**H I NARROW SELF-ABSORPTION IN DARK CLOUDS**

D. Li1,2 and P. F. Goldsmith2

Received 2002 June 21; accepted 2002 November 20

**ABSTRACT**

We have used the Arecibo telescope to carry out a survey of 31 dark clouds in the Taurus/Perseus region for narrow absorption features in H I (21 cm) and OH (1667 and 1665 MHz) emission. We detected H I narrow self-absorption (HINSA) in 77% of the clouds that we observed. HINSA and OH emission, observed simultaneously, are remarkably well correlated. Spectrally, they have the same nonthermal line width and the same line centroid velocity. Spatially, they both peak at the optically selected central position of each cloud, and both fall off toward the cloud edges. Sources with clear HINSA features have also been observed in transitions of CO, 13CO, C18O, and C 1. HINSA exhibits better correlation with molecular tracers than with C 1. The line width of the absorption feature, together with analyses of the relevant radiative transfer, provides upper limits to the kinetic temperature of the gas producing the HINSA. Some sources must have a temperature close to or lower than 10 K. The correlation of column densities and line widths of HINSA with those characteristics of molecular tracers suggests that a significant fraction of the atomic hydrogen is located in the cold, well-shielded portions of molecular clouds and is mixed with the molecular gas. The average number density ratio [H i]/[H2] is 1.5 × 10^{-3}. The inferred H I density appears consistent with, but slightly higher than, the value expected in steady state equilibrium between formation of H I via cosmic-ray destruction of H2 and destruction via formation of H2 on grain surfaces. The distribution and abundance of atomic hydrogen in molecular clouds are critical tests of dark cloud chemistry and structure, including the issues of grain surface reaction rates, PDRs, circulation, and turbulent diffusion.

Subject headings: ISM: molecules — radio lines: ISM

1. INTRODUCTION

Two relatively distinct phases are generally assumed to exist in the neutral interstellar medium (ISM): atomic and molecular. The atomic phase of the ISM, consisting mainly of hydrogen atoms, is traced by the H I hyperfine transition at 21 cm. The molecular phase of the ISM, whose major component—molecular hydrogen—lacks a permanent electric dipole moment and readily excited transitions at temperatures generally encountered, is primarily traced by emission from rarer molecular species such as carbon monoxide. The conversion from atomic to molecular forms occurs on dust grains, where atomic hydrogen sticks and forms H2. This exothermic reaction releases H2 into the gas and keeps molecular clouds molecular. Dissociative processes maintain a population of atoms even inside molecular clouds. Recently, there has been increased interest in atomic species, which prove to be important probes. Two important examples are C i, which is accessible at submillimeter wavelengths (e.g., Phillips et al. 1980; Huang et al. 1999; Plume et al. 2000), and O i, which can be observed in the far-infrared (e.g., Herrmann et al. 1997; Kraemer, Jackson, & Lane 1998; Liseau et al. 1999; Lis et al. 2001).

Inside molecular clouds, dissociating UV photons are blocked by both grains and H2 line absorption (Hollenbach, Werner, & Salpeter 1971). A significant H I population exists inside molecular clouds maintained by cosmic-ray destruction of H2 and additionally as a remnant of the H2 formation process in a chemically young cloud. The atomic hydrogen component inside molecular clouds has fractional abundance ([H]/[H2]) of ≃0.1% (discussed in § 6) and is thus the third most abundant gas-phase species, after H2 and He. Because the balance of H I and H2 involves grain surface reactions, the density of atomic H I in dark clouds serves as a test of complete chemical networks with reactions both in the gas phase and on grain surfaces. The H I abundance in well-shielded regions can be increased by relatively rapid turbulent diffusion (Willacy, Langer, & Allen 2002) or by general mass circulation (Chieze & Pineau des Forêts 1989). It is therefore important to establish the presence of H I in the molecular ISM and to determine accurately its abundance.

A unique probe of this component is H I narrow (which we define to be less than that of CO) line width self-absorption, which we denote HINSA. The absorption dips seen in the spectra of 21 cm emission are often denoted H I self-absorption. The prefix “self” is widely used to differentiate this phenomenon from absorption against a background continuum source. For the origins of H I absorption toward nearby dark clouds, separate Galactic background H I emission and cold foreground H I material are both needed. A typical configuration is shown in Figure 1.

The existence of cold H I associated with dark clouds was recognized more than 25 years ago. Knapp (1974) conducted a survey of 88 dark clouds and detected absorption features in fewer than half of them. The optical depth of cold H I was derived from the profiles of the absorption lines. The molecular content of the clouds observed was traced by their dust extinction. The H I fractional abundance, [H]/[H2], was thus determined to be 1%–5%. In terms of the observational limits and conclusions, this early work typifies most self-absorption studies that have followed.

With the 140 foot (43 m) telescope, Knapp’s survey has an angular resolution of 21′ and a velocity resolution of ~0.5 km s^{-1}. Similar resolutions have been achieved with the 85 foot (26 m) antenna at Hat Creek (Goodman &
Heiles 1994) and the 120 foot (37 m) antenna of the Haystack Observatory (Myers et al. 1978). The 76 m Lovell telescope (12" angular resolution, ~0.5 km s\(^{-1}\) velocity resolution; the same convention in what follows) has been employed for a study of six dark clouds in the Lynds (1962) catalogue (McCutcheon, Shuter, & Booth 1978) and the Riegel-Crutcher (1972) cloud (Montgomery, Bates, & Davies 1995). Additional studies have been conducted with the Effelsberg 100 m telescope (9", 0.5 km s\(^{-1}\) velocity resolution; the same convention in what follows). The Taurus molecular cloud 1 (TMC-1) has been mapped by Wilson & Minn (1977). The complex region around B18, also known as Kutner's cloud, has been mapped by Batrla, Wilson, & Rahe (1981) and Poppel, Rohlfis, & Celnik (1983). The Arecibo telescope with the line feed system (3", 1 km s\(^{-1}\)) has been used to study H I absorption (e.g., Burton, Liszt, & Baker 1978; Baker & Burton 1979; Bania & Lockman 1984). Baker & Burton (1979) also raise the possibility that the absorption can help resolve the near-far ambiguity in kinematic distances, a topic that is further explored by Jackson et al. (2002).

Interferometers have also been used to obtain higher angular resolution, but the usual penalty has been lower velocity resolution to augment the sensitivity. Van der Werf, Goss, & van den Bout (1988) mapped L134 and van der Werf et al. (1989) mapped L1551 with the DRAO and the VLA (1.5", 1.3 km s\(^{-1}\)). The interferometer studies are well suited for mapping structures having a scale of arcminutes. However, their velocity resolutions of about 1.5 km s\(^{-1}\) can easily miss or suppress narrow absorption features, which occupy at most a couple of velocity channels in such spectra. To compound this problem, the H I emission is structured. Multiple peaks and wide troughs are not rare in Galactic 21 cm profiles (see, e.g., Fig. 2). If a map is based on the integrated area of an absorption line (or lines), the wide troughs that may not be associated with dark clouds will be more prominent than are the narrow features. Reliable analysis of the HINSA profile requires a velocity resolution better than 0.3 km s\(^{-1}\).

The general scientific objectives of narrow-line H I absorption studies are to explain its origin and to determine the abundance of atomic hydrogen. For the first question, the association of HINSA with dark clouds is inconclusive in the literature. On the positive side, Sherwood & Wilson (1981) find a good correlation with extinction in TMC-1. McCutcheon et al. (1978) give a higher detection rate (six to eight out of 11 Lynds clouds) than Knapp (1974). Cappa de Nicolau & Poppel (1991) find HINSA in the “darkest” cores in the CrA complex embedded in an H I emission ridge. On the other hand, the association between H I absorption features and dense regions is ambiguous in a recent DRAO H I survey, in which Gibson et al. (2000) find cloudlike absorption structures both correlated and uncorrelated with CO emission. They label these features HISA, shorthand for H I self-absorption. This is the situation in which the distinction between HISA and HINSA must be made. As seen in the DRAO survey, the HISA probably reflects temperature fluctuations in the atomic ISM. The HISA is spectrally wider and flatter and could have its origin in the same location as the 21 cm emitting gas, making its name appropriate. HINSA refers to narrower absorption features, which are produced by cold foreground molecular clouds and are not prominent in the DRAO survey with 1.3 km s\(^{-1}\) velocity resolution. To further complicate the issue, H I has also been seen in emission in possible halos around molecular clouds, such as B5 (Wannier et al. 1991). H I halos are a distinct environment for atomic hydrogen compared to either HISA or HINSA, and they are easily distinguished observationally (see §7).

The difficulties in obtaining the H I abundance through HINSA are threefold. First, the early studies are hampered...
mainly by limited knowledge of the dark cloud itself. The H$_2$ column density is often obtained from low angular resolution extinction data (e.g., Knapp 1974; Batrla et al. 1981) or H$_2$CO (e.g., Wilson & Minn 1977; Poppel et al. 1983), a molecule whose fractional abundance is not very certain. Second, with one profile, it is impossible to obtain both the optical depth and the spin temperature accurately. An assumption about the spin temperature is often made, which may not be realistic. Third, the issue of foreground emission is often ignored.

With some or all of the three uncertainties, the [H]/[H$_2$] ratio has been derived to be ranging from a few percent (e.g., Knapp 1974; Saito, Ohtani, & Tomita 1978) to $5 \times 10^{-4}$ (Winnberg et al. 1980).

The requirements of reasonable angular resolution, good sensitivity, and high-frequency resolution make the upgraded Arecibo Gregorian system a valuable tool with which to study the HINSA. The large instantaneous bandwidth allows OH 1665 and 1667 MHz spectra to be obtained simultaneously with that of H$_1$.

We describe the new observations including an H$_1$ survey to examine the correlation between HINSA and OH in dark clouds and complementary mapping in carbon monoxide isotopologues, OH, and C$_1$ in § 2. In § 3 we present a
three-component model for radiative transfer and correction for foreground material, allowing accurate H\textsc{i} column densities to be obtained. We analyze OH and C\textsuperscript{18}O emission in § 4, and the results of our survey and observations of L1544 are given in § 5. We review the general issue of atomic hydrogen in molecular clouds in § 6, discuss our results in § 7, and summarize our conclusions in § 8.

2. OBSERVATIONS

The sources included in our survey of H\textsc{i} in dark cloud cores are mainly chosen from a dark cloud catalog based solely on optical obscuration (Lee & Myers 1999). The observed cores meet the following constraints: (1) right ascension $2^h–6^h$, (2) angular diameter close to or larger than observed cores meet the following constraints: (1) right ascension $2^h–6^h$, (2) angular diameter close to or larger than $0\arcsec$--$3\arcsec$, (3) declination angle $0\degr–35\degr$, and (4) other observing considerations, such as minimizing slewing time. A total of 28 cores have thus been chosen for this Arecibo survey of dark clouds. Their names, coordinates, presence of HINSA, and association with a young stellar object are given in Table 1.

In addition, two well-studied dark clouds in Perseus, Barnard 1 (B1) and Barnard 5 (B5), are included in our survey. B1 is one of the few dark clouds with a positive Zeeman

| Source Name | R.A. | Decl. | HINSA Detection | EYSO Presence |
|-------------|------|-------|-----------------|---------------|
| B1          | 03 30 12.0 | 30 57 26 | N | Y |
| B5          | 03 44 28.7 | 32 44 33 | N | N |
| L1498       | 04 07 51.8 | 25 01 35 | ? | N |
| L1506B      | 04 16 03.9 | 25 13 00 | ? | N |
| B213-7      | 04 22 12.8 | 26 26 10 | N | N |
| L1524-1     | 04 26 17.8 | 24 31 26 | Y | Y |
| L1524-2     | 04 26 16.9 | 24 25 02 | Y | Y |
| L1521E      | 04 26 17.2 | 26 07 34 | Y | N |
| B18-2       | 04 29 34.4 | 24 45 46 | Y | N |
| L1536-2     | 04 29 50.7 | 22 53 29 | Y | N |
| TMC-2-3     | 04 29 57.6 | 24 11 26 | Y | N |
| L1536-1     | 04 30 19.7 | 22 36 51 | Y | N |
| B18-4       | 04 32 34.0 | 24 02 48 | Y | Y |
| L1527A-1    | 04 35 05.1 | 26 08 37 | Y | Y |
| L1534       | 04 36 36.4 | 25 35 14 | Y | Y |
| TMC-1 CP    | 04 38 38.5 | 25 36 30 | Y | N |
| L1507-2     | 04 39 53.4 | 29 38 25 | Y | N |
| L1517C      | 04 51 33.6 | 30 30 54 | Y | N |
| L1517B-2    | 04 51 56.4 | 30 38 03 | Y | N |
| L1517B      | 04 52 07.2 | 30 33 18 | Y | N |
| L1512       | 05 00 54.4 | 32 39 00 | Y | N |
| L1541       | 05 01 14.0 | 25 07 00 | Y | N |
| L1523       | 05 03 02.7 | 31 37 30 | Y | N |
| L1582A      | 05 29 11.9 | 12 28 20 | Y | N |
| L1622A      | 05 52 17.1 | 01 56 55 | ? | N |
| L1621-1     | 05 53 23.0 | 02 17 39 | ? | N |
| L1574       | 06 05 08.9 | 19 28 40 | Y | N |
| L1578-2     | 06 05 40.4 | 18 12 00 | Y | Y |
| CB 45       | 06 06 02.0 | 17 50 48 | Y | N |
| L1633       | 06 22 04.0 | 03 23 53 | Y | N |

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. A question mark (‘?’) in the “HINSA” column means that possible absorption is indicated by a shoulder in the line profile. The “EYSO” column indicates the identification of a young stellar object (or objects) based on IRAS data (Lee & Myers 1999).
Each ON source position was observed for an integration time of 5–10 minutes. At the current sensitivity of Arecibo (\(T_{\text{sys}} \sim 35\ \text{K}\)), Galactic H I profiles without ambiguity caused by noise can be obtained in an even shorter time. The rms noise level of less than 0.1 K in all our spectra is set by the requirement of detecting OH lines, which typically have antenna temperatures in the range of 0.5–1 K. The beam efficiency for data taken in 2001 February is significantly higher than it was previously, as a result of surface readjustment to the primary. Relative calibration and consistency checks are carried out using the strongest source, TMC-1 CP, which was observed both before and after the readjustment to the primary. Relative calibration and consistency checks are carried out using the strongest source, TMC-1 CP, which was observed both before and after the surface readjustment. The data from 2001 observations were scaled to those obtained at the earlier epoch, when extensive quasar calibration observations were made.

To determine the H2 column density reliably, C18O data on cores with clear HINSA were obtained in 2000 October at the Five College Radio Observatory (FCRAO). The “footprint” size of the 16-element SEQUOIA focal plane array is 5.9 \(\times\) 5.9. We use four pointings to make a beam-sampled map of each source and convolve it with the Arecibo beam. The data are corrected for the main-beam efficiency to give the best estimate of the total mass in the beam as discussed above. By combining C18O and H I data, the abundance \([\text{H}_2]/[\text{H}_2]\) can be obtained. At FCRAO, CO and 13CO spectra were also obtained for comparison with H I absorption line profiles.

The 492 GHz ground-state fine-structure line of atomic carbon (C i) has also been observed by the Submillimeter Wave Astronomy Satellite (SWAS) toward clouds with clear HINSA features. In PDR models, C i should be abundant only in low-extinction regions. We compare its line characteristics to those of HINSA to examine the importance of photodissociation in maintaining populations of low-temperature H I.

3. THREE-COMPONENT RADIATIVE TRANSFER AND FOREGROUND CORRECTION

3.1. Radiative Transfer

The standard approach for analyzing absorption is to reconstruct the emission spectrum from observing one or multiple “OFF” positions, where the absorption is absent. As noted in §2, identifying such OFF positions is problematic for HINSA. However, the emission spectrum can still be estimated for HINSA because the absorption line is much narrower (typically a factor of 20) than the background emission. The instrumental baseline is both flat and stable, which allows us to use only the ON spectra.

The reconstruction is carried out by fitting a fifth-order polynomial across the frequencies affected by the absorption in the HINSA spectrum to define the profile as if there were no absorption present. The details and uncertainty associated with such a fit will be discussed in the following subsection.

The classical problem of deriving two quantities, the optical depth and the excitation temperature, from one profile is compounded by the possible foreground contamination, which adds more unknowns to the mix. A careful look at the radiative transfer is necessary before any quantitative analysis of the HINSA can be carried out with confidence.

A three-component model is outlined in Figure 1. It represents a general view of the H I absorption in the galaxy. The parameters are defined as follows:

1. \(T_b\): background H I temperature.
2. \(T_f\): foreground H I temperature.
3. \(\tau_b\): background H I optical depth.
4. \(\tau_f\): foreground H I optical depth.
5. \(T_x\): excitation temperature of H I in the dark cloud.
6. \(\tau\): optical depth of H I in the dark cloud.
7. \(T_c\): continuum temperature, including the cosmic background and Galactic continuum emission.

The antenna temperature produced by the three-component system is

\[
T_A = [T_e e^{-\tau} + T_h(1 - e^{-\tau})]e^{-\tau} 
+ T_x(1 - e^{-\tau})e^{-\tau} + T_f(1 - e^{-\tau}).
\]

(1)

To focus on the effect of the intervening dark cloud, the Galactic atomic gas is assumed to be of uniform temperature \((T_h)\) and small optical depth \((\tau_h)\) at 21 cm. We can then write

\[
T_h = T_b = T_f
\]

(2)

and

\[
\tau_h = \tau_f + \tau_b.
\]

(3)

To consolidate the variables, we define

\[
\tau_b = p\tau_h.
\]

(4)

For our ON spectra, a linear baseline is removed along with the passband shape. Since the background continuum is flat across the band in our observations, it is also removed through our baseline fitting procedure. Thus, the effective spectrum is given by

\[
T_R = T_A - T_c.
\]

(5)

Another quantity is obtained from the spectrum by fitting a polynomial to the portion of the spectrum without the absorption. We call this quantity \(T_{\text{Hi}}\),

\[
T_{\text{Hi}} = (T_h - T_f)(1 - e^{-\tau_f}),
\]

(6)

which is the H I temperature that would be observed if there were no absorbing cold cloud and under the assumption outlined in equations (2) and (3).

Taking the difference of \(T_{\text{Hi}}\) and \(T_R\), we can obtain, as a positive quantity, the absorption temperature

\[
T_{ab} = T_{\text{Hi}} - T_R = [(T_c - T_x)e^{-\tau} + (T_h - T_x)e^{-\tau}](1 - e^{-\tau}).
\]

(7)

For small foreground and background H I opacities and with the definitions of \(p\) and \(T_{\text{Hi}}\), the absorption temperature can be written as

\[
T_{ab} = [pT_{\text{Hi}} + (T_c - T_x)(1 - \tau_f)](1 - e^{-\tau_f}),
\]

(8)

where \(T_{ab}\) and \(T_{\text{Hi}}\) are observables and \(\tau\) is the quantity desired from the analysis. The explicit dependence on the H I emission temperature \(T_h\) is eliminated. Let us examine the remaining unknowns, \(p\), \(T_c\), \(T_x\), and \(\tau_f\).

The fraction of the H I along the line of sight lying beyond the cloud responsible for the absorption, \(p\), can be
calculated from a model of the local H\textsc{i} distribution. To first order, the Galactic H\textsc{i} disk can be approximated by a single Gaussian with an FWHM vertical extent \( z \) equal to 360 pc (Lockman 1984). The percentage of H\textsc{i} in the background is thus given by the complementary error function

\[
p = \text{erfc} \left( \frac{\sqrt{4 \ln(2)} D \sin(b)}{z} \right),
\]

where \( D \) is the distance to the absorbing cloud, \( b \) is its Galactic latitude, and \( \text{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \, dt \).

The Galactic background emission is estimated to be about 0.8 K by extrapolating the standard interstellar radiation field (ISRF) to \( L \) band (e.g., Winnberg et al. 1980). \( T_c = 3.5 \) K is thus used in the analysis that follows.

The excitation temperature of the 21 cm line in dark clouds, \( T_x \), is determined earlier, and for a temperature \( \tau_f \) of the latter reference are considerably smaller than values of the assumptions behind and modeling of the radiative transfer.

First, the imperfect knowledge of the Galactic H\textsc{i} disk and the cloud distance results in uncertainties in \( p \). For five clouds, the distance is not known and \( p \) cannot be modeled. The remaining clouds have an average \( \langle p \rangle = 0.83 \). The difference between unity and this average provides us with an idea of the uncertainty in \( p \). According to equation (12), this results in a 30% uncertainty for the derived optical depth and, in turn, the column density.

Second, the fitting to the background is somewhat arbitrary. The top panel of Figure 3 demonstrates the effect of using different orders of polynomial. The maximum difference in the fitted temperatures is 1.1 K and that in line width is 0.14 km s\(^{-1}\). Higher orders of polynomial usually do not work well. A Gaussian fit to the background is not feasible for sources with very structured H\textsc{i} emission profiles, such as L1574 and L1633. The magnitude of the uncertainties also depends on the position of absorption relative to the peak emission. When absorption occurs closer to the emission center than the situation shown in Figure 3, the uncertainty in the antenna temperature becomes larger and the uncertainty in the line width becomes smaller. We take 2 K as a representative value of uncertainty in the temperature and 0.15 km s\(^{-1}\) as that for our HINSA observations. This means that \( T_{ab} \) becomes smaller as a result of the existence of foreground H\textsc{i} gas.

Finally, the peak optical depth of the absorption feature at the centroid velocity can be obtained using equation (8):

\[
\tau_0 = \ln \left[ \frac{pT_{H_1} + (T_c - T_x)(1 - \tau_f)}{pT_{H_1} + (T_c - T_x)(1 - \tau_f - T_{ab})} \right],
\]

which in turn gives the column density of HINSA as

\[
N(\text{HINSA}) \text{ cm}^{-2} = 1.95 \times 10^{18} \tau_0 \frac{\Delta V}{\text{km s}^{-1}} \frac{T_k}{\text{K}},
\]

where \( \Delta V \) is the FWHM of the absorption line from a Gaussian fit.

In summary, the recipe we have used for obtaining the HINSA column density involves (1) fitting the emission-line profile to determine \( T_{H_1} \), (2) using a model of the Galactic H\textsc{i} to determine \( p \), and (3) deriving the peak optical depth of the cold H\textsc{i} through equation (12). Fourth, we use equation (13) with the line width fitted to the absorption feature, to determine the column density. By fitting the emission and absorption portions of the spectra separately and using these two fits, the optical depth of the absorption alone can be derived without explicitly knowing the background and foreground temperatures, as long as they are equal and the Galactic H\textsc{i} emission is optically thin.

### 3.2. Uncertainties

The OH intensities are 10–200 times smaller than those of H\textsc{i} emission. At the current level of integration, which is chosen to ensure good OH detections, the noise in H\textsc{i} spectra is insignificant. The uncertainties in the derived HINSA column density result primarily from three aspects of the assumptions behind and modeling of the radiative transfer.

First, the imperfect knowledge of the Galactic H\textsc{i} disk and the cloud distance results in uncertainties in \( p \). For five clouds, the distance is not known and \( p \) cannot be modeled. The remaining clouds have an average \( \langle p \rangle = 0.83 \). The difference between unity and this average provides us with an idea of the uncertainty in \( p \). According to equation (12), this results in a 30% uncertainty for the derived optical depth and, in turn, the column density.

Second, the fitting to the background is somewhat arbitrary. The top panel of Figure 3 demonstrates the effect of using different orders of polynomial. The maximum difference in the fitted temperatures is 1.1 K and that in line width is 0.14 km s\(^{-1}\). Higher orders of polynomial usually do not work well. A Gaussian fit to the background is not feasible for sources with very structured H\textsc{i} emission profiles, such as L1574 and L1633. The magnitude of the uncertainties also depends on the position of absorption relative to the peak emission. When absorption occurs closer to the emission center than the situation shown in Figure 3, the uncertainty in the antenna temperature becomes larger and the uncertainty in the line width becomes smaller. We take 2 K as a representative value of uncertainty in the temperature and 0.15 km s\(^{-1}\) as that for
the line width. These values are also included in Tables 2 and 3. The bottom panel of Figure 3 shows the change in
the peak HINSA optical depth produced by the uncertainty in the fitting of the background $^1$H emission. A deviation of
2 K in temperatures (both $T_{Hi}$ and $T_{nb}$) results in a change in $\tau_0$ by 0.04. This is 14% relative to the average
optical depth of the absorption.

Third, we consider the uncertainties in the $(T_c - T_x) \times (1 - \tau_f)$ term. In order to conform to the general assumptions
of an optically thin $^1$H emission ($\tau_b < 1$), the value of $\tau_f$ is thus between 0 and about 0.1. With $T_x = 10$ K,
$T_c = 3.5$ K, and typical numbers for $T_{Hi}$, this corresponds to a change in $\tau$ of absorption of about 0.01, which is 4% relative
to the average optical depth. We conclude that the uncertainty in the derived HINSA column density is dominated by systematic effects, and the overall uncertainty is approximately 50%.

4. ANALYSIS TECHNIQUES FOR SPECTRAL LINES
WITH SMALL OPACITIES

4.1. OH Column Density

From the definition of opacity, the column density of OH can be written as

$$N_{\text{OH}} = \frac{8\pi k T_B}{A_{1667} c h} \frac{16}{5} \int \tau_{1667} dV,$$

where $A_{1667} = 7.778 \times 10^{-11}$ s$^{-1}$ is the $A$-coefficient of this transition and $T_B$ is its excitation temperature. Under the
assumptions of negligible optical depth and no background emission, the column density can be calculated from the integrated intensity (in K km s$^{-1}$) of the 1667 MHz line through (e.g., Knapp & Kerr 1973; Turner & Heiles 1971)

$$N_{\text{OH}} \frac{\text{cm}^{-2}}{\text{K} \text{ km s}^{-1}} = 2.22 \times 10^{14} \int T_{\text{mb}}(V) dV \frac{\text{K} \text{ km s}^{-1}}{	ext{K} \text{ km s}^{-1}}.$$

The satellite component of this $A$ doubling line at 1665 MHz can be useful in determining the optical depth and excitation temperature. For emission without anomalies, the antenna temperatures of the two components satisfy

$$\frac{T_A^{1667}}{T_A^{1665}} = \frac{1 - e^{-1667}}{1 - e^{-1665}} = \frac{1 - X}{1 - X^{0.352}},$$

where $X = e^{1667}$. The ratios for our sources range from 1.2 to 1.9, with the majority being around 1.8. This confirms that we are seeing thermal emission from dark clouds and that the opacity is only modest. Equation (16) gives a unique solution for $X$, which leads to

$$T_x = T_A^{1667} \frac{1 - X}{1 - X^{0.352}} + T_B.$$

Except for one source, the excitation temperature of OH ranges from 5 to 9 K, which is not much larger than the background temperature. At this level of excitation, the assumption of negligible background temperature made for equation (15) results in underestimation of $N_{\text{OH}}$ by a factor of 1.6–2.3.

Because of weaker line emission at 1665 MHz and the exponential dependence of the antenna temperatures on the
optical depth, the satellite line ratio method is very sensitive to uncertainties in the spectra of the satellite component. In
some cases, the line widths of the main and the satellite line are not the same, which may be a result of the low signal-to-
noise ratio of the satellite component. To present a more self-consistent correlation study of $^1$H and OH, we only use the 1667 MHz data in determining OH column density, but note that these results likely underestimate the OH column density by a factor $\approx 2$.

4.2. C$^{18}$O Column Density

In order to determine the molecular content of dark clouds, we have chosen as a tracer the $J = 1\rightarrow 0$ transition of
C$^{18}$O, which is optically thin (or close to it), and which has relatively uniform abundance relative to H$_2$, $\sim 1.7 \times 10^{-7}$ (Frerking, Langer, & Wilson 1982). The C$^{18}$O column density in the $J = 1$ level can be calculated from

$$\frac{N(C^{18}\text{O})}{\text{cm}^{-2}} = 3.72 \times 10^{14} \left(1 - \frac{e^{h\nu/kT_x}}{e^{h\nu/kT_B} - 1}\right)^{-1} \int T_{\text{mb}}(V) dV \frac{\text{K} \text{ km s}^{-1}}{\text{K} \text{ km s}^{-1}},$$

(18)
### Table 2

**Survey of Dark Clouds: Spectral Line Characteristics**

| Source          | $V_{LSR}$ (km s$^{-1}$) | $\Delta V_{int}$ (km s$^{-1}$) | $T_{eq}$ (K) | $T_{upper}$ (K) |
|-----------------|-------------------------|---------------------------------|-------------|-----------------|
|                 | H$_1$                   | OH                              | C$^{18}$O   | C$_1$           | H$_1$ | OH | C$^{18}$O | $^{13}$CO | CO | C$_1$ | $T_{eq}$ | $T_{upper}$ |
| L1524-1         | 6.33±0.08               | 6.42±0.05                       | 6.47±0.04   | 5.6±0.4        | 0.8   | 0.51±0.15 | 0.75±0.05 | 0.69±0.06 | 1.0±0.2 | 1.46±0.07 | 5.3±0.3 | 15.8±0.5 | 26 |
| L1524-2         | 6.39                    | 6.33                            | 6.37        | 6.5            | 0.80  | 0.74    | 1.02     | 0.75     | 1.0     | 1.54     | 2.2    | 22.1    | 28 |
| L1521E          | 6.57                    | 6.51                            | 6.72        | 6.6            | 0.81  | 0.00    | 0.76     | 0.51     | 0.7     | 0.96     | 1.2    | 6.7     | 35 |
| B18-2           | 6.15                    | 6.19                            | 6.20        | 6.8            | 0.80  | 0.38    | 0.54     | 0.39     | 0.5     | 0.98     | 1.9    | 13.2    | 29 |
| L1536-2         | 5.73                    | 5.79                            | 5.87        | 6.0            | 0.79  | 1.00    | 0.72     | 0.69     | 0.9     | 1.21     | 1.6    | 32.1    | 29 |
| TMC 2-3         | 6.16                    | 6.23                            | 6.57        | 6.5            | 0.80  | 1.53    | 1.09     | 0.53     | 0.8     | 1.16     | 2.5    | 61.3    | 23 |
| L1536-1         | 5.58                    | 5.58                            | 5.62        | 5.8            | 0.80  | 0.34    | 0.35     | 0.39     | 0.7     | 1.01     | 1.9    | 12.5    | 32 |
| B18-4           | 5.98                    | 5.98                            | 5.92        | 6.0            | 0.81  | 1.34    | 0.86     | 0.66     | 0.8     | 1.13     | 1.9    | 49.5    | 27 |
| L1527A-1        | 6.08                    | 6.17                            | 6.26        | 6.3            | 0.82  | 1.28    | 0.86     | 0.49     | 0.7     | 1.22     | 1.3    | 46.0    | 20 |
| L1554           | 6.11                    | 6.15                            | 6.30        | 6.3            | 0.82  | 1.42    | 0.87     | 0.67     | 1.0     | 1.38     | 2.5    | 54.3    | 15 |
| L1607-2         | 6.36                    | 6.25                            | 6.29        | 6.4            | 0.87  | 1.22    | 0.68     | 0.50     | 0.7     | 1.06     | 4.2    | 11.1    | 44 |
| L1517C          | 5.36                    | 5.49                            | 5.58        | 5.4            | 0.90  | 0.80    | 0.41     | 0.50     | 0.5     | 0.78     | 3.5    | 24.2    | 41 |
| L1517B-2        | 5.86                    | 5.93                            | 6.02        | 6.2            | 0.90  | 0.42    | 0.65     | 0.61     | 0.7     | 0.78     | 1.2    | 13.9    | 44 |
| L1517B          | 5.78                    | 5.78                            | 5.84        | 5.9            | 0.90  | 0.34    | 0.35     | 0.35     | 0.4     | 0.57     | 1.4    | 12.6    | 43 |
| L1512           | 7.00                    | 7.03                            | 7.10        | 7.2            | 0.90  | 0.00    | 0.29     | 0.27     | 0.4     | 0.52     | 1.6    | 6.8     | 35 |
| L1544           | 6.96                    | 7.10                            | 7.18        | 7.8            | 0.87  | 0.49    | 0.44     | 0.42     | 0.5     | 0.65     | 3.8    | 15.3    | 39 |
| L1523           | 6.90                    | 6.96                            | 7.02        | 7.0            | 0.78  | 0.00    | 0.25     | 0.25     | 0.4     | 0.41     | 1.9    | 6.8     | 28 |
| L1582A          | 10.07                   | 10.10                           | ...         | 10.3           | 0.62  | 1.5     | 0.55     | ...      | ...     | ...      | 1.8    | ...     | ... |
| CB 37           | 1.26                    | 1.10                            | 1.13        | 1.3            | 1.00  | 1.60    | 1.77     | 1.45     | 1.7     | 2.23     | 2.8    | 65.7    | 50 |
| L1574-b         | 0.90                    | 0.13                            | 0.16        | 0.1            | 1.00  | 0.89    | 1.03     | 0.58     | 0.8     | 1.46     | 1.7    | 27.4    | 57 |
| L1574-f         | 3.27                    | 3.29                            | ...         | 3.5            | 1.00  | 1.1     | 1.67     | ...      | ...     | ...      | 3.1    | 38.8    | 66 |
| L1578-b         | -0.60                   | -0.85                           | -0.48       | -0.9           | 1.00  | 1.31    | 1.62     | 0.74     | 1.0     | 1.45     | 2.2    | 47.6    | 44 |
| CB 45           | 0.76                    | 0.61                            | 0.66        | 1.4            | 0.95  | 0.97    | 1.18     | 0.73     | 0.9     | 1.28     | 1.6    | 30.4    | 64 |
| L1633           | 9.65                    | 9.40                            | 9.48        | 9.9            | 1.00  | 1.75    | 1.20     | 1.85     | 1.9     | 2.54     | 3.1    | 77.1    | 63 |
| **Average**     | ...                     | ...                             | ...         | ...            | ...   | 0.8     | 0.83     | 0.64     | 0.8     | 1.17     | 2.3    | ...     | ... |

**Note:** Cols. (2), (3), (4), and (5) give the rest velocities. The nonthermal line width, $\Delta V_{int}$, is defined by eq. (22). A zero $\Delta V_{int}$ means that the total line width is smaller than the thermal line width at 10 K. The upper limits to kinetic temperatures, $T_{eq}$ and $T_{upper}$, are discussed in § 5.1. Col. (6) represents the portion of H$_1$ in the background based on a single Gaussian disk model (eq [9]). A value of $p = 1.0$ means that the source distance is unknown.

---

*The 1σ statistical uncertainty is based on a Gaussian fit. This value is representative of the sample. The uncertainty varies for individual sources as a result of the difference in signal-to-noise ratio and in the degree by which a profile deviates from a Gaussian.

b The uncertainty is estimated based on the variations in fitted background temperature when different orders of polynomials are used (Fig. 3). The statistical uncertainty is insignificant compared to this.*
where $T_x$ is the excitation temperature of the $J = 1 \rightarrow 0$ transition, $T_B$ is the background temperature, and the integrated intensity is corrected for the main-beam efficiency. The LTE approximation is then used to justify substituting $T_x$ for $T_B$ for all transitions in converting $N^i(C^{18}O)$ to the total column density of $C^{18}O$. The smoothing of the FCRAO (45° beam) data to the Arecibo resolution gives a physical meaning to the $[H]/[H_2]$ thus derived: it is the ratio between the total number of H atoms and $H_2$ molecules in a 3° beam.

5. HI SURVEY STATISTICS AND CHARACTERISTICS OF HINSA

As described in Sec. 2, we surveyed 30 nearby dark clouds, unbiased in terms of HI absorption. In this sample, 23 have a clear narrow absorption dip at the same velocity as that of the OH emission (Figs. 4a and 4b). Four more clouds (L1498, L1506B, L1622A, and L1621-1) have hints of an absorption feature coincident in velocity with the OH emission, which correspond to a “shoulder” on the HI profile (Fig. 5). The remaining three clouds (B1, B5, and B213-7) have no indication of narrow absorption features. Counting the clouds with the “shoulder” features as nondetections, the detection rate of HINSA toward optically selected dark clouds is 77%. This high detection rate strongly supports the association of HINSA with dark clouds. Further analysis given below based on comparisons of specific tracers reinforces this association.

In our sample of 30 dark clouds, seven are found to contain embedded young stellar objects (EYSOs; Lee & Myers 1999). The ratio of cores with EYSOs to starless cores is thus 0.3, the same as found in these authors’ larger sample. If the detection rate of HINSA is independent of EYSOs, we would expect to find 17.6 clouds with HINSA in starless cores and 5.4 clouds with HINSA in EYSO cores. The actual numbers in our sample are 17 and 6, respectively. Thus, our observations indicate that the presence of an embedded YSO does not significantly affect the likelihood of finding HINSA.

In our sample, the HI spectra are often structured and some are most likely as a result of multiple absorption features (e.g., L1517C, L1512, L1523, CB37, CB45, and L1633). Out of these multiple absorption features, only those with corresponding molecular emission are believed to be associated with molecular clouds. In our sample, these features exhibit a line width comparable to that of $^{13}$CO at the same velocity. We therefore define HI self-absorption features with corresponding CO emission and line width smaller than that of CO as HI narrow self-absorption (HINSA). This view is compatible with the findings of cold HISA features without molecular counterpart in the Galactic Plane Survey (Gibson et al. 2000; Koo & Brunt 2001). The Arecibo HI survey of the Galactic ring (Kuchar & Bania 1994) also shows extended HI absorption features without overlaying CO clouds. The existence of atomic hydrogen colder (15–35 K) than the standard value (80 K) for the cold neutral medium (CNM), yet still independent of molecular clouds, has also been indicated in studies of absorption against continuum sources (e.g., Heiles 2001). Most of the HISA is thus likely a result of temperature fluctuations in the CNM. In the absence of molecular cooling, it is still not evident how atomic gas can be...
maintained at such low temperatures. In contrast, the low temperatures of HINSA have a straightforward explanation in terms of CO cooling if it arises in largely molecular regions. Clouds with HINSA are also less turbulent than typical “neutral hydrogen” clouds that may produce HISA, further emphasizing the distinction between the two.

5.1. Low Temperature of the HINSA

There are two ways to estimate the temperature of the atomic hydrogen detected in absorption. First, the line width of the absorption dip provides an upper limit to the kinetic temperature assuming that only thermal broadening is present. The equivalent temperature, derived from the fitted FWHM ($\Delta V$) of H I absorption

$$T_{eq} = \frac{m_H \Delta V^2}{8 \ln(2) k} ,$$

is given in column (13) of Table 2. There are 10 sources that have an absorption line width so narrow that the H I responsible must be thermalized, or be very close to thermalization, at a temperature lower than 15 K. The narrow line widths we have observed rule out the possibility that the HINSA could be produced in warm (e.g., cloud halo) gas with $T \approx 100$ K, even allowing for modestly subthermal excitation of the 21 cm transition.

Fig. 4.—Sources with clear HINSA features. The axes are the same as in Fig. 2.
Subtle complications in obtaining line parameters from an absorption feature arise when the dip is on the slope of the background emission. In general, the fitted absorption line appears to peak closer to the center of the emission feature and to be narrower than it really is. The corrections required in both cases are small compared to the line width of the narrow-line H i absorption. We do not correct for the displacement of velocity peak, since the average effect is zero as a result of the randomness of the dark cloud velocity with respect to that of the background H i emission. The correction for line width is on the order of 0.04 km s\(^{-1}\) (Levinson & Brown 1980), which is only significant when calculating \(T_{eq}\) for a couple of unusually narrow line width sources. The uncertainty thus introduced in \(T_{eq}\) for L1523, L1521E, and L1517B is between 0.5 and 1 K. For other sources, this correction can be neglected.

Second, the excitation temperature (or the spin temperature for the 21 cm line) can be estimated by rewriting equation (8):

\[
T_x = T_e + \frac{\sigma T_H}{\tau} \left[ 1 - e^{-\tau} \right] 
\]

The optical depth of the narrow-line absorbing gas is on the order of unity. Substituting an infinite \(\tau\) into the equation above overestimates \(T_x\). For the optical depth of the foreground emission \(\tau_f\), a nominal value of 0.1 is used, which is probably an overestimate obtained by assuming the total
optical depth of Galactic H i emission ($\tau_g$) to be unity. The upper limit of HINSA excitation temperature is thus

$$T_{\text{upper}} = T_c + \frac{p T_{\text{HI}} - T_{\text{ab}}}{0.9}.$$  \hspace{1cm} (21)

These upper limits are listed in column (14) of Table 2. Compared to the temperature limit set by the line width, this method has relatively large uncertainties resulting from the assumptions about $p$ and the optical depth. Nonetheless, it provides an independent estimate based on the depth of the HINSA profile. It also confirms our understanding that the majority of HINSA features come from cold gas ($\lesssim 40$ K) with some sources in the range of 10 K.

These two estimates of temperature upper limits reveal HINSA to be associated with cold gas. According to the lower value between the two upper limits, the average temperature upper limit to the 24 HINSA features is 23 K. Moreover, a significant fraction of the sources must have atomic gas as cold as 7–15 K. The well-shielded regions of molecular cloud cores are the most likely, if not the only, sites that can plausibly contain material this cold.

5.2. H i and OH Correlation

For sources with well-defined absorption features, the similarities between the OH and HINSA profiles are obvious. The two profiles are coincident in velocity as shown in Figure 6.

The line widths of different species are important indicators of the conditions in the regions in which they are found, as well as of the extent of the regions responsible for the spectral line in question. The well-known empirical velocity–line width relations all suggest larger line widths at larger spatial scales (e.g., Larson 1981; Caselli & Myers 1995). To compare the line widths of species with very different molecular/atomic weight, it is appropriate to separate the thermal from the nonthermal contributions to the line widths. This can be done by defining the nonthermal line width as

$$\Delta V_{\text{nt}} = \sqrt{\frac{\Delta V^2 - \frac{8 \ln(2) k T_k}{\mu m_H}}{\mu m_H}},$$  \hspace{1cm} (22)

where $\Delta V$ is the observed FWHM of the line, $\mu$ is the molecular or atomic weight, $m_H$ is the hydrogen mass, and $k$ is Boltzmann’s constant. For HINSA, the width is that of the Gaussian fitted to the absorption profile, while for the other species we fit the emission spectra. The correction for the thermal broadening is significant for the H i as a result of its low mass. The nonthermal line width gives a better indicator of the spatial extent of its progenitor, since the mass...
as would be expected if the gas producing the HINSA were in some peripheral zone of the clouds we have studied.3

5.3. Correlation with CO Isotopologues and C1

As listed in Table 2, all observed species, HINSA, OH, \( ^{13}\)CO, and C 1, have essentially the same velocity relative to the local standard of rest \( (V_{\text{LSR}}) \) in a given cloud. The \( V_{\text{LSR}} \) of the HINSA and of the \( ^{13}\)CO are plotted in Figure 6. The rms separation of our data points from the line of equal velocities is 0.03 \( \text{km s}^{-1} \), which is small compared to both the line width and the velocity resolution.

As traced by the line widths, the spatial distributions within the clouds of the CO isotopologues, the HINSA, and the \( \text{H} \) i appear to be somewhat different. As mentioned above, \( \text{H} \) i, OH, and \( ^{13}\)CO have, on average, the same line width. \( ^{13}\)CO has the narrowest line width \( (\langle \Delta V \rangle \approx 0.64 \text{ km s}^{-1}) \), presumably tracing the innermost core. The \( ^{12}\)CO line is wider with \( \langle \Delta V \rangle = 1.2 \text{ km s}^{-1} \), while the C 1 line is much wider still with \( \langle \Delta V \rangle = 2.3 \text{ km s}^{-1} \). The large nonthermal line width of the C 1 confirms this species to be a tracer of PDR regions, where more turbulence exists. HINSA seems to be mixed with relatively quiescent molecular material at higher extinction.

For individual sources, a positive correlation exists between the line width of OH and of HINSA, as shown in the top left panel of Figure 7. The probability of the null hypothesis (the two being uncorrelated) is \( r = 3.6 \times 10^{-5} \); the linear correlation coefficient is 0.76. A similar correlation exists between the OH line width and that of \( ^{13}\)CO. In contrast, no such correlation exists between the OH and C 1 line widths. Again assuming a linear correlation, the null hypothesis is very likely \( (r = 0.49) \).

For the column densities, only OH and \( ^{13}\)CO are definitely positively correlated. For HINSA, the correlation is not clear. This is somewhat expected from the standard \( \text{H}_2 \) formation model \((\S \ 6)\), as the column density of HINSA should be correlated rather with the cloud size than with that of \( \text{H}_2 \). For C 1, the assumption of small optical depth has not been tested in our study and thus may cause large uncertainties. The current data set does not definitively answer all questions about the correlation between column densities of the different species, a subject that deserves additional consideration.

5.4. L1544

To get a better idea of the spatial correlation of HINSA and molecular tracers, we mapped the quiescent dark cloud L1544. This object has relatively narrow line widths in molecular tracers \( [\Delta V(\text{CO}) = 1.0 \text{ km s}^{-1}; \Delta V(\text{C}^1\text{O}) = 0.44 \text{ km s}^{-1}] \). It is usually characterized as starless, as a result of there being no clear association with an IR source \( \text{(Ward-Thompson et al. 1994).} \) The inner 5' core region around the center of L1544 has been well studied and found to exhibit molecular depletion and infall motions \( \text{(Caselli et al. 2002; Tafalla et al. 1998).} \)

We mapped an extended region of L1544, which is the same area as outlined by extinction \( \text{(Snell 1981).} \) The rms of our \( \text{H} \) i and OH spectra is smaller than 0.1 K. At the cloud periphery, the OH 1667 MHz emission is generally weaker

3 We hesitate to use the term “limb brightening” to describe an increase in the depth of the absorption line, but if the \( \text{H} \) i in question were in an outer “onion skin” of the cloud, a map of the integrated area of the absorption would presumably exhibit this behavior.
All three tracers, OH, HINSA, and C$^{18}$O, delineate the same cloud (Fig. 8). The H$_2$ column density in the center of this cloud derived from C$^{18}$O and assuming standard fractional abundance is $6.5 \times 10^{21}$ cm$^{-2}$. Taking dimensions of the cloud core of $9' \times 16'$ gives a characteristic size of 0.49 pc at an assumed distance of 140 pc. This results in a characteristic volume density $n(H_2) = 4.3 \times 10^3$ cm$^{-3}$.

For a spherical cloud of uniform density in virial equilibrium ignoring magnetic fields and external pressure, the H$_2$ density is given by

$$n_v(H_2) = \frac{2.03 \times 10^3}{\mu} \left[ \frac{\Delta V}{(\text{km s}^{-1})} \right]^2 \left( \frac{R}{(\text{pc})} \right),$$

where $\Delta V$ is the FWHM line width, $R$ is the cloud radius, and $\mu$ is the mean molecular weight. Substituting the appropriate values yields $n_v(H_2) = 2.9 \times 10^3$ cm$^{-3}$. This is in reasonable agreement with the average density derived above and suggests that this cloud is in, or not far from, virial equilibrium.

The secondary maximum in OH located around offsets ($-8', 3'$) is due to a localized increase in the line width, indicating an increase in turbulence. At the center of the cloud the line width of the 1667 MHz OH emission is 0.47 km s$^{-1}$, while at ($-8', 3'$) it is 0.70 km s$^{-1}$. This second, more turbulent peak in the OH column density does not correspond to an enhancement in either C$^{18}$O or HINSA. A likely scenario is that the OH traces a low-extinction envelope, which exhibits fluctuations in MHD or some other kind of turbulence, while C$^{18}$O represents the total column density of quiescent material. HINSA produced by cosmic-ray dissociation (see § 6), which is unaffected by extinction, should also be able to trace the highest column density regions. On the other hand, if HINSA is produced mainly by photodissociation in the envelope, a limb-brightening effect should appear. Such an effect is not seen for L1544.
Both HINSA and C18O contours are at 50%, 60%, 70%, 80%, and 90% of their respective peak values. The C18O data are from Tafalla et al. (1998) and have been smoothed to the 30 cloud skins with $A_v$ of H), velocity between H atom and grains (essentially the velocity/C27 the gas phase, can be written as $n_{H_2} = 0.5 n_g n_1 \sigma v S \eta$, \hspace{1cm} (24)

where $n_g$ is the grain number density, $n_1$ is the H I density in the gas phase, $\sigma$ is the grain cross section, $v$ is the relative velocity between H atom and grains (essentially the velocity of H), $S$ is the sticking probability of an H atom on a grain, and $\eta$ is the formation efficiency. The total density of hydrogen atoms is $n_H = (n_1 + 2n_2)$, where $n_2$ is the density of hydrogen molecules. The grain and proton number densities are related through $n_g = g n_1$. The value of $g$ depends on the grain model and gas conditions. A “standard” dust grain is taken to have a radius of 0.1 $\mu$m and a density of 3 g cm$^{-3}$. In a molecular cloud, we can reasonably assume the following gas conditions: [He]/[H] equal to 0.09, most hydrogen gas in the form of H$_2$, and a gas-to-dust mass ratio of 100. Based on these assumptions about the dust grains and the gas, we determine $g$ to be $1.8 \times 10^{-12}$.

In the standard picture of H$_2$ formation (Hollenbach & Salpeter 1970), the timescale for H atoms deposited on the grain to “cover” the grain surface through tunneling processes is much shorter than the residence time of an adsorbed H atom. Since the H$_2$ formation reaction is exothermic (4.5 eV released), $\eta$ is taken to be 1 in their model as long as there are more than two H atoms on a grain. Equation (24) with a near unity $\eta$ works well in diffuse clouds with $S \approx 0.3$ (Hollenbach & Salpeter 1971; Jura 1975). A recent study of sticking probability on icy surfaces gives $S$ close to unity at low temperatures (Buch & Zhang 1991). A recent analysis including both chemisorption and physisorption on grain surfaces indicates that H$_2$ formation can be efficient over a wide range of temperatures (Cazaux & Tielens 2002), specifically including the 8–20 K range of interest for dark clouds. Adopting $S = 0.5$ and $\eta = 1.0$ for the following discussion, we obtain the equation

$R_{H_2} = 2.06 \times 10^{-18} n_H n_1 \sqrt{T}$, \hspace{1cm} (25)

where $T$ is the gas temperature, for the formation rate of H$_2$.

For typical dark cloud conditions with temperature of 10 K, $n_H \sim 10^4$ cm$^{-3}$, the H i-to–H$_2$ conversion timescale, $n_1/R_{H_2}$, is approximately 0.5 million years. Such a rapid conversion leaves an essentially “molecular” cloud in which the atomic component is maintained by cosmic rays in a steady state. The destruction rate of H$_2$ is $\xi n_2$ (cm$^{-3}$ s$^{-1}$), where $\xi = 3 \times 10^{-17}$ s$^{-1}$ is the cosmic-ray ionization rate. This parameter has approximately a factor of 3 uncertainty associated with it, as indicated by the varied results and range of fits obtained for different sources and models.
by, e.g., Caselli et al. (1998, 2002). In a steady state and assuming $n_2 \gg n_1$,

$$n_2 = \left(2.06 \times 10^{-18}\right) 2n_2 n_1 T^{1/2} - \xi n_2 = 0,$$

which, for 10 K, gives $n_1 = 2.3 \text{ cm}^{-3}$.

This H I density is independent of the local gas density. Therefore, the entire region containing molecular material can contain cold H I and be capable of producing HINSA, with essentially an equal contribution per centimeter of path along the line of sight. In our sample of clouds, the average column density of HINSA is $7.2 \times 10^{18} \text{ cm}^{-2}$. We adopt an angular size for the region with absorbing H I of 15", which is consistent with the typical size of Lynds clouds and Bok globules in the Taurus complex. This corresponds to a physical dimension equal to 0.6 pc at a distance of 140 pc. The average H$_2$ gas density that we derive from the average column density of C$^{18}$O and fractional abundance $1.7 \times 10^{-7}$ is equal to $2.5 \times 10^{18} \text{ cm}^{-3}$. The average H I fractional abundance [H I]/[H$_2$] in the dense molecular gas predicted from the standard theory is $9.2 \times 10^{-4}$. This is in reasonable agreement with the observed result $1.5 \times 10^{-3}$ (see Table 3 and Fig. 9).

Another obvious process for producing atomic hydrogen associated with molecular clouds is photodissociation. In a plane-parallel PDR model with microturbulence (Wolfire, Hollenbach, & Tielens 1993; Jackson et al. 2002), a large fractional abundance of H I ($> 10^{-2}$) can be produced at low extinctions ($A_V < 2$). We do not see this H I envelope, either in total column density or in morphology. One possible explanation is that the conditions in such regions are much less favorable for production of HINSA than the cold, quiescent regions of the clouds. If we ignore foreground and background absorption as well as any continuum, we see from equation (8) that the magnitude of the absorption line from the optically thin, thermalized gas responsible for the

HINSA in the cloud is

$$\frac{T^0_{ab}}{K} = 5.3 \times 10^{-19} \frac{N(\text{H I})/(\text{cm}^{-2})}{A V/(\text{km s}^{-1})} \left(\frac{T_{H_1} - T_x}{T_x}\right),$$

where $T_x$ is the excitation temperature of the atomic hydrogen. As the temperature in the PDR region rises, so does $T_x$, and the absorption intensity drops; as $T_x$ approaches the background temperature, the drop becomes precipitous. In these externally ionized and heated regions, it is reasonable that the turbulence, and hence the line width, is considerably greater than in the quiescent cloud material, which also weakens the absorption per hydrogen atom.

As pointed out by Wolfire et al. (1993), the microturbulent model has difficulty in reproducing CO 1–0 line profiles. Another scenario is clumpy cloud models with macroturbulence. The difficulty with such models is that the observed line profiles are usually very smooth, which is hard to reproduce by a clumpy structure. It would be very interesting to see the predictions of PDR models and radiative transfer calculations with numerous tiny clumps.

7. DISCUSSION

Through observations of HINSA, we have identified cold atomic hydrogen associated with molecular clouds. A detailed explanation of HINSA and related molecular species would require comprehensive models, which may involve PDR, clumpy structure, gas and grain surface chemistry (Ruffle & Herbst 2000), and possibly other effects such as turbulent diffusion (Wollcy et al. 2002). An accurate determination of the abundance of cold H I and its spatial distribution thus constitutes a severe test of the chemistry and physics of "molecular" clouds.

A steady state calculation using the standard cosmic-ray rate and H$_2$ formation rate is shown to produce approximately the amount of cold H I observed. The data do suggest, however, that there may be a need for modest additional sources of atomic hydrogen in cold molecular regions.

The simple steady state model may not be an accurate or complete picture, however; with improved confidence in the H$_2$ formation rate, the H I fractional abundance we have observed can be used to put an upper age limit on these clouds. The question of whether the H$_2$ formation rate does slow down in dense cores can be answered by observations at higher spatial resolution (<1'), which will either identify HINSA features correlated with high-density tracers or show HINSA to be smooth on such scales.

HINSA traces a different population of neutral hydrogen from that constituting the warm H I halos also associated with molecular clouds (Andersson, Wannier, & Morris 1991). The H I halos are mostly seen by virtue of the enhancement of H I emission around molecular clouds. Statistically, the H I emission maxima have been shown to lie outside the clouds as defined by their CO emission (Wannier et al. 1991). Such halos have to be warm to be seen in H I emission with the Galactic background. In fact, the absorption measurements against continuum sources place the halo temperature around B5 to be 70 K (Andersson, Roger, & Wannier 1992), well above the temperatures of HINSA. H I halos are also shown to be much more spatially extended than the CO emission (Andersson et al. 1991). This is also in contrast with our observations of HINSA, which

---

4 This is by no means a new result; e.g., Solomon & Werner (1971) showed that a constant $n_1$ was to be expected, although their value was more than an order of magnitude larger as a result of the large value of the cosmic-ray ionization rate that they adopted.
place cold H i inside CO clouds, a region of size between those characteristic of C\(^{18}\)O and 13CO emission.

8. CONCLUSIONS
We have surveyed 31 dark clouds using Arecibo, FCRAO, and SWAS. The analysis of these data shows the following:

1. The 21 cm H i narrow self-absorption (having line width smaller than that of the corresponding CO emission) is a widespread phenomenon, detected in \(\sim 77\%\) of our sample of dark clouds in the Taurus/Perseus region. We use the term HINSA to distinguish the narrow absorption definitely caused by molecular cooling from broader absorption features seen in other surveys of H i throughout the Galaxy.

2. The atomic hydrogen producing the HINSA absorption has significant column density with \(N(\text{HINSA}) \sim 7 \times 10^{18}\) cm\(^{-2}\).

3. The gas responsible for the HINSA is at low temperatures, between 10 and 25 K. Some sources (L1521E, L1512, L1523) must be thermalized at temperatures close to or lower than 10 K.

4. The nonthermal line width of HINSA is comparable to the line width of 13CO, only slightly larger than that of C\(^{18}\)O, and smaller than those of CO or C i. This suggests that HINSA is produced by cold atomic hydrogen in regions of moderate extinctions with \(A_v\) larger than a few.

5. In the maps of L1544, HINSA is morphologically similar to C\(^{18}\)O.

6. The low temperature, the absence of increased absorption at cloud edges, and the narrow line width of HINSA suggest that the atomic hydrogen producing HINSA is mixed with the gas in cold, well-shielded regions of molecular clouds.

The National Astronomy and Ionosphere Center is operated by Cornell University under a Cooperative Agreement with the National Science Foundation. The Five College Radio Astronomy Observatory is supported by NSF grant AST 97-25951. SWAS operations are supported by NASA contract NAS 5-30702. We thank M. Tafalla for letting us use his C\(^{18}\)O data on L1544. Numerous discussions with P. Myers and F. Bensch provided us with valuable insights. We gratefully acknowledge T. Bania for pointing out important references. We thank X. Zhuo for her kind help with illustrations and the anonymous referee for a number of suggestions that helped improve the paper.

REFERENCES

Allison, A. C., & Dalgarno, A. 1969, ApJ, 158, 423
Andersson, B.-G., Roger, R. S., & Wannier, P. G. 1992, A&A, 260, 355
Andersson, B.-G., Wannier, P. G., & Morris, M. 1991, ApJ, 366, 464

Baker, P. L., & Burton, W. B. 1979, A&AS, 35, 129
Bania, T. M., & Lockman, F. J. 1984, ApJS, 54, 513
Batrla, W., Wilson, T. L., & Rahe, J. 1981, A&A, 96, 202
Buch, V., & Zhang, Q. 1991, ApJ, 379, 647
Burton, W. B., Lizt, H. S., & Baker, P. L. 1978, ApJ, 219, L67
Cappa de Nicolau, C. E., & Poppel, W. G. L. 1991, A&AS, 88, 615
Caselli, P., & Myers, P. C. 1995, ApJ, 446, 665
Caselli, P., Walmsley, C. M., Terzić, R., & Herbst, E. 1998b, ApJ, 499, 234
Caselli, P., Walmsley, C. M., Zucconi, A., Tafalla, M., Dore, L., & Myers, P. C. 2002, ApJ, 565, 344

Chieze, J.-P., & Pineda des Forêt, G. 2002, ApJ, 575, L29
Field, G. B. 1958, Proc. IRE, 46, 240
Frerking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590

Gibson, S. J., Taylor, A. R., Higgs, L. A., & Dewdney, P. E. 2000, ApJ, 538, L91

Goodman, A. A., & Heiles, C. 1994, ApJ, 424, 208
Heiles, C. 2001, ApJ, 551, L105

Hollenbach, D., & Salpeter, E. E. 1970, J. Chem. Phys., 53, 79

1971, ApJ, 163, 155

Hollenbach, D. J., Werner, M. W., & Salpeter, E. E. 1971, ApJ, 163, 165
Huang, M., et al. 1999, ApJ, 517, 282
Jackson, J. M., Bania, T. M., Simon, R., Kolpak, M., Clemens, D. P., & Heyer, M. 2002, ApJ, 566, L81
Jura, M. 1975, ApJ, 197, 575
Knapp, G. R. 1974, AJ, 79, 527
Kraemer, K. E., Jackson, J. M., & Lane, A. P. 1998, ApJ, 503, 785
Kuchar, T. A., & Bania, T. M. 1994, ApJ, 436, 117

 Larson, R. B. 1981, MNRS, 194, 809
Lee, C. W., & Myers, P. C. 1999, ApJS, 121, 233
Levinson, F. H., & Brown, R. L. 1980, ApJ, 242, 416
Liu, D. C., Keene, J., Phillips, T. G., Schilke, P., Werner, M. W., & Zmuidzinas, J. 2001, ApJ, 561, 823

Liseau, R., et al. 1999, A&A, 344, 342
Lockman, F. J. 1984, ApJ, 283, 90
Lynds, B. T. 1962, ApJS, 7, 1

McCutcheon, W. H., Shiner, W. L., & Booth, R. S. 1978, MNRS, 185, 755
Montgomery, A. S., Bates, B., & Davies, R. D. 1993, MNRS, 273, 449
Myers, P. C., Ho, P. T. P., Schneps, M. H., Chin, G., Pankonin, V., & Winnberg, A. 1978, ApJ, 220, 864
Phillips, T. G., Huggins, P. J., Kuiper, T. B. H., & Miller, R. E. 1980, ApJ, 238, L103
Plume, R., et al. 2000, ApJ, 539, L133
Poppel, W. G. L., Rohlf, K., & Celnik, W. 1983, A&A, 126, 152
Pratap, P., Dickens, J. E., Snell, R. L., Miralles, M. P., Bergin, E. A., Irvine, W. M., & Schloerb, F. P. 1997, ApJ, 486, 862

Purcell, E. M., & Field, G. B. 1956, ApJ, 124, 542
Riegel, K. W., & Crutcher, R. M. 1972, A&A, 18, 55
Ruffe, D. P., & Herbst, E. 2000, MNRS, 319, 837
Saito, T., Ohtani, H., & Tomita, Y. 1981, PASJ, 33, 327

Shepherd, W. A., & Wilson, T. L. 1981, A&A, 101, 72
Snell, R. L. 1981, ApJS, 45, 121
Solomon, P. M., & Werner, M. W. 1971, ApJ, 165, 41
Tafalla, M., Mardones, D., Myers, P. C., Caselli, P., Bachiller, R., & Benson, J. P. 1998, ApJ, 504, 900
Turner, B. E., & Heiles, C. 1971, ApJ, 170, 453
van der Werf, P. P., Dewdney, P. E., Goss, W. M., & van den Bout, P. A. 1989, A&A, 216, 215
van der Werf, P. P., Goss, W. M., & van den Bout, P. A. 1988, A&A, 201, 311
Wannier, P. G., Licht, S. M., & Douglass, P. -G., & Morris, M. 1991, ApJ, 75, 987
Wannier, P. G., Licht, S. M., & Morris, M. 1981, ApJ, 268, 727

Ward-Thompson, D., Scott, P. F., Hills, R. E., & André, P. 1994, MNRS, 268, 276
Wild, J. P. 1952, ApJ, 115, 206
Willacy, K., Langer, W. D., & Allen, M. 2002, ApJ, 573, L119
Wilson, T. L., & Minn, Y. K. 1977, A&A, 54, 933

Wolfire, M. G., Hollenbach, D., & Tielens, A. G. M. 1993, ApJ, 402, 195
Young, J. S., Goldsmith, P. F., Langer, W. D., Wilson, R. W., & Carlson, E. R. 1982, ApJ, 261, 513