THE DISK-HALO CONNECTION AND WHERE HAS ALL THE GAS GONE?

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Abstract. The wealth of data in the past decades, and especially in the past 15 years has transformed our picture of the gas around the Milky Way and other spiral galaxies. There is good evidence for extraplanar gas that is a few kpc in height and is seen in all gaseous phases: neutral; warm atomic; and hot, X-ray emitting gas. This medium is seen not only around the Milky Way, but other spiral galaxies and it is related to the star formation rate, so it is likely produced by the activity in the disk through a galactic fountain. More extended examples of halo gas are seen, such as the HVC around the Milky Way and around M31. This gas is typically 10-20 kpc from the galaxy and is not seen beyond 50 kpc. This gas is most likely being accreted. A hot dilute halo ($10^6$ K) is present with a similar size, although its size is poorly determined. An ongoing controversy surrounds the relative amounts of outflow from the disk and accretion onto galaxies such as the Milky Way. There is good evidence for accretion of cold material onto the Milky Way and other galaxies, but it is not clear if there is enough to modify the gas content and star formation properties in the disk. The reservoir of accretion material is as yet unidentified. Some of these findings may be related to the issue that galaxies are baryon-poor: their baryon to dark matter ratio is well below the cosmological value. The absence of baryons may be due to extremely violent outflow events in the early stages of galaxy formation. We may be able to understand this stage of galaxy evolution by applying our deepening understanding of our local disk-halo environment.

1 Introduction

About 50 years ago, the concept of gas above the disk of the Milky Way was suggested by Spitzer (1956), based on properties of optical absorption line systems. In a remarkable paper, he discussed the nature of gas that might occupy the volume
above the disk, and its possible evolution. At that time, there were few observational tools to probe these suggestions, but that has changed enormously in the following decades. In the 1960’s, the discovery of the high velocity clouds of neutral hydrogen was a dramatic observational discovery and nearly every theoretical explanation placed this material above the disk (Oort 1970). Also, the amount of mass in the HVC could be substantial, depending on the distance to these clouds, which became one of the most difficult problems to resolve.

The next great observational insights occurred in the mid 1970s with the opening of two new wavebands, the X-ray and the rocket ultraviolet regions. The X-ray observations showed that gas of $\sim 10^6$ K is present in the Milky Way and that the Sun is located in a hot bubble. The presence of large million degree gas regions was quickly interpreted as the natural consequence of supernovae and led to a fundamentally new vision for our interstellar medium (on a personal note, as a graduate student, I first heard about this in a colloquium given by Don Cox, which had an important effect on my career). Our ISM no longer resembled “raisin-pudding”, where the cold HI clouds were the raisins while the neutral intercloud medium was the pudding. Now, we were told that most of the ISM was a very hot dilute medium in which colder gas also existed (Cox and Smith 1976; Ostriker and McKee 1977). The filling factor for this hot gas might be very high (values of 90% were suggested), which implies that the hot gas will flow easily above the disk, creating a halo (it is now believed that the filling factor is closer to 20%). Hot halo gas will not persist in hydrostatic equilibrium due to radiative losses, so the evolution of this gas was investigated, and the resulting weather pattern is referred to as a galactic fountain (Shapiro and Field 1976; Bregman 1980).

Another great advance occurred beginning around 1980 with the launch of the International Ultraviolet Explorer (IUE), which began the era of ultraviolet absorption line astronomy of stars above the disk (and including background AGNs; deBoer and Savage 1980). These observations revealed the presence of warm ionized gas species above the disk, with temperatures somewhere in the range $10^{5.5}-10^6$ K. From these observations, scales heights for the gas were deduced and we began to understand the physical scale of the halo material.

The improvements in instrumentation in every waveband have led to enormous advances in many aspects of this field. A number of the leading questions are on their way to being resolved, and I will discuss some of these advances, many of which will be described in more detail by several of the talks. Finally, the relationship of this field of halo gas to other fields of astrophysics has changed. At one time, it was a well-contained subfield that seemed to have little relationship to issues such as galaxy formation and evolution. Now, it is clear that many of the processes that we study are closely related to the formation and evolution of galaxies, some of the current “big” questions in astrophysics.

2 The Size of the Gaseous Halo of the Milky Way

One of the major issues in the field has been the location of the Galactic halo gas. For the neutral component, knowledge of the distance determines the mass
of the gas since the 21 cm measurement is a column density. The distance also
determines the size of the clouds and of the structures in which they reside, which
extend across an entire quadrant of the Galaxy in some cases. Not only are the
masses and sizes of the clouds fundamental quantities, they place strong constraints
on the models that might produce such structures.

This has been one of the most fruitful research areas in the past several years
and we now have a good general idea of the distances of the HVC and the in-
termediate velocity clouds (IVC). The observational technique has been to use
multiple stars at different heights in the halo, along with AGNs, which sample the
full halo. Against these objects, one can search for absorption, generally using the
optical absorption lines of Ca and Na and a variety of UV lines. For stars that
are projected against a HVC, an absorption line detection against a more distant
star but with a non-detection for the closer star leads to a distance constraint,
given certain assumptions about the smoothness of the cloud. There are many
time-consuming steps in this process, such as identifying halo stars that have suf-
ficiently simple spectra and are bright enough for observations. The results have
been worth the effort, and they show that the HVC lie at distances of 5-20 kpc
from the disk (Wakker et al. 2007, 2008; see Wakker, this volume). Related efforts
have probed the IVC, which lie closer to the disk, with typical distances of 0.5-4
kpc. As described below, the IVC are probably largely due to Galactic weather
(a galactic fountain) while the HVC (and especially the long coherent complexes)
are more likely due to accretion.

If the Milky Way is not unique, HVCs should be present in other galaxies, and
the easiest cases to study are in the Local Group. For M31, deep radio synthesis
maps show gas that can be HVC counterparts. This gas is found within 50 kpc of
M31 but never beyond 50 kpc. These clouds have diameters of about 1 kpc and they masses of $\sim 10^5$ M$_\odot$ (Westmeier et al. 2007). An important point is that there is no evidence for HI at hundreds of kpc from the Milky Way or M31. If there was neutral gas at such distances, it would imply that there are large reservoirs of HI. In this case, the gas could be detected in other groups of galaxies, but searches for this gas have only led to upper limits.

We have known about the scale heights of some ions for years, but the picture has been filled out with observations of OVI (Savage et al. 2003), the ion with the highest ionization potential among these ions. Whereas lower ionization state ions can be photoionized by starlight, the ionization energy needed to produce OVI from OVI is 114 eV. There is little starlight above 114 eV as this lies well above the He II ionization energy (54 eV), an important opacity in hot stars. Therefore, this ion is collisionally ionized and, in equilibrium, the peak of its ionization fraction is at $10^{5.45}$ K and the temperature range over which it is present is relatively narrow (order of magnitude decrease from peak fractional ionization occurs for $T < 10^{5.3}$ K, $T > 10^{5.7}$ K). Gas near $10^{5.5}$ K is near the peak of the radiative cooling curve, so this gas should cool in less than $10^7$ yr. This gas either represents an intermediary cooling stage for gas that began at a hotter temperature, or it is produced through turbulent mixing or conductive interfaces with a hotter medium. In either case, it implies the presence of a yet hotter medium.

The radiative cooling time of this gas is less than the time for the gas to free-fall onto the disk, so one would expect that cooler gas is produced, and with a scale height similar to that of OVI. This is indeed the case, as similar scale heights are seen for a variety of species. When making comparisons between ions, there are a number of important details that must be considered, such as the ionizing radiation field as a function of height and the vertical distribution of cooling gas (which appears as an effective source function in the fluid equations).

There is also evidence for hotter gas with a similar scale height in both the Milky Way and in other galaxies. In the Milky Way, the analysis of the Rosat All-Sky Survey showed a diffuse emission component that followed the Galactic disk (e.g., Pietz et al. 1998; Snowden et al. 2000). It has a scale height of about 4 kpc and a temperature near $10^6$ K. Thick disks of hot gas are seen around external edge-on galaxies, with scale heights of 3-5 kpc. Taken at face value, this would appear to be the hotter phase that radiatively cools, producing OVI, CIV, and the lower ionization ions that are studied in absorption. Around other galaxies, such as NGC 891, the X-ray emitting gas is most prominent above the parts of the disk that have active star formation, and this appears to be true for other galaxies. Furthermore, the intensity of these hot X-ray halos depends on the star formation rate, suggesting that star formation, and their subsequent supernovae are the driving elements for this gas (Tüllmann et al. 2006). This would fit in with the predictions of galactic fountains.

A somewhat lower scale height is deduced from the H$_\alpha$ survey (WHAM) and the pulsar dispersion measurements (Reynolds, Haffner, Gaensler, Berkhuijsen, this meeting). Depending on the assumptions that are made for the filling fraction of electrons with height, values of 0.3 - 1 kpc are obtained for the scale height, which
might seem in conflict with the scale heights for other halo components. However, this is a single scale-height fit, and for species that have strong disk components, the approach may be too simplified. The results do not exclude a more extended component, and the electron density of the X-ray emitting component is estimated to be $0.3-1 \times 10^{-3} \text{ cm}^{-3}$, is an order of magnitude below their last data point, at $z = 1 \text{ kpc}$. One topic where these dispersion measure values are crucial is in constraining a more extended ionized halo.

Searching for an extended hot halo in emission has been challenging because of current surface brightness limitations of X-ray astronomy. Early-type galaxies have hot halos that can be seen to 10-30 kpc (Trinchieri, this meeting) and hot gas in starburst galaxies is seen to about 10-20 kpc, but for spiral galaxies, the greatest extent is only about 8 kpc, in NGC 891. A difficulty is that the emission measure decreases with the square of the electron density and once the surface brightness drops to the level of the X-ray foreground (due to the Milky Way and solar scattered X-rays) plus background (unresolved AGNs), further detection is impossible.

The situation is a bit more promising when making absorption line observations of gas at the characteristic temperature of the Galactic potential well, $1-3 \times 10^6 \text{ K}$. The strongest lines in this temperature range are the resonance lines of He-like and H-like oxygen, OVII and OVIII, which occur at 574 eV and 654 eV. The fractional equivalent widths of absorption lines are inversely related to energy, and combined with the limited effective collecting area of X-ray telescopes (55 cm$^2$ for XMM-Newton), these lines can be detected only against the continuum of the brightest quasars. We have determined the equivalent widths (or upper limits) for the OVII resonance line for 17 extragalactic sitelines (Bregman and Lloyd-Davies 2007).

We examined whether the equivalent width distribution was suggestive of the
Local Group geometry or of the Milky Way. For the Local Group, one would expect the greatest column densities to occur near the long axis and in the general direction of M31 ($l = 121^\circ$), while the lowest columns would occur in the anti-M31 direction. In contrast, a Milky Way halo would have the greatest columns in lines of sight that go across our Galaxy. The data are not consistent with a Local Group but are consistent with a Milky Way halo (a hot medium must exist in the Local group, possibly at a slightly higher temperature than can be sensed with OVII). The observations do not restrict the size of the halo, but a radius of 10-100 kpc is most likely; the implied gas mass is $10^8-10^9 \, M_\odot$. This size range is consistent with the size of the HVC distributions around both the Milky Way and M31. There must be a dilute medium that fills the Local Group and is most likely hot. This medium is inferred from the apparent stripping of neutral gas from Local Group dwarfs that has left the ones within 250 kpc of the Milky Way or M31 as gas-poor (Blitz and Robishaw 2000; Putman, this conference). Blitz and Robishaw (2000) infer a density of $2.5 \times 10^{-5} \, \text{cm}^{-3}$ and a mass of $10^{10} \, M_\odot$ for this dilute medium.

A summary of the topics thus far is that there is excellent evidence for a halo of gas with a characteristic thickness of 3-5 kpc. This is a multi-temperature medium with a range of $10^2-10^6 \, K$. In addition, both neutral and $10^6 \, K$ gas extends out to a radius of a few tens of kpc. However, there is no evidence for a large reservoir of neutral gas in the Local Group.

3 Inflow Onto the Milky Way and Spiral Galaxies: Hot or Cold?

The issue of accretion onto galaxies bears on several factors: evidence that accretion has occurred or is occurring; an adequate reservoir of gas; and whether the gas is accreting hot or cold. Regarding accretion, there are two modes, one in which the temperature of the accreted gas is less than the characteristic temperature of the system. For a spiral galaxy like the Milky Way, the virial temperature is $2-3 \times 10^6 \, K$ and gas at this temperature emits in the X-ray band. Accretion of lower temperature gas cannot naturally support itself by thermal pressure so it free-falls and radiates through shocks. In either case, the luminosity liberated is

$$L = 4 \times 10^{40} \, (\text{Mdot}/1 \, \text{M}_\odot \, \text{yr}^{-1}) \, (T/3 \times 10^6 \, \text{K}) \, \text{erg/sec}$$

In considering the hot accretion mode, we note that the Milky Way has $L_X \approx 10^{39.3} \, \text{erg s}^{-1}$, and the X-ray luminosity from other spirals is about $10^{39.5} \, \text{erg s}^{-1}$, most of which appears to be related to star formation in the disk. If this X-ray emission is due to accretion and not a galactic fountain, then the hot accretion rate is no more than $0.2 \, \text{M}_\odot \, \text{yr}^{-1}$. However, Tüllmann et al. (2006) has shown that this X-ray emission is more likely galactic in origin, in which case, the hot accretion rate is probably less than $0.1 \, \text{M}_\odot \, \text{yr}^{-1}$.

In contrast, there is considerable evidence for cold accretion onto spiral galaxies at a rate of about $0.2 \, \text{M}_\odot \, \text{yr}^{-1}$. The HVC, including the Magellanic Stream is neutral material falling onto the Milky Way. In a few cases, we see evidence for a collision between the HI and the Milky Way disk, as in the case of the Smith Cloud (Lockman et al. 2008) and the leading arm of the Magellanic Stream (McClure-Griffiths et al. 2008). More evidence for cold accretion comes from the
distortions in the HI disks of spiral galaxies. Without accretion events, the disks of spirals would be approximately circularly symmetric, but a significant fraction show distortions that are best understood as the accretion of cold material onto the outer parts of the galaxy (review by Sancisi et al. 2008). The inferred accretion rate is $0.2 \, M_\odot \, yr^{-1}$, the same as the value deduced for the Milky Way.

There are two arguments that are often made for an accretion rate that is about an order of magnitude larger, about 1-2 $M_\odot \, yr^{-1}$. The first is the desire to resolve the G-dwarf problem, where there are too few G dwarfs with low metallicity (the metallicity “floor” is about 0.2 Z_⊙). A popular solution to the G dwarf problem is to have a steady inflow of low metallicity material onto the disk, at about a rate of 1-2 $M_\odot \, yr^{-1}$. This is not the only possible resolution to this problem and alternative explanations seem viable (Binney and Merrifield 1998). A natural solution to the G-dwarf problem is that the gas that formed the stellar disk was pre-enriched.

The other problem that accretion would resolve is the gas consumption problem. The problem for the whole galaxy is that, at the current star formation rate, most of the gas will be consumed in $\sim 10^{9.5}$ Gyr. This does not seem to be a serious problem because the volume-averaged star formation rate of the universe is decreasing sharply in time rather than being constant. However, for the inner part of a galaxy, the gas depletion timescale can be several times shorter (Blitz, private communication). Unless there is gas replenishment, star formation will diminish on a timescale less than 1 Gyr. In principle, gas replenishment could take the form of gas transfer from the outer to the inner part of a spiral galaxy, although models do not yet predict a smooth mass transfer rate $\sim 1 \, M_\odot \, yr^{-1}$. Such mass transfer might occur in large events, such as when Magellanic Stream material reaches the disk. This could lead to periods of significant mass transfer and a variable star formation rate. In the region near the Sun, the star formation rate has varied significantly (Rocha-Pinto et al. 2000), and in following a period of enhanced star formation 2 Gyr ago, the star formation rate dropped by a factor of four in a fraction of a Gyr. If radial mass transfer is ineffective, then accretion would need to occur onto the star-forming parts of spiral galaxies. The accreted gas would need to have just the right angular momentum distribution for this to work. In this area, I would like to see more theoretical work regarding the effectiveness of radial mass transfer and whether an accretion rate greater than the observed value of $0.2 \, M_\odot \, yr^{-1}$ is really required. A radial flow rate through the disk of $0.2 \, M_\odot \, yr^{-1}$ would require a flow velocity of no more than 1 km s$^{-1}$, which is below the limitations of such measurement, about 5-10 km s$^{-1}$ (Wong et al. 2004).

A related, and rather serious problem is that of the reservoir of the accreting gas. X-ray observations of galaxy groups and of spiral galaxies show that they are relatively poor in hot gas. As discussed above, the cooling rate is probably insufficient to supply accretion from the cooling flow mechanism. An alternative is that the gas is neutral, but HI surveys do not find a reservoir of $10^9$-$10^{10}$ $M_\odot$ of cold gas within a virial radius of galaxies (or a larger amount in galaxy groups). If such a reservoir of gas exists, it is either molecular or it is warm ionized material. A reservoir of molecular gas seems less likely because the gas that disturbs the
outskirts of spiral galaxies and the HVC are primarily neutral atomic gas. The remaining possibility is a reservoir of warm ionized gas ($10^3$-$10^4$ K), which would be a very low surface brightness emitter at the low pressures of the halo. This warm ionized material would be in pressure equilibrium with a hot ambient medium. If there is an extended hot halo around a spiral galaxy, there would be a negative pressure gradient until the material merged with the group medium. Thus, as the gas falls toward the galaxy, its density would increase and eventually recombine, as the recombination rate exceeds the photoionization rate.

Although it may be difficult to detect this material in emission, there is some evidence for it in absorption. Wakker (this volume) has examined the distance of low-redshift absorption systems from the nearest galaxy and finds that about half of these systems lie within 400 kpc of the host system. There is a lot of mass in such low redshift absorption systems: the ones within 400 kpc of the galaxies contain about three times the amount of baryons as are in the galaxies. This seems to be an adequate supply of gas, provided that it can fall in at the observed rate. To conclude, the most likely form for the reservoir of gas that falls onto spiral galaxies is warm ionized material.

4 Cold Flows, A New Paradigm?

A shift is occurring in the field of galaxy formation that may bear directly on some of the accretion issues discussed above. For massive galaxies, the formation
mechanism has resembled cooling flows, whereby gas falls into the dark matter potential, heats up to the characteristic temperature of the potential well in a standoff shock, and then radiatively cools to form the galaxy. The problem with this attractive theory is that it leads to relatively slow galaxy formation and it is unable to produce the luminous galaxies that are observed at early cosmological times. A solution to this problem was offered by Dekel et al. (2009), who argued that there are filaments of low entropy gas that, because of lack of buoyancy, would flow into the galaxy quickly. These cool filaments penetrate the standoff shocks in the hot gas, feeding the galaxy with cooler gas. Such cold flows are now being identified in high resolution simulations, although it may be a while before their importance is fully understood. The reason that I bring up the topic of cold flows is that the accretion onto galaxies today may be a very modest version of this phenomenon. At early epochs, cold flows would need to occur at a rate of \( \sim 10^1 \text{-} 10^2 \, \text{M}_\odot \, \text{yr}^{-1} \) to produce the galaxies seen at high redshift. If the regions surrounding these galaxies are not greatly disturbed (as would occur in a galaxy cluster), then it seems feasible that a more modest amount of material, initially near or beyond the virial radius, is falling in today. Understanding cold flows in greater depth may be quite important for interpreting the observations of galaxies today.

5 Galactic Winds

In addition to the infall of gas onto galaxies, there may be outflows as well. It seems that many astronomical objects both accrete and eject gas and spiral galaxies
Fig. 5. The distribution of OVII absorption lines as a function of angle from the Galactic Center. The OVII line is produced by $10^6$ K gas in a halo around the Milky Way. The new data indicates that a dilute extended halo is preferred to a halo where there is significant gas bound to the bulge, as is seen in elliptical galaxies (Lloyd-Davies and Bregman, in preparation).

...may not be very different. There are two likely mechanisms for the outflow of gas: cosmic rays; and thermally driven winds. The thermally driven winds occur because supernovae, and possibly AGN heating, raises the gas temperature above the escape temperature. This is the likely mechanism that keeps many early-type galaxies relatively free of gas and X-ray poor (especially the elliptical systems with $L < L^*$; Trinchieri, this meeting). It would not be too surprising if it occurred in the bulge of the Milky Way and the energetics are consistent with this picture.

Hot gas is present in the direction of the bulge as seen in all-sky X-ray surveys and in X-ray shadowing studies. If the gas were bound to the bulge, it would follow a radial density distribution similar to that seen in X-ray luminous elliptical galaxies, $S_x \propto (1+(r/r_c)^2)^{-3\beta+1/2}$, where $\beta = 0.5-0.7$, typically. This leads to a density distribution of hot gas of $n \propto (1+(r/r_c)^2)^{-3\beta/2}$. This implies that the density and column density of hot gas should rise rapidly into the bulge of the Milky Way, but no such rise is observed. This is consistent with an outflow of hot gas from the bulge and the outflow rate would be 0.1 $M_\odot$ yr$^{-1}$ if all of the mass shed from the stars partakes in the wind.

A cosmic-ray driven wind, extending beyond the bulge and into the disk is discussed at this meeting by Breitschwerdt and Evrett. This seems reasonable, but one of the frustrations is that we do not have sufficiently good knowledge of...
cosmic rays and magnetic fields to accurately predict the mass flux of such a wind (although the new calculations presented here are quite promising).

The winds from the Milky Way or even a low redshift starburst galaxy pales by comparison with some high redshift galaxies, which may be hundreds of times greater.

6 The Missing Baryons in Galaxies

There are two missing baryon problems, one for the local universe and another for individual galaxies. To appreciate the first problem, we consider the dark matter and the baryonic matter, where we can form the ratio known as the baryon fraction. This fraction is given from WMAP observations, but also from Big Bang Nucleosynthesis calculations, and the baryon fraction is about 17%, or $\Omega_{\text{baryon}} = 0.046$ and $\Omega_M = 0.27$. It had been assumed that the baryons all went into galaxies and if we took a census today, we would obtain the same ratio. However, when one examines the amounts of baryons in different components, one finds very little in the form of galaxies. Galaxies at low redshift constitute only about 4% of $\Omega_{\text{baryon}}$, with another 3% in hot gas in X-ray bright clusters and groups of galaxies (Fukugita and Peebles 2004). About 30% of $\Omega_{\text{baryon}}$ resides in warm gas responsible for Ly$\alpha$ absorption line systems and another 5-10% in OVI - bearing gas (about $10^{5.5}$ K; Danforth & Shull 2005)). That leaves about 50% unaccounted for and this is the “missing” baryon problem. These baryons are not really missing but are simply difficult to detect. Theory suggests that this material is hot ($10^5$-$10^7$ K) and dilute, with an overdensity of 10-100 and it has not collapsed into virialized structures (Cen and Ostriker 2006). This gas is expected to lie in the large unvirialized filaments that connect galaxy clusters and galaxy groups. If this is the correct model, it will be detected when X-ray absorption spectroscopy improves by an order of magnitude or more.

There is a second missing baryon problem that is much more local, being evident around individual galaxies. If you add together the stars and gas in the Milky Way and divide by the gravitational mass, you only account for 20-30% of $\Omega_{\text{baryon}}$. This is not an isolated incident. It applies to every galaxy. Another nearby galaxy, M33 only has 0.1 $\Omega_{\text{baryon}}$ (Corbelli 2003), and gravitational lensing studies also show that only 10-30% of baryons lie in moderate and large galaxies (e.g., Hoekstra et al. 2005, McGaugh 2007). The situation is even worse in the dwarf galaxies, many of which possess less than 0.1 $\Omega_{\text{baryon}}$. Relative to their dark matter content, galaxies are baryon-poor.

One might wonder whether any present day structure has the cosmological baryon-to-dark matter ratio. Deep potential wells, such as clusters of galaxies have nearly the cosmological value of this ratio. For potential wells deeper than about 1.5 keV ($2 \times 10^7$ K or 500 km/s rotational velocity), which are rich galaxy groups, the baryons are not missing.

There are two likely scenarios for the baryons absent in galaxies. Either the gas fell into the galaxy but was heated by supernovae and AGNs, leading to a galactic superwind. There is evidence for galactic superwinds at high redshift ($z = 2-3$)
outflow velocities of 300-1000 km/sec and mass loss rates of 100 M⊙ yr⁻¹. If this were to persist for 1 Gyr, it could account for the amount of baryons missing from galaxies. Unfortunately, the duration of such superwinds is unknown and even their mass fluxes are not accurately known. This superwind would pollute the surrounding medium with metals and it would heat the gas.

Another possibility is that the gas is heated before falling into the galaxy. If enough supernovae occur prior to the primary collapse of the galaxy components, the gas may have enough entropy to resist the infall. The energy needed to prevent the infall of gas is quite considerable, but it is about a factor of two less than the energy needed to drive it out as a galactic wind. If this gas resided within the virial radius of a galaxy like the Milky Way, it would have a very massive halo, with a mass of about 1-2×10¹¹ M⊙ within a radius of 200 kpc, the approximate virial radius. Such hot halos are not seen around galaxies, so the material must have been pushed well beyond the virial radius. Since the mass a dilute Local Group medium is estimated to be only 10¹⁰ M⊙ (Blitz and Robishaw 2000), it is likely that this ejected gas lies beyond the virial radius of the Local Group.

These important heating or feedback processes are generally not yet included in galaxy formation models, which typically predict that galaxies form with the cosmological baryon fraction. It is only when these processes are properly accounted for, along with the development of cold flows, that we can understand galaxies and the accretion or outflow processes that may be occurring today.

The problems and issues that I outlined above do not constitute an exhaustive list of topics represented by this meeting, or even a list of the most interesting
areas. They are a personal selection of some of the issues that I would like to know the answers to. Judging from the posters and talks in this meeting, we will learn a great deal about the progress in these areas, as well as many others.

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