H I Self Absorption Toward Molecular Clouds:

Theoretical Models

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Abstract

Although 21 cm H I self-absorption (HISA) is commonly observed toward molecular clouds, the origin of the cold atomic hydrogen remains unclear. Two mechanisms have been proposed: (1) photodissociation of molecular hydrogen on the skins of the molecular clouds exposed to ultraviolet radiation, or (2) cosmic ray chemistry deep inside the molecular clouds. We study H I self-absorption toward molecular clouds by modeling the chemical and thermal structure of molecular clouds exposed to ultraviolet radiation fields and calculating the radiative transfer of 21 cm radiation through these model clouds. We use the models of Kaufmann et al. (1999), as modified by Wolfire et al. (2003), which compute the physical and chemical conditions in a molecular cloud as a function of extinction for various ultraviolet radiation fields, densities, and metallicities. *We find that all model molecular clouds contain enough opacity in cold H I to exhibit self-absorption against strong 21 cm backgrounds (T_{BG} ~50 - 100 K).* The H I absorption opacity is dominated by cold atomic hydrogen formed by cosmic ray chemistry deep in the interiors of clouds. If all molecular clouds contain as much cold atomic hydrogen as the models suggest, then the presence or absence of H I self-absorption toward a molecular cloud can constrain its location in the Galaxy. In particular, in the inner Galaxy, the H I self- absorption can be used to resolve the kinematic distance ambiguity and therefore establish accurate distances to galactic molecular clouds (Jackson et al. 2002).

Observations

The three-dimensional (l,b,V_{lsr}) physical association of H I self-absorption with CO emission toward Galactic molecular clouds has been observationally demonstrated in the literature (see Jackson et al. 2002 for references). A quiescent Galactic molecular cloud imaged by the Galactic Ring Survey at (l,b)=(45.6^0, 0.3^0) (hereafter **GRSMC 45.6+0.3** or the **Filament**) was shown by Jackson et al. (2002) to be well associated with H I self-absorption detected by the BU-Arecibo Observatory H I (BUAO) Survey. The ^{13}CO data were resampled to the H I spatial grid, and spectra were extracted for identical positions.

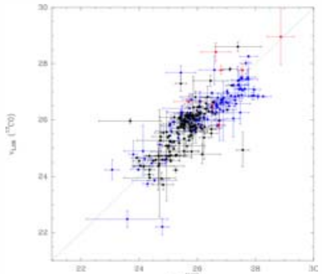


Figure 1

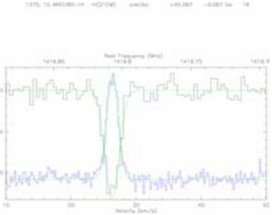


Figure 2

We extend the work of Jackson et al. (2002) for the Filament and fit the velocity centroids of H I absorption features associated with ^{13}CO emission. The spectra were simultaneously,but blindly, fitted for gaussian components lying between V_{lsr}=20-30 km s^{-1} (the ^{13}CO emission from the Filament peaks at ~26 km s^{-1}). This was done iteratively because of multiple gaussian components in some spectra. We find that the velocity centroids of H I and ^{13}CO are well correlated; the dashed line is simply a one-to-one correspondence. An ordinary least squares bisector fit to the data has a slope of 0.981+/-0.005, and no individual point has error bars larger than 4 km s^{-1} within the 10 km s^{-1} gaussian fit range. This clearly indicates that the H I and ^{13}CO gas are kinematically correlated throughout the Filament.

Theoretical Models

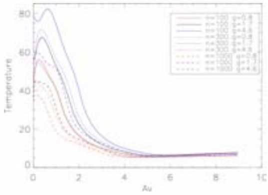


Figure 3

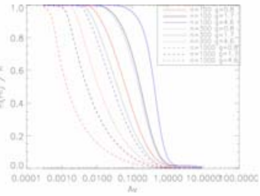


Figure 4

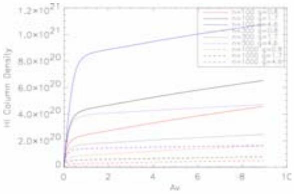
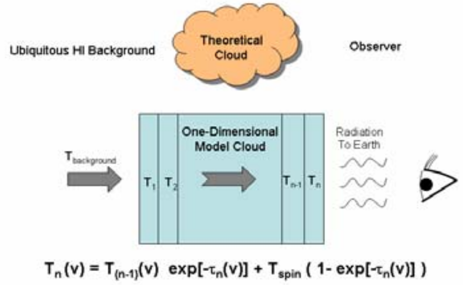


Figure 5

Estimating the location of HISA – whether well-mixed with the molecular gas within the cloud or in cool skins - is important in understanding chemistry, the influence of UV and cosmic rays, and the balance of heating and cooling in clouds. A molecular cloud requires the following conditions to be detected in HISA: (1) it must contain significant amounts of cold H I, (2) this HI must have sufficient opacity ($\tau > 1$), and (3) there must be sufficient background emission from warm H I. Photodissociation region (PDR) theory predicts that the skins of molecular clouds (A_v<2) exposed to typical Galactic UV radiation fields (~1G_0) will have the necessary opacity to show HISA against strong H I backgrounds (Tielens & Hollenbach 1985). In fact, observations by Andersson, Roger, & Wannier (1992) suggest evidence of H I surrounding molecular clouds. However, the PDR layers are physically thin and may not display enough contrast - low temperature and high optical depth – to be visible as an HISA signature. On the other hand, cosmic rays, which are not shielded by gas or dust, can easily affect the chemistry in cold cloud interiors. Specifically, cosmic rays can dissociate H_2 into H. We use the models of Kaufmann et al. (1999), as modified by Wolfire et al. (2003) to predict the strength of HISA of theoretical clouds in a uniform HI background. These one-dimensional slab models compute the physical and chemical conditions in a molecular cloud as a function of extinction for a given metallicity (z=1.0), and various ultraviolet radiation fields and densities. In total nine models were provided that included constant hydrogen nuclei densities of n=100, n=300, and n=1000, and UV radiation fields (in units of the Habing field) g=0.8, g=1.7, and g=4.6. Plots of spin temperature as a function of A_v, H I abundance relative to total density, and H I column density as a function of A_v are shown in figures 3, 4 and 5 respectively.

Results



$$T_n(v) = T_{(n-1)}(v)\ \exp[-\tau_n(v)] + T_{spin}\ (1 - \exp[-\tau_n(v)])$$

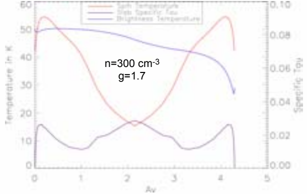


Figure 6

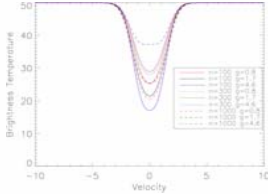


Figure 7

We use a simple radiative transfer analysis to compute HISA spectral line profiles (fig. 7) using the theoretical models of Wolfire et al (2003); the cartoon to the left describes our method. Realistic 10 pc clouds are constructed by adjoining model clouds at the A_v location equivalent to 5 pc. We experimented with different backgrounds, but present only the T_{bg}=50K models here. The differential optical depth is largest towards the edges of the clouds, for A_v<2; this corresponds to distances between 0-2 pc and 8-10 pc in the figure above. However, substantial optical depth is retained in the cloud interiors, and it is precisely this combination of *integrated* optical depth and low temperatures in cloud interiors that contributes to the bulk of the line absorption (this contrast is shown above in fig. 6). This is seen best in the plot of brightness temperature as a function of A_v into the cloud. The model with n=300 and g=1.7 was used for this visual comparison. For typical molecular clouds of densities of a few times 10^2 cm^{-3} and exposed to a few Habing UV radiation field, the bulk of the HISA is due to H I gas produced by cosmic rays well inside the region where molecules dominate the gas content of a cloud.

Summary

We find a substantial correlation of HI Self absorption and ^{13}CO emission line centers for the molecular cloud GRSMC45.6+0.3 (the Filament). Unlike previous studies we are able to localize the velocity of ^{13}CO emission with HISA - in a manner not previously possible with similar correlations using optically thick (and often self-absorbed) ^{12}CO. We anticipate a number of sources for which HISA and ^{13}CO correlate, allowing a sample of sources with Galactocentric position.

Using the models of Wolfire et al. (2003), we make synthetic profiles of the emergent H I spectrum. The H I which provides the bulk of the contrast (i.e. both low temperatures and high opacity) responsible for the predicted absorption is found to be well associated with molecular gas.

This analysis is consistent with the result of Jackson et al. (2002) and our presentation of velocity centroids in figure 1, supporting the notion that correlations of H I Self Absorption and ^{13}CO emission will break the near-far distance ambiguity.

For more information and available data, visit the GRS web page at *www.bu.edu/GRS*

Acknowledgements

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