New Views of the Magellanic Clouds
IAU Symposium, Vol. 190, 1999
Y.-H. Chu, N.B. Suntzeff, J.E. Hesser, and D.A. Bohlender, eds.

Interstellar Phases in the Magellanic Clouds

John M. Dickey

Univ. of Minnesota, 116 Church St. SE, Minneapolis, MN 55455, USA

Monika Marx-Zimmer, Christian Düsterberg, Ulrich Mebold

Radioastronomisches Instutut der Universität Bonn, Bonn, Germany

Snezana Stanimirović, Lister Staveley-Smith

Australia Telescope National Facility, Epping, NSW1710, Australia

H.A. Kobulnicky

Astronomy Dept., Univ. of California, Santa Cruz, CA 95064, USA

Abstract.

Surveys of λ21-cm absorption in the Magellanic System show that the cool phase of the HI is less abundant in the SMC than in the Milky Way, and may be so also in the LMC. The typical cool cloud temperature is colder than in the Milky Way, 30 to 40 K rather than 60 to 75 K. The lower abundance of cool phase HI can be traced to the lower heavy element abundances in the Magellanic environment. The cooler cloud temperatures are somewhat mysterious.

1. Background

The Magellanic Clouds contain interstellar matter showing the physical properties associated with all the various phases of the interstellar medium of the Milky Way. There is a hot (kinetic temperature $T_{kin} \simeq 10^5$ to 10^6 K) ionized medium traced by the soft X-ray emission and UV absorption (e.g. Snowden & Petre 1994; Wang et al. 1991; Bomans et al. 1996). There is abundant warm ionized medium ($T_{kin} \simeq 10^4$ K) both in classical HII regions and in diffuse ionized regions traced by Hα and many other emission lines (Kennicutt et al. 1995). There are clouds of molecular gas at temperatures from about 30 K to below 10 K, traced by emission from CO and other molecules (Israel et al. 1993; Rubio et al. 1993). Tracers of the molecular gas indicate that this phase is much less abundant in the Magellanic System than in the Milky Way, but this may be due to a lower ratio between CO emissivity and H_2 column density compared to that in the Galaxy (Maloney & Black 1988). In addition, the Magellanic Clouds contain abundant atomic hydrogen in both the warm ($T_{kin} \simeq 6000$ K) and cool ($T_{kin} \simeq 60$ K) neutral phases, similar to what is seen in the Milky Way (Milky Way reviews include Kulkarni & Heiles 1987, 1988, and Dickey & Lockman 1990). This paper concentrates on these latter two phases of the interstellar medium (ISM) of the Magellanic System.

To study the relative abundance and distribution of the warm and cool neutral gas requires observations of both emission and absorption spectra in the λ21-cm line. Though emission is relatively easy to detect, λ21-cm absorption toward compact background sources requires high angular resolution to separate from the emission. Thus it has only been possible to measure λ21-cm absorption through the Magellanic Clouds since the Compact Array of the Australia Telescope (ATCA) has become available. So all of our knowledge of the cool atomic phase of the ISM in the Clouds has come in the last five years or so.

The ultimate goal of HI absorption studies is to understand how the balance between heating and cooling of the HI in different environments sets the relative abundances of the warm and cool neutral media. The Magellanic Clouds are perfect as case studies in this subject, since they are so near, and yet so different from the Milky Way in their abundances of the elements critical for **cooling** (primarily C and O), and in their dust abundance which is critical for **heating.** By studying the distribution of temperatures in the HI we can determine how robust is the mixture of phases which we have in the solar neighborhood. If there are big differences in the phase mixture in the Magellanic environment, we must expect differences among galaxies, and with redshift as well. But if the mixture is similar to that in the Milky Way in spite of the differences in the environments, we may conclude that there is a universal mixture of HI phases which is somehow inescapable.

2. Surveys

The column density of HI is most easily traced by emission in the λ21-cm line, since the emission coefficient for this transition is proportional to density and independent of temperature. A survey of the brightness temperature of the line thus maps out the distribution of HI column density, $N_H \propto T_{em}$, with only small corrections needed for self-absorption. The optical depth, τ, is proportional to the column integral of density, n, divided by temperature. Thus cool gas shows itself prominently in absorption spectra, while the warm gas is almost undetectable in absorption, but the two phases both contribute to emission spectra in proportion to their masses. Thus comparing emission and absorption allows us to eliminate the density and measure the excitation temperature alone. The excitation temperature of the λ21-cm line is equal to T_{kin} since the spontaneous transition rate is extremely low.

Two kinds of absorption studies have been done with the ATCA : 1) surveys of ATCA absorption spectra toward many background sources, which have been paired with coarse resolution emission data taken in the same directions with the Parkes 64m telescope; and 2) a few full synthesis observations which compare the absorption with a high resolution map of the emission made with a combination of data from both Parkes and the ATCA. The former method is a quick way to measure the relative abundances of warm and cool gas in many directions, but to determine the temperature of the cool phase, T_{cool}, requires the latter approach. This is because a single Parkes emission spectrum (beamwidth 14′ or 200 pc at 50 kpc) and the absorption spectrum toward a compact background continuum source (typically 5″ in diameter) sample quite different volumes of gas. In order to sample nearly the same line of sight in emission as in absorption requires a small beam in the emission study, so as to get very close to the direction of the background source.

To analyse emission-absorption data taken in the quick survey mode we work with the velocity integrals of the spectra, assuming that the averages for the sample as a whole give representative information on the properties of the HI overall. Thus the mean excitation temperature,

$$< T_{spin} > \;=\; \frac{\sum \int T_{em}(v)\, dv}{\sum \int (1 - e^{-\tau})\, dv} \propto \frac{N_H}{\int \frac{n}{T_{kin}}\, ds}$$

measures the density weighted harmonic mean temperature of the gas, including both phases. (The sums are taken over all emission/absorption spectrum pairs in the survey, and the integral over ds is taken along the line of sight.) In the solar neighborhood we find a value of about 250 K for $< T_{spin} >$. To interpret this average we make the "two phase medium" assumption, i.e. that the warm gas is warm enough to make a negligable contribution to the absorption (in practice it must only be warmer than a few hundred K, though in general the warm phase is at least several thousand K). With this assumption, an observed value for $< T_{spin} >$ gives the relative fractions of HI in the warm and cool phases, f_{warm} and f_{cool}, if we know the value of T_{cool}. Thus :

$$f_{cool} \equiv \frac{N_{cool}}{N_{warm} + N_{cool}} = \frac{T_{cool}}{< T_{spin} >} = 1 - f_{warm}$$

As simple way to compare different environments we can assume the same value for T_{cool} and compute f_{cool} for each. For the Milky Way in the solar neighborhood we have some cases where T_{cool} is known to be 60±5 K, so this is a reasonable value to use for the comparison. Using this number gives $f_{cool} \simeq 25\%$ for the Milky Way.

Region	number of lines of sight	number with absorption	$< T_{sp} >$ (K)	f_c (%)	Reference
Halo & Stream	5	0	>600	<0.1	Mebold et al. (1991)
LMC	30	19	165	36	Dickey et al. (1994)
LMC	20	9	180	33	Marx-Zimmer et al. (1999)
Bridge & Halo	7	2	59	-	Kobulnicky and Dickey (1999)
30 Dor	5	5	30 - 40	→100?	Mebold et al. (1997)
SMC	32	11	465	13	Dickey et al. (1999)

Table 1. Magellanic Cloud λ21-cm surveys.

The table lists surveys of λ21-cm absorption in the Magellanic System. The overall result of all these studies is to show that the mixture of phases in the

HI **does** differ between the Magellanic Clouds and the Milky Way. Extensive observations of the LMC show that it contains **more** cool phase HI relative to warm phase than the Milky Way does (about 35% cool vs. 25% cool), though the warm phase still dominates. In the SMC the situation is reversed. There absorption is quite rare, indicating that no more than about 15% of the HI is in the cool phase. These numbers depend on the assumption that T_{cool} is the same in the Magellanic Clouds as in the Milky Way, if T_{cool} is lower there then f_{cool} would be lower in proportion.

We have some information on T_{cool} from two studies of the second type, listed as the last two lines on the table, which include full aperture synthesis of the emission (for the SMC taken from Stanimirović et al. 1999). These studies both show surprisingly cool temperatures, typically 30 to 40 K, for T_{cool}. Using this value would reduce the fraction of the HI needed in the cool phase to $f_{cool} \simeq 20\%$ and 8% for the LMC and the SMC, respectively. The question is, why should the kinetic temperature in the diffuse ISM clouds of the Magellanic System be so low, and why should that phase be so scarce in the SMC ?

3. Discussion

We can understand the balance between heating and cooling with reference to the theoretical study of Wolfire et al. (1995). They consider thermal equilibrium in an environment with low metallicity, which has the effect of raising the minimum pressure for which the cool phase can exist, and raising the maximum pressure for which the warm phase can exist. Thus decreasing the abundance of C and O makes it harder to have cool phase gas, and presumably would decrease the abundance of the cool phase relative to the warm phase. A similar result is obtained by increasing the UV radiation field. On the other hand, Wolfire et al. also consider decreasing the grain abundance, which reduces the heating rate. If both the metallicity and the dust-to-gas ratio decrease together, then the effect is similar to just reducing the metallicity, but less strong. Ultimately, heating by soft x-rays becomes more important than photoelectric heating, if the dust abundance is reduced far enough. In sum, the heating and cooling balance in an environment like that of the SMC can explain why the abundance of cool phase gas is decreased compared to the solar neighborhood.

Why the temperatures of the cool clouds are also lower than their Milky Way values is more of a puzzle. For this we may consider models of the equilibrium between molecule formation and destruction (e.g. Elmegreen 1993). With a much lower abundance of dust, and a higher intensity of UV which can photodissociate molecules, it may be that the molecular gas is driven deeper into the clouds, toward regions of higher protective column density, than in Milky Way clouds. Thus the HI could dominate over H_2 in some regions with quite high densities, $n \simeq 10^3$ cm^{-3}, perhaps. So in the Magellanic Clouds the HI absorption traces not only diffuse interstellar clouds, but dense, cold clouds as well. These clouds would be molecular if they were in the Milky Way, but in the Magellanic environment they remain predominantly atomic.

The presence of these cold, atomic clouds in the Magellanic System raises the question of whether a similar population exists in the Milky Way. A few examples of HI clouds with temperatures below 40 K have been noticed in studies of the Galactic ISM, but they are uncommon in the solar neighborhood. Surveys at low latitudes could reveal whether these "missing link" clouds, between the diffuse and molecular types, are common elsewhere in the Milky Way.

References

Bomans, D.J., de Boer, K.S., Koornneef, J., & Grebel, E.K. 1996, A&A, 313, 101.

Dickey, J.M., & Lockman, F.J. 1990, ARA&A, 28, 215.

Dickey, J.M., Mebold, U., Marx, M., Amy, S., Haynes, R.F., & Wilson, W. 1994, A&A, 289, 357.

Dickey, J.M., Mebold, U., Stanimirovic, S., & Staveley-Smith, L., 1999, in preparation.

Elmegreen, B.G. 1993, ApJ, 411, 170.

Israel, F.P., Johansson, L.E.B., Lequeux, J., Booth, R.S., Nyman, L.A., et al. 1993, A&A, 276, 25.

Kennicutt, R.C., Bresolin, F., Bomans, D.J., Bothun, G.D., & Thompson, I.B. 1995, AJ, 109, 594.

Kulkarni, S.R., & Heiles, C., 1987, in: *Interstellar Processes*, (eds.) D.J. Hollenbach & H.A.Thronson, (Dordrecht: Reidel), p. 87.

Kulkarni, S.R., & Heiles, C., 1988, in: *Galactic and Extragalactic Radio Astronomy*, 2nd ed., eds. G.L. Verschuur & K. Kellerman, (New York : Springer-Verlag), p. 95.

Kobulnicky, H.A., & Dickey, J.M. 1999, AJ, 117, 908

Maloney, P., & Black, J.H. 1988, ApJ, 325, 389.

Marx-Zimmer, M., Herbstmeier, U., Dickey, J.M., Staveley-Smith, L., Mebold, U., & Zimmer, F. 1999, A&A, in press.

Mebold, U., Greisen, E.W., Wilson, W., Haynes, R.F., Herbstmeier, U., & Kalberla, P.M.W. 1991, A&A, 251, L1.

Mebold, U., Dusterberg, C., Dickey, J.M., Staveley-Smith, L., Kalberla, P., Müller, H., & Osterberg, J. 1997, ApJ, 490, L65.

Rubio, M., Lequeux, J., Boulanger, F., Booth, R.S., Garay, G., et al. 1993, A&A, 271, 1.

Stanimirović, S., Staveley-Smith, L., Dickey, J.M., Sault, R.J., & Snowden, S.L. 1999, MNRAS. 302, 417

Snowden, S.L., & Petre, R. 1994, ApJ, 436, L123.

Wang, Q., Hamilton, T., Helfand, D.J., & Wu, X. 1991, ApJ, 374, 475.

Wolfire, M.G., Hollenbach, D., McKee, C.F., Tielens, A.G.G.M., & Bakes, E.L.O. 1995, ApJ, 443, 152.

Discussion

Dan Welty: You see evidence for a high percentage of cold gas in HI in the LMC, but heavy element abundances (from UV absorption lines) do not show evidence from "cold dust" depletions. Any comments/explanations?

Dickey - paraphrased: The bulk of the HI is still warm.

Unknown: How about the gas support in radial direction in the LMC, SMC and the Milky Way?

Dickey: I think the LMC is like the Milky Way in that it has a rotation curve, so the gas is supported by centrifugal force in the radial direction, not by a pressure gradient. For the SMC there is a velocity gradient, but it's not clear this is a rotating disk, so I don't know if we know the shape of the gravitational potential.