Observations and Modeling of the Disk-Halo Interaction in our Galaxy

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Abstract. Galaxies are surrounded by large halos of hot gas which must be replenished as the gas cools. This led Norman & Ikeuchi (1989) to propose the chimney model of the interstellar medium, which predicts that there should be on the order of a thousand such conduits connecting the disk and the halo of a galaxy.

Where then are these structures and other possible disk-halo connections in our galaxy? What do they look like, how can we detect them, and what do they tell us about the interstellar medium and about the Galaxy?

We present a review of the observational evidence for Galactic disk-halo connections, beginning with large scale searches and then concentrating on the characteristics of selected candidates. We summarize how modeling these structures can provide information on the structure of the interstellar medium in which they evolved, focusing on the W4 superbubble and the Anchor as illustrations.

1. Indications of and predictions for Galactic disk-halo interactions

1.1. Why do we need disk-halo interactions?

In his discussion of disk-halo interactions in external galaxies, Michael Dahlem (these proceedings) pointed out that attempting to study disk-halo interactions in our own galaxy leads to the old problem of not being able to see the forest for the trees. While it is true that our position within the system prevents us from gaining a global view, there is much to be learned from close-up examinations: the trees have much to tell us about their environment.

Not all galaxies show evidence of disk-halo interaction, in fact not all galaxies have a halo as indicated by Dahlem. So what of our galaxy? Does it have a halo and if so, do the disk and halo interact? Several observations suggest that they do.

The bulk of the atomic hydrogen (HI) is near the Galactic plane. Lockman et al. (1986) found two components to its distribution in the solar neighbourhood: 1) a Gaussian with $\sigma_z = 135$ pc (sometimes referred to as the HI cloud
layer, hereafter the thin HI disk), 2) an exponential with a scale height of 500 pc (sometimes referred to as the HI intercloud layer, hereafter the thick HI disk). However, ultraviolet absorption lines of highly ionized species (CIV, SiIV, NV) imply the existence of a halo of hot gas (greater than at least several \( \times 10^4 \) K) with a scale height of \( \sim 3 \) kpc (Savage & Massa 1987). This halo requires energy and momentum to maintain it, as well as a source of metals.

Within the halo there are clouds of colder gas, the Intermediate Velocity and High Velocity Clouds (IVCs and HVCs; see review by Wakker & van Woerden 1997). These cover more than 10% of the sky and may contain as much as 10% of the HI mass of the Galaxy. While some are related to the Magellanic Stream and others are seen as an Outer Arm extension, a third group requires some other explanation. In the context of the chimney model of the Galaxy (Norman & Ikeuchi 1989), these clouds are composed of gas that has cooled after flowing up chimneys; some are still rising while others are falling back towards the disk. Although metallicity determinations remain quite uncertain (by a factor of 3–5) for the HVCs and IVCs, there have been indications that their heavy element abundances are comparable to that of ordinary interstellar gas (Danly 1991), consistent with the picture of these clouds being cooled processed gas from the plane.

Closer to home, the so-called Reynolds layer (see the contribution by Reynolds in these proceedings) of warm, ionized gas has a scale height of \( \sim 1 \) kpc but its source of ionization is unclear. A significant fraction (\( \sim 15\% \), MacLow in these proceedings) of the ionizing photons from the Galactic O stars would suffice but these stars are almost exclusively confined to the disk and it is therefore difficult for their ionizing radiation to escape to higher latitudes. Chimneys could be the solution to this quandary by providing conduits through which the photons could travel unimpeded away from the disk. In addition, Norman (1991) suggested that the walls contribute to the ionization of upper Galactic layers through diffuse, re-emitted radiation, and that this would affect a much wider angular range than does the radiation escaping directly up the conduit.

A final element which was called upon by Norman & Ikeuchi in support of their model was the filling factor of the Hot Ionized Medium (HIM) in the disk, \( \leq 20\% \) at the solar circle (Ferrière, these proceedings) which is substantially lower than predicted in the McKee & Ostriker (1977) model of the ISM. By confining the hot gas to chimney conduits and evacuating it to higher latitudes, a lower disk HIM filling factor is obtained.

### 1.2. How many superbubbles and chimneys should there be?

Estimates of the number of chimneys in our galaxy vary considerably. Norman & Ikeuchi (1989) estimated that, for a steady state, there should be 1000 such conduits. However, this is an estimate of the total number of superbubbles, based on the rate of type II supernovae, the fraction of early type stars belonging to OB associations, and the expected number of supernovae in a single OB association. The assumption is then implicitly made that all superbubbles are chimneys. This is however unrealistic. Not all superbubbles will blow out of the disk and into the halo. In fact, the magnetic field of the Galaxy may prevent most superbubbles from blowing out (Tomisaka 1990, 1998).
A more reasonable estimate is the empirical one by Heiles et al. (1996). Based on an extrapolation of the worms observed in one quadrant, they predicted the existence of at least 50 and probably no more than 100 worms in our galaxy. However, worms are not necessarily chimneys, as explained below.

2. Where are the Galactic chimneys?

2.1. Wide field searches: Worms

While cataloguing HI shells and supershells, Heiles (1984) pointed out the presence of “wiggly gas filaments crawling away from the Galactic plane”. These he dubbed worms and postulated that they may be remnants of supershells that have opened at the top.

Following this introductory work, Koo et al. (1992) set about drawing up an inventory of worm candidates. To produce their list of 118 structures, they made use of two existing low resolution HI surveys (Weaver & Williams 1973; Kerr et al. 1986), some supplementary HI observations at the Hat Creek Radio Observatory, and the IRAS 60 µm and 100 µm images. They integrated the HI over the entire velocity range (–200 to +200 km/s) then applied a median filter to this image as well as to the infrared ones. An “object” present in all three was considered a worm candidate. While this method provides an objective sample of possible worms, the integration over all velocities will mask some true worms and possibly create false ones, and clearly many of the candidates are not proper worms because they are not perpendicular to the plane.

A second, less objective yet possibly less misleading catalogue was produced by Heiles et al. (1996) and contains twenty-seven worms. Their selection was based on morphology at 2695 MHz (data from Reich et al. 1990) and Radio Recombination Lines (RRLs). All of their worms are within the first quadrant of the Galaxy (ℓ_{max} = 61.5°) and twelve of the fifteen for which distances can be evaluated are within the Galactocentric azimuth range 90° < θ < 180°; this is the origin of the estimate mentioned in the previous section.

2.2. A few examples

With these catalogues of potential chimneys and superbubbles available, one would think that many of these structures would have been studied in detail. One would be mistaken. Only a very few structures possibly denoting a disk-halo interaction have been closely examined.

The Stockert Thermal Spur The Stockert Thermal Spur, or Stockert Chimney, was the first chimney candidate to receive attention (Müller et al. 1987). The structure originally studied was a spur extending from 2° to 8° in latitude, above the S54 HII region. Its spectral index indicated thermal emission, consistent with the chimney picture in which the walls are photoionized. At a kinematic distance of 2.9 kpc, this structure is 300 pc high, putting its tip above the thin HI disk.

While the position and velocity of S54 suggest a relationship between it and the spur, the stars in the HII region cannot have caused outflow up to 300 pc (the outflow velocity would far too great, ~4500 km/s) nor can they account for the ionization.
Figure 1. The W4 superbubble/chimney
The greyscales show the HI emission (white $\leq 0$ K, black $\geq 80$ K) at $-43.4$ km/s and the contours outline the radio continuum emission at 1420 MHz (5 K). The W3, W4, and W5 HII regions are labeled and the star symbols indicate the positions of the O-stars in the OCl 352 cluster. The scale given at the top of the cone assumes a distance of 2.35 kpc (Massey et al. 1995). These data are from the CGPS pilot project (Normandeau et al. 1997).

This structure is associated with a worm in the Heiles et al. (1996) catalogue (GW18.5+2.8). These authors point out that if this is the worm in its entirety then it is curious in that it is not limb brightened. Furthermore they detected RRL emission from $\ell \approx 15^\circ$ to $21^\circ$ and suggested that the thermal spur is in fact only one wall of a chimney or superbubble and that it is powered by the M16 cluster which is centred at the base of the region of RRL emission.

The W4 superbubble/chimney While the composite structure encompassing the Stockert Thermal Spur is suggestive of a superbubble which has burst, there is no indication of outflow towards higher Galactic latitude. The Canadian Galactic Plane Survey (CGPS) pilot project revealed a conical void in the HI distribution above the W4 HII region (Normandeau et al. 1996), within which there are features suggestive of such an outflow (Figure 1). The V-shaped streamers seen within the chimney at $-45.0$ km/s are the culmination of a development from a compact cloud at the latitude of the base of the V at $v_{LSR} = -33.5$ km/s which gradually extends as velocity becomes more negative.

The walls have an inner lining which is visible in the infrared as well as in the radio continuum, with a spectral index indicating thermal emission. There is an HI arc at $b \sim 3.8^\circ$ but it does not completely close off the shell and it was originally postulated that this is a remnant of the supershell that had burst to create the chimney. Recent observations have shown that the eastern wall, as seen in HI, extends to a latitude slightly greater than $6^\circ$ (Normandeau 1998).
The energy source powering this structure seems clear: at the base of the cone lies the OCl 352 cluster which contains nine O-stars, one of which is O4 and two are O5. The wind luminosity of these stars can certainly account for the evacuation of the cavity seen in the pilot data and their age is in agreement with the time required for the cavity to expand to its current size (see discussion in §4.1.), as well as allowing enough time for the streamers to have stretched to their present length.

Hα observations by Dennison et al. (1997) suggest the presence of a cap at $b \sim 7^\circ$, corresponding to a height of approximately 200 pc above the star cluster. While their detection is marginal and there is no evidence for closure of the supershell in the extended HI observations, this is not an impossible or even an improbable situation as shall be explained below when modeling is discussed. It suggests that while the W4 superbubble has certainly broken through the thin disk of atomic hydrogen, it has not broken out of the thick disk to connect to the halo. However, it has reached into the Reynolds layer and can contribute to its ionization.

The Anchor

More recently, the Galactic worm GW123.4–1.5 has been receiving attention (English et al. 1999). This anchor-shaped HI feature appears to be dangling from the Galactic plane at a longitude of 124° (Figure 2).

The stem extends 2.8° perpendicular to the plane of the Galaxy, and is topped by a 2.9° wide cap. The structure covers a total velocity width of $\sim 27$ km/s, with the cap being redshifted from the stem by $\sim 5$ km/s. The stem appears to be hollow and expanding radially. With a central velocity of $-41$ km/s the anchor is at a kinematic distance of 3.6 kpc. This would imply a stem length of 177 pc and the top of the cap would be $> 300$ pc from the plane. The scales indicate that once again we are looking at a structure connecting the thin disk and thick disk, rather than the disk and the halo.

The energy source of the Anchor remains a mystery. While the latitude of the HII region S185 places it at the base of the stem, its radial velocity is approximately $-3$ km/s, inconsistent with the velocities of the Anchor.

2.3. Where do we go from here?

Although disk-halo interactions in the form of chimneys would elegantly explain several observed Galactic phenomena, we have yet to see a clear-cut example of such a conduit, though we have begun examining structures connecting the thin disk and the layers directly above it.

The search for chimneys continues. Several avenues are possible. Catalogues of worms using various data sets should and are being compiled (e.g., from the Leiden-Dwingeloo HI survey, Burton & Hartmann 1994). Follow-up observations of worms and worm candidates should be carried out at higher resolution in the radio continuum, recombination lines, and HI spectral line. In addition, since the interior of a chimney is occupied by hot gas which is being evacuated to the halo, good candidates should be examined for X-ray emission and absorption lines of highly-ionized species.
Figure 2. The Anchor
Data from DRAO observations in the HI spectral line. Darker shadings correspond to brighter HI emission. The scales indicated are for a distance of 3.6 kpc. Figure courtesy Jayanne English.

3. Models of disk-halo interactions

There are several models in the literature which can be applied to a study of observed disk-halo interaction candidates. Some of these models are reviewed below since their general features can be used to interpret observations and gain insight into the disk-halo candidates and their environment.

The earliest blowout model is by Kompaneets (1960), who found an analytic solution for the shape of a blast wave propagating into an exponentially stratified atmosphere. This model simply calculates the shape of a strong shock propagating into a pressure-free environment, without taking into account the inertia of the swept up mass. Although initially motivated to study interactions with the Earth’s atmosphere, it can and has been applied in an astrophysical context as well. More sophisticated models of bubble expansion in an astrophysical context include the thin-shell approximation (MacLow & McCray 1988), which determines the expansion speed of the bubble through numerical integration of the momentum equation for various segments of the thin shell of swept-up gas. This approach accounts for the inertia of the swept-up shell, and external pressure and gravity can also be included. Finally, full numerical integration of the hydrodynamic equations (Tomisaka & Ikeuchi 1986; MacLow et al. 1989; Tenorio-Tagle
et al. 1990) and magnetohydrodynamic equations (Tomisaka 1990, 1998) yield the most complete solutions to date.

Though there are some differences between the various models (see Komljenovic, Basu & Johnstone, these proceedings), all the models reveal the following general scenario. The bubble maintains a near-spherical expansion while its radius is less than or equal to the atmospheric scale height $H$, and if it expands beyond this height, it begins a rapid acceleration in the (vertical) direction of stratification, while continuing a decelerating expansion in the lateral direction. By late times, and at the time of blowout, the ratio of radius at source height to atmospheric scale height $R(z = 0)/H \approx 2$. The Kompaneets model also predicts that the ratio of maximum radius to scale height $R_{\text{max}}/H \approx 3$ at late times.

Although the models with finite external pressure do show that blowout does not always occur (see MacLow & McCray 1988 for a blowout condition), the models alone cannot tell us whether or not blowout should be common in our galaxy. This is because the blowout condition depends on the scale height of interstellar gas (MacLow & McCray 1988) and the scale height of the interstellar magnetic field (Tomisaka 1998). A large scale height component in either quantity can effectively confine most superbubbles, but since these parameters (especially the magnetic field) are not well constrained observationally at high latitudes, it is uncertain whether blowout is common.

Further insight into the blowout process is best obtained by comparing models with the observed structures, as these may give us insight into their ambient environment and thereby whether blowout may be commonplace.

4. Modeling the observed structures

The W4 superbubble and the Anchor are the two structures connecting the thin disk of HI to the layers above for which the most detailed information is now available. With these two objects, we can take the first steps away from the generic models described in §3, toward models evolving in more specific environments. Such modeling can yield information about the interstellar medium and also highlight constraints on the formation of disk-halo interactions.

4.1. W4 superbubble

The conical shape of the HI cavity (Figure [4]) provides an ideal application for models of superbubble expansion in a stratified (but smoothly varying) atmosphere. The observed shape of the cavity bears many similarities to those predicted by the various models discussed in §3.

As mentioned earlier, the HI maps suggest that the cavity is open on top, i.e., it is a chimney. However, the H$\alpha$ map of Dennison et al. (1997), which extends to $b \sim 8^\circ$, reveals a shell of H$\alpha$ emission (presumably the swept up shell surrounding the cavity that is illuminated by the O stars) that reaches a maximum diameter at $b \sim 4^\circ$ and becomes narrower above, apparently closing at $b \sim 7^\circ$.

Recent modeling of the W4 superbubble by Basu, Johnstone & Martin (1999, hereafter BJM) reveals that an open cavity in HI and a closed shell in H$\alpha$ are mutually consistent, as discussed below. BJM fit the shape of the cavity and H$\alpha$ shell with an analytic Kompaneets profile, yielding straightforward estimates
of the atmospheric structure and bubble age. The dependence of the solution on various parameters is most transparent when using this model. Figure 3 shows the Hα map of Dennison et al. (1997) overlaid with the best fit Kompaneets profile. The unmistakable narrowing of the Hα shell diameter above $b \sim 4^\circ$ means that blowout has not yet occurred, according to any of the theoretical models described in §3.

The W4 superbubble is highly elongated, implying that it has already expanded through significant vertical stratification. The radius of the bubble near the cluster must be approximately two scale heights, as discussed earlier. By matching the model to the observation, BJM demonstrated the unavoidable consequence that $H \approx 25$ pc near W4. This is based on the distance estimate $d = 2.35$ kpc to the OCl 352 cluster (Massey et al. 1995), which is similar to various previous estimates of $d \approx 2$ kpc to the star cluster and HII regions.

How are we to interpret such a low value of $H$, in comparison to estimates $H \gtrsim 100$ pc for the mean scale height of the thin HI disk in our galaxy? The answer probably lies in the fact that W3/W4/W5 is one of the major star-forming complexes in the outer Galaxy, where significant vertical compression of the interstellar gas must have taken place. The superbubble has sampled the distribution of molecular and cold HI gas near the cluster. On the other hand, we also note that the Hα shell extends to some 240 pc above the cluster, and it is remarkable that the shell maintains its oval shape over such a distance. Various models of bubble expansion (e.g., MacLow & McCray 1988) have shown that a bubble changes shape dramatically when it travels from a relatively low scale height atmosphere (e.g., the thin HI disk) to one with greater scale height (e.g., the thick HI disk); that is, the bubble radius expands to become comparable to the local scale height. This has not happened to the W4 superbubble.
Figure 4. Ionization front (solid line) around the best-fit Kompaneets model for W4 (inner wall of shell in dashed line). The bubble is embedded in an exponential atmosphere $n(z) = n_0 \exp(-z/H)$. Parameters used are $\Phi_* = 2.3 \times 10^{50} \text{ s}^{-1}$ and $H = 25 \text{ pc}$, while $n_0 =$ (bottom to top) 1, 5, 10, 15, 20 cm$^{-3}$ (from BJM).

up to a height $z \approx 240 \text{ pc}$. In fact, Komljenovic, Basu & Johnstone (these proceedings) argue that the bubble is so highly collimated that even a single atmosphere hydrodynamic model cannot adequately fit its shape, although the simpler Kompaneets model can. They argue that a significant vertical component of the magnetic field can be collimating the upper portion of the bubble, and that this may also explain the apparent lack of a Rayleigh-Taylor instability in the upper Hα shell, which is presumably accelerating. However, this does not significantly change the scale height estimate given above.

In addition to the powerful stellar winds which drive the W4 superbubble, the nine O stars in the OCl 352 cluster also produce an extremely strong ultraviolet radiation field, with a flux of Lyman continuum photons $\Phi_* \simeq 2.3 \times 10^{50} \text{ s}^{-1}$. This flux encounters a highly stratified atmosphere, so the resulting ionization front does not have the simple shape of a Strömgren sphere. BJM have modeled the shape of the ionization front resulting from the interaction of this ionizing flux with an exponentially stratified medium which has an embedded cavity and swept-up shell of matter as predicted by the best fit Kompaneets model. Figure 4 shows the location of the ionization front for various choices of the mean density $n_0$ near the cluster. In all cases, the ionization front opens up in a cone-like manner at some height, meaning that ionizing photons can escape to the Galactic halo within the cone. This is due to the low column of matter in the upper portion of the shell, since the diverging streamlines of an expanding superbubble continually push matter to the sides and cannot transport much matter to large heights (see MacLow, these proceedings). The breakout of ionizing photons near the top explains why one will not observe neutral H I above the bubble, giving it the appearance of a chimney. This despite the fact that an upper shell exists and
can be distinguished from its surroundings in Hα emission. The curves in Figure 4 place the constraint that $n_0 \geq 5 \text{ cm}^{-3}$ in the W4 region, since the ionization front is observed to be bounded at the latitude of the cluster. Furthermore, the observed drop-off in HI emission at $z \approx 100 \text{ pc}$ is best fit by the $n_0 = 10 \text{ cm}^{-3}$ curve, so BJM adopt this as the most likely value. These values are in good agreement with the observational estimate $n_0 \sim 5 \text{ cm}^{-3}$ at the latitude of the cluster (Normandeau et al. 1996). Incidentally, in this model about 15% of the Lyman continuum photons from the cluster escape through the top of the shell and can ionize layers above the thin disk. Fortuitously, this is the same as the estimated 15% of Galactic O-star ionizing photons that is believed necessary to account for the ionization of the Reynolds layer (see contributions by MacLow and Reynolds).

It is interesting to note that although BJM’s estimates for $n_0$ and $H$ in the W4 region are considerably higher and lower, respectively, than the mean ISM values, the column density $n_0H$ is only slightly higher than the corresponding mean ISM value. By obtaining estimates for $n_0$ and $H$, and using an observational estimate for the wind luminosity $L_0$, BJM also found the age of the superbubble: $t \approx 2.5 \text{ Myr}$. This is in agreement with various age estimates for the cluster, and supports the idea that the superbubble is blown by stellar winds in a cluster which is too young to have experienced any supernovae.

4.2. The Anchor

Although initially classified as a “worm”, the Anchor is clearly not just a superbubble wall, but an object in its own right. A preliminary estimate of its kinetic energy, based on its velocity width and estimated mass, is $\sim 2 \times 10^{50} \text{ ergs}$ (English et al. 1999). Since these kinds of energies are most readily supplied by supernovae or stellar winds, it is natural to wonder whether the Anchor is another superbubble.

The unusual mushroom shape of the object defies a simple explanation, unlike the W4 superbubble which has the conical shape expected from most models. In particular, the extreme contrast between a narrow stem and wide cap is difficult to explain in the context of superbubble models. However, a stem plus cap morphology can be produced in some circumstances (see the models of Tenorio-Tagle et al. 1990). In particular, it requires a sharp break from a stratified atmosphere to an effectively constant density atmosphere. The stem is then the cylindrical cavity created by an effective “blowout” from the stratified atmosphere, and the cap is the result of quasi-spherical expansion when the hot gas reaches the uniform density “halo”. This kind of model was originally used to represent a true disk-halo interaction, but if the Anchor is a superbubble, then the interaction is occurring only a few hundred pc away from the Galactic plane. Perhaps it can represent the interaction between the thin disk and thick disk components of HI. However, the superbubble interpretation leads to the following conclusions: the radius of the stem must be approximately two local scale heights, and the bottom of the cap must correspond to the height at which the sharp break in the atmosphere occurs. The distance to the Anchor, as estimated from kinematics is $d = 3.6 \pm 1 \text{ kpc}$ (English et al. 1999), so using even the widest point of the stem yields a scale height $H \approx 20 \pm 6 \text{ pc}$ and “halo” (or thick disk) height $z \approx 170 \pm 47 \text{ pc}$. 
The above numbers show that the superbubble hypothesis requires a rather unusual atmospheric structure near the Galactic plane. Yet another concern with the superbubble hypothesis is the following: the Anchor is characterized by an apparent excess of HI emission relative to the background, rather than the cavity in HI (as with W4) that is expected to be occupied by hot $\sim 10^6$ K gas. The final word on this issue will await further analysis of observations, as there is some indication that the stem is hollow, and that the cap is redshifted out of the velocity interval of the Perseus arm. The latter could give the Anchor the appearance of being in a relatively empty region, when in fact the ambient gas would be displaced into different velocity channels (English et al. 1999).

The Anchor bears a striking resemblance to a thermal plume, e.g., the shape of a rising fireball after a nuclear explosion. Processes such as rising plumes or jets may need to be considered, although their origin in the ISM with energy $\geq 10^{50}$ ergs remains a mystery. An advantage of such processes is that they can more readily transport matter vertically, as the Anchor appears to be doing. In contrast, superbubbles are very inefficient at transporting matter upwards, as discussed earlier.

5. Conclusion

Observations point to the existence of a hot halo around our galaxy, yet its origin and the means by which it is maintained have not been conclusively determined. Disk-halo interactions such as chimneys seem likely and could account for the presence of hot coronal gas and HVCs within the halo, as well as allow the ionization of the Reynolds layer above the thin HI disk. A chimney model of the ISM would also account for the low filling factor of the HIM in the Galactic disk.

Observations to date have not shown structures clearly connecting the disk and the halo. The observed worms as well as the Stockert Thermal Spur, W4 superbubble, and the Anchor are all confined to within a few hundred parsecs from the Galactic plane, hence they probably connect the thin and thick components of Galactic HI, but there is no evidence that they extend all the way to the halo. However, the information that these structures yield about the ISM at low latitudes can have implications for the disk-halo relationship. If the cold gas in star-forming regions is as strongly stratified near the disk as implied by the W4 superbubble (and also the Anchor if it is indeed a superbubble), the hot gas in the bubbles will be efficiently channeled upwards, yielding a relatively low filling factor for the HIM in the disk (recall that the radius of the hot gas bubble in the disk does not exceed two local scale heights). The elongated cavities which break out of the thin HI disk will also allow a significant fraction of ionizing photons to escape upwards and contribute to the Reynolds layer.

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