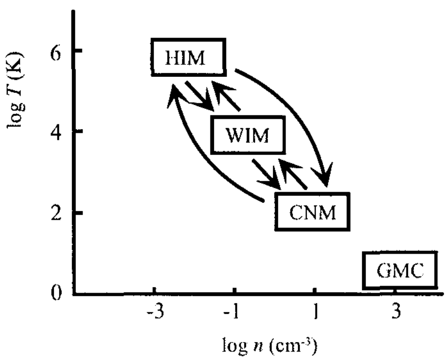

Fig. 2. Three-Phase Model

of superbubbles in Cygnus, Orion-Eridanus and Gum Nebulae. Superbubbles are formed by cumulative supernova explosions in an OB association, where massive star formation is active. McKee et al (1984) have explored the evolution of superbubbles within two-phase medium, taking account of photoevaporation of cold clouds. Moreover, McCray & Kafatos (1987) have proposed the self-propagating star formation due to the shock compression by supershells. Since the gas in the galactic disk is plane-stratified, the superbubble predominantly expands perpendicular to the disk and finally breaks through

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to the galactic halo. This gives rise to the picture of disk-halo connection, and a hot gaseous halo is naturally expected. In 1985, F.Lockman and J.Bregman organized a small workshop entitled "The Galactic Gaseous Halo" at Greenbank. After the session, we discussed the possibility of disk-halo connection while drinking wine in front of the fireplace. Just then, I got the idea of the Chimney Model (Ikeuchi 1988, Norman & Ikeuchi 1989) for superbubbles, which break through to the halo from the disk. The analogy is as follows: The fireplace is an OB association, and the firewood is OB stars and supernovae. The chimney wall is composed of cold gas expelled by supernova explosions. The smoke is hot gas heated by stellar winds and supernovae,and the falling acid rain is cooled gas in the halo, which is polluted by metals. The importance of superbubbles for the evolution of large scale structures in the ISM is clearly reviewed by Tenorio-Tagle & Bodenheimer (1988).

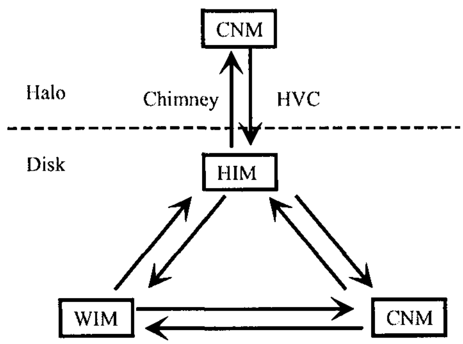

Fig. 3. Disk-Halo Connection

In the 1990s, the ISM picture extends from the Local Hot Bubble, superbubbles and worms to extragalactic gaseous halos probed by QSO absorption lines, and the observations extend from the radio, infrared, optical to the EUV and X-ray portions of the spectrum. Moreover, we can discuss the evolution of the ISM in relation to galaxy formation and evolution in the near future. That means that the structure of the local ISM is connected with cosmology. We may say that the study of the ISM has a bright future.

2 Evolution of Models of Superbubbles

There are two possibilities for the formation of superbubbles. One is cumulative supernova explosions in OB associations. In this case, massive stars form sequentially from giant molecular clouds, make giant HII regions and

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stellar wind bubbles, and then explode as supernovae within previous supernova remnants (SNRs). This type of superbubble is naturally expected in spiral arms. They look like chimneys because the supperbubbles are standing perpendicular to the disk and ample cold gas is associated with them.

The other possibility for the formation of superbubbles is the collision and merging of neighboring SNRs. In other words, a new supernova explosion occurs outside of another SNR. This type of superbubble can be expected in the inter-arm regions. The local superbubble corresponds to this type. Though I worked on these two cases in the past, I will concentrate to the former type in the following.

The historical evolution of Models of Superbubbles can be summarized as follows:

(a) Spherical Superbubble in an homogeneous medium (Tomisaka, Ikeuchi & Habe 1981).
(b) Superbubble in a plane-stratified medium (Tomisaka & Ikeuchi 1986, McLow, McCray & Norman 1989).
(c) Superbubble with magnetic field of
- **(i)** 2D calculation in an homogeneous medium (Tomisaka 1992),
- **(ii)** 2D calculation including the gravity of disk (Kamaya, Shibata & Mineshige 1996),
- **(iii)** 3D calculation in a plane-stratified medium (Tomisaka 1997).

(d) Superbubble in
- **(i)** differential rotating disk (Tenorio-Tagle, Bodenheimer & Rozyczka 1987, Bisnovatyi-Kogan & Silich 1995),
- **(ii)** non-coeval star formation history (Shull & Saken 1995),
- **(iii)** two-phase medium (Silich et al. 1996).

I shall give a brief overview of the important findings of these models. (I apologize that I could not mention many other works.)

(a) Spherical Superbubble in a homogeneous medium.

For any phenomenon, we should start from the simplest model in order to see the underlying physical processes and to confirm if the basic idea works. For wind bubbles in a homogeneous medium, the similarity solution had been found (Weaver et al 1977) and applied. In an OB association, supernova explosions occur within a wind bubble (Bruhweiler et al 1980). In that case, the supernova energy is not efficiently used for expansion of the remnant because the ambient medium is so rarefied that the kinetic momentum is not much transferred to the expanding shell. The similarity solution is not applicable to such a case. Therefore, it is necessary to calculate numerically the expansion of a superbubble and find the conditions for formation of a superbubble with the radius of several hundreds parsecs, such as is observed in Cygnus and Orion-Eridanus. Tomisaka, Ikeuchi & Habe (1981) first explored the expected supernova rate in a typical OB association, and showed that such a huge superbubble can be naturally formed in an OB association within several Myr. At the same time, we presented a simple analytic formula for the expansion law of a superbubble that is useful for estimating the size and age of a superbubble as functions of ejected energy and ambient gas density.

(b) Superbubble in a plane-stratified medium.

In the next step, we must study a more realistic model for comparison with observations. The gas density in the disk is not homogeneous but plane-stratified, although the exact distribution law is not well known. For this calculation, we must develope a 2D hydrodynamic code. Tomisaka & Ikeuchi (1986) have presented the first results of elongated superbubbles that stand perpendicular to the disk. In this 2D calculation, unknown parameters such as the height of the center of OB association and the scale height of the ambient medium must be varied. When the expanding front breaks through to the halo, the superbubble structure resembles a Chimney, as seen in Figure 4.

This break-through is very important for the disk-halo connection and the formation of hot gaseous halo. The definition of the Chimney is the break-through superbubble beyond the Reynolds layer, and if it does not blow out we may call it a supershell or worm (Heiles 1990). As a simple criterion, we presented the condition for break-through that the superbubble accelerates into the halo because of the rapid decrease of ambient gas density, that is, $d\ln Z_{up}/d\ln t = 1$, where $Z_{up} = Z_{OB} + R_s$ and Z_{OB} and R_s are the height of OB association and the radius of shock front, respectively. This criterion is usually satisfied when $Z_{up} \sim 2$ - 3 times of the scale height of the gas distribution. This is valid even now, and we consider this as the Chimney formation criterion. Recently, a chimney structure has been observed in the W4 region (Normandeau, Taylor & Dewdney 1996). We may expect more chimneys in nearby OB associations.

(c) Superbubble with magnetic field.

(i) 2D calculation in an homogeneous medium.

Since the strength of the general magnetic field in the disk is estimated to be several microgauss, the magnetic pressure is comparable to the gas pressure of the ISM, i.e., $P_{ISM} \simeq P_B = 10^{-12}(B/5\mu G)^2$ dyn cm^{-2}. Therefore, we must include the magnetic pressure for the evolution of a superbubble. Naturally, the magnetic pressure works to suppress the expansion of a superbubble and its break-through to the halo is highly hampered. By using a 2D magnetohydrodynamic code, Tomisaka (1992) has attempted to calculate the evolution of a superbubble in a homogeneous medium with a uniform magnetic field. As expected, the magnetic field strongly suppresses the expansion

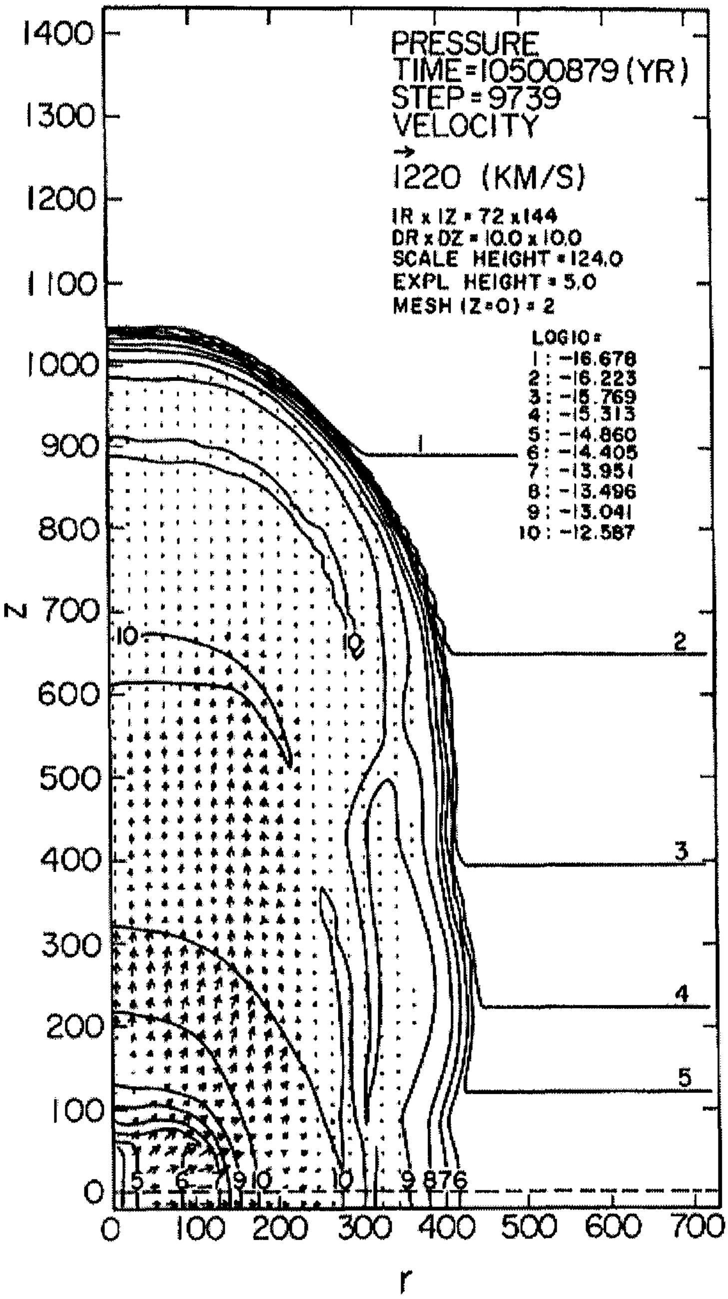

Fig. 4. Chimney formation in a plane-stratified medium

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perpendicular to itself. Thus, break-through is rarely expected unless sequential supernova explosions occur well away from the midplane of the disk. Since OB associations are rare in such a region, break-through of superbubbles to the halo is not expected when the ambient medium is homogeneous and the gravity of disk is not included.

(ii) 2D calculation including the gravity of the disk.

Kamaya, Shibata and Mineshige (1996) have presented results of 2D calculations with magnetic field, including the constant gravity perpendicular to the magnetic field. Though their calculation is limited to the case of adiabatic expansion, they have shown that the Parker instability is triggered by the inflated magnetic field and that it gives rise to the break-through of a superbubble into the halo. Although the radiative cooling must be considered, this provides another possibility for the formation of Chimneys.

(iii) 3D calculation in the plane-stratified medium.

Tomisaka (1997) has extended his calculation to the 3D case in order to include the ambient gas density distribution. He assumed a magnetic field parallel to the disk, which has a density decreasing with height. His results are as follows: When the magnetic field is constant, the density stratification does not accelerate the expansion of a superbubble in the Z-direction because the magnetic pressure dominates at high Z and suppreses the break-through. However, if the magnetic field is proportional to the square root of the ambient gas density, which means the Alfvén speed is constant, the expansion is accelerated due to the rapid decrease of ambient pressure with height in the halo. In this case, break-through can be expected even if the supernova explosions occur close to the midplain of the disk.

(d) Superbubbles under realistic conditions.

In recent years, the evolution of superbubbles has been explored under much more realistic conditions. I shall briefly summarize several results. The first is the effect of differential rotation of the galactic disk (Tenorio-Tagle, Bodenheimer & Rozyczka 1987; Bisnovatyi-Kogan & Silich 1995). Since the radius of a superbubble becomes larger than 100 pc at the final stage, the difference of rotation speeds between the innermost and outermost edges of a superbubble as measured from the galactic center becomes comparable to the expansion speed. This causes an elongation of the initially circular cross section of the superbubble. This phenomenon is observed in M31, where some of the HII regions, which frequently contain OB associations and may be windbubbles, are observed to have elliptical cross sections. The second is the effect of the two-phase nature of the ambient medium (Silich et al 1996). If diffuse clouds are distributed around a superbubble, they are compressed by the shock wave and evaporated by thermal conduction. As a result, the ambient gas density increases and radiative cooling is enhanced. This effect

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works to shorten the lifetime of a superbubble. The third is the effect of noncoeval star formation (Shull & Saken 1995). Since the star formation in an OB association is not coeval, the energy input rate by stellar winds and supernova explosions is time-varying. Generally, the peak of star formation results in faster shell growth and affects the dynamics of a superbubble.

3 Remarks on the Future

As seen above, superbubbles play an important role in the structure and evolution of the ISM. Here, I shall briefly summarize the future direction of research in relation to the evolution of galaxies, paying special attention to the role of superbubbles. The first point is that the disk-halo connection through chimneys will be very important for the dynamo mechanism of the galactic magnetic field, cosmic ray propagation in the galaxy, and energy storage in the halo. These processes should be reexamined in consideration of superbubbles. As an example, Ferrière (1992a,1992b,1993) has calculated the effect of superbubbles to the galactic dynamo. The second point is that the mass and momentum circulation between the disk and halo might affect the evolution of a galaxy. The mass mixing would give rise to a decrease in the metallicity gradient, and the energy and angular momentum supply from the disk to the halo would drive the evolution of the gaseous halo. This may be probed by QSO absorption lines, such as CIV and MgII. The third point is that the picture of the ISM in our galaxy can be applied to the evolution of young galaxies and starburst galaxies. At present and in the near future, we can get many more samples of high redshift galaxies that show various stages of evolution. In order to analyze such new phases of galaxy evolution, the theoretical and observational implications of the ISM in our galaxy will be very instructive. The Local Bubble is thus strongly connected with cosmology.

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