The Interaction of the Disk with the Halo

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Abstract. In this review I focus on how massive stars in the disks of galaxies determine the properties of the ionized, gaseous haloes of star-forming galaxies. I first examine the ionization state of the halo, and conclude that diluted radiation from massive stars, along with a possible secondary heating source such as shocks, appears sufficient to explain the observations. I then look at how single superbubbles evolve, as they must provide one of the main mechanisms for transfer of mass and energy to the halo, as well as opening up lines of sight for ionizing radiation to escape from the disk. Finally, I look at the interactions of superbubbles, as they will rarely evolve in isolation, and describe recent hydrodynamical and MHD simulations of the interstellar medium shaped by multiple superbubbles.

1. Introduction

The high temperatures and ionization fractions of the gaseous haloes of star-forming galaxies must be explained by energetic processes, most likely occurring in the disks of the galaxies (though external sources could contribute). The most likely energy source for these processes are massive OB stars.

Stellar winds and supernovae drive shock waves into the interstellar medium (ISM) in the disk that can create superbubbles large enough to blow out of the disk into the halo. Numerical models of these blowouts reveal that rather little mass is lifted out of the disk by superbubbles (typically only a few percent of the total mass swept up by the shell), although that may still be enough mass to dominate the low-density halo. However, radiation from massive stars that would normally be absorbed by dust and gas in the galactic disk can escape out into the halo through the holes carved by superbubbles. This radiation will ionize the halo and could even drive gas motions. The superbubble chimneys might also provide an avenue out of the disk for metals produced by the SNe of the massive stars in the plane, allowing metal redistribution, or, particularly for starburst galaxies, even metal ejection.

Understanding the overall structure of a halo controlled by massive stars requires understanding not just the structure of isolated superbubbles in a smoothly stratified background medium, but also the results of their interac-

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tions. Numerical models have started to appear that address this, though the challenge of including all the relevant physics (magnetic fields, radiation, heating and cooling, cosmic rays) remains a daunting one. However, such models are required to understand the actual structure of the chimneys that allow the existence of the halo. They will also tell us a great deal about the structure of the ISM in the disk, naturally.

I also briefly consider models of the galactic halo that rely primarily on magnetic field generation by gas motions in the disk followed by reconnection heating in the halo or even ejection of mass along open field lines in a galactic wind. In these models, the energy would primarily be carried by the magnetic field, although the source of energy for both field generation in the disk and for transport of field into the halo may remain the massive stars in the disk.

2. Ionized Gas

It has become clear through the efforts of Reynolds (1984, 1989) and others that a large fraction of the ionized gas in the ISM is contained not in traditional H II regions but rather in diffuse ionized gas with a scale height of a kiloparsec or more, as reviewed by Dettmar (1992). This gas has now been demonstrated by the Wisconsin H-Alpha Mapper (WHAM; Reynolds et al. 1998) and other surveys to be highly structured, and not a smooth, stratified medium.

Similar layers of Hα-emitting ionized gas are seen in external galaxies. They are most easily observed in edge-on spiral galaxies such as NGC 891 (Rand, Kulkarni, & Hester 1990, Dettmar 1990). Not all spiral galaxies show an observable extraplanar layer of ionized gas (Pildis, Bregman, & Schombert 1994; Rand 1996). Rather, the occurrence and intensity of such layers appears to be directly correlated to the star-formation rate per unit area in the disk of the galaxy (Rand 1996, 1998b).

The energy requirement for ionization of the diffuse ionized gas in the Galaxy, both in the plane and above it, is 100% of the kinetic energy contributed by supernovae, or 15% of the energy in ionizing radiation from hot OB stars (Reynolds 1984, 1987, Dettmar 1992). As it would be rather difficult to imagine a fully efficient method for transferring energy from supernovae to ionization of the diffuse gas, radiation from hot stars appears at first the most likely suspect.

However, this raises the question of how to get so much of the ionizing radiation out of classical H II regions into the diffuse gas hundreds or even thousands of parsecs away from the stars. Furthermore, the ionization state of the diffuse ionized gas at high altitudes is higher than in gas in H II regions in our own (Reynolds 1985a, b) and external galaxies (e.g., Dettmar & Schulz 1992, Golla, Dettmar, & Domgörgen 1996), as shown by observations of values of the line ratios [S II]/Hα and [N II]/Hα as much as twice as high as in H II regions.

A number of explanations of this problem have been advanced. Extragalactic ionizing sources will contribute to the ionization, but can ionize only very low column densities of neutral hydrogen (Maloney 1993, Corbelli & Salpeter 1993), so they cannot explain most of the diffuse ionized gas in the plane of the galaxy. Local heating by shocks is suggested by the high [S II]/Hα and [N II]/Hα

line ratioes, but again runs into the question of the energy source. It may well be an important secondary source of ionization to help explain the high line ratioes above the plane of the galaxy (e.g. Martin 1997, Rand 1998a). Similarly, turbulent mixing layers in the walls of superbubbles might contribute to the heating (Begelman & Fabian 1990; Slavin, Shull, & Begelman 1993). Scattering of ionizing radiation by dust should harden the radiation field with altitude (Ferrara et al. 1996), explaining the increasing line ratioes. However, Domgörgen & Dettmar (1997) observed similar increases in line ratioes with altitude in the metal-poor galaxy NGC 2188, where dust should have played a smaller part, suggesting that this explanation fails.

Local heating by reconnection of twisted magnetic field lines is another possibility that has only been modeled in principle (Birk, Lesch, & Neukirch 1998), as I discuss in the final section. Similarly, dissipation of MHD turbulence has been proposed by Minter & Spangler (1997). A more exotic proposal by Sciama (1990, 1998) is that the ionization is due to the decay of neutrinos with a mass of 27.4 ± 0.2 eV, a value that may soon be directly comparable with experimental results from Super-Kamiokande, which has already measured a difference in masses between electron and muon neutrinos of only 0.07 eV (Fukuda et al. 1998).

The most convincing explanation for the behavior of the ionization with altitude still seems to me to be simple dilution of the ionizing radiation field with distance from the stellar sources (Domgörgen & Mathis 1994). Although it cannot explain all the details, it appears to account for the general pattern of ionization. Some secondary sources of heating or ionization may also be at work, but they do not dominate the energetics. This model also predicts that about 4% of the ionizing radiation from OB stars actually escapes the Galaxy entirely.

There are now quantitative measurements of the amount of ionizing radiation escaping the Galactic disk. High-velocity H I clouds provide one screen upon which escaping radiation can be observed. They are located several kpc above the Galactic disk (Wakker & van Woerden 1997) outside of the observed diffuse ionized gas. Observations of them in Hα by Tufte, Reynolds, & Haffner (1998) and Bland-Hawthorn et al. (1998) have detected weak emission associated with them. Similarly, the Magellanic Stream provides another screen, from which Weiner & Williams (1996) have also detected weak Hα emission. These observations have been interpreted by Bland-Hawthorn & Maloney (1998) as implying the equivalent of an optical depth $\tau = 3$ in a uniform galactic disk. This is fully consistent with the prediction of Domgörgen & Mathis (1994).

These models still neglect the question of exactly how the radiation reaches great distances from OB associations. Presumably the existence of superbubbles and other large-scale structures helps radiation to travel long distances. However, although the propagation of radiation in a uniform stratified disk has been studied (Miller & Cox 1993; Dove & Shull 1994), as has the radiation from thermally ionized mixing layers in the walls of blown-out superbubbles (Begelman & Fabian 1990; Slavin, Shull, & Begelman 1992), the propagation of radiation through a medium structured by superbubbles has not (although a poster by Basu et al. at this conference took first steps in that direction). Certainly, the

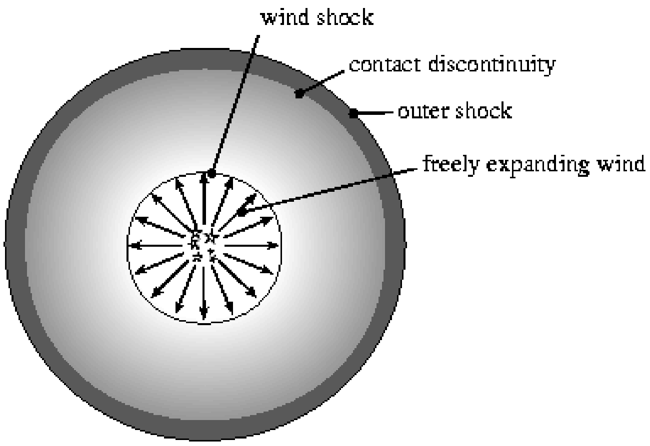

Figure 1. Structure of typical superbubble before blowout, showing freely expanding winds and blast waves, inner termination shock, hot shocked gas, contact discontinuity, cold, dense shell, and outer shock.

observed morphology of the diffuse ionized gas does not strongly resemble the ionization cones computed by Miller & Cox (1993) or Dove & Shull (1994).

3. Single Superbubbles

Most ionizing OB stars remain in their parent associations, where ten to a thousand massive stars have formed in a small region. All the stars within an OB association heavy enough to become SNe at all will do so within 50 Myr of the formation of the association. The resulting superbubble must be at least part of the explanation of how ionizing radiation can travel such long distances from the ionizing stars. Figure 1 shows the structure of a typical superbubble (Castor, McCray, & Weaver 1975, McCray & Kafatos 1987). Winds and SN blast waves freely expand until they reach an inner termination shock. The kinetic energy of the expanding gas is converted to thermal energy, producing a hot, shocked region. The pressure of this region drives a shock into the surrounding interstellar gas, sweeping it up into a shell. The temperature of the hot, shocked region is held down to a few million degrees by conductive evaporation off the swept-up shell. In the rest of this section, I describe the development of superbubbles as they interact with stratified density distributions in dwarf and spiral galaxies. (This topic has also recently been carefully reviewed by Bisnovatyi-Kogan & Silich 1995, with a focus on thin-shell methods).

The most basic question to ask is when will a superbubble blow out of a stratified ISM—that is, when will it accelerate until it reaches a uniform halo or intergalactic medium? A dimensional analysis calibrated by the semi-analytic model of Mac Low & McCray (1988) can give the answer (see Koo & McKee 1990 for a similar treatment). The relevant scales for this problem are the mechanical luminosity of the OB association L_m, the scale height of the density distribution H, and the midplane density ρ_0, and pressure P_0. The time scale is then the time for a spherical superbubble to reach dimensions comparable to a scale height (Castor *et al.* 1975), $t_1 \sim H^{5/3}(\rho_0/L_m)^{1/3}$. The sound speed at the midplane $c_s = (\gamma P_0/\rho_0)^{1/2}$ gives a velocity scale. This can be compared to the velocity of the superbubble when it reaches a scale height,$v_1 = (3/5)(H/t_1)$. The Mach number of the superbubble when it reaches a size comparable to a scale height $M_1 = v_1/c_s$ determines whether a superbubble will ultimately blow out or be pressure-confined by the external medium.

The actual calibration of this criterion must be done using semi-analytic techniques. Kompaneets (1960) showed that a blast wave in a zero-pressure, exponential atmosphere will always blow out. The thin-shell approximation that he used can be adapted to the present problem. The assumptions used are that the shell of swept-up gas is thin and that the interior pressure acting on it is uniform everywhere. The latter assumption is equivalent to assuming that the sound speed in the interior is far greater than the expansion velocity of the shell. Mac Low & McCray (1988) divided the shell up into a number of segments and numerically integrated the equations of motion of the shell in an arbitrary, finite-pressure, stratified atmosphere to find its shape and expansion velocity. They find that if a bubble has $v_1/c_s > 5$ it will blow out of an exponential atmosphere.

When the shell begins to accelerate upward, it becomes Rayleigh-Taylor unstable, as the rarefied interior effectively supports the dense shell. Numerical models show that the shell then fragments and releases its internal pressure (Mac Low, McCray, & Norman 1989, and see the review by Tenorio-Tagle & Bodenheimer 1988). The subsequent evolution has been analytically modeled by Koo & McKee (1990). It is notable that when a shell blows out, only a very small fraction of its mass is actually accelerated up at any significant velocity. For example, Mac Low *et al.* (1989) found that only 5% of the shell mass ended up in the portion of the shell accelerated upwards.

The models of superbubble blowout described so far assumed a stratified but isothermal atmosphere, typically with a temperature of 10^4 K typical of the diffuse ionized gas. The alternative extreme was later studied, with a warm disk, and a hot halo with temperatures of order 10^6 K (Igumentschev, Shustov, & Tutukov 1990; Tenorio-Tagle, Różyczka, & Bodenheimer 1990), showing that blowouts would eject small amounts of warm gas into a hot halo. These models also included simple approximations to thermal conduction, although the conclusion was reached that this indeed doesn't make much difference to shell structure.

Magnetic fields can strongly influence superbubble structure. The actual strength of the field in the Milky Way is estimated to be between 3μG and 5μG. If the field is towards the upper end of this range, it is sufficiently strong to confine most superbubbles and contain much of the kinetic energy injected by supernovae as magnetic pressure (*e.g.* Slavin & Cox 1992). The behavior of magnetized superbubbles was first studied using a semi-analytic "thick-shell" model by Ferrière, Mac Low, & Zweibel (1991), and using a 2D numerical model by Tomisaka (1992). Using slab-symmetric 2D models, Mineshige, Shibata, & Shapiro (1993) demonstrated that sufficiently strong magnetic fields could prevent immediate blowout. Tomisaka (1990, 1998) has now done three-dimensional models demonstrating confinement, and also showing that fields can lead to sig-

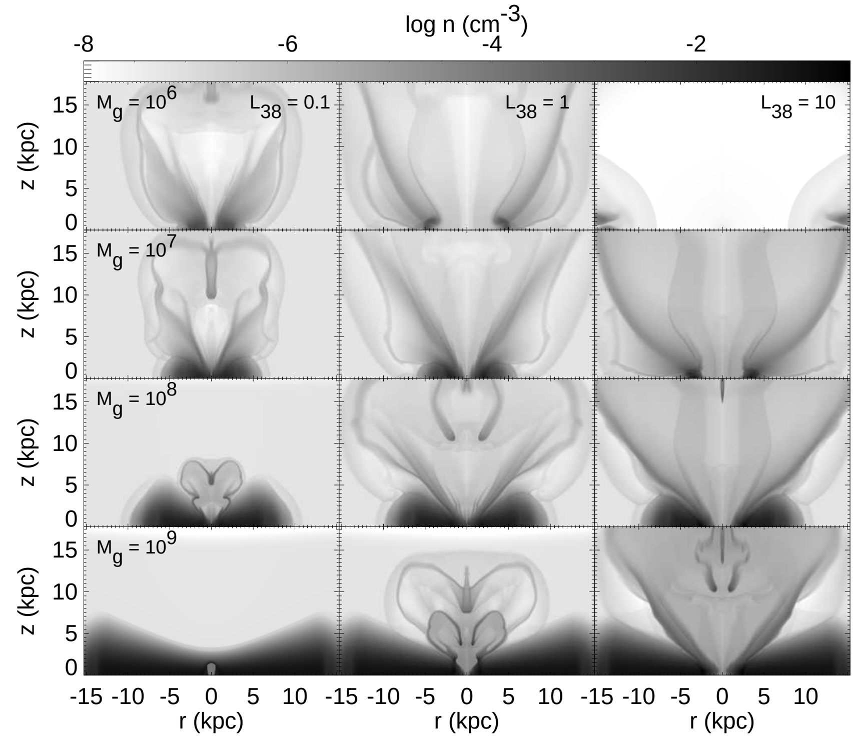

Figure 2. Density distributions of models of galaxies by Mac Low & Ferrara (1999) with the given gas masses in solar masses, containing starbursts of the given mechanical luminosities in units of 10^{38} erg s^{-1} at a time of 100 Myr, some 50 Myr after the end of energy input from the starbursts, with the values of density given by the colorbar at the top of the figure. The gravitational potentials from dark matter haloes were included in these simulations. Luminosities are equivalent to supernovae every 30,000 to 3 million yr.

nificant elongation of the bubbles, giving them the structure of a flat slice of a mushroom (or, for readers who have spent time in the US, a slice of Wonder Bread).

The most extreme case of the action of a single superbubble on the ISM is the case of a starburst in a dwarf galaxy, where the combined supernova explosions were even thought to be able to eject the entire ISM from the potential well of the galaxy (Dekel & Silk 1986). This question has been studied using thin-shell models by Silich & Tenorio-Tagle (1998), and using two-dimensional gas dynamical simulations by Mac Low & Ferrara (1999). Both groups show that the coupling between the ISM in the galaxy and the energy injected by the supernovae is poor because of the blowout of the resulting superbubble from the galaxy. Mac Low & Ferrara (1999) show that it is impossible with reasonable numbers of supernovae to completely blow away the ISM for galaxies with gas mass $> 10^7 M_\odot$, as shown by the parameter study shown here in Figure 2. On the other hand, they also show that metal-enriched ejecta from the Type II supernovae resulting from the starburst escape easily, as first suggested by Vader (1986), providing a powerful selective depletion mechanism that might explain the observed odd abundance patterns.

4. Many Superbubbles

Superbubbles do not, in fact, expand into a smooth, stratified interstellar medium, much as theorists might wish otherwise. Rather, they expand into a medium strongly structured by previous superbubbles, isolated supernovae (especially in the halo; see Shelton 1998), ionization fronts, and radiative cooling. Models must take this into account in order to make contact with the observations at anything more than the most qualitative level.

The first serious attempts to do this numerically were initiated by Chiang & Bregman (1988) using a multi-fluid code that followed the gas and a star "fluid" in two dimensions. The two fluids were coupled by a density-dependent star formation term and by energy input from the star fluid to the gas. This approach was developed in a series of papers by Rosen & Bregman (1995; Rosen, Bregman, & Norman 1993; Rosen, Bregman, & Kelson 1996), adding physics, increasing resolution, and computing observable quantities. These computations were the first to make clear that observed structures are not isolated objects but just particularly recognizable parts of an active, complex medium. The difficulties encountered by radio observers in picking structures out of the HI is not accidental, but due to the very structure of the gas under observation. Attempts to model these structures as isolated objects will naturally then run into serious difficulties and should be embarked on only with the greatest caution.

Large-scale models are now being developed by several different groups. Vázquez-Semadeni discusses his group's two-dimensional models of the plane of the Galaxy including magnetic fields in these proceedings. The first three-dimensional models of the integrated system were performed by Avillez, Berry, & Kahn (1997) using an adaptive mesh refinement technique to achieve 10 pc resolution. They explicitly included both correlated and random supernova energy input in discrete events. They found that a patchy, inhomogeneous Reynolds layer shown in Figure 3 was naturally generated if enough supernovae went off, quite regardless of the initial density profile they started with. Observed chimneys and worms formed due to interactions of superbubbles, not as isolated superbubbles blowing out of the disk, and so have rather different dynamics than would be expected from isolated objects (Avillez 1998a, 1998b).

Magnetic fields will be important in determining the actual interactions between superbubbles and other energetic structures in the interstellar medium. The models described up to this point have neglected the effects of magnetic fields due to their numerical difficulties, however. Semi-analytic models of superbubbles driving a galactic dynamo to maintain the magnetic field of the galaxy are discussed by Ferrière in these proceedings. Her models, in combination with observational constraints, yield the vertical distribution of hot gas above the plane of the galaxy, with high filling factors of hot gas occurring at altitudes of more than a scale height or so (Ferrière 1995, 1998). This suggests that the observed warm ionized gas at high altitudes might actually be confined to thin sheets with very low filling factor.

An exciting development in the last year has been the attempt by Korpi et al. (1998), described by them as well in these proceedings, to include magnetic fields in a fully three-dimensional large-scale model of the interstellar medium including energy input from correlated and random supernova explosions as well as the effects of galactic shear and stratification, as shown in Figure 4.

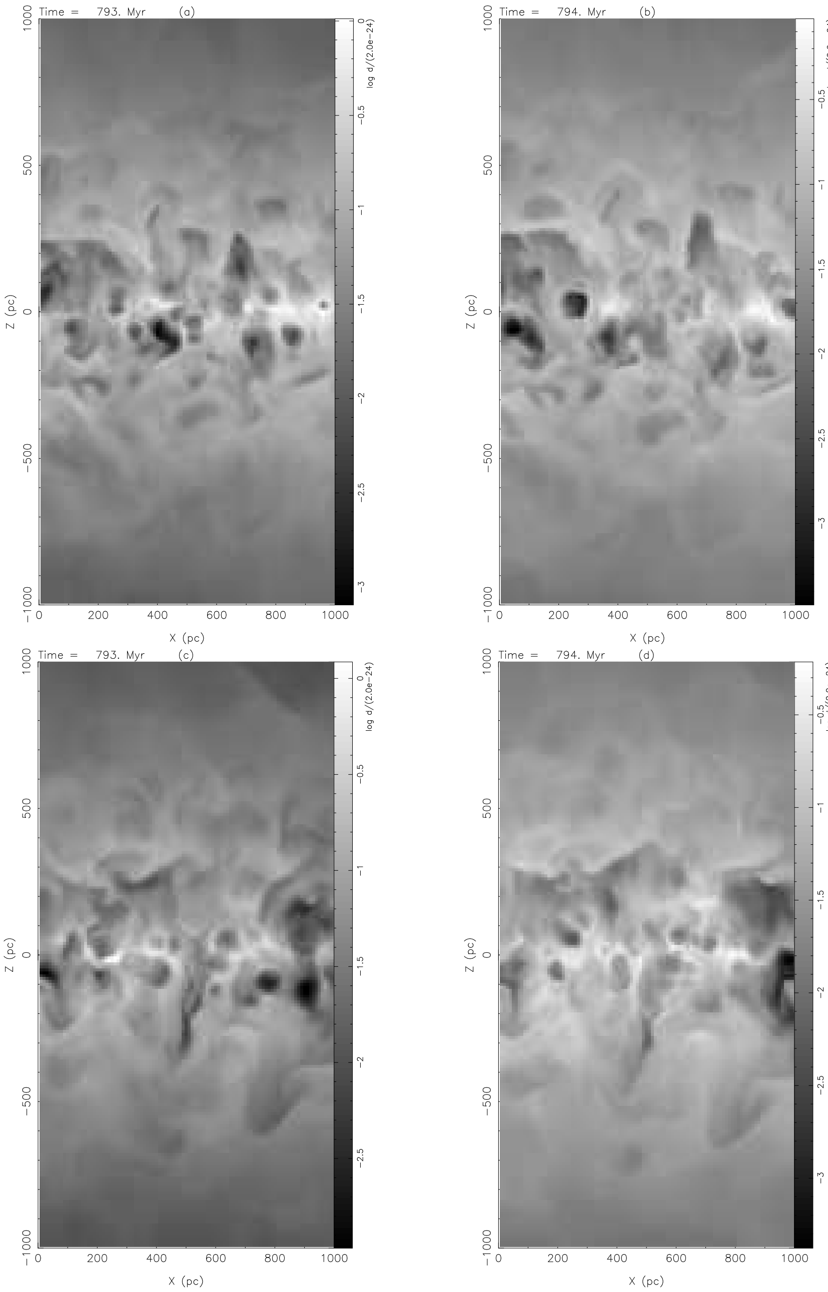

Figure 3. Grey-scale maps showing the evolution of the disk gas in three-dimensional models by Avillez, measured at two locations in the disk: $y = 480$ pc ((a) and (b)) and $y = 980$ pc ((c) and (d)). The times of these images are 793 Myr ((a) and (c)) and 794 Myr ((b) and (d)). Globally the disk has similar structure in all the images, although locally there are variations. Note the global expansion of warm gas carving through the thick disk and the constant presence of the wiggly cold disk in the midplane. Local outbursts such as the chimney located at $x = 500$ pc and $z = -100$ pc ((c) and (d)) are also seen.

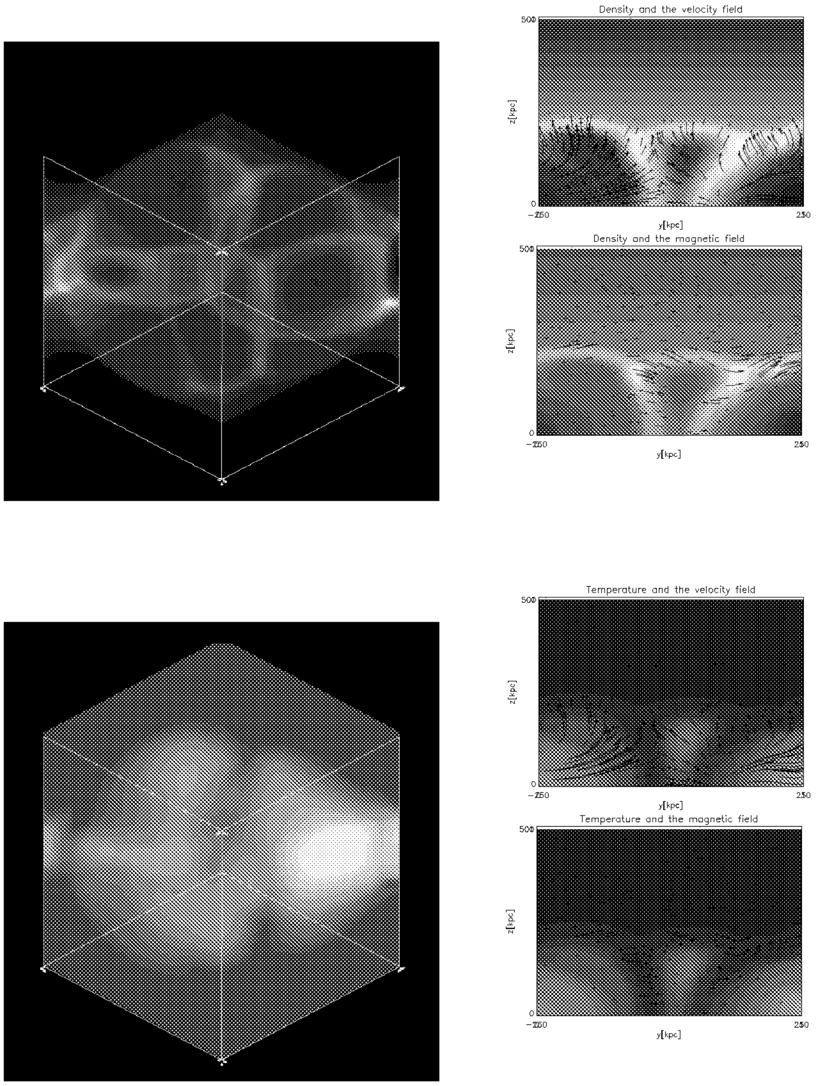

Figure 4. A local 3D MHD simulation of the Galaxy by Korpi, *et al.* (1998, also see this volume), with $L_x = L_y = \frac{1}{2}L_z = 0.5kpc$. The disk is heated by supernova explosions, which produce hot bubbles surrounded by thin, dense and cool shells (see upper and lower left panels: 3D plots of density and temperature are shown). Supernovae can interact and form superbubbles: in the upper left panel, smaller bubbles are produced by single supernovae, while the larger ones contain multiple supernovae. Due to density stratification in the vertical direction, the bubbles become elongated vertically, as shown in the 2D cuts on the right of density (above) and temperature (below). Hot matter is effectively transported outwards from the Galactic plane (as shown by the velocity vectors in the top of each pair of panels on the right; the bottom of each pair includes magnetic field vectors.

5. Magnetic Coronas and Galactic Winds

In addition to the interactions of magnetic fields with superbubbles already described above, other magnetic effects on the structure of the halo have also been proposed. By analogy with the solar corona, local reconnection of turbulent magnetic fields has been suggested as an extra heating mechanism in the halo in order to explain the anomalous line ratioes discussed above (Birk, Lesch, & Neukirch 1998). However this mechanism would require reconnection sheets 300 to 3×10^4 km wide throughout the halo. Producing so much fine structure with the relatively large-scale driving mechanisms available such as supernova remnants and superbubbles seems difficult. If it were indeed present, however, one might expect it to be visible in measurements sensitive to such small scales, such as pulsar scintillation observations.

At the other extreme of size scale, open field lines extending from the galactic disk, produced by superbubbles blowing out, Parker instabilities, or some combination thereof, might allow galactic winds driven by large-scale gradients of cosmic rays (Breitschwerdt, McKenzie, & Völk 1991, 1993; Zirakashvili *et al.* 1996, Ptuskin *et al.* 1997). These models seem directly relevant to the radio synchrotron haloes observed around star-forming galaxies (e. g. Dahlem, Lisenfeld, & Golla 1995, and see the review by Dettmar 1992), but no direct comparisons have yet been made, to my knowledge. Such comparisons would be fruitful.

6. Conclusions

- Diffuse ionized gas seen in Hα emission is most likely ionized by dilute radiation from hot stars, perhaps with some secondary heating from shocks or other sources.
- Full understanding of the diffuse gas will requre models combining the effects of dynamics and ionizing radiation.
- Interactions between superbubbles may be as important as the development of isolated superbubbles.
- The Reynolds layer is probably not continuous, but rather fragmentary and incomplete, only becoming a full layer in very active star-forming galaxies like the Milky Way or NGC 891.
- Superbubble blowouts transfer energy and metals to the halo and intergalactic medium, but not significant mass.

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