CONFERNCIE SUMMARY: THEMES AND QUESTIONS ABOUT THE DISK-HALO INTERACTION

John M. Dickey

Abstract. The papers in this volume represent a broad spectrum of observational, theoretical, and computational astrophysics, sharing as a unifying core the Disk-Halo Interaction in the Milky Way and other spiral galaxies. This topic covers a wide range of Galactic and extragalactic research, built on a foundation of numerous and diverse physical processes. This summary groups the papers according to six themes, with some historical background and finally a look to the future. The final message is that the astrophysical techniques discussed and reviewed at this conference will grow over the next decade to answer even more fundamental questions about galaxy evolution and the history of the universe.

1 Historical Background

This conference on the Disk-Halo Interaction in Galaxy Evolution has been a showcase for many exciting new results in a broad spectrum of Galactic and extragalactic research. Later in this summary I will briefly consider the significance of some of these results, and how they show the way forward. But first a few paragraphs of historical background, for the benefit of people who are new to the field. These concepts were implicit in many of the papers at the conference, but were not often mentioned explicitly.

For astrophysicists, the Disk-Halo connection is almost as old as the interstellar medium itself. By the early 1950’s it was clear that both cosmic rays and interstellar clouds must sometimes leave the disk. A series of papers culminating in Spitzer’s seminal 1956 analysis (Spitzer [1956], Shklovsky [1952], Pickelner [1953], based on the gravitational potential of the disk determined much earlier by Oort [1932]), predicted a hot gas halo above and below the disk. The need for cosmic ray (CR) leakage into this halo implied that magnetic fields must connect it with the disk. In the decade that followed, detailed astrophysical calculations of the...
heating and cooling rates of the neutral and ionized gas in the interstellar medium (ISM) showed that thermal equilibrium between different phases at very different temperatures could be achieved at a range of pressures that depends on the heavy element abundance and the radiation field intensity (Field et al. 1969, Dalgarno & McCray 1972). Meanwhile, by the early 1960’s the high velocity clouds seen in 21-cm line surveys were interpreted as evidence for both a population of neutral clouds in the halo, and a surrounding hot gas through which they were falling toward the disk (Oort 1966, 1970).

Dramatic observational confirmation of the existence of hot ISM gas in the Milky Way disk came in the early 1970’s from soft x-ray emission (Williamson et al. 1974, Sanders et al. 1977) and uv absorption (Jenkins & Meloy 1974, York 1974). This hot gas was immediately identified with that predicted by Spitzer for the halo, and the cycling of gas between the disk and halo was proposed soon after by Shapiro & Field (1976) c.f. Bregman 1980. It was soon clear that the hot phase gas occupies much of the disk and connects with the halo, in part from interpretation of the anticorrelation between nearby atomic and molecular clouds and the soft x-ray emission (McCammon et al. 1976, Mebold et al. 1985).

The theoretical framework for understanding the hot phase of the ISM developed in the early 1970’s as well, as the role of old supernova remnants (SNR) in pressurizing the disk was explored quantitatively (Cox & Smith 1974, Salpeter 1976, McKee & Ostriker 1977). By the mid-1980’s it was clear that the McKee-Ostriker paradigm was insufficient to describe the real ISM. The Milky Way (MW) and many other spiral galaxies have star formation rates high enough to drive hot gas out of the disk, and with it energy in thermal and mechanical forms (Cox & McCammon 1986, Cowie 1987, Norman & Ikeuchi 1989, Heiles 1990), which is not included in the Mckee-Ostricer model. Meanwhile the power of computational astrophysics was brought to the problem of SNR evolution (Chevalier & Gardner 1974, Mansfield & Salpeter 1974, Struck-Marcell & Scalo 1984, MacLow et al. 1989, Cioffi & Shull 1991), culminating in two- and finally three-dimensional simulations of the global ISM (Rosen & Bregman 1995, Vázquez-Semadeni et al. 1995, Avillez 2000).

One of the threads running through all of these works, observational and theoretical, is that we cannot fully understand the ISM of the MW disk without understanding also that of the halo and how the two media interact and exchange matter. In the last two decades our observational data on the ISM in the MW halo has improved dramatically. Even more dramatic progress has been made in studies of the ISM of other galaxies. We can see clearly now that galactic fountains operate in some spiral galaxies, and not in others. We see examples of disks with infall and outflow. It is even becoming possible to trace these processes as functions of redshift. One of the goals of this conference is to bring our detailed knowledge of the disk-halo interaction in the MW to bear on the much larger question of galaxy evolution over cosmic time.
2 Themes of This Conference

This conference has been ambitious in its combination of topics, including observational, theoretical, and computational studies of the MW disk and halo, the disks and halos of nearby galaxies, and gas infall and outflow in galaxies at intermediate and high redshifts. The papers reviewing these topics allow us to look back and also ahead, to see what will become possible in the next decade or so as powerful new telescopes become available. Rather than try to summarize the papers individually, I will consider a few themes, and group the papers accordingly. Of course any such grouping is arbitrary and does not do justice to the depth and complexity of the papers or their subjects, but there is not room for much more detail. Citations given as names without dates refer to papers presented at this meeting and their written versions that appear in this volume.

3 Theme – Magnetic Fields and Cosmic Rays Link the Disk and Halo

It has been understood for a long time that the ISM is subject to a magnetic Rayleigh-Taylor instability wherein the light fluids constituted by the magnetic field and the relativistic CR electrons can move through the heavier fluid constituted by the thermal phases of the gas to escape the gravitational potential of the MW disk (Parker 1966). But how much impact this has on the dynamics of the gas in the disk and halo is still not known. One approach is to map the interstellar magnetic field to see where and how the field joins the disk with the halo. It is possible in various ways to map the field in the disk, as explained in the papers by Beck and Vallée. Searching for a vertical component of the field in the solar neighborhood is particularly interesting, as reported by Mao, based on Faraday rotation surveys at high latitudes. Troland’s paper explains how Zeeman splitting observations at 21-cm give values for $\beta \equiv \frac{P_{\text{kinetic}}}{P_{\text{magnetic}}}$. This quantity is about 0.3 for the thermal pressure (with kinetic velocities given by the temperature) but $\beta \simeq 1.2$ when non-thermal bulk velocities are included. This reflects the typical Mach number of about 4 for turbulent velocities in cool, neutral medium (CNM) clouds. Thus the magnetic field is dynamically important in this phase, and probably in all other phases of the ISM, but it is not completely dominant. It is significant, however, that magnetic pressure is much higher than thermal gas pressure, as this could moderate the rate of cooling. Ferrière’s paper supports Troland’s in these conclusions, and gives an overview on a larger scale of the magnetic field structure of the disk.

The dynamical importance of the magnetic field has recently been included in simulations of the structure and dynamics of the ISM, as reported at this conference by Breitschwerdt, Asgekar, Hanasz, and Woltanski. Including the CR pressure, which Breitschwerdt couples to the gas through a spectrum of magneto-acoustic waves, drives the gas quite effectively out of the disk, in good agreement with the analytical prediction of Everett. The extensive review by Dogiel presents several fundamental equations and observations that describe CR propagation through the disk and halo. Some well established results from this are the scale
height of the CR population (3 kpc), the propagation path length (3 Mpc), and hence the travel time ($10^7$ yr). Clearly there is a lot of energy available in the form of magnetic fields and CR's; the CR acceleration processes alone have luminosity of more than $10^{42}$ erg s$^{-1}$. Further, per unit energy density, the CR's are more efficient at driving mass out of the disk and into the halo than is simple gas pressure, as Everett explains. On the much larger scales of clusters of galaxies, the paper by Bernet reviews the evidence for magnetic fields to at least redshift $z=1.3$ as traced by Faraday rotation. Thus we can infer that magnetic fields and cosmic rays have been escaping from galaxies, at least some galaxies in some environments, for a very long time.

4 Theme – The Mixture of ISM Phases in the Milky Way

The different thermal phases of the ISM are typically studied with different spectral lines or other tracers, so understanding the juxtaposition and relative abundances of the different phases is like putting together separate pieces of a puzzle. Ferrière's, Jenkins', and Vázquez-Semadeni's papers review concepts of pressure equilibrium, thermal equilibrium, transition of gas from one phase to another, and how the mixture of phases depends on height above the plane, $z$. The scale heights of the warm and cool phases are discussed further by Gaensler, Reynolds, and Kalberla. The ISM phases in M31 are discussed in the papers of Berkhuijsen, Bogdan, and Braun. The phase-mixture of the MW ISM is one of the central topics of the conference, and the papers in this volume represent the considered opinions of people who have been leaders of this field for decades. Yet the numbers presented here, particularly the scale heights and their variation with Galactic radius, differ in some cases by 30% to 50% from estimates made a few years ago. Clearly the diffuse ISM of the MW needs further research! But the papers presented at this meeting reinforce the general consensus that we do understand the ISM in the MW disk fairly well, and we can confidently extend our observing techniques and analysis tools to the halo, to nearby galaxies, and on to high redshifts.

5 Theme – Structures in the MW Halo

The scale heights of the phases do not completely describe the structure of the ISM in the MW halo. As Lockman puts it in his presentation, in the halo we see “hydrogen that has a story to tell about how it got there.” One of the most dramatic examples is Smith’s Cloud (Smith [1963] Lockman et al. [2008]), a high velocity cloud (HVC) with mass greater than $10^6$ M$_\odot$ and total space velocity of about 300 km s$^{-1}$, approaching the Galactic plane at some 75 km s$^{-1}$. This is large compared to typical HVC’s described in Wakker’s review, but by no means the largest, as Complex C is estimated to have mass $4 \times 10^7$ M$_\odot$. Typical distances above or below the plane, $|z|$, are in the range 5 to 15 kpc for these large HVC complexes. Assuming that they represent primordial material, their mass accretion rate averages to about 0.5 to 1 M$_\odot$ yr$^{-1}$. As Putman points out in her paper,
maintaining an accretion rate of \(1 \, \text{M}_\odot \, \text{yr}^{-1}\) over the last 5 to 7 Gyr would require a primordial reservoir of as many as 500 dwarf galaxies with HI mass \(10^7 \, \text{M}_\odot\), or 5000 HVC complexes of \(10^6 \, \text{M}_\odot\). This is a lot, there certainly do not seem to be nearly that many such systems in the Local Group remaining to be accreted. So it is important to work out the stories that the HVC complexes have to tell, by detailed studies such as those described by Ford, Dedes, Madsen, Haffner, Leiter, and Hill. The larger objective of such work is to determine what their precursors were. Some of today’s HVC complexes may have come from dwarf galaxies that were tidally disrupted and captured by the MW, or they may have come from tidal stripping of an existing Local Group member, like the Magellanic Stream discussed in the papers by Madsen, Wakker, and Putman, or perhaps they have somehow been part of the MW halo since the epoch of galaxy formation.

There seems to be a clear distinction between the large, 21-cm selected HVC complexes and the much lower mass clouds that dominate optical and uv surveys toward distant halo stars, described by Wakker, Ben-Bekhti, Nasoudi-Shoar, and Fox, and earlier by Smoker et al. (2003), Lockman & Savage (1995), and see the historical data discussed by Benjamin & Danly (1997). The clouds seen in these surveys are similar to clouds seen in extragalactic absorption studies; at least some of them are classical fountain-return clouds. Some of the HI HVC’s are probably in this category as well. For launching the fountain, the large Galactic chimneys and supershells are leading contenders, as described by McClure-Griffiths, Sato, Pidopryhora, Gonçalves, and Dawson. These concentrate and direct the energy provided by many supernova remnants to drive hot gas out of the plane and into the lower halo. Such structures appear to be common in nearby spiral galaxies. The structure of the M82 superwind is reminiscent of a galactic chimney driven to the extreme by the starburst nucleus, as discussed by Westmoquette and Trinchieri.

6 Theme – HVC’s in Nearby Galaxies and Groups

One of the most successful aspects of this conference has been the seamless merging of Galactic and extra-galactic observations and theory. This shows the maturity of the field, in that the same astrophysical phenomena that we study in detail in the MW we can trace more broadly in nearby spirals, and with fair sensitivity even at intermediate to high redshift. Thus many of the themes in Dettmar’s review of disk-halo interaction in nearby galaxies echo those of Ferrière’s review of the same topic in the MW, and many other reviews include both Galactic and extragalactic examples. In particular, the HI HVC’s in the Local Group and nearby galaxy groups reviewed by Putman, Oosterloo, and Chynoweth, are analogous to the large HVC complexes in the MW halo. But their morphology can be completely different. Unlike the Local Group, the M81-M82-NGC3077 group has a neutral intra-group medium, probably a massive tidal feature, as described by Chynoweth. The Local Group is more typical, apparently cases like the M82 group are rare. But it is critically important to get more sensitive HI surveys of many more nearby groups, in order to interpret the data from absorption surveys at intermediate and high redshifts. This will come from new arrays with enhanced surface brightness
sensitivity, like the Australian Square Kilometre Array Pathfinder (ASKAP).

7 Theme – The Halos of Spiral Galaxies seen Edge-On

Spiral galaxies seen very nearly edge-on are excellent subjects for study of the $z$ distribution of the ISM phases, and the structure of the gas in their halos. Such studies are the topics of the papers by Rossa, Wu, Rand, Heald, Howk, and Oosterloo’s poster, and they are included in the reviews by Dettmar and Reynolds. From these studies we learn what a range of fountain activity there is in spiral galaxies, depending on the star formation rate (SFR). The lower halos of the edge-on spirals that have been studied in detail show how different the scale heights of the diffuse neutral and warm ionized media can be, ranging from a few hundred pc to a few kpc. Rossa also makes the point that the morphology of the diffuse ionized gas changes with SFR, with the high SFR galaxies showing a smooth ionized halo, and the intermediate (lower) SFR galaxies showing many wisps that probably trace large chimneys, bubbles, and supershells.

Another critical question that edge-on spirals can help answer is how the rotation velocity of the gas in the halo departs from that of the disk below. Heald and Benjamin discuss this based on observations, and Fraternali reviews theoretical and computational studies. Here again, the SFR seems to play a critical role. Values for the gradient in rotation velocity with $z$ vary from -8 to -30 km s$^{-1}$ kpc$^{-1}$, with the higher values seen in the galaxies with lower SFR’s. This may imply that high fountain activity strengthens the dynamical connection between the disk and lower halo, essentially acting as a viscosity that depends on SFR. Similar numbers for the Milky Way are still a bit controversial; Levine et al. (2008) find $-22\pm 6$ km s$^{-1}$ kpc$^{-1}$, see also the review by Kalberla & Kerp (2008).

A series of major surveys of nearby galaxies including SINGS (Kennicutt et al. 2003), THINGS (Walter et al. 2008), and SONG (Regan et al. 2001) are mentioned in a few papers in this conference, including those of Leiter and Portas. These surveys are primarily concerned with the disks of nearby spiral galaxies. They are rich in information on the mixture of ISM phases, and the links from the ISM to star formation. They will also prove useful for understanding the disk-halo connection. These surveys are particularly interesting for revealing the structure of the outer disks, beyond the area of active star formation. Conditions in such outer disks are in some ways intermediate between those in the inner disk and in the halo, as discussed by Kalberla and Dickey for the MW. These surveys give a hint of the even more powerful studies of nearby galaxies that will be possible in the coming decade with telescopes such as ALMA, JWST, and the SKA.

8 Theme – Outflows from Galaxies at High Redshift

Surveys of absorption lines in the spectra of QSO’s at high redshift are a very powerful way to trace the abundance of gas clouds intervening along the path to the continuum source. Studies of the Lyman alpha forest can detect clouds with atomic
Summary: Themes and Questions

Hydrogen column densities as low as $10^{13}$ cm$^{-2}$. Ranges of progressively increasing column densities are sampled by metal line systems, Lyman limit systems, and damped Lyman alpha systems finally reaching column densities of $10^{22}$ cm$^{-2}$ or higher. A remarkable result from forty years of such studies is that the abundance of absorbing systems as a function of column density, $n(N_H)$, can be described as a power law over this entire range of column densities, with $\frac{dn}{dN_H} \propto N_H^{-1.58}$, as reviewed by Richter. Many of these absorption lines originate in the halos or outer disks of intervening galaxies; we infer that some of these clouds are driven by galactic fountain processes similar to those we see in the MW and nearby galaxies.

The ISM in high redshift galaxies can also be studied using emission line tracers, particularly at mm and sub-mm wavelengths, as reviewed by Greve. As ALMA comes on-line in the next few years, this field will grow rapidly, and we may hope to detect galaxies like the MW at redshift $z \sim 1$. For now, most of the galaxies studied at such great distances are at the high end of the CO and far-IR luminosity functions, typically starburst and ultra-luminous IR galaxies plus some QSO’s.

With the power of 8m class optical telescopes, absorption lines can be studied not only toward bright QSO’s, but also using the light of normal galaxies at high redshift. The DEEP survey described by Koo, and the specific examples presented by Rubin, show the amazing accomplishments of high z spectroscopy at the Keck Telescope. Both outflow and infall are seen in galaxies in the DEEP sample, with outflow correlating with infrared luminosity, but infall not. Results of stacked spectra give very useful numbers, such as that 10% of absorption lies beyond the escape velocities of the galaxies, and the fact that almost all galaxies have at least some outflow gas. A further result is that it is not the dwarfs but the more massive galaxies, like the MW, that dominate the total outflow that ultimately enriches the inter-galactic medium with heavy elements.

To calibrate the present abundance of absorbing clouds vs. the numbers in the early universe requires low redshift surveys of the far-uv lines, seen shifted into the optical and near-IR at high redshift, using far-uv telescopes like FUSE. The papers by Fox and Richter give useful comparisons among different line tracers in the optical and uv. An interesting twist is the appearance of two populations of Mg II absorbers. The stronger class of lines is more reliably a tracer of outflows.

Theories and questions involving galaxy evolution and the history of disk-halo interactions were presented by Bernet, Jachym, Fangano, Martin and Bregman. There are some very big issues involved, such as the “missing baryon problem” raised by Bregman, and the metal enrichment of the IGM discussed in detail by Martin. Martin makes the point that “What you see is not everything that is there.” It is very important to remember that outflows can and do happen at temperature and density combinations for which we have no sensitive tracers. For example, at temperature $T \sim 10^7$ K (1 KeV x-rays) we can hardly make out the winds even from nearby galaxies, let alone high redshift systems, as Trinchieri explains.
What Next?

Telescopes that will become available over the next decade will bring improvements in resolution and sensitivity of an order of magnitude or more in many wavebands. With such improvements over current capabilities it will become possible to study galaxies like the MW at \( z=1 \) with the same level of detail that we now apply to galaxies in nearby groups. This conference has demonstrated that extragalactic and Galactic astrophysics merge when the observational data get that good. The point is, the questions we are asking now about nearby galaxies are the same ones we have been asking and answering in the MW for decades. Soon we may be doing the same for galaxies at \( z=1 \) and beyond.

Experts in this field, albeit self-appointed ones like many of us attending this conference, stand to gain academic ground in studies of galaxies at high redshift, as the science shifts into our purview. We can start thinking now about what we would do if we had images and spectra of galaxies at cosmological distances as good as those we have now for, e.g., M81 and M82. Here are some questions that we might begin to answer:

- Do disks assemble by satellite accretion? Why doesn’t this disrupt the disk? Does it lead to SF bursts? If there are SF bursts, do they denude the disk? Does SF have a negative feedback “governor” that limits its speed in a disk where the ISM can easily be lost to a wind or fountain?

- Is the intra-cluster medium (ICM) that we see in nearby rich clusters representative of the inter-galactic medium (IGM), in metallicity and in the ratio of total baryon mass to galaxy light? If so, how and when did all the baryons escape from the galaxies? Was this happening at the same time as the accretion that built galaxies?

- Did the magnetic field build up slowly through a dynamo process in galaxy disks, or was it rapidly generated during the epoch of galaxy formation? How much seed field came from the big bang itself? Is there an IGM of magnetic fields and CR’s similar to those seen in the ICM of rich clusters?

In the next decade we may be confronted with the data we need to answer these questions. “Confronted” because we may not be ready to understand it all. For want of more profound insight, the interpretation of that data will probably follow astrophysical analysis paths similar to those discussed in this volume as applied to the disk and halo of the MW and nearby galaxies. We can look forward to extending what we have learned about our own disk-halo connection to galaxies on much larger scales. If this brings deeper understanding of the history of the universe, then we can hope for more conferences as interesting as this one in years to come.

References

Avillez, M.A., 2000, MNRAS 315, 479.
Benjamin, R.A., & Danly, L., 1997, ApJ 481, 764.
Bregman, J.N., 1980, ApJ 236, 577.
Chavalier, R.A. & Gardner, J., 1974, ApJ 192, 457.
Cioffi, D.F., & Shull, J.M. 1991, ApJ 367, 96.
Cox, D.P. & Smith, B.W., 1974, ApJ 189, 105.
Cox, D.P. & McCammon, D., 1986, ApJ 304, 657.
Cowie, L.L., 1987, in Interstellar Processes, eds. D.J. Hollenbach & H.A. Thronson, (Dordrecht: Reidel), p. 245.
Dalgarno, A., & McCray, R.A., 1972, ARA&A 10, 375.

Field, G.B., Goldsmith, D.W., and Habing, H.J., 1969, ApJ Lett. 155, L149.
Heiles, C., 1990, ApJ 354, 483.
Jenkins, E.B., and Meloy, D.A., 1974, ApJ 193, L121.
Kalberla, P.M.W. & Kerp, J., 2008, ARA&A 47 in press.
Kennicutt, R.C., Armus, L., Bendo, G., Calzetti, D., Dale, D.A. et al. 2003, PASP 115, 928.
Levine, E.S., Heiles, C., & Blitz, L., 2008, ApJ 679, 1288.
Lockman, F.J., Benjamin, R.A., Heroux, A.J., & Langston, G.I., 2008, ApJ 679, L21.
Lockman, F.J. & Savage, B.D. 1995, ApJS 97, 1.
MacLow, M.-M., McCray, R., & Norman, M.L., 1989, ApJ 337, 141.
Mansfield, V.N. & Salpeter, E.E., 1974, ApJ 190, 305.
McCammon, D., Meyer, S.S., Sanders, W.T., and Williamson, F.O., 1976 ApJ 209, 46.
McKee, C.F. & Ostriker, J.P., 1977, ApJ 218, 148.
Mebold, U., Cernicharo, J., Velden, L., Reif, K., Crezelius, C., & Goerigk, W., 1985 A&A 151, 427.

Norman, C.A. & Ikeuchi, S., 1989, ApJ 345, 372.
Oort, J.H., 1932, Bull. Astron. Inst. Neth. 6, 249.
Oort, J.H. 1966 Bull. Astron. Inst. Neth. 18, 421.
Oort, J.H. 1970 A&A 7, 381.
Parker, E.N., 1966, ApJ 145, 811.
Pickelner, S.B. 1953, C.R. Acad. Sci. URSS, 88, 229.
Regan, M.W., Thornley, M.D., Helfer, T.T., Sheth, K., Wong, T., et al. 2001, ApJ 561, 218.

Rosen, A. & Bregman, J.N. 1995, ApJ 440, 634.
Salpeter, E.E., 1976, ApJ 206, 673.
Sanders, W.T., Kraushaar, W.L., Nousek, J.A., & Fried, P.M., 1977, ApJ 217, 87.
Shapiro, P.R. & Field, G.B., 1976 ApJ 205, 7625.
Shklovsky, I.S., 1952, Astr. J. U.S.S.R., 29, 418.
Smith, G.P., 1963, Bull. Astron. Inst. Netherlands, 17, 203.
Smoker, J.V., Rolleston, W.R.J., Kay, H.R.M., Kilkenny, D., Arnal, M., et al. 2003, MNRAS, 346, 119.
Spitzer, L., 1956, ApJ 124, 20.
Struck-Marcell, C. & Scalo, J.M., 1984, ApJ 277, 122.
The Role of Disk-Halo Interaction in Galaxy Evolution: Outflow vs Infall?

Vazquez-Semadeni, E., Passot, T., & Pouquet, A., 1995, ApJ 441, 702.
Walter, F., Brinks, E., de Blok, W.J.G., Bigiel, F., Kennicutt, R.C., Thornley, M.D., & Leroy, A., 2008, AJ 136, 2563.
Williamson, F.O., Sanders, W.T., Kraushaar, W.L., McCammon, D., Borken, R., & Bunner, A.N., 1974, ApJ 193, 133.
York, D.G. 1974, ApJ 193, 127.