THE INTERSTELLAR DISK-HALO CONNECTION IN GALAXIES: REVIEW OF OBSERVATIONAL ASPECTS

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An impressively large amount of data was presented at this meeting and a review by an ordinary human cannot hope to do full justice to either the authors or the research. Accordingly, I shall concentrate on those aspects that particularly piqued my interest and apologize to those authors whom I overlook. I shall give references in the usual style except for references to papers presented at this meeting, for which I shall simply mention the author(s) with no date.

I had considerable difficulty deciding how to organize this review. First I discuss the various gas components in rough order of increasing scale height. Section 1 discusses neutral gas, section 2 the 'warm' and 'not-so-warm' ionized gas, section 3 the $T \sim 10^5$ K component at higher z that is detected in UV absorption and emission, section 4 the high-velocity neutral gas, section 5 the cosmic-ray halo as revealed by synchrotron emission, and section 6 the magnetic field. Next, section 7 covers the interaction between the low-z gas and the halo, which is the main topic of this symposium; and finally, section 8 discusses some aspects of the interstellar medium that are relevant to this interaction, with emphasis on the uncertainties.

1. NEUTRAL GAS

1.1. H I

Lockman reviewed the distribution of Galactic H I. It is concentrated toward the plane, but has a high-z low-density 'tail' originally discovered by Shane (1971). This tail has a scale height $h_{HI} \sim 500$ pc for Galactocentric radius $3 \lesssim R_G \lesssim 9$ kpc. For larger R_G the thickness increases dramatically. For $R_G \lesssim 3$ kpc the high-z component of the H I does not exist.

The velocity dispersion of the H I is gravitationally commensurate with its scale height at the Solar Galactocentric radius $R_G \approx 9$ kpc. However, as emphasized by H. de Boer, the constancy of the scale height over the range $3 \lesssim R_G \lesssim 9$ kpc is puzzling because the z-component of the gravitational field increases strongly

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towards smaller R_G. This might be understandable if the velocity dispersion of the H I increased together with the gravity, but the dispersion appears to be independent of R_G (Kulkarni and Heiles 1987; KH). Why, then, should h_{HI} remain constant over this range of R_G? This is a long-standing puzzle.

1.2. CO

In the Galaxy, most of the CO resides in molecular clouds and, locally, has z scale height $\sim$ 100 pc (Scoville and Sanders 1987). However, there is a distinguishable minority component ($\sim$ 15% of the molecular cloud component near the Sun) seen at high latitudes (Blitz). Much of this component is not located in clouds, but instead is associated with H I filaments and sheets (Blitz 1988), and it seems reasonable to infer that the CO is formed in shocks associated with expanding H I shells. The local scale height of this component is about the same as that of the cloud component, which is somewhat smaller than that of the H I (KH), which may imply that the CO is only formed on the low-z side of the shells. The velocities of the extended-component CO clouds are comparable to those of the H I, which are somewhat larger than the velocities of molecular clouds.

Three of the high-latitude clouds have anomalously large negative velocities, ranging as high as –45 km s^{-1}. They appear to be somewhat unusual objects from the standpoint of morphology. One is part of the Draco complex, which has been modelled as an interaction between high-velocity (section 4) and low-velocity gas, and one is colliding with a low-velocity H I cloud. The distance to the Draco complex is not absolutely certain, but Goerigk and Mebold (1986) have derived a distance of $\sim$ 800 pc. In this one case, then, high velocity probably implies high z. Does high velocity generally imply large z? This question seems important, because if so there is a population of molecular clouds at z-distances far beyond those we ordinarily associate with molecular clouds.

In the edge-on galaxy NGC891, Garcia-Burillo (using the 30-m IRAM telescope) and Handa *et al.* (using the Nobeyama array) presented CO data indicating that most of the CO has $h_{CO} \approx 140$ pc, which is larger than that of the Blitz clouds. This is larger than the mean Galactic h_{CO}, which is $\sim$ 45 pc in the Galactic interior. Apart from the quantitative difference in scale height, it would be nice to be able to conclude that the molecules in NGC891 are reasonably well-confined to the galactic plane, as they are in the Galaxy. However, the IRAM results also show a 'plateau' component with $h_{CO} \approx 840$ pc. This component is not seen at Nobeyama. It is important to determine whether this component is indeed real: the Nobeyama observations may not be sensitive enough, and the IRAM observations may be affected by effects that can plague single-dish observations such as sidelobes. If this extended component is real, it drastically departs from our standard notions of molecular clouds as being confined, in the main, to very small z-heights. However, it might have the same scale height as the H I in NGC891, for which only an upper limit of 1 kpc has been established (Sancisi and Allen 1979). Or if the 'plateau' component is real, it might be completely different, for example if it has high velocities.

2. THE WARM IONIZED MEDIUM (THE WIM; ALSO CALLED THE DIFFUSE IONIZED GAS, THE DIG)

2.1. The $\sim 10^4$ K component

Walterbos reviewed the WIM in both our Galaxy and external galaxies. It is a diffusely-distributed, $T \sim 10^4$ K gas, distinguished from ordinary H II region gas by its several-times higher [S II]/Hα line ratio, which is characteristic of gas that is photoionized by a very weak radiation field from distant O stars (Mathis 1986). In external galaxies, where in some senses it is easier to observe, it contributes a significant fraction $\sim 30\%$ of the total Hα luminosity and much of the emission is in sheet or shell structures. The properties of this 'Reynolds component' in our Galaxy were reviewed by Reynolds and are rather well-determined by pulsar and Hα observations. The total column density from $z = 0$ to ∞ is $\approx 10^{20}$ cm^{-2} and the scale height $h_e \approx 1$ kpc; the volume filling factor is $\sim 10\%$ in the Galactic plane and increases with z (KH). Energetically this component may be somewhat less important than it is in the external galaxies.

The WIM is also seen in NGC891. Dettmar and Dahlem find $h_e \approx 600$ to 1000 pc, depending on position; if this is correct, it implies that NGC891 is comparable to our own Galaxy as regards the WIM. However, Hester *et al.* (also Rand, Kulkarni, and Hester 1990) find a completely different result, $h_e \approx 4$ kpc. It is important to resolve this discrepancy. Both groups see lots of structure in NGC891 that resembles Galactic worms and supershells. In another galaxy, NGC3079, Hester *et al.* see many such structures in Hα, and many are remarkably well correlated with structure seen in the nonthermal radio continuum by Irwin and Seaquist.

The source of ionization of the WIM has long been a mystery. The total energy requirement is comparable to the total power output of supernovae in our Galaxy (Reynolds 1990), and analyses of the problem have shown that only the young, massive O stars produce enough ionizing photons to produce the WIM. The problem lies in getting the photons from the stars to the gas. The neutral gas is so opaque to ionizing photons, and the neutral gas is itself so pervasive, that the ionizing photons cannot get very far. However, the cylindrical cavities indicated by the presence of worms and by the H I 'holes' observed in our own and in external galaxies (section 7) provide unobstructed pathways for the ionizing photons. The photons can escape the stars in straight lines, providing cones of ionizing radiation with the apex located at the stars and the cone angle defined by the diameter of the cylindrical cavity. In addition, Norman pointed out that the photons can also scatter off of the sides of the cavities; however, the importance of this mechanism depends on the reflection efficiency, which remains to be worked out. This mechanism would probably change the photon energy distribution in such a way as to reproduce the observed [S II/Hα] ratio and to produce a broad, lower-z region. It would be very nice if these ionization mechanism were to work well enough to solve the 'ionization source problem' for the WIM.

2.2. The 'Not-so-Warm Ionized Gas' (the 'NSWIM')

Israel presented observational evidence for a new component of the ISM, a cool ionized phase with (for the clumpy model) $n_e \approx 1.0$ cm^{-3}, $T \lesssim 1000$ K (possibly $\ll 1000$ K), scale height $h_{NSWIM} \sim 2$ kpc, and a filling factor $\sim 10\%$ (Israel and Mahoney 1990). As this component is in some sense similar to the WIM but has much lower temperature, we temporarily adopt the somewhat awkward name 'not-so-warm ionized medium', and anticipate the day when a better name is invented by somebody more clever than we. Cox reminded us that such a component was predicted back in the early 1970's when time-dependent models of the ISM were popular (Gerola, Kafatos, and McCray 1974); it can exist because the cooling time scale is shorter than the recombination time scale. Thus from the *physical* standpoint, the NSWIM is likely to be different from the WIM, because we regard the WIM to be in ionization equilibrium and, in contrast, the NSWIM is likely not to be.

My knee-jerk reaction is to question the reliability of the observational evidence. However, the observed effect is a correlation with the inclination angle of a deficiency the low-frequency nonthermal radiation (relative to the power-law extrapolation from higher frequencies). Such a correlation is difficult to ascribe to selection effects or measurement errors, because an external galaxy has no knowledge of our location. The correlation strongly implies an opacity effect.

Our Galaxy exhibits no obvious NSWIM component. The low-frequency absorption of our Galaxy is easily produced by the same WIM that emits the Hα radiation (KH). However, the properties of the Galactic ionized gas are derived from the latitude dependence of the absorption and Hα emission, so are restricted to the Solar vicinity's 'Local Bubble' (Cox and Reynolds 1987); the local properties may not be representative of those in the Galaxy as a whole. Perhaps our Galaxy is unusual in not having the NSWIM; alternatively, perhaps it does, or perhaps the low-frequency observations or their interpretation might be incorrect.

The existence of this component is an important issue that should be confirmed on a larger sample of galaxies. The low-frequency observations were performed at Clark Lake Observatory in the U.S.A.; unfortunately, the U.S. National Science Foundation used its well-known quality of wisdom to decide that the relatively small operating costs for this observatory, which had only recently been made fully functional under NSF funding, were too costly. Thus further observations will have to be done elsewhere.

3. HOT IONIZED GAS

Savage reviewed the high-z ionized gas. Observations of UV absorption lines are best matched by a gas having $N_e \approx 2 \times 10^{18}$ cm^{-2} and $T \approx 2 \times 10^5$ K. Thus the mass of this gas is negligible compared to the mass of the neutral and WIM components. The scale height is determined from distances of the background stars and is $h_e \approx 3$ kpc. UV emission lines have recently been observed at high Galactic

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latitudes (Martin and Bowyer 1990), and if it is the same gas as seen in absorption then we have $n_e \approx 10^{-2}$ cm $^{-3}$ and $T \approx 10^5$ K, yielding a pressure $P/k \approx 1300$ cm^{-3} K. This is probably close to the pressure expected at $z = 3$ kpc.

A major question is what keeps this gas warm. Its cooling time is $\sim 2 \times 10^5$ yr. Looked at in another way, the locally-observed gas has a cooling rate of nearly *half the local supernova power!* The cooling time is much shorter than the infall time.

Martin and Bowyer (1990) argue (from detections at only 6 positions) that the observed line intensity increases towards the Galactic pole, that the gas resides not just locally, and that the gas is part of the Galactic Fountain. Personally, I am not completely convinced by their arguments. In my opinion, we need more data to establish statistical reliability; at that point a definitive interpretation can ensue. If this gas is truly globally distributed within the Galaxy, it will be one of the most important components of the ISM from the standpoint of energetics and, hence, theoretical significance (section 7). Clearly, more extensive observations are urgently required.

From the relatively short cooling time one might infer that the gas is not in thermal equilibrium. One possibility is that the gas represents the turbulent mixing layer between a cool ($T \sim 10^4$ K?) 'cloud' component moving within a much hotter ($T \sim 10^7$ K?) diffuse component; the mixing layer tends to take on a temperature which is roughly the geometric mean between the two components (Begelman and Fabian 1990).

4. HIGH-VELOCITY CLOUDS (HVC'S)

Galactic HVC's were long ago discovered by the Dutch astronomers, led by Oort (1966), whose presence at this meeting we are privileged to have. They are prominent in the 21-cm line and cover a non-trivial $\sim 7\%$ of the sky (Wakker). Braun reported that 'HVC's' also exist in some other galaxies, although it is my impression that any extragalactic HVC that is in fact observable is a much bigger entity than a Galactic HVC.

In her review, Danly reported that the HVC's are seen in UV absorption lines against extragalactic objects. This shows that the HVC heavy-element abundances are consistent with those of ordinary interstellar gas, although the uncertainties leave a wide margin for differences between the abundances. Nevertheless, the significant heavy-element abundances make it unlikely that the HVC's are primordial gas.

K. de Boer and Kuntz and Danly showed convincingly that the previous distance limits of Songaila, Cowie, and Weaver (1988), derived from optical observations of Ca II lines against background stars, are based on incorrect interpretation of the data. Thus we must revise our thinking concerning the cloud distances: 'Complex A', which we assume to be representative of the classical HVC's located at positive Galactic latitudes, is more distant than 4 kpc (Schwarz and van Woerden).

Where do HVC's come from? Mirabel analyzed the velocity distribution of HVC's, restricting himself to sectors toward the Galactic center and anticenter,

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locations chosen to eliminate the complications of Galactic rotation. He concludes that the clouds have little angular momentum, so are presumably extragalactic, and are falling towards the Galactic center. In contrast, Wakker examined the entire sample at all longitudes. He finds that the velocity distribution is consistent with Galactic rotation plus a large random component, and concludes that the clouds may be the returning 'fountain' gas.

It is curious that two such completely different models fit the data. Mirabel's model is based on a restricted sample of HVC's, which perhaps argues against it, but I find the correspondence between the data and his model quite impressive. Could there be two (or more?) populations of HVC's?

I would like to make some possibly extraneous comments on the HVC's. First, why are they neutral? They are located in an environment comparable to that of the other halo gas, all of which is much hotter and quite highly ionized. The volume density inside an HVC is much larger than that of the ambient halo gas, and this must be in part responsible for the difference in ionization state. Nevertheless, an HVC should have an ionized edge, because of either photoionization or evaporation. One such edge has probably been detected (Kutyrev and Reynolds 1989), and such work is worth further effort.

Second, HVC's must be confined by the ambient halo gas. Thus there is an interface between the cool, neutral HVC gas and the ambient halo gas. It seems to me that this interface should depend on at least two things: one, the physical conditions of the ambient halo gas; and two, whether the interface is on the front or the back of the HVC (as defined by its direction of motion). We might learn something by studying these interfaces.

Third, HVC's have reasonably large column densities and might be detectable in gamma rays produced by interaction of the high-z cosmic rays with the gas. Because of their location in the halo, they are unique probes of the cosmic rays in the halo, and perhaps this information would be useful in understanding the role of cosmic rays in halo structure.

5. THE COSMIC RAY HALO

Direct observations of the cosmic rays come only from the intensity of synchrotron emission. However, the synchrotron emission traces only the electron component, which is a poor substitute for the far more dominant proton component. When cosmic rays are produced, the energy of the electron component is usually taken to be the canonical 1% of the total component. Even if this fraction is universally valid, the electrons are subject to loss mechanisms that hardly affect the protons. Energy losses for electrons are observationally demonstrated by the steepening of the spectral index in regions far from where the electrons are produced and as reviewed by Hummel their lifetimes are inferred to be of order 4×10^7 yr. Thus the *absence* of synchrotron emission cannot be taken to be a reliable indication of the absence of cosmic rays. On the other hand, the *presence* of synchrotron emission does definitely indicate the existence of cosmic rays.

Cosmic rays were reviewed by Dogiel. Indirect evidence for a cosmic ray halo comes from theoretical arguments based on the roughly constant cosmic ray density within the Galaxy, lifetimes, and grammage. These arguments are compelling. Thus, whether or not our Galaxy has a synchrotron-emitting halo, we must conclude that it does have a cosmic-ray halo—and, correspondingly, a magnetic-field halo.

6. MAGNETIC FIELDS

Information on the magnetic field comes from both the intensity and the polarization of synchrotron emission. As with cosmic rays, the intensity is not a perfect tracer of magnetic field, because relativistic electrons are also required.

Hummel reviewed the morphology of synchrotron emission observed in edge-on galaxies. Galaxies exhibit a thin disk, a thick disk, and in some cases a halo. Often non-axisymmetric structures such as jets and plumes are seen. The thin disk scale height is typically ~ 1 kpc, and occasionally as large as 3.5 kpc. The morphology of the synchrotron emissivity of our own Galaxy is not directly observable because we are immersed within it, but it can be obtained by modelling the observed angular distribution of intensity. These models indicate that our Galaxy has both a thick disk and a halo.

The strength of the local Galactic field can be inferred both from observations and from theory. Observationally, there are two independent results. One is Faraday rotation: the recent study of pulsars by Rand and Kulkarni (1989) derives a field strength of $\approx 5\ \mu$G, most of which is in the 'random' component. The other is synchrotron emissivity: as reviewed by K. de Boer, consistency with both the angular distribution of intensity and the measured spectrum of relativistic electrons is also obtained with a field strength of $\approx 5\ \mu$G, although Phillips *et al.* (1981) derive a somewhat smaller value, $\approx 4\ \mu$G. Theoretically, Cox presented a straightforward argument favoring a high magnetic field for the Galaxy: the weight of the interstellar gas must be supported by pressure, but the pressure of gas and cosmic rays appears to be inadequate. A field strength of $\approx 5\ \mu$G is required. However, this estimate is uncertain, both because the total weight is uncertain and because H I line widths always exceed the thermal width (KH) so that a significant portion of the gas pressure arises from 'turbulence'. Relying on the observational data alone, it seems that the canonical value of the field strength in the Galactic plane near the Sun should be taken as 4-5 μG.

Beck reviewed observations of the magnetic field in external galaxies. The direction of the field is revealed by linear polarization of synchrotron radiation. Polarization observations of edge-on galaxies reveal the direction of the field relative to the plane of the disk. At low z, one galaxy has $\vec{B}$ primarily perpendicular to the disk, 4 have $\vec{B}$ parallel to the disk, and 2 show polarization in limited, bubble-like regions. If we include our own Galaxy in these statistics, which also has $\vec{B}$ parallel to the disk, the 4 become 5. In the 4 external galaxies, $\vec{B}$ is not everywhere parallel but is sometimes perpendicular; this tends to happen in regions that are 'active' in some way, characterized by morphological features in the disk such as perturbed nonthermal emission, star formation, or holes in the disk. It also tends to happen in the outer parts of disks and higher in the halo. Above $z \sim 3$ kpc, the halo fields tend to become tangled.

The fact that $\vec{B}$ is sometimes perpendicular to the disk in active regions implies a direct connection to the halo, one that was probably produced by the activity. This is most important for the topic of this conference.

The fact that $\vec{B}$ is parallel to the disk says nothing about its direction within the disk. We consider the field to be a spiral, which may be so tightly wound in some cases that the field is essentially circular. The direction of the field in this spiral can be revealed only by Faraday rotation. For a spiral galaxy tilted with respect to the line of sight, the Faraday rotation indicates whether the plane-of-the-galaxy field points towards or away from the observer. If it points towards the observer on one side of the galaxy and away on the other, then the field winds around the galaxy in one direction and is referred to as an Axially Symmetric Spiral (A.S.S.); otherwise, it winds into the center on one side and out on the other and it is called a BiSymmetric Spiral, or B.S.S., field. Of those galaxies for which reliable measurements exist, two are A.S.S., two (plus possibly one more) are B.S.S., and three (including our Galaxy) are neither.

For those galaxies which the configuration can be reliably determined to be either A.S.S. or B.S.S., the data—which consist of the variation of rotation measure along the major axis—are usually quite unambiguous, in the sense that the systematic variation is obviously larger than the uncertainties and is statistically significant. In some cases the degree of statistical significance varies with R_G. Also, sometimes there occur very large departures from the pattern, which are most reasonably interpreted as isolated large perturbations instead of a poor fit to the model. These departures tend to be associated with other morphological oddities, which reinforces the perturbation idea.

In the verbal version of this paper I suggested that the fact that there are more 'neither' than A.S.S. or B.S.S. galaxies suggests that perhaps the 'neither' category is the basic one and that A.S.S. or a B.S.S. configurations might be only the first term in a Fourier-series representation of the randomness that characterizes the actual field distribution in cases that are, fundamentally, 'neither'. However, after some reflection I now believe this suggestion is incorrect.

Instead, it is my impression that at least one of the representatives of each class (IC342 [Krause, Hummel, and Beck 1989] and M31 [Beck 1982] for A.S.S.; M81 [Krause, Beck, and Hummel 1989] for B.S.S.) seems qualitatively different from the 'neither' galaxies. In these representatives, the intrinsic polarization of the synchrotron emission is higher than for the 'neither' galaxies, which means that the uniform component of the large-scale field is more important, relative to the random component. Also the rotation measures are larger for these representatives, again an indication that the uniform field component is larger. For these three galaxies, the ratio of uniform to random component ≈ 0.8, while for our Galaxy (a representative of the 'neither' case) it is ≈ 0.3. These numbers are subject to error from various depolarization effects; Beck and his colleagues are addressing this issue with multiwavelength observations. The larger uniform component should imply that the dynamo, which is responsible for the uniform component, is better established in these cases. Beck provides additional arguments against the 'neither' hypothesis.

The large-scale field distribution is a fascinating topic, and of course should be a direct probe of the dynamo processes in a galaxy. Existing data show that the distribution can take on any of the simplest forms with roughly equal probability. We would like to know how the field configuration, and thus the dynamo, is related to other properties of a galaxy. Obtaining reliable field configurations is a difficult observational task, but to address these questions we need a larger sample—more objects observed!

7. SUPERSHELLS VS. WORMS VS. CHIMNEYS ...

We now come to the most important part of this summary, at least in terms of the topic of this meeting. The connection between the gaseous disk and halo almost certainly arises in the chimneys.

On Wednesday night I asked for a vote on the *existence* of worms and related structures. The response was almost unanimously positive. Based on evidence presented at this meeting, this is hardly surprising!

Sofue showed that vertical dust lanes are prominently visible in some spiral Galaxies. Beck showed that the magnetic field, which tends to lie in the plane of a galaxy, sometimes runs vertically to high z in active regions. Braun showed that both M31 and M33 contain > 100 H I holes, and IC10 and the Magellanic Clouds also contain prominent holes. Some are also seen in Hα and are associated with peculiar velocities. Koo cataloged > 100 worms, supershells, and H I holes in our Galaxy in H I, IRAS emission, and radio continuum; also, the impressive dm-wavelength radio continuum maps in both the southern (Jonas and Baart) and northern (reviewed by Reich) hemispheres seem to exhibit many such structures.

These structures are seen in magnetic fields, Hα, dust absorption, and non-thermal radio emission in external galaxies; and in H I, IR emission, and radio continuum emission in our own Galaxy. The appearance in these different observables corresponds extremely well in many cases. The structures tend to be oriented perpendicular to the disk. Theoretically, such vertical structures are expected as a result of large explosions in a sufficiently thin disk, and the interpretation of their having been produced by multiple supernova explosions and injection of stellar winds seems unassailable. The existence of these structures in the Galaxy and in all external galaxies so far observed implies that these are widespread and common phenomena.

Clearly, I asked the wrong question on Wednesday night. As emphasized by Walterbos in his review, the *real* question is whether these structures do, in fact, connect the disk to the halo. To phrase it another way, the question is whether or not these structures are really *chimneys*. Many observers call these structures chimneys as a descriptive term, but this nomenclature implies more than the observations actually provide. We observers must adhere to Cox's first moral principle: we must never give an empirically-defined object a name that connotes a physical effect suggested by theory. The theory may be incorrect, or it may change, but the empirically-defined object remains itself, to be modified only by the evolution of observational technique and accumulated data.

There are two excellent reasons for believing that most worms are *not* chimneys. Theoretically, the thick disk of low-density WIM electrons makes it difficult for shells to break out of the disk and connect to the halo. This is seen in numerical treatments (e.g. Mac Low, McCray, and Norman 1989; Palouš; Shapiro; Tomisaka) which show that adding just the H I z-extended component, which is only about half the thickness of the WIM layer, considerably reduces the chance for breakout. Observationally, a very important fact (Cox) is that in those galaxies that have been studied, no more than 1% of the total supernova power is emitted as diffuse X-rays from $T \sim 10^6$ K gas. A qualification for the Galaxy: this estimate rests on assuming that the observed X-rays, which are sampled only locally because of absorption by intervening neutral matter, are representative of the whole Galaxy.

If gas flows up into the halo from the disk through chimneys, driven by correlated supernovae, it must be hot. If it is hotter than $\sim 7 \times 10^6$ K, it will escape as a wind (Heiles 1987) unless it cools rapidly enough either by expansion or radiation, in which case it will eventually reach the 10^6 K at which it would be easily observable in X-rays. If the gas is injected at $T < 10^6$ K, it must have lost thermal energy either during the explosion process or on its way out to the halo; current theory does not suggest that this occurs.

Alternatively, worms may be chimneys. Suppose that the halo gas lies between $\sim 2 \times 10^6$ K and 7×10^6 K so that it is neither observable in X-rays nor escapes the Galaxy, and that the energy is emitted by the $T \sim 10^5$ K halo gas observed in UV absorption and emission (section 3). If this gas is distributed over the whole Galaxy, then the total luminosity in these lines really amounts to half the total supernova power. If the gas really lies above the WIM at $z \gtrsim 1$ kpc, then the supernova power permeates the halo and we are almost forced to conclude that most of the worms *are* chimneys.

Thus, while the absence of observable X-ray emission, particularly at this level of 1% of the supernova power, is a powerful constraint, it may not be relevant. It is intriguing that these UV emission lines, which are so very difficult to observe, might highlight the most energetically important phase of the diffuse ISM! We desperately need more observations of the UV emission lines to definitively establish their pervasiveness.

Given these uncertainties, observers *must not* call these objects chimneys. We do not know whether they connect to the halo or not. We can imagine that a worm does either: when it dies it may go to heaven (up into the halo) or not. Thus the term 'worm', or some other suitable term defined on a purely *empirical* basis, is better for these entities that are empirically defined by their sharp, well-defined typically vertical structure.

Observationally, how can we determine whether a worm is indeed a chimney? We cannot use the mere existence of an H I hole, because only if the hole continues all the way through the higher-lying WIM can we be sure that there is a direct connection. We cannot use the cones of ionization caused by O stars located within H I holes because the WIM does not absorb those photons; these cones should exist whether or not there is a hole in the WIM.

I can think of just two observables, neither being very promising. One is to observe the upward-moving gas itself. It should be very hot; it might be detectable in X-ray emission or in absorption lines of specific highly-ionized species. Another is to observe the hole in the WIM itself. This is difficult, because the WIM has a very low emission measure and its *presence* is barely detectable; detecting its *absence* is even more difficult. But if holes in either the WIM or in the higher-z, $T \sim 10^5$ K gas can be detected, they would be indications of breakout into the halo.

We regard it as essentially certain that supershells and worms are produced by clusters of supernovae and stellar winds. However, there is another mechanism that operates in certain specific cases. Observationally, evidence for interaction of HVC's and disk gas to produce the Galactic 'anticenter shell' was reviewed by Mirabel, and in external galaxies evidence for spectacular interactions of HVC and ambient gas was reviewed by van der Hulst. Theoretically, the very largest supershells cannot be produced by correlated supernovae because the energy gets transferred to vertical instead of horizontal motion in the disk, unless the disk is very thick. It would be nice to economize by invoking the minimum number of mechanisms to produce the observed effects and assume that *all* supershells and worms are produced by HVC interaction. However, the total energy in HVC's is only $\sim 1\%$ that in supernovae and is insufficient for the task.

There are a number of fundamental, currently unanswered questions concerning superbubbles and related structures. The holes they produce in a galactic disk should be round, except as modified by differential rotation with age (Palouš, Franco, and Tenorio-Tagle 1990); thus, when observed in external galaxies, H I hole shapes should follow a well-defined distribution which depends on the inclination angle and the rotation curve of the galaxy. The holes are supposed to have been produced by shocks, which sweep up the matter in the hole and, after becoming radiative, deposit it in a dense shell on the outside of the hole; these dense shells have never been observed in either atomic or molecular gas. Why? Supershells are almost never observed as complete spheres, but only as hemispheres or less. Is this because the supernovae that produce them blow up next to dense molecular clouds, so that the explosion energy is free to drive a fast shock in only one direction? If so, what happens to the molecular cloud, and from the theoretical standpoint what are the shell dynamics in such a macroscopically inhomogeneous medium? What is the effect of the partly ordered, mainly random ambient interstellar magnetic field on the shell dynamics?

Braun estimated that the observing time required to attack these problems on some of the world's great telescope arrays runs into several months. Similarly, I suspect, the computing time required on the world's greatest computers also seems prohibitive. However, I suggest that both we and the directors of such facilities alter our attitudes. Most observatories parcel out time in small chunks in order to satisfy a large group of users, and never award very large amounts of time to individual, important projects. However, there are some projects that are so important to our understanding of fundamental issues that the expenditure of significant resources—be they observing time or money—is justified. Some of the small satellites, such as IRAS and COBE, are prime examples. Similarly, I believe, a few well-selected projects that will elucidate the fundamentals of the disk-halo interaction have enough merit to justify altering our traditional criteria for awarding telescope time.

8. BASIC PROPERTIES OF THE ISM

Theorists cannot concoct applicable theories for conditions that differ from those they assume. As observers, we have the responsibility to provide this information. After decades of work and the expenditure of much telescope time and taxpayers' money, I'm afraid we have failed. This is not entirely our fault. The ISM is a complicated multiphase medium, and whenever we make a new type of observation that highlights any temperature we in fact see gas at that temperature. Interpretational difficulties are compounded by the facts that the optical, UV, X-ray, and most high-latitude observations can sample only nearby material, and the local region is not very representative (Cox and Reynolds 1987).

What component of the ISM occupies most of the volume? Back in the 1960's, the two-phase model was popular and predicted that the warm neutral medium (WNM) would do so. This is quite consistent with the observations: H I is distributed rather smoothly over the sky, from which we infer that it is rather smoothly distributed in 3-d space.

The theoretical picture changed in the 1970's with the realization, mainly by Cox and Smith (1974) and McKee and Ostriker (1977), that supernovae are more than just perturbers of the ISM: instead, they dominate it. The interior of a supernova remnant is filled with hot gas (the hot ionized medium, or HIM), and the remnants grow so big that this gas should fill most of space. This picture seemed to agree with the observation of soft X-ray emission from thermal gas located in the Solar vicinity, but seems to disagree with the H I data. Recently, Cox has changed his mind for reasons he has explained in this meeting.

Meanwhile, H I observers have been trying, in spirit if not in fact, to accommodate the theoretical picture of HIM filling most of space. Braun, who I believe was talking primarily of M31, expressed this possibility in discussing the idea of having a large *2-d*, or *area*, filling factor together with a small *3-d*, or *volume*, filling factor. In spirit, I personally have come to realize that a large 2-d filling factor of H I, which is what we really mean by saying that the H I distribution as observed from the Earth looks 'smooth', does not necessarily imply a large 3-d filling factor. Much of the H I is distributed in sheets or shells. A bedsheet covers a bed but does not occupy very much volume, and if the interstellar H I covers the Galactic plane in the same way a sheet covers a bed we might reproduce the H I observations—with a large 2-d but a small 3-d filling factor, as might be produced in a HIM-dominated ISM. Observationally, the point is this: we tend to assume that gas at different velocities lies at different distances. This is certainly not always the case. To what degree is it 'not always the case'? This question needs to be answered, but the answer will not come easily.

We don't even know whether H I 'clouds' are primarily filaments or sheets. We often observe real shells, and these are certainly best described as sheets. The *Copernicus* satellite definitively established the existence of sheets, for example in front of ζ Oph (Morton 1975). However, H I maps also exhibit objects that look more like filaments. They are curved, and reminiscent of shells, but their insides have very low column densities; we discuss the specific case of the 'NCP' shell below. However, the fact that something ***looks*** like an isolated filament does not mean that it *is* one. The reason is that most shells are not complete. An incomplete shell, if approaching us, is recognizable as a portion of a shell. But an incomplete shell that moves across our line of sight looks more like a filament because only the 'tangentially viewed' portion of the shell exists. In principle we should be able to distinguish a filament from a partial shell from the velocity distribution, because the radial velocity of the tangentially-moving portion of a shell varies rapidly with line-of-sight distance. Unfortunately, detailed studies of a reasonable sample have never been done.

Not only do we not know the geometry of the ISM, we do not know its topology. Many theoretical models predict a 'Swiss cheese' structure for the ISM; others predict a 'spaghetti' type structure, with or without 'meatballs'. Some of these models predict that the cold H I clouds fill the holes in the cheese, and others that the HIM bubbles, immersed in a much cooler medium, fill the holes. Other models (now out of fashion) have predicted that the HIM fills tunnels—a spaghetti structure, which has never been either observed or ruled out. We observe cold H I and molecular filaments, which are either true filaments or the caustics of nearly edge-on sheets. Topologically, what is the connectedness of any particular ISM component?

Filling factors of the various components of the ISM are uncertain. So is the magnetic field. And what little knowledge we do have of all these matters is generally restricted to the Solar circle, or more specifically the Solar neighborhood.

The well-defined arching structure centered near $(l, b) \approx (130°, 28°)$ is an excellent example of some of these points. I call this the 'North Celestial Pole', or NCP shell, because it passes right through the pole. Studies of this object have been the subject of several excellent poster papers presented at this meeting. This object does not appear to be a complete shell because its interior area is almost completely empty—it has one of the lowest H I column densities anywhere in the sky. Meyerdierks and Heithausen model it as a cylindrical cavity formed by collision of nearby HVC's with the ordinary disk gas. Alternatively, such a cylindrical cavity might be a chimney viewed end-on! However, the cylindrical geometry is not the only interpretation. Grenier models it as gas ejected from a nearby well-defined expanding shell. And we at Berkeley believe that it may be a portion of a shell, oriented such that it expands primarily in the plane of the sky; we see the shell portion tangentially so it looks like a filament. The NCP shell has a strong magnetic field (Heiles 1989), which presumably should be incorporated in a successful model.

Another point about the NCP shell is that it seems to cause spectacular scintillation of background radio sources. There is a new class of scintillating radio sources whose intensity varies by very large factors (Fiedler *et al.* 1987); their 'light curves' make it appear as if the sources are being occulted by interstellar structures. These 'extreme scattering events' are probably a result of 'refractive scintillation' (Coles *et al.* 1987). The archetype is the source 0954+658, located at $(l, b) = (146°, 43°)$, which lies behind the NCP shell. The scintillation is caused by very small scale high-density fluctuations in electron density that have scale lengths across the line of sight of the order of 1 a.u. (1.5×10^{13} cm) and electron column densities along the line of sight of order 10^{18} cm (Clegg, Chernoff, and Cordes 1988). If they are produced by a thin sheet such as a shock with a line-of-sight length 100 times the sheet thickness—an assumption designed to minimize the inferred electron density n_e—then $n_e \sim 10^3$ cm^{-3}. This corresponds to an enormous gas pressure! It strikes me that we might learn a lot about the dynamics of shells, supershells, worms, and the ISM in general by having excellent statistical studies of these events. A related observation is the study of time variability of pulsar dispersion measures.

I believe that one way to learn much about the ISM, and particularly the influence of various forces on it such as supernovae and gravity, is to compare its properties at different Galactocentric radii R_G and in different galaxies. Supernova rates vary from galaxy to galaxy, and with R_G within a galaxy. So does the z-component of the gravitational field. In the extreme cases of starburst galaxies, the Heckman 'superwinds' reviewed by Norman give us relieved confidence that extreme supernova rates do, in fact, produce the expected effects. Walterbos presented some of the first comparative results concerning the WIM in external galaxies; a much larger sample of galaxies is needed!

With regard to H I, Braun's study of temperatures in M31, using background continuum sources to measure the absorption, is an admirable first step. He finds that the H I in M31 is warmer than that in the Galaxy. Another admirable step, not presented at this meeting, is the determination of H I temperatures as a function of R_G within our Galaxy by Garwood and Dickey (1989); they found that the Galactic H I gets warmer toward the center of our Galaxy.

These are contradictory results in at least one sense. The supernova rate *increases* toward the center of our Galaxy, and the rate is thought to be *smaller* in M31 than in the Galaxy. But the H I temperatures are higher in *both* regions. This implies that the H I temperature is not affected strongly by the supernova rate. This is a disappointing result because theoretically the gas temperature and the supernova rate should be linked. Wang and Cowie (1988) argued that the ISM pressure should increase with SN rate, and Cioffi (1985) found that the ISM pressure should increase with the fraction of SN that are correlated. For both reasons, the gas pressure should increase towards the Galactic interior. Increased pressure should result in higher-density, cooler clouds.

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