New Views of the Magellanic Clouds
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Modeling the ISM: Molecular Gas, Ionizing Radiation, and Numerical Simulations

Joel N. Bregman

Dept. of Astronomy, Univ. of Michigan, Ann Arbor, MI 48109, USA

Abstract. Three different topics regarding the ISM in the Magellanic Clouds are discussed. First, we examine how the Magellanic Stream can be used as a tracer of the ionizing radiation leaking out of Galaxy and the Magellanic Clouds. We show that the radiation reaching the Magellanic Stream is less than 1% of the ionizing radiation produced by Galactic O and B stars. Since about 14% of the ionizing radiation from these stars is required to ionize the Reynolds layer, which is within 1 kpc of the disk, most of this radiation must be absorbed before reaching the Stream.

Second, we examine the reliability of using CO as a tracer of H_2 in regions of low or modest column densities (not giant molecular cloud complexes). For our Galaxy, the usual CO to H_2 conversion factor overlooks a considerable amount of H_2 and the evidence suggests that this may be true in the LMC as well. Finally, we present numerical hydrodynamical calculations of the interstellar medium in disk galaxies for a region of size 2 kpc along the plane and 15 kpc out of the plane. The simulations reveal a rich structure of low density hot regions separated by cold dense material, with the resulting position velocity diagrams being qualitatively similar to the recent HI studies of the LMC. A number of other aspects of these simulations are discussed also.

1. Introductory Comments

I would like to discuss a few different topics in regard to the interstellar medium in the Magellanic Cloud region, with an effort to avoid topics already discussed by others at this conference. The interstellar medium can be studied in order to understand its structure and properties, or it can be used as a tool to study some other phenomenon. I will consider both types of topics, dealing with the radiation field of the Milky Way, of the molecular gas content of the LMC, and of the structure of the HI gas in the LMC.

2. The Magellanic Stream and the Ionizing Radiation from the Milky Way

The Magellanic Stream passes over the south Galactic pole, so it is directly exposed to the radiation escaping from the Milky Way. The flux of ionizing radiation reaching the Stream is the amount escaping the Galactic disk, less the absorption of this radiation in the 50-80 kpc journey to the Stream. We know that significant amounts of ionizing radiation escape the Galaxy because in order to maintain the Reynolds layer, the warm ionized gas within about 1 kpc of the plane, 5-15% of the ionizing radiation from all OB stars is required. We will show that this amount of ionizing radiation never reaches the Magellanic Stream, becoming absorbed by an intervening medium.

In the Magellanic Stream, the ionizing radiation field should be composed of three components, the metagalactic radiation field, radiation from the Milky Way, and radiation from the SMC & LMC. For the ambient metagalactic ionizing radiation field, Kulkarni and Fall (1995) estimated the field based upon the "proximity effect" of absorption line systems, and they find that $J \approx 0.006 \times 10^{-21}$erg cm^{-2} s^{-1} Hz^{-1}sr^{-1}, or equivalently, $\phi \approx 3 \times 10^3$ photons cm^{-2} s^{-1}. The Galactic contribution can be estimated, the relevant quantity being the amount of ionizing radiation leaking out of the Galaxy into the halo. When $\approx$10% of the ionizing radiation from the disk escapes into the halo (e.g., Bregman & Harrington 1986; Reynolds 1991; Bland-Hawthorn & Maloney 1997), the radiation field in the lower halo would be $\phi \approx 2 \times 10^6$ photons cm^{-2} s^{-1}, orders of magnitude larger than the metagalactic radiation field. Therefore, the ionizing radiation field from the Galaxy should dominate the local environment to at least a distance of 200 kpc, as elegantly demonstrated by Bland-Hawthorn & Maloney (1997). At the distance of the Magellanic Stream, the radiation contribution from the Galaxy would be $0.6 - 1 \times 10^6$ photons cm^{-2} s^{-1}, without the contribution from the Magellanic Clouds. The contribution from the LMC & SMC upon the Stream is difficult to assess for two reasons. It is hard to estimate the amount of radiation escaping the neutral disk of the Clouds without having a tracer such as the "Reynolds" layer around the Galaxy. Also, the Stream may be close to the plane of the LMC & SMC disks, which is the worst orientation for the escape of photons. If ionizing radiation escapes from the LMC & SMC as easily as from the Galactic disk, their contribution to the radiation field will be comparable to that of the Galaxy (especially for the parts of the Stream closest to the LMC & SMC), so the estimated radiation field could be a factor of two higher than the above value in parts of the Stream.

Because the column density of the Stream is typically 5×10^{19} cm^{-2}, the HI is highly opaque to ionizing radiation ($\tau \approx 30$), so in a steady-state, the number of ionizing photons into the Stream must be balanced by the emerging recombination photons. This leads to a simple relationship between the ionizing radiation field and the $H\alpha$ radiation field:

$$\varepsilon = 450(\phi/1 \times 10^6 \text{photons/cm}^2\text{/s})\ mR$$

So depending upon location in the Stream, the Galaxy should produce an intensity of about 300-500 mR. A study of $H\alpha$ emission from the Stream was conducted by Weiner and Williams (1996), who looked at the leading edge of the Stream subunits MS II, MS III, and MS IV. In addition, they looked at regions that were not on the leading edge. They found that the leading edge regions were always detected, at levels of $\sim$200 mR. However, they found that the regions not at the leading edges were either very weak or were undetected, with the strongest limit obtained toward MS IVA of < 40 mR. They argue that if photoionization from an ambient radiation field were responsible for the emission, the clouds would be lit up nearly equally since the line intensity would be proportional to the radiation field, with some variation due to the geometry of the surfaces and the shadowing of one cloud by another. Since there is at least an order of magnitude variation in the emission, and the leading edges are always emitters, they suggest that the ionization at the leading edges is due to ram pressure heating of the neutral clouds through a hot halo of dilute gas. They present feasibility calculations in support of this interpretation.

We find that their upper limits are of particular interest since it places upper limits on the emission that is an order of magnitude lower than originally expected. This has the important implication that the ionizing radiation field from the Galaxy that reaches the Stream is an order of magnitude lower than expected, implying that most of the ionizing radiation is absorbed somewhere between 1 kpc and 50 kpc above the disk. An order of magnitude decrease corresponds to an optical depth in the ionizing continuum (near 14 eV) of 1.2, or a column density of neutral gas of $\sim 3\times10^{17}$ cm^{-2} (the opacity may be greater since several of the $H\alpha$ measurements are upper limits). Although it is hardly surprising to find this amount of neutral gas above the disk with a covering factor of unity, it means that very little Galactic ionizing radiation escapes to large distances. If this is generally true for spiral galaxies, then the contribution by spiral galaxies to the metagalactic radiation field can be neglected. Another implication of this result is that it becomes difficult if not impossible to use $H\alpha$ intensities to determine distances to HI clouds in the vicinity of the Galaxy and the Magellanic clouds. It had been hoped that if the radiation field were known a priori, $H\alpha$ intensities would vary only as the distance of the gas cloud, but in the "test" case (the Stream), the wrong answer would have been returned.

3. Missing Molecular Gas

If the ISM in the Magellanic Clouds bears certain similarities to the Galaxy, the amount of molecular gas may be underestimated by a substantial amount. To understand this situation, we need to look at the Milky Way, where the Copernicus observatory showed that for $N_{HI} > 5\times10^{20}$cm^{-2}, H_2 is very prevalent and is a significant fraction of the total neutral column (25% of the total $HI+H_2$ column; Savage et al. 1977). In a completely independent study, where molecular gas is identified through the absorption strength of the HCO^+ millimeter line, HCO^+ absorption is seen in 18/22 lines of sight below 39° (Lucas & Liszt 1996), which corresponds to column densities above 5×10^{20} cm^{-2}; this is consistent with the Copernicus result. In another independent study in yet another waveband, X-ray absorption toward extragalactic sight lines indicates substantial absorption when $N_{HI} > 5 \times 10^{20}$cm^{-2} (at latitudes below 40°). The only possible ISM component that could be responsible for the extra absorption is H_2, which would account for about 40% of the total neutral gas column (Arabadjis & Bregman 1999), consistent with the above results.

These three results paint a consistent picture of the H_2 content in the Solar circle, but it differs from the picture that one obtains from CO studies, which find that CO is not prevalent in the Solar neighborhood. Recently, there was a survey of CO at latitudes away from the plane detected little CO (Hartmann, Magnani, & Thaddeus 1998). They found a covering factor of 0.004-0.008 and employing the usual CO to H_2 conversion ratio, a mass surface density of 0.015-

0.035 $M_\odot$ pc^{-2}. The inferred H_2 mass is about 50-130 times less than the H_2 mass determined from the studies above.

The difference between these two determinations of the H_2 mass can be understood by noting that the interaction between molecules and the radiation field is different for CO and H_2 at these column densities. This interaction is discussed by van Dishoeck & Black (1988; and others), who show that for the ambient radiation field in the disk, H_2 can shield itself against photodestruction when $A(V) > 0.25$ mag, which corresponds to $N_H > 5 \times 10^{20} cm^{-2}$. However, CO is still easily destroyed under these conditions, which leads to the situation where CO is nearly absent while H_2 is still abundant. This can lead to values for the CO to H_2 conversion factor (X) that is orders of magnitude larger than the value derived for giant molecular clouds. Therefore, for the Galaxy, CO observations can lead to an underestimate of the molecular gas mass when using the typical value of X.

This raises the issue of whether the molecular gas content in the LMC (or SMC) has been underestimated by the CO observations, and there is a hint that this may be the case. An important tracer is the [CII] 157 μm line, which usually arises from warm regions at the surface of molecular clouds (in the Galaxy). It is easily detected in the LMC but it is not correlated with CO emission (Israel et al. 1996). The 157 μm line emission is correlated with IRAS emission, which probably traces the entire neutral gas column. One likely explanation for this set of observations is that the [CII] emission traces the molecular gas that contains H_2 but where the CO cannot survive.

Programs to study the H_2 content directly are possible by using the UV absorption lines, as Copernicus did for our Galaxy. In this case, one needs UV-bright targets in or behind the LMC and SMC and a telescope capable of working in the 900-1100 A region. ORPHEUS is one such telescope, and it has observed a few hot stars in the LMC & SMC and has detected H_2 in absorption (see de Boer, this conference). In the near future, FUSE will be launched and it can observe many sources in or behind the LMC & SMC, which will lead to a more detailed census of the prevalence of H_2 in these systems.

4. Models for the Structure of the Cold Gas in the Clouds

One of the landmark observations in the study of the ISM in the Clouds has been the high-quality and rather beautiful HI maps obtained by Stavely-Smith and collaborators (Kim et al. 1998). These observations provide one of the most powerful constraints on any model of the ISM and I will describe a global hydrodynamical model that can be compared to these data.

The model for the ISM that we have developed is meant to simulate the density, temperature, and velocity structure of the multiphase medium in the disk. In this model, the gas is treated as one fluid and the stars as a second fluid, the two fluids being coupled through star formation, mass loss, and heating of the gas by the stars (supernovae plus stellar winds; see Rosen & Bregman 1995, and Rosen, Plewa, & Bregman, in preparation). The part of the disk for which I will show you a simulation is 2 kpc wide and the gas is followed to ±15 *kpc* from the disk, although nearly all the gas lies within a few kpc of the disk. The simulations are carried out in two spatial dimension (one in the plane and one perpendicular to the plane) and the results shown here are an improvement from previous models because they are at higher resolution (600×1200 cells).

A typical example of the density, temperature, and velocity distribution is shown in Figure 1, which reveals a highly structured ISM. This type of structure changes in detail throughout the run, but not in its general nature. The densest cool gas is contained within several hundred parsecs of the midplane, while the warm gas (3×10^3-$10^5 K$) and the hot gas ($> 10^5 K$) have greater scale heights. The interaction between the stars and gas pushes the gas into dense regions, often with the shape of filaments (shells or partial shells in three dimensions) that often surround large volumes of low density gas (either warm or hot; these are bubbles in three dimensions). There is a characteristic length scale to the low density regions of a few hundred parsecs, largely due to effects such as the star formation time in associations and the propagation time of star-forming regions.

Although supernovae preferentially occur in denser than average gas, because they usually occur near sites of star formation, those that occur in the low density regions can be extremely destructive, causing rapid heating of gas. In these simulations, bubbles often connect, become quite large, and "break out" of the disk. Chimney-like structures develop that are typically 0.5-1 kpc wide and extend a few kpc out of the disk, and there are examples of this in Figure 1. This hot gas rarely escapes the galaxy, eventually cools (often in the upward flow), and the cooled material, having lost its buoyancy, falls backward to the disk. The return of the cooled gas is not randomly distributed over the disk, but occurs in a number of organized downward flow regions. In this sense, this "galactic fountain" has an organization such as is seen in convection.

These properties of the simulations are extremely robust for the gas density and supernova heating rate found in the LMC and the Galaxy. The implication for the LMC is that it should possess the same gaseous components as the Galaxy: a hot halo, a thick ionized gas layer, in addition to the usual HI and molecular gas components. Failure to detect the hot halo and thick ionized layer would lead to a major revision in these models.

The evidence for halo gas around the LMC is tantalizing, but to this point, rests largely on a single study. Some of the first observations of hot LMC stars with the IUE showed the presence of high ionization ions, similar to those seen in the halo of the Milky Way. Although it was tempting to conclude that the LMC has a hot halo like the Milky Way (de Boer & Savage 1980), there was the concern that the high ionization ions were an effect local to the hot stars, being produced by their intense ionizing radiation field (Chu et. al. 1994). Recently however, absorption by high ionization ions were seen toward four stars believed to be too cool to have produced them by photoionization, giving us the strongest current evidence that the LMC might have a hot halo (Wakker et al. 1998).

The other usual tracers of hot gas are presently ambiguous regarding the LMC halo. X-ray emission is detected over regions of the galaxy (Snowden & Petre 1994), but this emission, which is often associated with superbubbles, could be confined to the plane, rather than tracing halo gas. Another potential tracer is the pulsar dispersion measure, which measures the column density of electrons (possibly from hot gas) along a line of sight toward a pulsar. The three pulsars projected upon the LMC (McConnell 1991) have dispersion measures 2-3

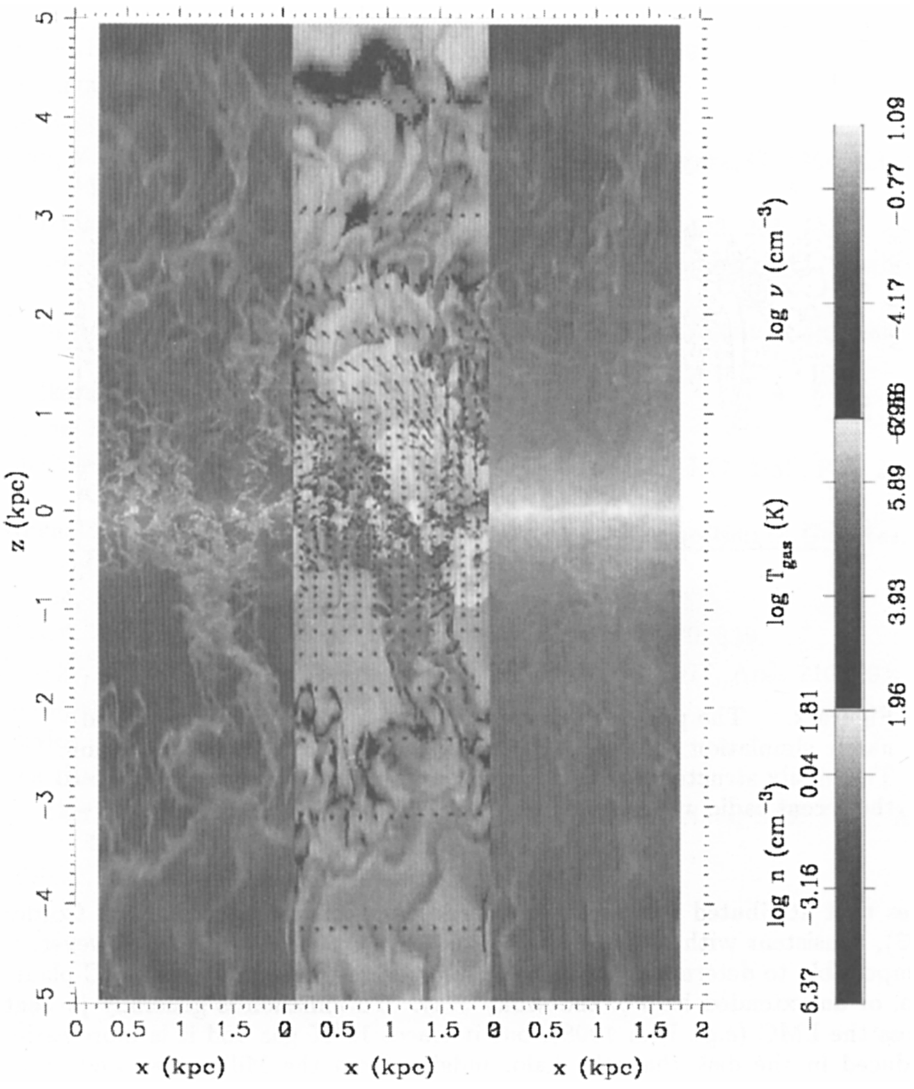

Figure 1. The gas density, gas temperature, and Population I stellar density in the simulation which is a two-dimensional cut through the midplane. The low density regions correspond to high temperature regions because the gas tries to approach pressure equilibrium. The stellar density is considerably smoother than the gas, which shows many examples of connected hot bubbles, cool clouds and shells, as well as a halo of material due to a galactic fountain.

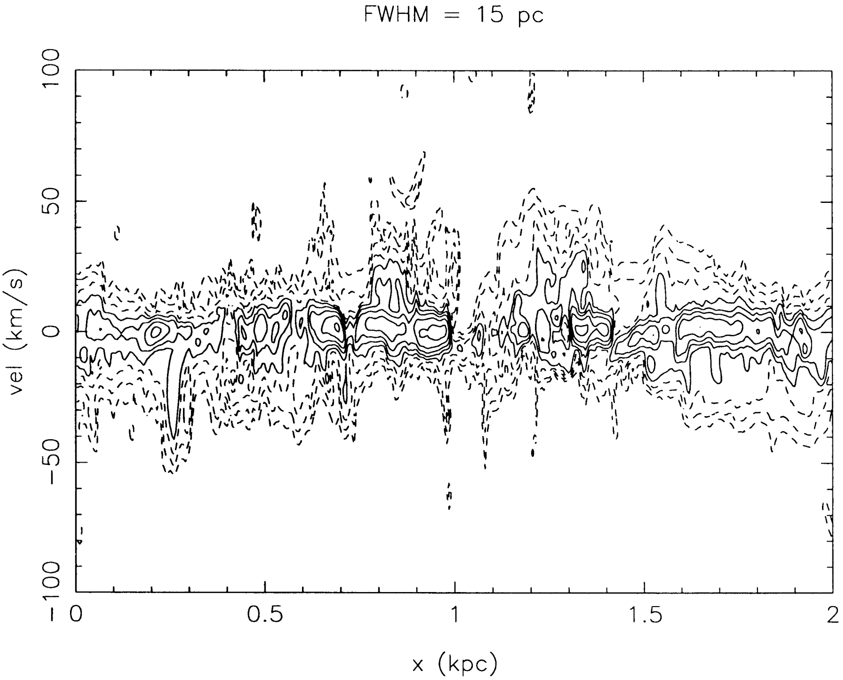

Figure 2. The position velocity diagram of the numerical hydrodynamic simulation for the cool material, smoothed to 15 pc resolution. The highly structured cool material bears a qualitative resemblance to the recent radio synthesis HI maps.

times that attributed to the Milky Way in that direction (Taylor and Cordes 1993), consistent with a model of hot halo gas around the LMC. However, it is impossible to determine whether the electron column lies in the LMC plane, halo, or an extended halo of the Milky Way. $H\alpha$ emission is generally present across the LMC (*e.g.*, Kim 1998), but it traces $10^4 K$ gas and it is more easily produced in the disk than the halo, judging from the Milky Way and other galaxies.

Another point of comparison between our simulations and the data is in the HI, and here the easiest comparison is for position-velocity diagrams. Our position-velocity diagrams (Figure 2) show a wealth of structure down to scales typical of the recent synthesis array survey. Although the minima of our $p - v$ diagrams may be deeper than the observed minima, the similarity in the nature of the distinct structures with observations presented elsewhere in this meeting is rather striking. The comparisons will become more meaningful when they can be made quantitatively and when the zero spacing data has be incorporated into the synthesis HI maps, and we hope to carry out work of that nature in the coming year.

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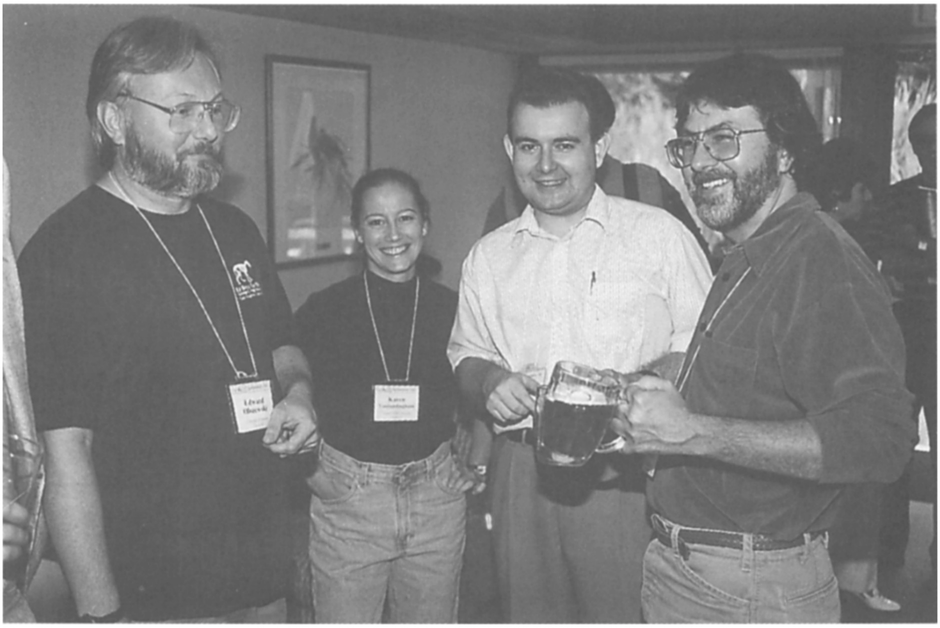

As the smiles indicate on the faces of (left to right) Ed Olszewski, Karen Vanlandingham, Paul Scowen and Don Garnett, it is always easier to solve the problems of the Universe with a pint in one hand!