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THE DISK-HALO INTERACTION: SUPERBUBBLES AND THE STRUCTURE OF THE INTERSTELLAR MEDIUM

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ABSTRACT

The Type II supernovae in our Galaxy are spatially and temporally correlated and the consequences of such correlations are superbubbles and supershells fed by tens or hundreds of supernovae per bubble. These objects evolve and expand rapidly, and they soon break out of the disk of the Galaxy. The collimated structures formed in this process are called chimneys.

We assume that the interaction between the disk and the halo is dominated by the upward flow of mass, energy, momentum, and magnetic flux convected in the chimneys. As cooling occurs, the cycle is completed by the downward flow, from the halo to the disk, of gas that has cooled and formed clouds. These clouds rain down onto the disk, returning to it both mass and magnetic flux, and some energy and momentum in the resulting shocks, as the clouds strike the disk. This is similar to the galactic fountain model but with a highly concentrated upward energy flow in chimneys rather than over the entire disk.

We make the further simplifying assumption that these superbubbles dominate the energy input into both the disk as well as the halo and examine the consequences of this model for our understanding of the structure of the interstellar medium and the gaseous halo. This admittedly extreme assumption, necessary for our simplified analysis, is motivated by recent observations of the structure of the interstellar medium in our own Galaxy and external galaxies.

Our theory indicates a modification in the understanding of the nature of both the interstellar medium and the halo. The essential difference here from the 1977 McKee-Ostriker theory is that, at least currently, for our own Galaxy, the filling factor of the hot gas in the disk is significantly less than unity. We describe the structure of the interstellar medium using as the fundamental parameters the clumping of the Type II supernovae rate and the mean ambient density. We sketch how, for galaxies of various types, the interstellar medium can be three-phase, chimney, or two-phase. The state of the interstellar medium may also vary within a given Hubble type as a function of galactocentric radius. Temporal variations occur when a galaxy changes its star formation rate, for example, if it is triggered into the starburst mode.

Some of the additional implications of our model are noted here including aspects of dynamo theory, quasar absorption lines, and starburst galaxies.

Subject headings: interstellar: matter — stars: supernovae

I. INTRODUCTION

In the last two decades, the picture of the interstellar medium (ISM) has changed considerably mainly due to observational discoveries of new phases utilizing newly developed instruments. In his pioneering work on the physical processes in the interstellar medium, Spitzer (1968) summarized most of the fundamental processes in the interstellar medium (ISM). He presented a picture in which the standard H I clouds are confined by the pressure of a pervasive ambient medium. This picture was subsequently discussed by Field, Goldsmith, and Habing (1969). They investigated the thermal processes in the ISM, namely heating by cosmic rays and cooling by radiation. The condition for thermal balance gives rise to two thermally stable phases which are in pressure equilibrium. One is the cold cloud phase with temperature $T_c \sim 30$ K and the density $n_c \sim 100\ \mathrm{cm}^{-3}$, and the other is a warm, partially ionized phase with the temperature $T_w \sim 8 \times 10^3$ K and $n_w \sim 0.4$ atoms cm^{-3}. Their model corresponds reasonably closely to Spitzer's concept of the interstellar medium.

This picture has had to be modified, at least, in the solar neighborhood due to the discovery of the hot gas component of the ISM observed in the X-ray and UV spectral ranges. The diffuse soft X-ray background originates in hot gas with temperature $\sim 10^6$ K. This X-ray emission is probably local in origin with a size of order ~ 100 pc (Hayakawa *et al.* 1978; Tanaka and Bleeker 1977). Since the solar neighbourhood is not an unusual place in the Galactic disk, it seems highly probable that such a region of hot gas may occupy a significant fraction of the volume. The absorption line spectra seen at UV wavelengths due to highly ionized ions like O VI (Jenkins and Meloy 1974) give another constraint. If, as is usually assumed, these ions are collisionally ionized, the gas temperature should be several times 10^5 K, which is somewhat lower than that of the X-ray–emitting gas. Because the column density of O VI ions increases with the distance to ultraviolet sources, one can infer that these ions are not circumstellar but interstellar in origin (Jenkins 1978). Since the cooling time of these hot gas components is of order $\sim 10^6$ yr at densities of order $\sim 10^{-2}$ cm^{-3}, some continuous, bulk heating process is necessary in order to maintain them. Therefore, the picture of the ISM changes from a static equilibrium to a dynamically stirred one. As possible heating sources, Weaver *et al.* (1977) proposed violent stellar winds from massive stars such as Wolf-Rayet or OB stars, and Cox and Smith (1976) proposed the cumulative effect of supernova remnants. Smith (1977) initiated simulations of the formation processes of hot interstellar tunnels by supernova remnants. In essence, these models attempted to explain the presence of hot gas within an essentially two-phase picture. An excellent account of this is given in Field (1986).

Based upon these observations and their new ideas on the dynamical state of the ISM, McKee and Ostriker (1977, hereafter MO) presented a revolutionary model, in which the hot gas component with $T_h \sim 5 \times 10^5$ K and $n_h \sim 3 \times 10^{-3}$ atoms cm^{-3} occupies about 75% of the volume, and both the cold clouds and the surrounding warm ionized gas are distributed within the pervasive hot gas. These three gas components can not be in static equilibrium locally, but can be in both mass and pressure balance globally. From this point of view, MO formulated the three-phase model of the ISM. Ikeuchi, Habe, and Tanaka (1984) calculated models of the time variation of each component by considering the mutual exchange processes driven by supernova remnants. They concluded that the interstellar medium can be in a state consisting of either two phases or three phases. The structure of ISM is determined by two parameters: the supernova explosion rate, S, and the total gas density, n. As is easily understood, in the low S and/or high-n case, the two-phase structure arises, and in the high-S and/or low-n case, the three-phase structure dominates.

In the last decade after the exposition of the three-phase model by McKee and Ostriker (1977), many observational facts have been accumulated. Although they are fragmentary, it seems that they demand a new, or at least significantly modified, picture of the ISM.

Our understanding of the interstellar medium seems to be as follows (Ikeuchi 1988). There are a number of phases in rough pressure balance distributed throughout the disk. There is a source of energy that keeps the higher temperature phases heated. It is generally accepted that this is ultimately due to supernovae. Hot gas can flow up into the halo from the disk where it cools and subsequently falls back to the disk (Shapiro and Field 1976). The details of the structure of both the disk and halo interstellar media are complex and subject to considerable debate. One key issue that we discuss here is the filling factor of hot gas in the disk. Arguments are presented for a filling factor significantly less than unity. Furthermore, this estimation of a lower filling factor for the hot gas is due in the most part to the clumped energy input of tightly bunched aggregations of Type II supernovae that generate very large structures called supershells or superbubbles. Superbubbles naturally occurring in evolving OB associations are obviously a major constituent of the Galaxy (cf Kulkarni and Heiles 1988). The large, ubiquitous holes seen across the face of M31 in the Westerbork survey seem to be quite similar to the superbubble and associated supershell phenomenon (Brinks 1984). A local example of a superbubble is probably the Local bubble seen in X-ray and UV observations (Cox and Reynolds 1987). Typical energies and scales of superbubbles are 10^{54} ergs and 100–1000 pc, respectively. Starburst systems show extreme examples of such superbubbles as evidenced by the prodigious outflows (1–100 $M_\odot$ yr^{-1}) observed by Heckman, Armus, and Miley (1987). The coronal gas surrounding our own Galaxy requires both energy and momentum for its heating, support, and possibly (collisional) ionization. The relevant observations which we summarize in § II include the *Tenma* observations of a smooth 10^7 K X-ray–emitting ridge: *IUE* observations of highly ionized species in the Galactic halo; and observations of an infalling neutral hydrogen component, the so-called high-velocity clouds. Metal lines of, for example, C IV seen at large distances from the centers of the associated galaxies demonstrate that hot, highly (photo)ionized halos have significant extent, typically of order tens of kiloparsecs.

For recent overviews of our knowledge of the interstellar medium in both halos and disks and flows from disk to halo, one should consult Bregman and Lockman (1986), Hollenbach and Thronson (1987), and Spitzer (1988). Recent work on fountains and halo gas is described in Corbelli and Salpeter (1988). Other authors who have stressed the importance of the type of more inhomogeneous models presented here include Heiles (1986, 1987), Cox (1986), Ikeuchi (1987), and Norman and Ikeuchi (1988).

In this paper, we summarize the observational evidence which suggests a new picture in § II. We describe our new model, which we call the chimney model, and present a simple analysis of its underlying physical principles. The crucial point of the chimney model is that the galactic disk and halo are connected by chimneys. These are a consequence of superbubbles bursting out of the disk forming these collimated structures through which the global mass and energy exchange flows from disk to halo.

We find that for canonical Galactic parameters the chimney phase is associated with a mass flow rate of 0.3–3 $M_\odot$ yr^{-1} and a global power input of 10^{40}–10^{42} ergs s^{-1}. These numbers which emerge naturally from the calculation are those conventionally thought to apply to the Galaxy and give us additional confidence in the applicability of the chimney model to the Galaxy. In § V a number of implications for the evolution of galaxies are discussed, and a short summary of the paper is presented.

II. SUMMARY OF NEW OBSERVATIONAL FACTS

a) Evidence for the Chimney Model

i) *Superbubbles*

Cash *et al.* (1980) have discovered an extended X-ray–emitting shell with size of order ~450 pc in the Cygnus region. They called this region a superbubble and suggested similar candidates in the Orion-Eridanus region and the Gum nebula. In the Eridanus region, X-ray emission is also seen and extended H I and Hα loops with sizes ~250 pc have been found (Reynolds and Ogden 1979; Cowie, Songaila, and York 1979). These superbubbles are seen in the soft X-ray band at ~0.1–0.6 keV indicating the presence of hot gas at a temperature of several million degrees associated with the shells. A component of hard X-ray flux is found in the Cygnus superbubble (Koyama 1986; Koyama, Ikeuchi, and Tomisaka 1986). The X-ray spectrum measured by the *Tenma* satellite clearly shows iron lines at 6.7 keV, indicating the presence of hot gas at a temperature $\sim 6 \times 10^7$ K if the gas is primarily at the peak temperature for this ion. Such a high temperature suggests the energy input has occurred within $\sim 10^3$–10^4 yr, which is much shorter than the age of the Cygnus superbubble. Therefore a continuous energy supply to the superbubble is occurring even at the present epoch.

ii) *Supershells*

Heiles (1979, 1984) discovered many shells, loops, arcs, and fragments in his extensive study of the cool neutral hydrogen distribution in the Galaxy. He reported about 50 clouds with size of order ~ 100 pc–3 kpc that he called supershells. Some of them are currently expanding, and others are stationary. In the filtered pictures that enhance the smaller structures, the H I clouds look like worms which crawl out from the disk. These worms and supershells may originate from multiple highly correlated Type II supernovae explosions. As an example, it is found that the geometrical center of a particular supershell corresponds to the Cygnus OB association, which is presumably the energy source of the Cygnus superbubble. It is thus very suggestive that cold H I shells emanate from the disk due to dynamical processes similar to those described above. We suggest that these wormlike H I structures should be associated with the walls of chimneys.

iii) *OB Associations and Their Environment*

There are three local candidates of superbubbles in which giant molecular clouds, OB associations, H II regions, and H I loops coexist. Some of them like the Cygnus region and the Orion-Eridanus region are associated with supernovae remnants, X-ray superbubbles, and pulsars. These facts indicate the possibility of some form of sequential star formation, and the consequences are rapid energy input by stellar winds or multiple supernovae resulting from OB associations formed in this way. Tomisaka, Habe, and Ikeuchi (1981) showed that superbubbles with size ~ 300–1000 pc can be formed if sequential supernova explosions occur every 10^5 yr during the lifetime of a giant molecular cloud, canonically taken to be ~ 1–2×10^7 yr. Further, if such sequential explosions occur in a plane-stratified medium like the Milky Way, superbubbles will expand into the halo region while accelerating upward forming a quasi-cylindrical or conelike structure perpendicular to the disk (Tomisaka and Ikeuchi 1987; Mac Low and McCray 1988). The cooled supershells produce H I chimneys with the heights of order ~ 1 kpc emanating from the disk and the hot gas goes up through the chimney to the halo. We expect that many of these chimneys stand out from the galactic disk. We return to this picture in the next section (§ III), but we first discuss some of the observational evidence relevant to the halo disk connection in our own Galaxy and in external galaxies.

b) *Observations of New Hot Gas Component*

i) *X-ray Ridge*

According to McKee and Ostriker (1977), the temperature of hot gas prevalent over the disk is, at most, 10^6 K. Observations by *EXOSAT* (Warwick *et al.* 1985) and *Tenma* (Koyama *et al.* 1986) indicate the presence of a hotter gas component with temperature $\sim 10^7$ K. This X-ray–emitting region is like a ridge. Such high-temperature gas can not be in a diffuse form because it easily escapes from the disk. The distribution of X-ray flux normal to the disk shows that it is confined to the disk with the same structure as Population I objects. This result indicates that the X-ray–emitting sources seem to be a number of sources, and the most reasonable candidates seem to be an ensemble of binary sources or a population of supernova remnants. Since the fluctuation of X-ray intensities in different directions is small, the number of sources in a line of sight should be greater than of order of $\gtrsim 10$ (Koyama 1985). There is no obvious way to make the observed 6.7 keV Fe line in binaries. Koyama *et al.* (1986) examined the possibility that the X-ray ridge is formed in a population of supernova remnants younger than 10^4 yr. Their conclusion is that the Type II supernova explosion rate must be higher than 0.1 SN per year, which seems to be too high. This may suggest that supernova explosions do not occur randomly but are correlated (Kulkarni and Heiles 1988) as is envisaged in the superbubble model (see Tomisaka and Ikeuchi 1987). As is seen later, the X-ray variation from one line of sight to another is less than that of the observations even though the supernova explosions are correlated.

ii) *Highly Ionized Ions in the Galactic Halo*

By analyzing the absorption lines present in spectra of halo stars, the properties of the gas in the Galactic halo have been studied with the *IUE* satellite (Savage and Massa 1987). The detection of C IV, Si IV, and N V absorption lines due to the diffuse halo gas indicates the presence of hot gas with a temperature higher than, at least, several $\times 10^4$ K with a scale height of order ~ 3 kpc. Although the relative dominance of photoionization versus collisional ionization is not yet clear, both processes seem to work efficiently in order to explain the abundances of highly ionized ions (Savage 1986; Ito and Ikeuchi 1988). Therefore the hot gas supplied from the disk probably does, in fact, contribute to the absorption.

iii) *Halo Clouds*

The halo gas supplied from the disk is cooled within $\sim 10^7$ yr and returns back to the disk as clouds (Bregman 1979, 1980; Habe and Ikeuchi 1980). Such a fountain model is supported by observations of halo clouds with both positive and negative velocity. Van Woerden, Schwarz, and Hulsbosch (1985) compared the velocity distributions of halo clouds in the sky with those predicted by Bregman (1980) and confirmed that the velocity patterns are consistent.

c) *External Galaxies*

i) H I *Holes in M31*

Brinks and Bajaja (1986) undertook a detailed H I survey of M31. They found many H I holes with typical sizes of order ~ 100 pc–1 kpc, projected onto the plane of the disk. If we were to observe the superbubbles from outside the Galaxy, they would be seen as H I holes. Of course, the inclination of the plane of the disk to the line of sight and the inclination of the superbubbles to the disk should lead to various elliptical figures of H I holes. It will be interesting to compare the distributions of H II regions, radio continuum contours, and X-ray sources in the same galaxy and between galaxies.

ii) *Big Gaseous Halos around Distant Galaxies*

The absorption-line systems in quasars probably originate in the intervening material. The narrow metallic-line systems with the redshifts smaller than the emission redshifts of quasars are thought to be due to the gas in the halo around distant galaxies. This hypothesis has been strengthened by Bergeron's (1988) discovery of galaxies with emission lines at the same redshift as the Mg II absorption lines in quasars. In this case, the average extension of the halo gas containing Mg II ions is about 60 kpc because the line of sight to the quasar runs at this distance from the disk. General statistics of observed frequencies of Mg II systems indicates that the average radius of intervening galaxy halos at redshifts $z \sim 0.5$ should be ~ 50 kpc. The high-ionization C IV systems have not been directly confirmed as occurring in distant galactic halos, in contrast to the lower ionization Mg II systems, but the two-point correlation of C IV systems is at least consistent with that of galaxies (Young, Sargent, and Boksenberg 1982). We assume here the C IV systems are also associated with galactic halos. The observed frequency of absorbers indicates that the average radius of distant galaxies at $z \sim 2$ is ~ 90 kpc. We expect that isolated galactic halos and big H I disks have shrunk considerably by the present epoch (see Wolfe 1988).

iii) *Starburst Galaxies*

Active star formation regions are now reported in many galaxies such as M51, M82, M83 and MGC253 where the energy input from newly born stars and many supernovae is clearly evident. Ultraluminous *IRAS* galaxies such as Arp 220 show such especially violent star formation activity that the energy output from the galaxy in the infrared band amounts to $\sim 10^{45}$ ergs s^{-1}. This starburst activity is generally seen in the central regions of the galaxy, and the huge energy output associated with a starburst can produce a bipolar flow from the nucleus (Heckman 1986; Tomisaka and Ikeuchi 1988). These are extreme examples of gigantic chimneys that emit hot gas from both sides of the disk. This may be the cause of formation of enormous halos in distant galaxies at earlier epochs during their formation phase or as a consequence of galaxy interactions (Norman 1988*a*, *b*, *c*).

III. CHIMNEY MODEL OF ISM

In the initial stages of its evolution, a superbubble will expand according to the standard bubble solution driven by a continuous energy input assuming spherical geometry (Castor, McCray, and Weaver 1975; Tomisaka, Habe, and Ikeuchi 1981). However, as the bubble propagates through a scale height or so of an exponential atmosphere, it will accelerate down the rapidly decreasing pressure gradient and break out of the disk with an opening angle given approximately by the inverse of the Mach number at the point of breakout. The resulting structure is a wide angle jet or chimney acting as a conduit for material to flow from the disk to the halo (Tomisaka and Ikeuchi 1987; Mac Low and McCray 1988).

a) *Bunched Supernova Explosions in an OB Association*

It is highly probable that all the Type II supernovae do not occur randomly as has been conventionally assumed, but are to be found bunched in OB associations (Kulkarni and Heiles 1988) and associated with tracers of spiral arms such as giant H II regions (Huang 1987). If all Type II supernovae originate in massive stars, the average rate, $\gamma_{\rm OB}$ of type II supernova explosions in an OB association is estimated as follows (Tomisaka, Habe, and Ikeuchi 1981): (1) the Type II supernova rate is estimated to be $\gamma_{\rm II} \sim 0.01$ yr^{-1} (Tammann 1977; van den Bergh, McClure, and Evans 1987; Cappellaro and Turatto 1988); (2) the fraction of early-type stars belonging to OB associations is asserted to be ~ 0.7 (Cowie, Songaila, and Yah 1979); and (3) the total number of OB associations in our galaxy is $N_{\rm OB} \sim 4000$ (Blaauw 1964). From the above we have

$$\gamma_{\rm OB} \sim \gamma_{\rm II}\, f_{\rm OB}/N_{\rm OB} \sim 1.8 \times 10^{-6}\ {\rm yr}^{-1}\ , \tag{1}$$

that is, we may expect the average time interval of supernova explosions in a single association to be $\tau_{\rm OB} \sim \gamma_{\rm OB}^{-1} \sim 5 \times 10^5$ yr. Considering that the lifetime for maintaining these OB associations will be of order several $\times 10^7$ yr, the expected total number of supernovae is $N_{\rm SN} \sim 10^2$ (Bruhweiler *et al.* 1980). In reviewing three additional methods of determining this number, Tenorio-Tagle and Bodenheimer (1988) conclude that a reasonable average value for $N_{\rm SN}$ is ~ 40 with an upper bound of ~ 400. We will use $N_{\rm SN} \sim 10^2$ here as a good parameterization. This gives the expected formation rate of superbubbles to be

$$\gamma_{\rm SB} \sim \gamma_{\rm II}\, f_{\rm OB}/N_{\rm SN} \sim 7 \times 10^{-5}\ {\rm yr}^{-1}\ . \tag{2}$$

Therefore, roughly about 1000 superbubbles can be expected in the steady state, if the lifetime of a superbubble is of order $\sim 10^7$ yr.

The expansion law of a superbubble is approximated as (Tomisaka, Habe, and Ikeuchi 1981; Tomisaka and Ikeuchi 1987)

$$R_{\rm SB} = 64.3 n_a^{-0.26} t_6^{0.43} {\rm pc}\ , \tag{3}$$

where n_a and t_6 are the average gas density at the disk and the age of the superbubble in units of 10^6 yr. The differences between this expansion law and others that have been recently derived have been discussed extensively in Mac Low, McCray, and Norman (1988). The Tomisaka-Ikeuchi law was derived from a simulation that allowed gas to be entrained across the shell's interface into the cavity interior, enhancing the cooling and reducing the expansion law from $R_{\rm SB} \propto t^{3/5}$, for a wind with no interior cooling, to $R_{\rm SB} \propto t^{2/5}$. Clouds probably do, in fact, penetrate the shell and cool the interior. Our estimates of the filling factor are far more sensitive to the value of $N_{\rm SN}$ than to this expansion law as we discuss below. The probability that an arbitrary point in the disk is inside a superbubble with radius smaller than $R_{\rm SB}(\propto t^\eta)$ is given by

$$\begin{aligned} Q &= \frac{\gamma_{\rm SB}}{1+2\eta}\left(\frac{R_{\rm SB}}{R_g}\right)^2 t_{\rm SB} \\ &\sim 0.36\left(\frac{n_a}{0.1\ {\rm cm}^{-3}}\right)^{-0.52}\left(\frac{t_{\rm SB}}{10^7\ {\rm yr}}\right)^{1.86} \\ &\quad \times \left(\frac{R_g}{10\ {\rm kpc}}\right)^{-2}\left(\frac{\gamma_{\rm SB}}{7\times 10^{-5}\ {\rm yr}^{-1}}\right), \end{aligned} \tag{4}$$

where η is 0.43 and R_g is the radius of the disk. This filling factor is smaller than that deduced by Heiles (1987) who pointed out that his derived filling factors were far too high to fit the observations. We use here a higher value of $N_{\rm SN} \sim 10^2$ which is consistent with the most reasonable solution he proposed to resolve the dilemma.

On the other hand, the upward motion of the superbubble is also approximated by equation (3) in the deceleration phase if we replace n_a by the gas density $n(z)$ at the height of the shock front (Tomisaka and Ikeuchi 1987)

$$z_{\rm SB} \sim 64.3[n(z_{\rm SB})]^{-0.26} t_6^{0.43}\ {\rm pc}\ , \quad {\rm at}\ t < t_{\rm crit}\ . \tag{5}$$

At the critical time, $t_{\rm crit}$ the upward motion of the shock wave changes to acceleration, giving

$$\frac{\partial \ln z_{\rm SB}}{\partial \ln t} > 1\ , \quad {\rm at}\ t \geq t_{\rm crit}\ , \tag{6}$$

due to the density stratification in the disk (Sakashita and Hanami 1989). In this acceleration phase, the expansion within the disk is limited, and the superbubble predominantly evolves and extends into the halo to a scale height of order $\gtrsim 1$ kpc.

b) *Chimneys*

Within a chimney the rising hot gas has a typical density $n_{\rm SB} \sim 10^{-3}$ cm^{-3} and temperature $T_{\rm SB} > 3 \times 10^7$ K (Tomisaka and Ikeuchi 1987; Mac Low, McCray, and Norman 1988). The total X-ray flux from such a superbubble driven chimney is

$$
\begin{aligned}
l_x &\sim \pi R_{\rm SB}^2 z_{\rm SB} n_{\rm SB}^2 \Lambda(T_{\rm SB}) \\
&\sim 3 \times 10^{34} \left(\frac{n_a}{0.1 \text{ cm}^{-3}}\right)^{-0.78} \left(\frac{n_{\rm SB}}{10^{-3} \text{ cm}^{-3}}\right)^2 \\
&\times \left(\frac{T_{\rm SB}}{3 \times 10^7 \text{ K}}\right)^{1/2} \left(\frac{t_{\rm SB}}{10^7 \text{ yr}}\right)^{1.29} \text{ ergs s}^{-1} , \quad (7)
\end{aligned}
$$

where $\Lambda(T)$ is the standard cooling function. The total X-ray flux from the thousand chimneys expected in the steady state is $L_x \sim 10^3\ l_x \sim 3 \times 10^{37}$ ergs s^{-1} which is somewhat smaller than the observed flux of the X-ray ridge. Since the space density of chimneys is $N \sim 10^3/\pi R_g^2$ (300 pc) $\sim 10^8$ pc^{-3}, this is larger than the lower limit determined from the homogeneity of X-ray intensity of the ridge (Koyama 1985).

The energy deposited in a chimney is the order of 3×10^{51} ergs in thermal ($E_{\rm th}$) and kinetic ($E_{\rm kin}$) energy, respectively (Tomisaka and Ikeuchi 1987). Therefore, the energy supply rate from the disk to halo through chimneys is

$$
\dot{E} = E_{\rm th} \gamma_{\rm SB} \sim 7 \times 10^{39} \left(\frac{E_{\rm th}}{3 \times 10^{51} \text{ ergs}}\right) \times \left(\frac{\gamma_{\rm SB}}{7 \times 10^{-5} \text{ yr}^{-1}}\right) \text{ ergs s}^{-1} . \quad (8)
$$

The mass supply rate to the halo from the disk through chimneys is

$$
\begin{aligned}
\dot{M} &\sim 2(E_{\rm kin} \gamma_{\rm SB}) \langle v \rangle^{-2} \\
&\sim 0.5 \left(\frac{E_{\rm kin}}{3 \times 10^{51} \text{ ergs}}\right) \left(\frac{\gamma_{\rm SB}}{7 \times 10^{-5} \text{ yr}^{-1}}\right) \\
&\times \left(\frac{\langle v \rangle}{200 \text{ km s}^{-1}}\right)^{-2} M_\odot \text{ yr}^{-1} , \quad (9)
\end{aligned}
$$

where $\langle v \rangle$ is the average upward velocity of hot gas as derived from the numerical calculations. The scale height of the hot gas in the halo is taken to be $H_h \sim 3$ kpc which fits the scale height of the highly ionized species such as C IV and Si IV. This is approximately 3 times the scale height of a chimney, and the dynamical time of the gas to this height is $t_d \sim H_h/\langle v \rangle \sim 1.5 \times 10^7$ yr. The average gas density in this region is given by

$$
\begin{aligned}
n_h &\sim \dot{M} t_{\rm cool}/(2\pi R_g^2 H_h m_p) \\
&\sim 1.5 \times 10^{-4} \left(\frac{\dot{M}}{0.5 M_\odot \text{ yr}^{-1}}\right)^{0.5} \left(\frac{T_h}{10^5 \text{ K}}\right)^{0.8} \\
&\times \left(\frac{R_g}{10 \text{ kpc}}\right)^{-1} \left(\frac{H_h}{3 \text{ kpc}}\right)^{-0.5} \text{ cm}^{-3} , \quad (10)
\end{aligned}
$$

where the cooling time of the halo gas is estimated to be

$$
\begin{aligned}
t_{\rm cool} &\sim 3kT_h/\langle n_h \rangle \Lambda(T_h) \sim 1.5 \times 10^7 \left(\frac{T_h}{10^5 \text{ K}}\right)^{0.8} \\
&\times \left(\frac{R_g}{10 \text{ kpc}}\right) \left(\frac{H_h}{3 \text{ kpc}}\right)^{0.5} \left(\frac{\dot{M}}{0.5\ M_\odot \text{ yr}^{-1}}\right)^{-0.5} \text{ yr} \quad (11)
\end{aligned}
$$

which is comparable to the dynamical flow time. Note we have used $T_h \sim 10^5$ K here since we are concerned with the halo temperature at the top of the halo where the cooling occurs. Recall that at the base of the chimney the temperature is of order $\sim 3 \times 10^7$ K which has cooled due to adiabatic losses by the time it reaches the top of the halo. The gas rises to of order 3 kpc and returns to the disk after a dynamical time with an infall velocity of order $\lesssim 10^2$ km s^{-1}. Thus, we expect a large-scale circulation of the gas through the galactic halo. The exact motion of the gas in the halo is not yet clear in part because the rotation law of the halo is extremely difficult to determine from observations.

c) *Global Picture*

The firewood powering the chimneys is the giant molecular clouds, and they catch fire as OB associations. The ultraviolet flux and energetic winds ionize the clouds and provide significant momentum input. Due to sequential explosions of supernovae, a big chimney is formed with a dense cool wall of neutral gas and a central flow of hot gas. The hot gas goes up to the halo through this chimney, and the average height of hot halo gas is several kiloparsecs. After (2–3) $\times 10^7$ yr, this halo gas cools to form clouds, and they orbit back to the disk. Therefore the total gas circulation time will be (3–5) $\times 10^7$ yr.

The number of chimneys in a galaxy will be of order a thousand, and they stand along the spiral arms because the giant molecular clouds in which massive OB associations originate are predominately accumulated (or formed) in the arm regions. The direction of chimneys depends upon the original height of molecular clouds at the disk, on the upper side or lower side. Chimney walls with scale heights of order kiloparsecs are in fact seen and have been described as worms crawling out normal to the disk (Heiles 1984). Heiles (1986, 1987) found that superbubbles give too large a filling factor to explain the observations and suggested modifications in either or both the theory and observed parameters to reconcile the discrepancy. Our larger value of $N_{\rm SN} \sim 10^2$ is the essential reason for the difference between our calculations. In addition, our expansion law with its effective interior cooling due to effective cloud entrainment and a somewhat shorter bubble lifetime, $t_{\rm SB} \sim 10^7$ yr, tends to lower the filling factor estimates to values more consistent with the observations. We use these reasonable parameters as a basis for our study of the disk-halo interaction.

Generally, a large-scale mass circulation is set up with a commensurate energy and momentum input into the halo from superbubbles. As the gas rains back down onto the disk there will be a further exchange of mass, energy, and momentum—this time from the halo to the disk. Chimneys should be observed as independent entities from hard X-ray measurements in our own Galaxy and from absorption line studies, H I observations, etc. of external galaxies.

The above picture is described by using the following metaphor. The correlated supernovae with chimneys are lined up along the spiral arms, and the smoke of hot gas is puffed up from chimneys. In this gas, the metals would be abundant because many supernovae contribute. Such a metal-polluted gas is injected to the halo, and it eventually infalls to the disk.

d) *Two-Phase, Chimney, and Three-Phase Components of the Interstellar Medium*

Let us begin by presenting a rough sketch of some of our basic results. A particularly important parameter to determine is the extent to which the hot component of gas is more or less all-pervasive or merely occupies a small part of the volume of the overall interstellar medium of the disk.

One way to look at this is to study the dependence of filling factor on the clumping of supernovae which is, of course, intimately related to the number and strength of the resulting superbubbles. It is convenient to include the analysis of the dependence of this parameter on the mean ambient density. Normalizing to an average power injected into the interstellar medium of order 10^{42} ergs s^{-1}, we find that the Galaxy has a filling factor of about 10% for the hot gas component. We emphasize that this is exactly the region in parameter space where the chimney model applies. The standard McKee-Ostriker model seems more applicable to systems with ambient densities and superbubble rates lower by almost an order of magnitude each. A two-phase model (see Field 1986) will be relevant to galaxies with significantly higher densities than would be found in later type galaxies. Clearly the chimney model has pleasing aspects of both the two-phase and three-phase models. It is essentially a two-phase model with the third hot phase being the hot chimneys with their current Galactic filling factor of about 10%.

We can conveniently delineate the regions of parameter space occupied by the two-phase and three-phase homogeneous models and this model of chimneys. A crucial point is to isolate the region within which the filling factor, Q, of the hot gas formed by the random explosions of supernovae is unity.

Here, we define the random explosion rate γ_R to be the difference between the average supernova rate γ_{AV} and the rate of supernovae clumped in superbubbles γ_{SB} formed by a number, N_{SN}, of correlated supernovae explosions, to be

$$\gamma_R = \gamma_{AV} - \gamma_{SB} N_{SN} . \tag{12}$$

Following the equation (2) of MO,

$$Q = 10^{-0.29} n_a^{-0.14} \tilde{P}_4^{-1.30} E_{51} S_{R,13} \tag{13}$$

where $\tilde{P}_4$ is the ambient gas pressure in units of 10^4 cm^{-3} K, E_{51} is the supernova energy in units of 10^{51} ergs, and $S_{R,13}$ is the random supernova rate per unit volume in units of 10^{-13} SNs yr^{-1} pc^{-3}. Then, the fraction of supernovae occurring in superbubbles is

$$\frac{\gamma_{SB} N_{SN}}{\gamma_{AV}} = 1 - 10^{0.29} Q n_a^{0.14} \tilde{P}_4^{1.30} E_{51}^{-1} S_{AV,13}^{-1} , \tag{14}$$

where $S_{AV,13}$ is the total supernova rate per unit volume in units of 10^{-13} SNs yr^{-1} pc^{-3}. In Figure 1, we plot the representative cases $Q = 1$ for the three-phase model and $Q = 0.1$ for the chimney model. For these illustrative constant filling factor lines in Figure 1, we hold constant the parameters $E_{51} = 1$, $\tilde{P}_4 = 1$, and $S_{AV,13} = 1$.

To form chimneys from multiple supernovae, the bubble must evolve sufficiently rapidly so that the characteristic dynamical time to reach one scale height is shorter than the cooling time (Mac Low and McCray 1988). To see this we define the parameter D_{cool}, which is the ratio of the total superbubble input power in the disk, with scale height H_{SB}, to the radiative losses.

This parameter is given as

$$D_{cool} = \gamma_{SB} E_{SB} / \pi R_{SB}^2 H_{SB} n_{SB}^2 \Lambda(T_{SB}) N_{SB} , \tag{15}$$

where N_{SB} is the total number of superbubbles. T_{SB}, n_{SB}, and E_{SB} are their mean interior temperature, density, and energy, respectively. Then, the fraction of energy injected to superbubbles is written as

$$\frac{\gamma_{SB} E_{SB}}{\gamma_{AV} E_{SN}} = 124 D_{cool} n_{SB}^{2.6} \tilde{P}_{SB,4}^{-0.6} N_{SB,3} H_{SB,0.5}^3 E_{51}^{-1} \gamma_{AV,0.03}^{-1} , \tag{16}$$

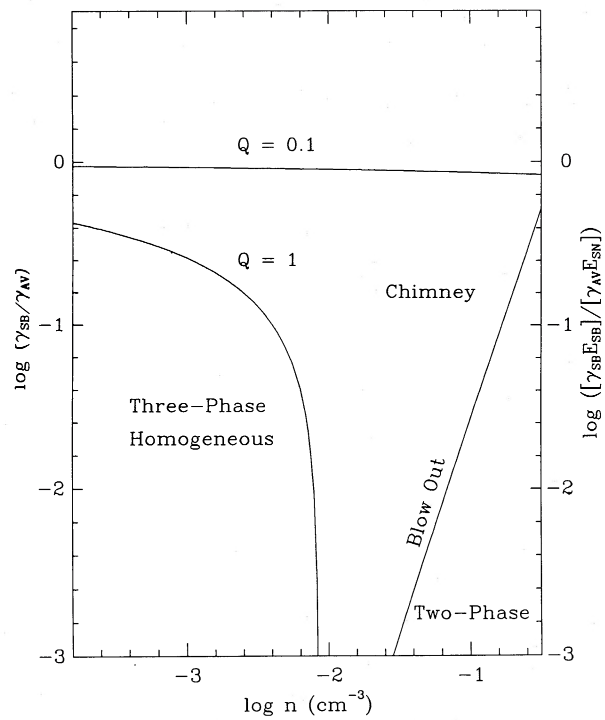

FIG. 1.—The relative frequency and power input from superbubbles as a function of ambient density. The three-phase homogeneous ISM is formed in the region $Q \geq 1.0$ for random supernova explosions, and the chimney mode is expected in the region $1 \geq Q > 0.1$ and that region where the blowout condition ($D_{cool} \geq 1$) is satisfied. If superbubbles can not blow out from the disk, the two-phase model of ISM is maintained.

where E_{SN} is the typical supernova energy, $\tilde{P}_{SB,4} = n_{SB} T_{SB}/10^4$ cm^{-3} K, $N_{SB,3} = N_{SB}/10^3$, $H_{SB,0.5} = H_{SB}/0.5$ kpc, $\gamma_{AV,0.03} = \gamma_{AV}/0.03$ yr^{-1}, and we estimate the cooling rate at the phase of $R_{SB} \sim H_{SB}$. We will call $D_{cool} = 1$ the blowout condition. In Figure 1, we plot the blowout condition for $\tilde{P}_{SB} = 5 \times 10^5$.

The various models are clearly separated in the diagram. The Galaxy lies in the region where $\gamma_{SB} N_{SN}/\gamma_{AV}$ is of order one-tenth and the mean ambient (or volume-averaged) density is of order 0.03–0.1 cm^{-3} (Kulkarni and Heiles 1988). Two-phase models occur at higher densities possibly applicable to later type galaxies. Note that the recent work by Kennicutt, Edgar, and Hodge (1989) shows that the total number of massive stars that power OB associations and eventually give supernovae, N_{SN}, rises to greater than 10^3 in late-type systems; therefore, these can have a substantial chimney mode. Three-phase models apply to systems with ambient densities and superbubble rates lower by about almost an order of magnitude each.

The chimney model clearly incorporates features of both the two-phase and three-phase model. The disk, in this case, is almost a two-phase medium with a large filling factor of the warm neutral component. The chimneys themselves are the third hot phase and have a filling factor of order $\sim 10\%$ as they stand up above the disk.

Another way to characterize the different models of the interstellar medium is to study the global mass and energy flow from the disk to the halo. We consider a hot gaseous halo with a characteristic scale height H_h and cylindrical radius R_g. We have chosen to parametrize our model with these quantities since at least for external galaxies they are directly observable.

However we note that for a given total mass surface density in the disk, Σ, the scale height of the gaseous halo is given by $H_h = C_S^2/\Pi G\Sigma$. This is a situation where we vary the scale height as a function of halo temperature and the mass surface density of the underlying galaxy.

The energy flow rate, $\dot{E}$, is simply related to the mass flow rate, $\dot{M}$, as $\dot{E} = C_S^2 \dot{M}$, where C_S is the isothermal sound velocity. The cooling time of this flowing gas is given by

$$t_{\rm cool} = 4.5 \times 10^{-11} n_h^{-1} \dot{E}^{1.6} \dot{M}^{-1.6} , \qquad (17)$$

and the flow time is

$$t_{\rm flow} = H_h/C_S = H_h \dot{E}^{-0.5} \dot{M}^{+0.5} . \qquad (18)$$

Since for a hot halo, $t_{\rm flow} \leq t_{\rm cool}$, the critical relationships are found by equating these two timescales. We have

$$\dot{E} = 8.5 \times 10^4 (H_h n_h)^{0.48} \dot{M} , \qquad (19)$$

corresponding to the condition that the halo column density is a cooling column density. The steady value of gas mass in the halo is

$$M_{\rm halo} = 2\pi m_p n_h R_g^2 H_h = t_{\rm flow} \dot{M} , \qquad (20)$$

where m_p is the mass of a gas particle. Combining equations (18)–(20) we finally get the relation

$$\dot{E} = 1.1 \times 10^{41} \left(\frac{R_g}{10 \text{ kpc}}\right)^{-0.78} \left(\frac{H_h}{3 \text{ kpc}}\right)^{0.39} \dot{M}^{1.39} \text{ ergs s}^{-1} , \qquad (21)$$

where the mass flow rate $\dot{M}$ into the halo is given in units of $1\ M_\odot \text{ yr}^{-1}$. As this energy flow is supplied from superbubbles, we equate this expression to $\gamma_{\rm SB} E_{\rm SB}$ in equation (16), leading to

$$\dot{E} = 6.9 \times 10^{40} D_{\rm cool}^{0.77} N_{\rm SB,3}^{-1.23} \dot{M}^{1.90} H_{\rm SB,0.5}^{3.70} \left(\frac{H_h}{3 \text{ kpc}}\right)^{1.70} \times \left(\frac{R_g}{10 \text{ kpc}}\right)^{0.60} P_{\rm SB,4}^{-0.6} \text{ ergs s}^{-1} . \qquad (22)$$

The halo will suffer a wind if the binding energy per gram exceeds that sufficient for escape from the galaxy's gravitational potential and if $t_{\rm cool} \geq t_{\rm flow}$. This can be written

$$\dot{E} = 5.5 \times 10^{40} \dot{M} V_{\rm esc,400}^2 \text{ ergs s}^{-1} , \qquad (23)$$

where the escape velocity $V_{\rm esc}$ is given in units of 400 km s^{-1}. We consider three cases. The hot homogeneous halo has negligible cooling (case I) so that

$$\dot{M} = M_{\rm halo}/t_{\rm flow} = M_{\rm halo} C_S/H_h = M_{\rm halo}(\dot{E}/\dot{M})^{1/2}/H_h , \qquad (24)$$

which gives rise to

$$\dot{E} = 1.5 \times 10^{35} n_h^{-2} \left(\frac{R_g}{10 \text{ kpc}}\right)^{-4} \dot{M}^3 \text{ ergs s}^{-1} . \qquad (25)$$

If cooling is important, and the blowout condition is not satisfied, the halo will cool and will not be relevant here (case III). If the blowout condition is satisfied even though cooling occurs, we have chimneys in an inhomogeneous hot halo (case II), so that

$$\dot{M} = M_{\rm halo}/t_{\rm cool} = 2.2 \times 10^{11} M_{\rm halo} n_h \dot{E}^{-1.6} \dot{M}^{1.6} , \qquad (26)$$

where we use equation (17) for the cooling time. This expression is rewritten as

$$\dot{E} = 1.4 \times 10^{44} n_h^{1.25} \left(\frac{R_g}{10 \text{ kpc}}\right)^{1.25} \left(\frac{H_h}{3 \text{ kpc}}\right)^{0.625} \dot{M}^{0.375} \text{ ergs s}^{-1} . \qquad (27)$$

Important relationships are shown in Figures 2 and 3. The parameter range for our Galaxy estimated in the previous subsection is from equations (8) and (9), a mass flow rate between 0.3 and 3 $M_\odot$ yr^{-1} and a power input of 10^{40}–10^{42} ergs s^{-1}. *This region is associated with the chimney phase.*

In Figure 2, we illustrate the relation between the energy and mass flow rates for the above three cases. In the upper left of the cooling curve ($t_{\rm cool} = t_{\rm flow}$), the case I solution holds and the halo gas expands as a galactic wind. For the case of a low-energy flow and a high-mass flow, a cooling flow in the halo is expected (case III). Between the above two cases, a steady halo is formed due to the gas circulation through chimneys (case II). For the usual parameters in our Galaxy, the gas blowout ($D_{\rm cool} = 1$) occurs.

In Figure 3, the close-up view for the mass flow of $\dot{M} \sim$ 0.1–3.0 $M_\odot$ yr^{-1} is shown. Along the Hubble sequence of disk galaxies, the energy and mass input can vary, and the disk-halo connection can change from a wind to chimneys to two-phase cooling halos. This behavior is shown schematically in Figure

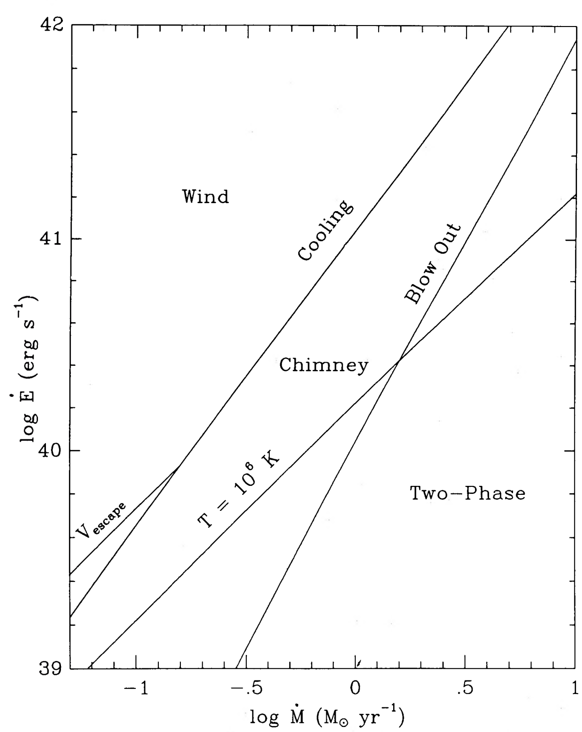

FIG. 2.—The state of the interstellar medium in the halo as a function of the total power input and the mass flow into the halo. Three types of halo structures are expected. In case I, the halo is not cooled and a galactic wind is expected. In case III, the radiative cooling is efficient within a flow time and the blowout condition can not be satisfied. This gives a two-phase medium. Between the above two cases, the cooling affects the gas motion in the halo, but the blowout condition is satisfied. The chimney model is expected in this case (case II). Two other interesting regions are the bound hot halo region below the escape line and above the cooling line, and the three-phase partial wind region below the cooling line and above the continuation of the escape line. Note the line labeled $V_{\rm esc}$ is drawn for the value $V_{\rm esc} = 400$ km s^{-1}.

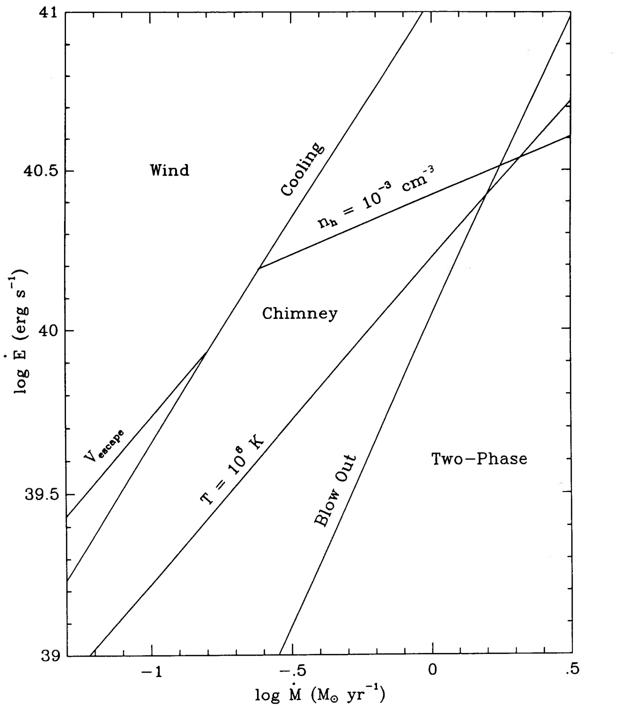

FIG. 3.—The close-up view of Fig. 2 in the mass input rate range $\dot{M} \sim 0.1$–$3.0\ M_\odot\ \mathrm{yr}^{-1}$.

4. These sequences of halo structures can also be considered to be the evolutionary sequences. In the early explosive era, a huge extended halo can form and the halo gas can escape as a wind. The halos in this burst phase may be detected as absorption systems with highly ionized gas. The present structures in our Galaxy and Sb type galaxies appear to be in the chimney mode when the halo has shrunk to several kiloparsecs. The circulation of gas between the disk and halo occurs. With decreasing the star formation activity, the blowout condition for superbubbles cannot be satisfied and the gaseous halo disappears.

IV. HALO STRUCTURE

Our halo model is one where most of the physical quantities circulate flowing from disk to halo and back again. For example, the flow of mass, metallicity, and magnetic field is schematically shown in Figure 5. The mass flow, for example, is injected at a distance from the disk of approximately 1 kpc as the chimney structure widens appreciably and the material is subsequently injected from the top of the chimney into upper halo. In the upper halo we assume that more or less complete mixing occurs. Cooling takes place, condensation into clouds occurs, and these rain back down on to the disk closing the mass flow cycle from disk to halo and back to the disk. The overall mass flow can be determined observationally by using the full range of measurements available including neutral hydrogen studies in both emission and absorption of the gas distribution and its kinematics, X-ray measurements in both the hard and soft energy bands, and quasar absorption-line studies. Radio continuum studies of the thermal and nonthermal distribution and its spectral index variation are also potentially important indicators of the size and distribution of shock waves propagating into the halo. It is important to emphasize that, in this model, the chimney is in a crucial even prima donna role regulating the overall pressure balance, and the mass and energy flow between the halo and the disk. In many ways it has a similar physical role to the all-pervading hot gas in the McKee-Ostriker model. The connectivity of the hot gas is not achieved, however, in the disk, but via the chimneys to the general halo gas.

A difference between the chimney model and the homogeneous three-phase model is that for chimneys the hot gas is injected into the halo at large scale heights of order ~ 1 kpc, and for MO the hot gas flows into the halo from the base of the corona at the disk. This results in a significantly different temperature structure for the halo. The reason is that for the chimney model, the hot gas passing through the chimney duct does not suffer so much adiabatic cooling, while for the MO model the temperature of the hot gas escaping from the disk monotonically decreases due to the adiabatic expansion. Therefore the chimney model has this definite prediction that can be tested in the future by ultraviolet absorption lines of highly ionized ions such as O VI, N V, Fe X, and Si VI that are excellent temperature probes to ascertain the real temperature profile of the halo.

As illustrated schematically in Figure 6, such absorption-line studies should ideally include stars in front of, behind, and in chimneys at a variety of distances from the disk. In the X-ray region we predict there should be a localized hard X-ray component ($\gtrsim 1$ keV) associated with the hot gas streaming through the chimneys. A more diffuse component may eventually be seen emitted from the hot halo. This model has interesting consequences for the large-scale neutral hydrogen component extended normal to the disk. There are three sources of this component: supernova injection of H I filaments from the disk; injection from scale heights of the order of ~ 1 kpc from fragmentation of the walls of the chimney; and formation of H I clouds by thermal instability in the overall halo at scale heights above ~ 1 kpc. We are as yet uncertain of the relative populations, but we give a sketch of the kinematical ranges of the different populations. The clouds generated by the thermal instability process will acquire typical (negative) velocities above $|v| > 50$ km s^{-1}. The clouds injected directly from the disk will have low velocities as observed $|v| \sim 10$ km s^{-1}, and those clouds formed from chimney walls in the intermediate halo are expected to have intermediate velocities. The Heiles supershells and worms observed in our Galaxy are probably the chimney walls before instability and fragmentation. A detailed cloud number density-velocity diagram should show them as distinct populations. While the high-velocity and low-velocity components will not depend strongly on galactocentric radius, the intermediate velocity clouds will follow the superbubble population which is correlated with the giant molecular clouds and spiral arms.

Current radio studies are consistent with the existence of a Galactic halo but have not yet reached the stage where many important details can be observed, apart from some loops and spurs related to chimney walls. The MO model predicts a spectral index that decreases with distance from the plane due to standard adiabatic losses. Superbubbles will propagate shocks high into the halo causing substantial particle reacceleration and a significant flattening of the spectral index. Therefore from more detailed radio observations, we could significantly constrain the physical parameters of the shocks.

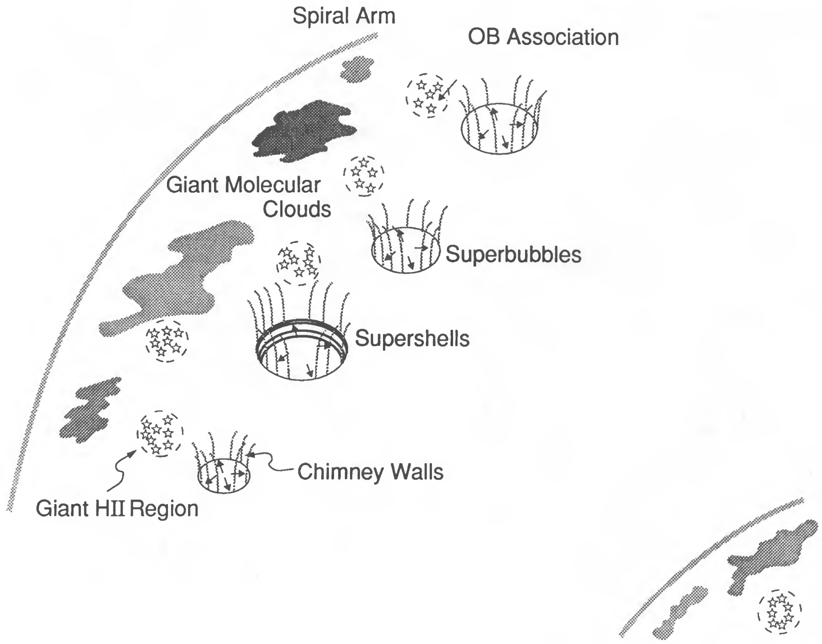

FIG. 4*a*

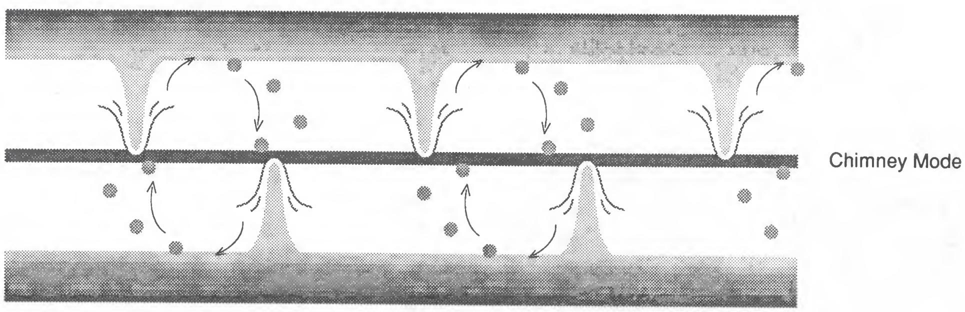

FIG. 4*b*

FIG. 4.—Schematic diagram of (*a*) superbubble formation in the disk powered by massive OB associations formed from giant molecular clouds associated with spiral arms and (*b*) superbubble evolution into the halo and circulation from disk to halo and back again.

V. IMPLICATIONS AND SUMMARY

Our model has a number of interesting consequences for the physical understanding of quasar absorption lines, the dynamo mechanism in spiral galaxies, the nature of cosmic rays, starburst galaxies, and the structure of edge-on galaxies, and we present here some qualitative speculations on these points and then go on to summarize our picture of the structure of the interstellar medium in galaxies.

a) *Quasar Absorption Lines*

During the galaxy formation epoch, extended wind-driven halos can form with loci positioned above the cooling line in Figures 2 and 3. The subsequent evolution as galaxies settle down and evolve toward their current state, with a more or less constant star formation rate, may be roughly a diagonal line crossing Figures 2 and 3 from top right to bottom left, thus evolving through the stages of wind-driven halo, to chimney driven halo, to cooling halo. Quasar absorption lines of highly ionized species like Fe XV will be seen at high redshift. In the chimney phase, a mixed ionization state is expected. At later evolutionary stages typical low-ionziation species such as Mg II should be associated with the cooler halos. As the evolution proceeds, the halo size will decrease.

For C IV absorbers, for example, the absolute number is consistent with the sizes of halos being of order ~ 50 kpc. The evolution of the comoving number density of the low-ionization Mg II systems is consistent with the evolution of halos to lower ionization states with decreasing redshift (Kunth 1987). Of course more detailed observational work is needed here, and in particular it is important to establish the link between these objects and the damped Lyman-Alpha systems discovered by Wolfe and collaborators (see Wolfe 1988) that seem to have a covering factor of $\sim 10\%$ of the sky at redshift $z \sim 2$–3 and may account for most of the baryonic mass in the universe.

b) *Galactic Dynamo*

The Galaxy is evidently in the chimney mode. Consequently, transport of magnetic flux tubes above the disk into the halo is not driven by buoyancy. It is, in fact, more efficiently driven by convection up through chimneys. Coriolis force and shear both act to twist and reconnect the loops above the chimneys in the halo. As a result a steady state toroidal magnetic field is main-

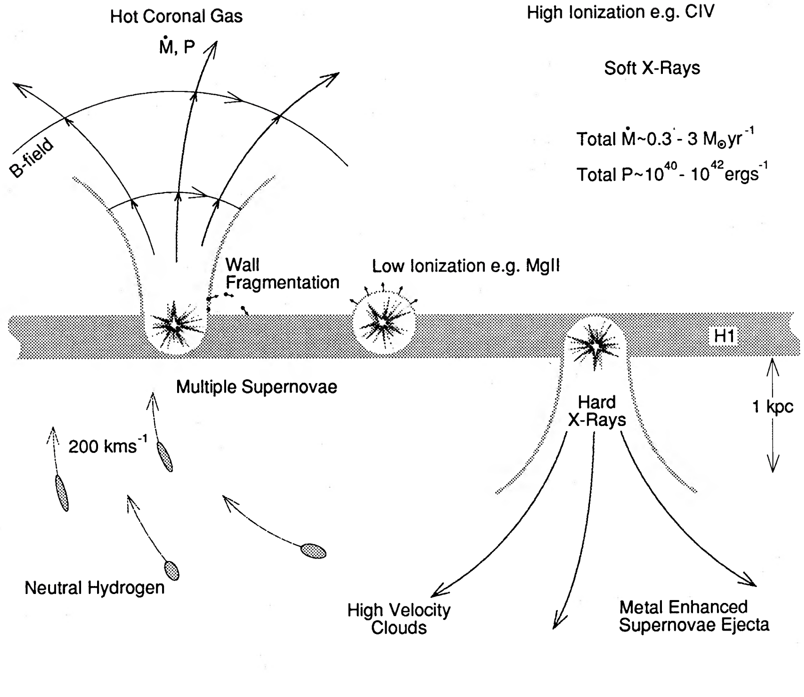

FIG. 5.—A sketch of some of the obvious qualitative aspects of the halo structure in the chimney model. The observational characteristics and effects on galaxy evolution of these disk-halo connections are discussed in §§ IV and V.

tained in the Galactic disk. This forced magnetic flux circulation will change the nature of the standard α-ω disk dynamo (Parker 1971; Field, Norman, and Ikeuchi 1989).

c) Cosmic Rays

The chimney model gives a realistic basis for the convection-diffusion model for cosmic-ray propagation since simultaneously, convective propagation occurs in the chimneys and diffusive propagation takes place in the hot pervasive halo. Canonical estimates for the convective flow velocity in a halo with a 10% filling factor for chimneys is of order $\sim 10^2$ km s^{-1}, and the convective scale length is approximately 1–3 kpc. Two components of the cosmic-ray flux may arise naturally. One component is a local, short-lived, highly spallated (>10 g cm^{-2}) population that is associated with the esentially two-phase disk and a long-lived component that resides mainly in the halo and consequently interacts with a low grammage of material.

d) Observations of Nearby Galaxies

Many of the characteristic properties of our model can be observed in nearby galaxies. We shall note here a few such cases. M31 has hundreds of H I holes (Brinks 1984) that are presumably an indication of the presence of superbubbles, so we assume that M31 has of order 10^2–10^3 chimneys. Walls of chimneys like Heiles's observation of worms in our Galaxy should also be seen in M31. Moreover, the vertical dust lanes in M31 can be considered to be the walls (Sofue 1988). The

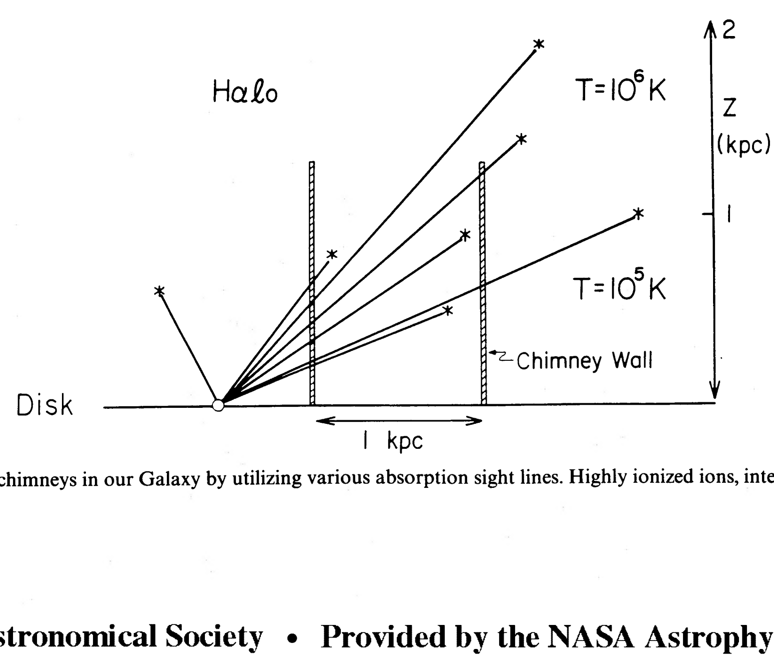

FIG. 6.—Probing the structure of chimneys in our Galaxy by utilizing various absorption sight lines. Highly ionized ions, intermediate and low ionized ions, and H I component coexist in the halo.

outer regions of M101 contain large H I masses and holes. Here also detailed H I observation should show the chimney structure. Of particular interest are edge-on galaxies such as NGC 891 where the detailed vertical structure of our chimney model should be observable and also the magnetic field configuration could be inferred from polarization measurements. A simple question to be resolved is whether the vertical field structure is related to an even or odd dynamo. We predict that the chimney-driven halos should be also found in M33, M51, M83, NGC 253, NGC 6946, and IC10.

e) *Interstellar Media of Galaxies*

i) *Elliptical Galaxies*

The concepts of global mass and energy flow into galactic coronae can also be utilized to consider the X-ray emitting halos of elliptical galaxies. We also see the range of physical parameters relevant to elliptical galaxies in Figure 2. The current observed supernovae rates and inferred mass injection rates are too low to power observed halo radiation fluxes. Therefore cooling of these halos will occur on a long time scale. The diagram should be viewed as a *cooling* diagram with the eventual evolution of any elliptical halo moving downward to the left along the cooling line. We note that the gravitational energy liberated is given by

$$\dot{E} = 10^{41} \dot{M}(M_{\rm halo}/10^{12} M_\odot) R_{\rm halo,\,23}^{-1} \text{ ergs s}^{-1} . \quad (28)$$

We translate the horizontal axis of Figure 3 as the mass cooling and accreting onto the galaxy with its associated liberation of gravitational energy given above.

The early stages of an elliptical galaxy halo will have *large* energy input and mass input from supernova and winds during the initial process of galaxy formation and evolution. These halos do *not* necssarily blow away, and therefore these halos will be found in the top right-hand portion of the diagram. Then, after formation, they evolve down the cooling line.

ii) *Starburst Galaxies*

The powerful, very luminous starburst systems such as M82 and Arp 220 have greater than or of order one supernova per year, i.e., a power input above 10^{44} ergs s^{-1} and the mass ejection rates are of order 10–100 $M_\odot$ yr^{-1}. With these parameters these systems are above the cooling line and prodigous ejection of supernovae driven winds does occur. These are, in fact, observed as bipolar flows and loop and arc structures around these galaxies (Heckman, Armus, and Miley 1987).

iii) *Dwarf Galaxies*

Dwarf galaxies are located in the bottom left part of the diagram in Figure 2. The medium is clearly in the two-phase mode. In the quiescent state, winds do not occur. However, since the binding energy is low and the escape velocity is of order 50 km s^{-1}, any starbursts that occur in these objects forming superbubbles will easily break out into the halo and eject enriched material (Ikeuchi and Norman 1987).

The state of the interstellar media in disk galaxies may be roughly determined by studying Figure 1 and locating where a galaxy lies using the best estimates of its observed Type II supernovae rate and its mean ambient density. We expect a trend from three-phase homogeneous to chimney to two-phase as we move from early to late type. The mean ambient density increases by of order 3–10 across the Hubble sequence S–Irr. There is also a strong increase in the number of massive stars, $N_{\rm SN}$ in the most massive H II regions in a galaxy as a function of type. In later type systems, the value of $N_{\rm SN}$ can exceed 10^3 (Kennicut, Edgar, and Hodge 1989). There are two additional important points to note. The parameters $\gamma_{\rm II}$ and n_a can vary as a function of galactocentric distance so that even in the same galaxy different phases may occur at different radii. Second, these parameters, and particularly $\gamma_{\rm II}$, can vary as a function of time particularly for galaxies that undergo bursts of star formation. Thus the state of a particular galaxy's interstellar medium as located on Figure 1 may vary between the phases both as a function of time and galactocentric distance.

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