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H I SELF-ABSORPTION AND THE KINEMATIC DISTANCE AMBIGUITY: THE CASE OF THE MOLECULAR CLOUD GRSMC 45.6+0.3

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ABSTRACT

We report on a three-dimensional (l, b, V_{LSR}) physical association of H I self-absorption with ^{13}CO emission toward the Galactic molecular cloud GRSMC 45.6+0.3. Photochemical models indicate that a significant column density of cool ($T \lesssim 25$ K) H I exists in the skins ($A_v \lesssim 2$) of typical Galactic molecular clouds. The H I self-absorption can thus be produced by the cool cloud skin absorbing the warm ($T_{SPIN} \sim 100$ K) background H I emission that is ubiquitously distributed throughout the Galaxy. Liszt, Burton, and Bania have suggested that because cool H I in a molecular cloud will absorb warmer H I background line emission, H I self-absorption can be used to resolve the kinematic distance ambiguity for molecular clouds in the inner Galaxy. Clouds at the near distance should show H I self-absorption, whereas clouds at the far distance will not since there is no background to absorb. The near kinematic distance of 1.8 kpc for the GRSMC 45.6+0.3 molecular cloud is independently confirmed by its morphological correlation with foreground optical extinction.

Subject headings: Galaxy: kinematics and dynamics — Galaxy: structure — ISM: atoms — ISM: clouds — ISM: molecules

1. INTRODUCTION

Self-absorption of the H I 21 cm line provides an important measure of the structure of the neutral interstellar medium (ISM). It is a key signature of the cold, dense atomic gas phase. The first detailed analysis of H I self-absorption (SA), the absorption of background 21 cm H I line radiation by cooler foreground H I gas, was done by Knapp (1974), who surveyed nearby dark clouds. Baker & Burton (1979) subsequently identified numerous SA features in H I maps of the Galactic plane made with the Arecibo telescope, and Burton, Liszt, & Baker (1978) demonstrated that many of these H I SA features correlate with CO emission features (see also Garwood & Dickey 1989). Liszt, Burton, & Bania (1981, hereafter LBB) extended this work and found that the detection rate of the SA depends very strongly on the observational angular resolution. Their general conclusion was that Galactic molecular clouds must contain residual H I, a conclusion subsequently supported by a number of observational studies (e.g., Wannier et al. 1991; Andersson & Wannier 1993; Kuchar & Bania 1993; Reach, Koo, & Heiles 1994; Williams & Maddalena 1996).

Bania & Lockman (1984) made a pilot H I survey with Arecibo and found that objects showing H I SA had a surface density of ∼20 clouds per square degree. To exploit Arecibo's ability to resolve H I SA clouds, the Boston University Arecibo Observatory (BUAO) Galactic H I Survey (Kuchar 1993; T. M. Bania 2002, in preparation) imaged about 50 deg^2 of the inner Galaxy in the 21 cm H I line at 4′ resolution. This survey and more recent surveys such as the Canadian Galactic Plane Survey (Gibson et al. 2000) provide powerful tools for investigating the relationship between the atomic and molecular gas components of the ISM.

Following a suggestion by Baker & Burton (1979) for atomic clouds, LBB proposed that H I SA might provide a robust method for determining the distance to molecular clouds. They reasoned that if cold H I is associated with every molecular cloud, then clouds on the near side of the Galaxy are more likely to exhibit H I SA than clouds on the far side. Thus, the presence or absence of H I SA would establish whether a molecular cloud lies at the near or far kinematic distance. This technique, hereafter called the "LBB hypothesis," has the potential to resolve the long-standing "near-far kinematic distance ambiguity" for molecular clouds.

Establishing detailed correlations between H I SA features and molecular clouds has proved difficult, however, because previous CO surveys of the first quadrant suffer from some combination of poor angular resolution, angular undersampling, and choice of CO isotopomers. The Boston University–Five College Radio Astronomy Observatory (FCRAO) Galactic Ring Survey (GRS), a new high-resolution (46″) survey of the distribution of ^{13}CO ($J = 1 \rightarrow 0$) emission in the inner Galaxy, coupled with the BUAO H I survey, provides a new database to investigate the relationship between cold atomic and molecular gas. The GRS samples the sky at better than half-beam spacing and thus images all structures resolvable with the FCRAO 14 m telescope. Unlike ^{12}CO ($J = 1 \rightarrow 0$), which suffers from velocity crowding, ^{13}CO has narrower line widths due to its lower optical depth. These smaller line widths allow for a cleaner separation of velocity components. Furthermore, the use of the optically thin ^{13}CO line avoids the difficulties of self-absorbed line profiles commonly found in ^{12}CO.

In this Letter, we investigate the LBB hypothesis for the case of the GRS molecular cloud located at $(l, b) = (45\overset{\circ}{.}6, 0\overset{\circ}{.}3)$ (hereafter GRSMC 45.6+0.3), a quiescent molecular cloud. Because of its pronounced optical extinction, GRSMC 45.6+0.3 must lie at the near kinematic distance. Thus, the LBB hypothesis would require GRSMC 45.6+0.3 to exhibit H I SA. In fact, GRSMC

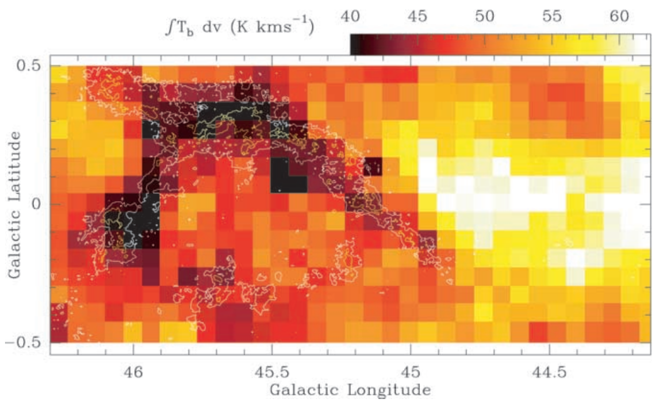

FIG. 1.—Comparison of ^{13}CO (*contours*) and H I (*colors*) integrated intensites for the V_{LSR} range 25–30 km s^{-1}. The ^{13}CO contours are drawn at 1.0 and 2.0 K km s^{-1}, and black indicates the lowest H I integrated intensities. The spatial correlation of H I absorption and ^{13}CO emission is due to the absorption of warm background H I by cold atomic gas within the molecular cloud.

45.6+0.3 exhibits strong H I SA, and so the H I SA technique to establish kinematic distances is confirmed for this cloud.

2. ATOMIC AND MOLECULAR OBSERVATIONS

As of 2001 November, the GRS has sampled ~20 deg^2 of the inner Galaxy. We are using the FCRAO 14 m telescope equipped with the SEQUOIA array receiver, which currently has 16 High Electron Mobility Transistor receivers arranged in a 4 × 4 array. The ^{13}CO beam size is 46″ FWHM, and the survey samples the sky on a 22″ grid. The velocity resolution is 0.26 km s^{-1}, and the rms sensitivity level in each pixel is typically T_{MB} = 0.4 K (see Simon et al. 2001 for more details).

The BUAO H I survey sampled ~50 deg^2 of the inner Galaxy, made with the Arecibo 305 m telescope between 1986 and 1990. At 21 cm wavelength, Arecibo's angular resolution is 4′, the best of any single-dish radio telescope. The velocity resolution is 1.03 km s^{-1}, and the rms sensitivity is T_{MB} = 0.52 K (see Kuchar & Bania 1993 for more details).

3. RESULTS

The molecular cloud GRSMC 45.6+0.3 is a large filamentary structure with a ^{13}CO distribution roughly 1°.7 × 1°.2 in extent, centered approximately at (l, b) = (45°.6, 0°.3) with an LSR velocity of 27 km s^{-1}. Figure 1 shows the ^{13}CO emission (*contours*) from the GRS over the velocity range 25–30 km s^{-1} and H I 21 cm emission (*color halftone*) over the same velocity interval. H I SA is evident as a decrement (*dark regions*) of the 21 cm intensity. There is a remarkable morphological correspondence between the ^{13}CO emission and H I SA. Clearly, cold H I, as manifest by H I SA, is associated with the molecular gas throughout the cloud.

To quantify the correlation between H I SA and ^{13}CO emission in GRSMC 45.6+0.3, we have plotted in Figure 2 the H I intensity versus the ^{13}CO intensity for each position in the surveys in the region $44°.8 < l < 46°.3$, $-0°.5 < b < 0°.5$. For this figure, the GRS ^{13}CO data have been convolved to the same angular resolution as the BUAO H I data and sampled on a common 4′ grid. The GRS ^{13}CO data were also resampled spectrally to match the channel spacing of the BUAO survey (0.52 km s^{-1}).

In a plot such as Figure 2, a correlation between H I SA and ^{13}CO emission reveals itself as an *anticorrelation* between the H I and ^{13}CO intensities. Figure 2*a*, which includes all velocity channels from V_{LSR} = −5 to 85 km s^{-1}, shows a group of points with a clear anticorrelation. In Figure 2*b*, those points with the same velocity range (25 km s^{-1} < V_{LSR} < 27 km s^{-1}) as GRSMC 45.6+0.3 are colored red. The strong H I SA is obviously confined to the velocity of GRSMC 45.6+0.3. Moreover, the trend is approximately linear; the brighter the ^{13}CO

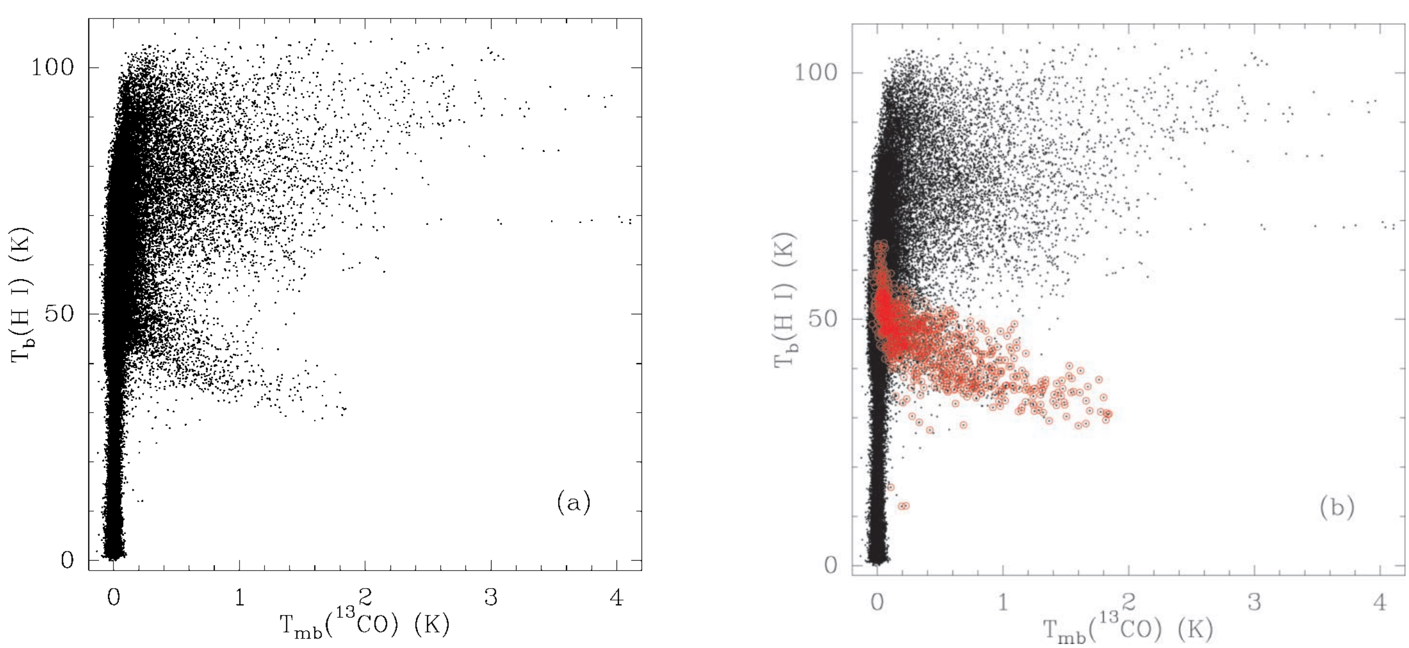

FIG. 2.—Plot of ^{13}CO vs. H I emission for every independent position in the GRS and BUAO survey in the region, $44°.8 < l < 46°.3$, $-0°.5 < b < 0°.5$, and −5 km s^{-1} < V_{LSR} < 85 km s^{-1}. The GRS ^{13}CO have been convolved to the same angular resolution and spectral resolution as the BUAO H I data (4′ and 0.52 km s^{-1}). (*a*) All points in the enclosed region. (*b*) Data with velocities in the range 24 km s^{-1} < V_{LSR} < 26 km s^{-1}, the same velocity as GRSMC 45.6+0.3, are displayed in red. The ^{13}CO emission is correlated with H I SA for GRSMC 45.6+0.3.

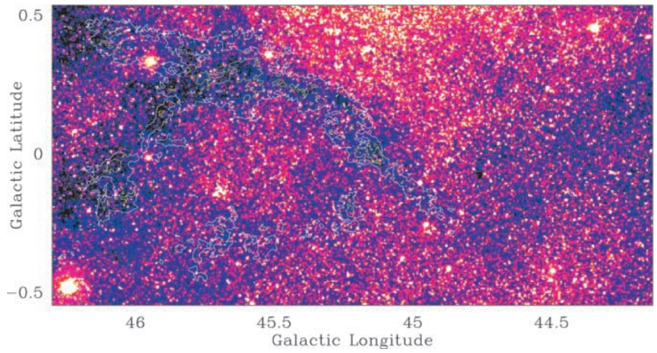

FIG. 3.—Comparison of the Fig. 1 ^{13}CO distribution with the POSS I optical image. The correlation between ^{13}CO emission and visual extinction demands that the molecular cloud be at the near distance.

emission, the deeper the H I absorption. Figures 1 and 2 demonstrate that H I SA and ^{13}CO are associated in GRSMC 45.6+0.3.

The GRSMC 45.6+0.3 cloud is also associated with significant optical extinction. Figure 3 shows the same ^{13}CO contours superposed on the POSS I Digital Sky Survey image of the region. There is a striking correspondence between the ^{13}CO contours and the obvious visual extinction spanning the field. Figure 4 shows the GRS ^{13}CO (*black line*) and BUAO H I spectra (*red line*) for $(l, b) = (45\overset{\circ}{.}33, 0\overset{\circ}{.}13)$. The velocity match at 27 km s^{-1} between the ^{13}CO emission and the H I SA is obvious.

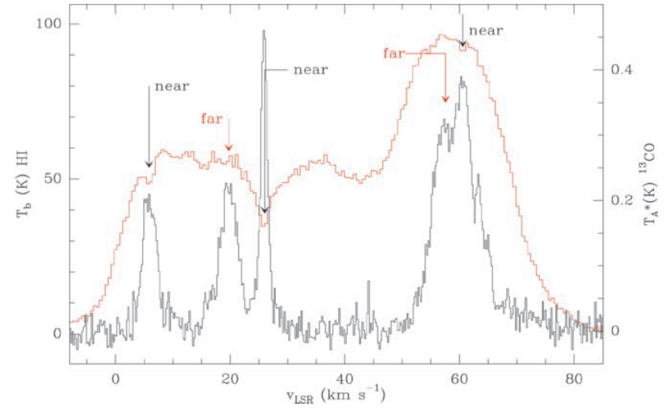

FIG. 4.—Typical ^{13}CO and H I spectra (*red*). The ^{13}CO spectrum shown is the result of smoothing the GRS data to the 4′ H I resolution. The ^{13}CO emission component at 27 km s^{-1} is clearly associated with H I SA.

4. DISCUSSION

The high optical extinctions in the Galactic plane limit the distance to which molecular clouds can be seen as optical extinction features to at most a few kiloparsecs. Consequently, the morphological match between the ^{13}CO distribution and that of the optical extinction clearly demonstrates that GRSMC 45.6+0.3 is nearby. If GRSMC 45.6+0.3 were at its far kinematic distance of 10.1 kpc, this cloud could not be seen in optical extinction.

Using the Clemens (1985) rotation curve, we locate the cloud at the 1.8 kpc near kinematic distance. We can now use the Figure 4 spectra to estimate the properties of GRSMC 45.6+0.3 using standard H I SA and ^{13}CO analyses (Bania 1983; Simon et al. 2001). Assuming an H I excitation temperature in the absorbing gas of $T_{SPIN} \sim 25$ K, we obtain an H I optical depth of 1.1 and a column density of $N(\mathrm{H\ I}) = 1.6 \times 10^{20}$ cm^{-2}. Assuming a ^{13}CO excitation temperature of 10 K, we obtain an H_2 column density of $N(H_2) = 1.4 \times 10^{21}$ cm^{-2}. Altogether, ~5% of the protons in this $1.8 \times 10^4\ M_\odot$ molecular cloud are in atomic form.

4.1. *Photodissociation and* H I *Self-Absorption*

To be detected in H I SA, a typical molecular cloud must satisfy three criteria: (1) it must contain significant amounts of cold H I, (2) this H I must have sufficient opacity ($\tau \sim 1$), and (3) there must be sufficient background emission from warm H I. Photodissociation region (PDR) theory predicts that the skins of typical molecular clouds exposed to typical Galactic UV radiation fields will have the necessary physical conditions to show H I SA against strong H I backgrounds (Tielens & Hollenbach 1985). A UV field impinging on a molecular cloud will photodissociate molecular hydrogen on its surface and create a region where the dominant form of hydrogen is atomic. Since the local average interstellar radiation field is strong enough to photodissociate H_2, even clouds far from OB stars should contain significant amounts of H I in their skins. Indeed, there is ample observational evidence for H I surrounding molecular clouds (e.g., Andersson, Roger, & Wannier 1992).

Many groups have modeled the chemical and physical structure of clouds exposed to UV radiation as a function of extinction. We use here the models of Wolfire, Hollenbach, & Tielens (1993). For a typical molecular cloud ($n \sim 10^3$ cm^{-2}) exposed to a UV field comparable to the local interstellar radiation field ($\chi \sim 1$; expressed in Habing units; Habing 1968), the models suggest that the abundance of H I in the surface layer ($A_v \lesssim 2$) is significant: $[\mathrm{H}]/[H_2] \gtrsim 10^{-2}$ (in good agreement with our estimate for GRSMC 45.6+0.3). Furthermore, the gas in this region has a predicted temperature $T \sim 10$–25 K, much colder than the ~100 K average H I spin temperature.

Molecular clouds are thus expected to have significant amounts of cold H I in their outer layers. Does this cold H I have sufficient opacity to be detected in SA? The opacity per unit velocity interval in units of nepers (km s^{-1})$^{-1}$ is $\tau_v = 5.56 \times 10^{-19} N_v / T_{SPIN}$, where N_v is the column density per unit velocity interval in units of atoms cm^{-2} (km s^{-1})$^{-1}$ and T_{SPIN} is the spin temperature in kelvins. To estimate the H I opacity of a molecular cloud, we assume that the H I spin temperature equals the gas kinetic temperature. The models show that for typical line widths of a few kilometers per second, any cloud with $A_v \gtrsim 2$ will have $\tau \gtrsim 1$. Since molecules will only survive inside clouds with $A_v \gtrsim 2$, *we conclude that typical molecular clouds have significant opacity in the* 21 cm H I *line*.

These results are consistent with cool H I being associated with the skins of *every* molecular cloud or cloud core. Whether a cloud reveals H I SA depends on whether the telescope has sufficient resolution to isolate the SA signal and whether there is a sufficient column density of warm H I behind the cloud.

4.2. *Relevance to Establishing Molecular Cloud Distances*

Since the Milky Way rotates differentially, a cloud's LSR radial velocity directly corresponds to its Galactocentric radius. In the inner Galaxy, however, any given Galactocentric radius corresponds to two distances along the line of sight, known as the "near" and "far" kinematic distances. This so-called near-far kinematic distance ambiguity compromises our ability to establish reliable distances to molecular clouds.

The likelihood of detecting H I SA favors the geometry in which a molecular cloud lies at the near kinematic distance. Since warm atomic gas is ubiquitous throughout the Galaxy, H I emits at essentially every allowed velocity. For clouds at the near kinematic distance, there is an ample amount of H I at the far distance and at the same velocity against which a cold molecular foreground cloud can be seen in silhouette. If the same cloud were placed at the far distance, however, there would be little or no background H I, and the SA feature would be absent. Moreover, any weak SA for far clouds would be filled in by emission from warm clouds at the near distance. Thus, the presence of H I SA suggests that the cloud lies at the near kinematic distance, and its absence suggest that the cloud lies at the far kinematic distance. This argument led LBB to propose the use of H I SA to help resolve the ambiguity.

Of course, under special circumstances, H I SA might occur for clouds at the far kinematic distance. For instance, noncircular velocities due to random cloud motions or streaming motions due to spiral density waves might change a distant cloud's velocity enough to place it in front of a significant column of gas at the same LSR velocity but located behind the cloud at the far kinematic distance. For significant SA, however, the random or streaming velocity must be directed almost entirely along the line of sight, and this situation must be rare. Another possibility is that warm H I is created by photodissociation on the back side of the cloud (e.g., Andersson & Wannier 1993). Such warm H I halos could be produced by clouds exposed to intense UV fields ($\gtrsim$1000 Habing fields) from nearby OB stars. Most reports of warm H I halos, however, suggest that only a small fraction (~10%) of the total H I column density along the line of sight actually resides in the H I envelope (Williams & Maddalena 1996); the dominant background is still the general Galactic H I emission. Moreover, current PDR models do not predict H I envelopes sufficiently large or dense to produce a bright H I background against which one could see significant H I SA. Even if a sufficient column of warm H I were produced, the front side of the cloud should also have a large column of warm H I, and any SA feature would tend to be filled in by emission from the front side. Although *some* molecular clouds at the far kinematic distance no doubt exhibit SA, special kinematic or morphological asymmetries are required. Thus, a molecular cloud at the near distance is much more likely to exhibit H I SA.

A close examination of Figure 4 shows five ^{13}CO emission components; two of these have no H I SA and three of them do. If the LBB hypothesis is correct, then we can assign the molecular clouds lacking H I SA to the far kinematic distances and those exhibiting H I SA to the near kinematic distance. These assignments are indicated in Figure 4.

In this Letter, we have confirmed the LBB hypothesis for the case of GRSMC 45.6+0.3, for which we have independently established the near kinematic distance via its optical extinction. Future work will determine whether the H I SA technique can be generalized to resolve the kinematic distance ambiguity for all molecular clouds.

5. SUMMARY

The LBB hypothesis suggests that the presence or absence of H I SA can resolve the near-far distance ambiguity and thus establish the distances to Galactic molecular clouds. Models of PDRs indicate that typical molecular clouds ($n \sim 1000$ cm^{-3}, $\chi \sim 1$) should have enough opacity to detect H I at the near kinematic distance in SA against the usual Galactic H I backgrounds. On the other hand, molecular clouds at the far distance will be much less likely to show H I SA because they lack the required warm H I background emission. The Galactic molecular cloud GRSMC 45.6+0.3 is presented here as a case study of this technique. For this cloud, the H I SA near kinematic distance determination is confirmed by the morphological spatial correlation between the observed distributions of ^{13}CO emission and optical extinction.

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