THE TRANSITION FROM ATOMIC TO MOLECULAR HYDROGEN IN INTERSTELLAR CLOUDS: 21 cm SIGNATURE OF THE EVOLUTION OF COLD ATOMIC HYDROGEN IN DENSE CLOUDS

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ABSTRACT

We have investigated the timescale for formation of molecular clouds by examining the conversion of H\textsc{i} to H\textsc{2} using a time-dependent model with H\textsc{2} photodissociation including self-shielding. H\textsc{2} formation on dust grains and cosmic-ray destruction are also included in one-dimensional model slab clouds that incorporate time-independent density and temperature distributions. We calculate 21 cm spectral line profiles seen in absorption against a background provided by general Galactic H\textsc{i} emission and compare the model spectra with H\textsc{i} narrow self-absorption (HINSA) profiles absorbed in a number of nearby molecular clouds. The time evolution of the H\textsc{i} and H\textsc{2} densities is dramatic, with the atomic hydrogen disappearing in a wave propagating from the central, denser regions, which have a shorter H\textsc{2} formation timescales, to the edges, where the density is lower and the timescales for H\textsc{2} formation longer. The model 21 cm spectra are characterized by very strong absorption at early times. Emission at early times produced by the warm edges of the cloud is difficult to separate from variations in the background spectrum, when the background temperature is low. The minimum time for cloud evolution based on the model spectra is set by the requirement that most of the H\textsc{i} in the outer portions of the cloud be removed. The characteristic time that has elapsed since cloud compression and initiation of the H\textsc{i} → H\textsc{2} conversion is a few \(10^{14}\) s, or \(\approx 10^7\) yr. This sets a minimum time for the age of these molecular clouds and thus for star formation that may take place within them.

Subject headings: ISM: atoms — ISM: evolution — ISM: individual (hydrogen) — ISM: molecules

1. INTRODUCTION

It is generally accepted that stars form from dense interstellar clouds in which hydrogen and most other elements are largely in molecular form. Studies of the later phases of star formation have progressed rapidly thanks to improved instrumental angular resolution, sensitivity, and frequency coverage, but the formation of molecular clouds themselves has been rather neglected of late, and this remains a major poorly understood step in the overall process of converting interstellar material into young stars. A variety of processes have been postulated to explain molecular cloud formation, many of which are reviewed by Elmegreen (1991). The majority of the scenarios for forming molecular clouds (whether massive giant molecular clouds [GMCs] or less massive dark clouds) involve compressing and increasing the column density of previously atomic material, thus reducing the photodestruction rate of H\textsc{2} (and other) molecules, and thus leading to the transformation from atomic to predominantly molecular form.

It is of considerable interest to determine whether there is any signature in molecular clouds of their past history as primarily atomic objects and to examine whether any information can be extracted about their evolutionary timescale. It was pointed out more than 30 years ago by Shu (1973) that the atomic hydrogen in molecular clouds may be a residue of their previous state and, as such, could be used to place an upper limit on their age of \(10^7\) yr.

One powerful tool for studying atomic hydrogen is absorption of radiation from a distant source by relatively cool H\textsc{i} in a nearby cloud. If the background radiation is itself H\textsc{i} emission, the foreground cloud is said to be producing H\textsc{i} self absorption (HISA). The literature on HISA is currently so large that a reasonably complete listing of papers would be very difficult and probably not immediately helpful. In previous papers (Li & Goldsmith 2003, hereafter Paper I; Goldsmith & Li 2005, hereafter Paper II) we referenced a number of papers that have focused particularly on the issue of H\textsc{i} narrow self-absorption, as this is directly relevant to the issue of the relationship of atomic and molecular clouds. Some early papers that were not referenced in Paper I or Paper II but should have been are those of Heeschen (1955), Radhakrishnan (1960), and Sancisi & Wesselius (1970). In addition to the references cited in Papers I and II, the relationship of atomic gas traced through H\textsc{i} absorption and molecular gas traced by carbon monoxide emission was studied by Sato & Fukui (1978), Liszt et al. (1981), Peters & Bash (1987), Hasegawa et al. (1983), Garwood & Dickey (1989), and Feldt & Green (1993).

Observations of both the atomic and molecular constituents of dense clouds have improved considerably in recent years (e.g., Paper I). These authors found that dense condensations (or cores) within molecular clouds contain significant amounts of atomic hydrogen, which in terms of line velocity, line width, and line depth, could be identified as coming from cold (\(T \leq 20\) K) regions, which are well shielded from the interstellar radiation field. The term H\textsc{i} narrow self-absorption (HINSA) was used to describe this component of atomic hydrogen in the interstellar medium (ISM), with the narrow being defined as having nonthermal line width no larger than that of accompanying 12CO, whose presence is required for HINSA. In Figure 1 we show some examples of HINSA spectra in relatively nearby dark cloud cores. Not included are the corresponding spectra of molecular emission. The velocities and nonthermal line widths of OH, 13CO, and C18O agree very closely with those determined for HINSA features.

A subsequent paper (Goldsmith & Li 2005) used detailed observations of the distribution and quantity of cold H\textsc{i} within relatively well-isolated molecular cores to determine their ages to be between \(3 \times 10^5\) and \(\geq 3 \times 10^7\) yr. In this context “age” refers to the time since the clouds, initially having hydrogen completely

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in atomic form due to rapid destruction of molecular hydrogen by photodestruction, had this source of H₂ destruction instantaneously turned off and were allowed to evolve, with the hydrogen gradually becoming molecular. Destruction of H₂ by cosmic rays maintains a small residual amount of atomic hydrogen at times long after the beginning of this evolutionary process.

The clouds studied in Paper II have an atomic hydrogen abundance slightly exceeding that predicted to characterize steady state conditions. The age that is derived (being close to the characteristic time to achieve a steady state $H_1/H_2$ ratio) is indicative of a relatively long lifetime for these objects, and thus has significant potential implications for understanding the overall process of molecular cloud and star formation. It is thus worthwhile to examine cloud evolution in more detail, trying to take into account the critical physical processes that determine the rate of conversion of atomic to molecular hydrogen. This is a complex issue, particularly when one considers that the line width, temperature, density, and fractional abundance variations all play a role in determining the observed line profiles.

In the present work we take one step toward the ultimate goal of developing a complete model for the evolution of 21 cm line profiles in evolving molecular clouds by employing a simplified model in which we do not include any dynamical evolution, considering a cloud to have fixed temperature and density profiles that are functions only of the distance from the surface of the cloud. These profiles are chosen to mimic those obtained in other studies for a steady state solution including chemistry and thermal balance. We model the cloud as a one-sided slab, taking into account H₂ destruction by the interstellar radiation field together with shielding by dust and the critical process of self-shielding. Cosmic-ray destruction of H₂ occurs throughout the cloud, as does H₂ formation on grain surfaces, parameterized in a conventional manner. Thus, our results predict only approximately what may be happening early in the evolution of the system and are most

![Figure 1: H₁ spectra of four nearby dark cloud cores taken with the Arecibo Observatory 305 m telescope. The data have been corrected for the main beam efficiency of 0.60. The spectra are at the central position of each source, with coordinates given in Papers I and II. The rms statistical noise in these spectra is approximately 0.09 K (5 minute on-source integration with 0.382 kHz channel bandwidth) off the H₁ emission features, and 2–3 times this level on the lines. The noise is less than 1% of the emission intensity and, thus, 30 times smaller than even "weak" HINSA features. The statistical noise is barely visible on the flat-topped portion of the L.1544 spectrum. The cold H₁ coextensive with the molecular component of each cloud core produces the narrow absorption feature seen in each spectrum. The absorption profile in TMC1 CP comprises two (marginally resolved) velocity components, which together significantly broaden the observed line profile. Various complex spectral structure with less rapid variation of intensity as a function of velocity is visible in some sources, including in the 4–14 km s⁻¹ velocity range in B227. Its origin is much less certain than that of the sharp, narrow absorption, and may be a combination of variations in the temperature of the background emission gas and absorption by intervening atomic gas with $T \lesssim 80$ K.]
relevant for interpreting the later stages of the atomic to molecular conversion process.

We describe our model for cloud structure and evolution in § 2. We discuss the relevant molecular and atomic processes and present results for the distribution of atomic and molecular gas in two different cloud models in § 3. In § 4 we present 21 cm spectral line profiles for model clouds observed in absorption, and we discuss the implications of our results in § 5.

2. CLOUD MODEL WITH TIME-DEPENDENT H I AND H₂ ABUNDANCES

The transition from the atomic to molecular phase of the ISM may have, as discussed above, a variety of triggers. While star formation occurs in molecular clouds located throughout the Milky Way, the rate of star formation is observed to be enhanced in spiral arms (e.g., Seigar & James 2002). The common feature is typically a rapid compression with accompanying increase in extinction, as described by Elmegreen (1996). This has led to a number of studies in which atomic clouds evolving toward a molecular state have been tentatively identified (Minter et al. 2001; Gibson et al. 2005; Kavars et al. 2005). Given the general belief that molecular clouds are finite-lived structures, an important initiator of cloud compression and the process of atomic to molecular hydrogen conversion is shocks produced by Galactic spiral density waves, discussed by Shu et al. (1972) and recently modeled by Dobbs et al. (2006). Outflows from young stars and shocks from expanding H II regions and supernovae have also been put forth as the agents responsible for what is sometimes called triggered or stimulated star formation (Elmegreen 1992; Patel et al. 1998; Karr & Martin 2003; Hosokawa & Inutsuka 2006). Cloud collisions may drive compressive shocks into atomic clouds that can result in conversion of material to molecular form (e.g., Bergin et al. 2004). Compression due to shocks from colliding flows has been investigated extensively in recent years, including the studies of Hennebelle & Pérault (1999, 2000), Audit & Hennebelle (2005), and Vázquez-Semadeni et al. (2006). Instabilities may then result in the formation of “individual” molecular clouds (Koyama & Inutsuka 2000, 2002), but these processes may not always result in gravitationally bound regions.

While it would be desirable to follow the post-shock evolution of an interstellar cloud including dynamics, chemistry, and thermal balance, we here restrict ourselves to the highly idealized situation of a cloud that is assumed at $t = 0$ to be characterized by its steady state temperature and density distributions, and follow only the evolution of atomic to molecular hydrogen under these conditions. Although this represents a significant approximation, in most models the cloud compression is relatively rapid. The cooling time is the ratio of the thermal energy per unit volume to the cooling rate per unit volume,

$$
\tau_{\text{cool}} = \frac{3/2n kT}{\Delta},
$$

where $n$ is the density and $\Delta$ is the cooling rate in ergs cm$^{-3}$ s$^{-1}$. The dominant coolants for an evolving cloud change significantly as a function of time. Early on, the cloud will be largely atomic and ionic in composition and the primary coolant will be

An alternative view is that large molecular clouds are assembled from pre-existing small molecular clouds, as discussed by Pringle et al. (2001).

In Bergin et al. (2004) the time for shock compression is $\lesssim 1$ million yr for shock velocities greater than 15 km s$^{-1}$, but approaches 10 million yr for the lowest shock velocity considered, 10 km s$^{-1}$.

### TABLE 1

| Parameter of Both Cloud Models | Value |
|--------------------------------|-------|
| Total proton column density    | $1.0 \times 10^{23}$ cm$^{-2}$ |
| Central temperature            | 10 K  |
| Central H I thermal line width | $0.29$ km s$^{-1}$ |
| Central total line width       | $0.45$ km s$^{-1}$ |
| Edge proton density            | 103 cm$^{-3}$ |
| Edge temperature               | 58 K  |

$^a$ Values for one-sided slab; for a symmetric two-sided slab model the total column density is $2.0 \times 10^{22}$ cm$^{-2}$, corresponding to visual extinction of 10 mag.

$^b$ One-dimensional rms line width.

$^c$ One-dimensional rms combined thermal and nonthermal line width.

While atomic hydrogen (H I), while as one moves to regions with at least a few magnitudes of extinction, once molecules have had time to form, CO will dominate the cooling (see Stahler & Palla [2004, p. 200] for atomic and ionic cooling rates and Goldsmith [2001] for molecular rates). The cooling rate per unit volume is highest at early times, and the cooling time is shortest. The cooling rate drops steadily as the cloud cools and the characteristic cooling time lengthens. For a representative situation in a cloud well evolved toward molecular steady state (density $= 10^2$ cm$^{-3}$ and $T = 30$ K), the molecular cooling rate is $1.5 \times 10^{-23}$ ergs cm$^{-3}$ s$^{-1}$ (Goldsmith 2001) and $\tau_{\text{cool}} \approx 10^4$ yr. This is still far shorter than the H I $\rightarrow$ H$_2$ conversion time. Thus, assuming that the cloud immediately attains its steady state density and temperature configuration should be sufficient for predicting the H I line profiles at all but the earliest times.

An interesting aspect of the cloud thermal evolution is the heating provided by the initial formation of H$_2$. As discussed by Flower & Pineau des Forêts (1990), this results in a secondary temperature plateau following the initial compression and cooling of the cloud. The H$_2$ formation heating phase ends when the steady state abundance of H$_2$ attains; the subsequent heat input from H$_2$ formation is a part of the cosmic-ray heating rate, which provides the steady state gas temperature of $\pm 10$ K in well-shielded regions. However, the H$_2$ heating phase has a duration given by the H I $\rightarrow$ H$_2$ conversion time $\tau_{\text{H I} \rightarrow \text{H}_2} = 2.6 \times 10^9/\eta_0$ yr, where $\eta_0$ is the proton density in cm$^{-3}$ (Paper II). The cooling time is thus very short compared to the H$_2$ heating phase, so once the latter is completed, the final cool down is very rapid. Given the much more rapid conversion of H I to H$_2$ in the central portion of the cloud than at the edge, and the accompanying more rapid subsequent cooling, the evolving cloud will thus assume a cold-core/warm-edge configuration within $<10^3$ yr, although the temperature distribution will continue to evolve, especially in the outer portion of the cloud.

In this paper we do not solve for temperature and density profiles. Rather, these are chosen to follow those describing a slab illuminated on one side by the standard interstellar radiation field (Le Bourlot et al. 1993). That cloud model includes photoelectric and cosmic-ray heating and atomic fine-structure and molecular rotational transition cooling. We have two model clouds that are described in Tables 1 and 2. The parameters of these clouds are chosen to reproduce those of the clouds studied in Paper II, while the density structure mimics that typically found for small dust clouds (Arquilla & Goldsmith 1985; Yun & Clemens 1991; Strafella et al. 2001). Both models are characterized by a proton density density equal to $10^{22}$ cm$^{-2}$; the difference is basically the central density, and since the form of the density variation is the same, the sizes of the clouds differ as indicated in Table 2.
The proton density and temperature for model 2 as a function of proton column density measured from the outside of the cloud are shown in Figure 2. A more realistic cloud seen in absorption against the Galactic background comprises a back-to-back pair of such slabs. The simplification in calculating the photo-dissociation rate by considering only photons incident from a single boundary should produce only a small error in the H$_2$ photodissociation rate, since this is either negligible or dominated by the photon flux from the nearer boundary. The double-slab model is used to calculate the spectra presented in § 4.

The density, temperature, and column density profiles as a function of distance from the center of the cloud are shown in Figures 3 and 4. Note that since these are one-sided slabs, the equivalent column density for a two-sided cloud would be double this value, corresponding to $N_0 = 2 \times 10^{22}$ cm$^{-2}$ and a total visual extinction of 10 mag. In the following discussion we use the term “radius” to describe the distance from the high-extinction boundary of the one-sided slab, since this would be the center of the symmetric double slab cloud model. The density profiles for both models have a constant density core surrounded by an approximately $r^{-2}$ envelope. As well as reproducing the observational results described above, this form is similar to the predictions of the isothermal Bonner-Ebert sphere, as given by the approximate solution of Tafalla et al. (2004).

The line width is a function of position within the cloud due to variation of the kinetic temperature, which is shown in Figures 3 and 4. In addition, we assume that there is a nonthermal contribution to the line width varying as

$$\delta v_{\text{nthrm}}(r) = \delta v_{\text{nthrm}}(0)(r/r_0)^\beta,$$

where the line widths are one-dimensional rms line widths, $\delta v_{\text{nthrm}}(0)$ is the nonthermal line width at the center of the cloud, $r$ is the distance from the center of the cloud, and $\beta$ is a parameter that we have set to 0.4. This relationship has been adopted to reproduce the generally observed trend of line width increasing with cloud size (e.g., Goodman et al. 1993). The nonthermal line width is 0.34 km s$^{-1}$ at the center of the cloud, which, as indicated in Table 1, when added in quadrature to the thermal line width at 10 K results in a rms line width of 0.45 km s$^{-1}$. These line widths enter very weakly into the determination of the self-shielding rates for H$_2$ as well as directly into the radiative transfer in the 21 cm line.

### 3. TIME-DEPENDENT CALCULATION OF H$_1$ AND H$_2$ DENSITIES

In order to calculate the time-dependent evolution of the atomic and molecular hydrogen densities, we adopt the purely rate-equation approach described in Paper II. The intent is to include the key processes that determine the abundance of atomic and molecular hydrogen in a cloud model. In addition to cosmic-ray destruction, we include photodissociation of H$_2$, together with self-shielding. We use simplified model clouds that have a plausible density variation in only one dimension. The physical conditions within the cloud are fixed; only the abundances of atomic and molecular hydrogen vary with time. This allows us to calculate, in particular, the H$_1$ density as a function of time and position within the cloud, which is the basic input for the calculation of spectral line profiles described in § 4.

We adopt the rate derived in Paper II for H$_2$ formation on grains, $k'_{\text{H}_2} = 1.2 \times 10^{-17}(T/10\text{ K})^{0.5}$ cm$^3$ s$^{-1}$, and the H$_2$ cosmic-ray destruction rate $\zeta_{\text{CR}} = 5.2 \times 10^{-17}$ s$^{-1}$. The position-dependent photodestruction of H$_2$ is of critical importance in determining the distribution of the species throughout the cloud. To treat this, we use the shielding function derived by Draine & Bertoldi (1996) and given as their equation (37). We adopt an unshielded photodissociation rate $\zeta_{\text{diss}}(0)$ equal to $1.0 \times 10^{-11}$ s$^{-1}$. This is reduced from what may be considered the “standard” value by about a factor of 3 to account for the fact that the type of dense clouds we are modeling are typically embedded in more tenuous extended material, which will provide some shielding. The results of the calculation do not depend sensitively on this value in any case, as the shielding parameter has to drop to below $10^{-4}$ to reduce the fractional abundance of atomic hydrogen significantly so that a

### Table 2

**Model-Specific Parameters**

| Model | $n_0$(central) | Size$^a$ | Size$^b$ | Edge Line Width$^b$ | Sphericalized Mass$^c$ |
|-------|----------------|---------|---------|-------------------|-----------------------|
| 1     | $1.6 \times 10^4$ | $4.5 \times 10^{18}$ | 1.46    | 1.03              | 108                   |
| 2     | $7.4 \times 10^4$  | $2.8 \times 10^{18}$ | 0.91    | 0.94              | 20                    |

$^a$ Distance from center to edge of one-sided slab cloud.

$^b$ One-dimensional rms combined thermal and nonthermal line width.

$^c$ Mass of spherical cloud having same density structure as slab used in the present work.

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5 The H$_1$ column density is converted to reddening using the result of Bohlin et al. (1978) together with the average total to selective extinction ratio determined by Wegner (1993). There is relatively small scatter around the mean value quoted in the latter study (3.1 ± 0.05), but $R_e$ shows significant variations relative to this mean value when studied in dense regions, so that the conversion of proton density measured from the outside of the cloud is used to calculate the spectra presented in § 4.

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**Fig. 2.—Variation of model 2 cloud parameters as function of displacement from the edge of the cloud, measured in terms of the proton column density. This model has a higher central density and a smaller physical size than does model 1. The full cloud consists of two such slabs back-to-back, with hot edges and a cold center. The central region is at a temperature of 10 K; the temperature rises when dust attenuation of the external radiation field drops resulting in the photoelectric heating rate exceeding that from cosmic rays (see Le Bourlot et al. [1993] for details).**
large change in the unshielded value $\zeta_{\text{diss}}(0)$ produces only a very slight shift in the location of a specific value of $n(\text{H})/n(\text{H}_2)$.

The rate of change of the H$_2$ density is the difference between the formation and destruction rates. The former is proportional to the product of the atomic hydrogen density and the grain density (and thus the total proton density). The molecular destruction rate is proportional to the H$_2$ density, with which we can write

$$\frac{dn_{\text{H}_2}}{dt} = k_{\text{H}_2}^f n_{\text{H}_1} n_0 - \zeta_{\text{H}_2} n_{\text{H}_2},$$

(3)

with the total proton density defined by

$$n_0 = n_{\text{H}_1} + 2n_{\text{H}_2},$$

(4)

and the total dissociation rate $\zeta_{\text{H}_2}$ equal to the sum of the cosmic-ray dissociation rate $\zeta_{\text{CR}}$ and the photodissociation rate,$^6$

$$\zeta_{\text{H}_2} = \zeta_{\text{CR}} + \zeta_{\text{diss}}.$$  

(5)

The photodissociation rate $\zeta_{\text{diss}}$ is given by equation (40) of Draine & Bertoldi (1996), which includes both self-shielding and attenuation of the dissociating radiation field by dust. In addition to the value of $\zeta_{\text{diss}}(0)$ given above, we have adopted a ratio $\varphi(1000 \text{ Å})/A_v = 5.5$, following discussion in Draine & Bertoldi (1996).

The cloud was divided into 40 layers, and equation (3) was solved using the routine odeint from Press et al. (1992) with the accuracy parameter set to $2 \times 10^{-6}$. For each time step the column density of H$_2$ between each layer and the surface of the cloud was calculated and used to determine the contribution of the H$_2$ self-shielding to the shielding function.$^6$ There were no problems with the behavior of the solution; a very low level of numerical noise, with fluctuations in the atomic hydrogen density of $\pm 5\%$ in the steady state solution for the densest portions of the cloud, with $n_{\text{H}_1}$, approximately equal to $10^{-4} n_0$, was sometimes visible.

$^6$ In principle, the self-shielding depends on the line width (the $b$-parameter employed by Draine & Bertoldi 1996). The combination of thermal and nonthermal line width in the models used here changes by a factor somewhat greater than 2 from cloud center to edge. However, the line width has an appreciable effect on the self-shielding only for H$_2$ column densities $\lesssim 10^{18} \text{ cm}^{-2}$. Even in the outermost layer, for times after few $\times 10^{14}$ s, the self-shielding is essentially independent of the line width in the region. Our use of the line width within a given layer to calculate the self-shielding by H$_2$ external to that layer thus results in a negligible error.
The behavior of the atomic hydrogen density for the two model clouds is shown in Figures 5 and 6. There is reason to be cautious about the detailed behavior at the earliest of the times shown here due to the approximation made in this model of an instantaneous evolution to centrally condensed structure with high central density and low temperature. Compared to a more realistic model in which the temperature decreases as the density increases, there are two effects: (1) underestimating the temperature underestimates the H$_2$ formation rate, which varies as $T^{0.5}$, and (2), overestimating the density overestimates the H$_2$ formation rate, which varies as $n_0$ (e.g., Paper II). These two effects will to a significant extent cancel, but it is still possible that we are somewhat overestimating the rate of conversion of H$_i$ to H$_2$, since it is likely that effect (2) is greater than effect (1).

With this modest caveat, we see the same quite striking behavior in the evolution of both high- and low-density clouds. Some of the highlights are as follows.

1. There is a wave of H$_2$ formation and accompanying disappearance of atomic hydrogen, which begins in the core of the cloud and propagates outward.

2. The dependence of the H$_i \rightarrow$ H$_2$ conversion timescale on density results in the core of H$_i$ density dropping too close to its steady state value while the situation in the outer parts of the cloud has hardly evolved at all.

3. The cloud core reaches its steady state value of $n$(H$_i$) after $\approx 3 \times 10^{13}$ s ($1 \times 10^6$ yr) for the low-density cloud (model 1) and after $\approx 1 \times 10^{14}$ s ($3 \times 10^5$ yr) for the high-density cloud (model 2).

4. When the entire cloud has reached a steady state situation, there is a substantial core with $N_0 \geq 10^{22}$ cm$^{-2}$ that has H$_i$ density equal to that defined by the equilibrium between H$_2$ destruction by cosmic rays and formation on grain surfaces.

For a region in which $k_{\nu} n_0 \gg \zeta_{H_2}$, the rate of H$_2$ formation exceeds that of H$_2$ destruction until a steady state is reached in which $n$(H$_i$) $\ll n$(H$_2$). From equations (3) and (4), this steady state H$_i$ density is given by

$$n_{i,H} = \frac{\zeta_{H_2}}{2 k_{H_2}}. \quad (6)$$

For the central region of the cloud, the attenuation of the ultraviolet (UV) radiation field provided by the dust alone is $f_{\text{shield}} = e^{-27.5}$ [for $N_0 = 10^{22}$ cm$^{-2}$, $A_V = 5$ mag, and $\tau(1000 \text{ Å}) = 27.5$]. This is sufficient to reduce the photodissociation rate to a level well below that from cosmic rays, even for a purely atomic cloud with no H$_2$ self-shielding. Thus, the central H$_i$ density drops to a steady state value

$$n^*_{i,H} = \frac{\zeta_{CR}}{2 \lambda_{H_2}}. \quad (7)$$
which with the parameters given above is equal to 2 cm$^{-3}$, even while the outer portions of the cloud have far less H$_2$ and thus offer relatively little self-shielding for the inner regions until a relatively late time in the evolution of the cloud.

During the moderately early phase of cloud evolution, the H$^i$ volume density has a peak at a particular radius. This is a result of the interplay of the density, which is increasing as a function of distance from the cloud edge, and the conversion to molecular form, which occurs more rapidly in the inner portion of the cloud, as discussed above. At later times, the density of atomic hydrogen drops monotonically as function of distance from the cloud edge due to the increasing shielding by dust and by H$_2$ self-shielding.

In Figure 7 we show the variation of the fractional abundance of H$^i$ as a function of position within the cloud and of time. In steady state even the outermost layer of the model clouds has a significant amount of H$_2$, with $n_{H_2}/n_{H^i} \simeq 0.75$. This is a result of the very effective self-shielding of the H$_2$, especially for the very narrow line widths that we are dealing with here. For a column density of H$_2$ equal to $10^{19}$ cm$^{-2}$, the self-shielding function has dropped to a value $\approx 2 \times 10^{-4}$, while the dust-shielding function is essentially unity. This is sufficient to reduce the H$_2$ photodestruction rate to $\approx 2 \times 10^{-15}$ s$^{-1}$, comparable to the formation rate at a proton density equal to $10^2$ cm$^{-3}$, if $n_{H_2} \approx n_{H^i}$.

The drop in the fractional abundance of atomic hydrogen in the outer layer of the cloud as the cloud evolves is only a factor of a few, very modest compared to that in the well-shielded inner portion of the cloud, where the abundance drops by a factor of order $10^4$. The timescale for H$^i \rightarrow$ H$_2$ conversion (see Paper II for additional details) is given by

$$
\tau = \frac{1}{2k_{H_2} n_0 + \zeta_{H_2}}.
$$

As indicated in equation (5), the total H$_2$ destruction rate is the sum of the cosmic-ray and photodestruction rates. Photodestruction, even with self-shielding, is the dominant destruction pathway for H$_2$ in the outer portion of the cloud and, being comparable to the formation rate, contributes modestly to the timescale, which for our model cloud is $\tau_{edge} = 1.3 \times 10^{14}$ s = $4.1 \times 10^6$ yr. In the central region of the cloud the timescale is determined entirely by the first term in the denominator of equation (8), and for model 1 with $n_0 = 1.6 \times 10^4$ cm$^{-3}$, we find that $\tau_{center} = 2.6 \times 10^{12}$ s = $0.83 \times 10^5$ yr. In the central region of the cloud, a time
approximately equal to \(10 \tau_{\text{center}}\) is required to reach steady state due to the large reduction in \(n_{\text{H}}\), that takes place, while at the cloud edge, only about \(2 \tau_{\text{edge}}\) are required to approach steady state. These different timescales and times to reach steady state play critical roles in determining the evolution of the \(\text{H}_i\) line profiles, which we discuss in \(\S\) 4.

The evolution of the column densities of atomic and molecular hydrogen for the two cloud models is shown in Figure 8. For model 1 with \(n_0(\text{central}) = 1.6 \times 10^4 \text{ cm}^{-3}\) the \(\text{H}_i\) and \(\text{H}_2\) column densities are equal at time \(t = 7 \times 10^{12} \text{ s} (2.2 \times 10^3 \text{ yr})\), but this situation is reached in only \(1.7 \times 10^{12} \text{ s} (5.4 \times 10^5 \text{ yr})\) for model 2 with \(n_0(\text{central}) = 7.4 \times 10^4 \text{ cm}^{-3}\). This essentially reflects the ratio of the central densities, which determines the overall timescale in the region of the cloud that is dominant in terms of number of protons. The \(\text{H}_i\) column density has fallen to within \(10\%\) of its final value in time \(t = 4 \times 10^{14} \text{ s} (1.3 \times 10^7 \text{ yr})\) for model 1 and \(3.9 \times 10^{14} \text{ s} (1.2 \times 10^7 \text{ yr})\) for model 2. These times are not very different, since the number densities in the outer regions of the two models are quite similar. It is in this region that the timescale for \(\text{H}_i\) to \(\text{H}_2\) conversion is longest, and hence it dominates the global timescale for this process.

The 2 order-of-magnitude difference in timescales is of considerable importance in appreciating the ability of 21 cm HINSA observations to determine or at least to set lower limits on the age of clouds in which the \(\text{H}_i\) abundance is very low. While the cold \(\text{H}_i\) in the dense, well-shielded cores dominates the narrow absorption lines characterizing HINSA, its presence can easily be confused or completely hidden by residual \(\text{H}_i\) in the outer regions of the cloud. Thus, as discussed further in \(\S\) 4, the timescale for the entire cloud must be considered when analyzing observations, not just the shorter timescale for the dense cloud core.

Table 3 gives the steady state global properties of \(\text{H}_i\) and other parameters of the model clouds. The clouds are predominantly molecular, with \(N_{\text{H}_i}/N_{\text{H}_2} = 0.007\) when the entire cloud is included. If we restrict ourselves to the cold \(\text{H}_i\), defined here as that having \(T \leq 12 \text{ K}\), there is some difference between the models, with \(N_{\text{H}_i}(T \leq 12 \text{ K})/N_{\text{H}_2}\) between 2 and \(2.6 \times 10^{-4}\). Additional insight into the steady state distribution of atomic hydrogen within a molecular cloud can be obtained from Figure 9, for a single-sided model 1 cloud; the \(\text{H}_i\) column density is \(3.9 \times 10^{19} \text{ cm}^{-2}\), the \(\text{H}_2\) column density is \(4.98 \times 10^{21} \text{ cm}^{-2}\).
while the total proton column density is $1.0 \times 10^{22} \text{ cm}^{-2}$. The integrated H\text{\textsc{i}} column density increases linearly with distance from the cloud center in the inner portion of the cloud; this is a result of the constant H\text{\textsc{i}} density, which results from the steady state high-density limit discussed above. The H\text{\textsc{i}} column density increases more rapidly as one includes the outer portion of the cloud, because the H\text{\textsc{i}} number density there increases rapidly due to the reduced shielding. Even so, approximately half the column density of atomic hydrogen is located in relatively cold regions at temperatures less than 30 K. This cold H\text{\textsc{i}} dominates the narrow absorption spectra due to its greater optical depth per atom resulting from low temperature and narrow line width, as discussed further in §4, and consistent with the results of Flynn et al. (2004). The results for model 2 are essentially the same, except that the total column density of atomic hydrogen is a factor $\approx 1.2$ lower due to the smaller cloud size.

4. 21 cm SPECTRA FROM EVOLVING CLOUDS

In calculating the H\text{\textsc{i}} spectral signature of our model cloud we make a number of simplifying assumptions. These include (1) there is a background H\text{\textsc{i}} emission source of specified brightness temperature and line width that is uniform over the antenna beam, (2) there is no H\text{\textsc{i}} between that source and the model cloud or between the model cloud and the observer, and (3) the model cloud is uniform over the two dimensions defining the antenna beam and varies only in the third, line-of-sight dimension. In the Rayleigh-Jeans limit and assuming that the level populations are in local thermodynamic equilibrium (LTE) at the kinetic temperature ($T_{\text{spin}} = T_{\text{kin}}$), we calculate the optical depth within each slab comprising the cloud, and solve the equation of radiative transfer in a stepwise fashion starting from the background. In order to be somewhat closer to the observations, all of the model spectra presented here are for double-sided clouds, which are two single-sided clouds discussed above combined into a slab cloud with two warm edges and a dense, cold central region. There are thus 80 layers in the double-sided cloud, with density, temperature, H\text{\textsc{i}} density, and line width defined in §2. The H\text{\textsc{i}} density in each layer for each of the time steps is stored and is used with the background line profile to calculate the optical depth and the emergent line profile as a function of time.

The background line intensity plays a critical role in many situations. This is a direct consequence of the fact that the outer layers of the cloud we are studying have temperature comparable to that of the background 21 cm emission. It is thus possible for the foreground cloud to add to the emission while the cold gas in its center simultaneously produces a narrow absorption feature. There

Fig. 7.—Fractional abundance of atomic hydrogen as a function of proton column density from the surface of model 1 cloud at times between $2 \times 10^{12}$ s ($6.4 \times 10^4$ yr) and $3 \times 10^{15}$ s ($1 \times 10^8$ yr). Top: Proton density as a function of position. Bottom: Ratio $n_{\text{H\text{\textsc{i}}}}/n_0$ as a function of position for different selected times during the evolution of the cloud.
are thus a large number of combinations of cloud models, times, and background emission. We here restrict ourselves to presenting representative results that (1) illustrate the range of spectra that can be produced and (2) focus on the time evolution of the H\textsubscript{i} narrow self-absorption features in order to constrain the time required to obtain results that are broadly consistent with observations.

### 4.1. General Results

In Figure 10 we show the results for a double-sided model 1 cloud at six different times. In this case, the background source is modeled as a line having peak temperature of 60 K and a full-width at half maximum (FWHM) line width of 30 km s\textsuperscript{-1}. The H\textsubscript{i} column density has fallen to within 10\% of its final value in time $t = 4 \times 10^{14}$ s (1.3 \times 10\textsuperscript{7} yr) for model 1 and $3.9 \times 10^{14}$ s (1.2 \times 10\textsuperscript{7} yr) for model 2.

**TABLE 3**

| Model | Total $N_{\text{H}_2}$ (cm\textsuperscript{-2}) | Total $N_{\text{H}_2}$ (cm\textsuperscript{-2}) | $N_{\text{H}_2}$ at $T \leq 12$ K (cm\textsuperscript{-2}) | $R(T \leq 12$ K)$^a$ (cm) | $R(A_v \leq 1$ mag)$^b$ (cm) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | $5.0 \times 10^{21}$ | $3.9 \times 10^{19}$ | $3.2 \times 10^{18}$ | $1.5 \times 10^{18}$ | $9.5 \times 10^{17}$ |
| 2     | $5.0 \times 10^{21}$ | $3.2 \times 10^{18}$ | $1.0 \times 10^{18}$ | $4.8 \times 10^{17}$ | $2.8 \times 10^{17}$ |

**Note.**—Clouds are one-sided slab clouds; all values are twice as large for more realistic double-sided slab models.

$^a$ Distance from center of cloud to the point where the temperature has risen from 10 to 12 K.

$^b$ Distance from center of cloud to the point where the visual extinction to cloud edge is equal to 1 mag.
The absorption profile is complicated by the temperature gradient within the foreground cloud. For example, at time equal to $3.9 \times 10^{13}$ s (1.2 $\times 10^6$ yr), the total H\textsc{i} column density through the cloud is $\approx 10^{21}$ cm$^{-2}$ and the peak optical depth $\approx 30$. At line center one sees into a layer close to the surface, where the temperature is relatively warm, with $T \approx 40$ K. As one moves off line center, the optical depth drops, and one sees the temperature deeper into the cloud, where the temperature is lower. The optical depth is equal to unity at velocity offsets of $\approx 1.6$ km s$^{-1}$, corresponding to a depth in the cloud at which $T = 25$ K. This defines the two sharp minima in the absorption spectrum. For larger velocity offsets, the absorbing line becomes increasingly optically thin, and the line profile joins that of the background emission.

The column density of H\textsc{i} in the cloud is sufficient for the line to remain optically thick until approximately $10^{14}$ s (3 $\times 10^6$ yr) have elapsed. After about $2 \times 10^{14}$ s (6.4 $\times 10^6$ yr), the column density of H\textsc{i} has dropped sufficiently that we see an optically thin profile. The final profile presented here, at time $5.7 \times 10^{14}$ s (1.8 $\times 10^7$ yr), is essentially that characteristic of the absorbing cloud in a steady state. In this situation, the peak optical depth of the model 1 cloud is 0.71.

The line profiles for the earliest times may, as suggested above, be inaccurate in detail since we have assumed that the cloud has instantaneously evolved to its final density and temperature profile. Thus, we may not expect to see quite such striking absorption features and peculiar line profiles, but again as discussed previously, the general evolution of the cloud from large H\textsc{i} column density to having a relatively low fractional abundance of atomic hydrogen is certainly robust. The different timescales for the H\textsc{i} $\rightarrow$ H$_2$ conversion in regions of different densities will also generally characterize gravitationally bound clouds that are, in general, centrally condensed. What is clearly evident from the spectra shown here is that in order to see profiles similar to those observed (e.g., Fig. 1), the abundance of H\textsc{i} in the warm envelope must be dramatically reduced relative to that in the initially purely atomic cloud. This means that the much longer timescale for the lower density region enters into determining when we can see the very narrow self-absorption profiles, which are primarily

![Figure 9](image-url)
produced in the colder central regions of the cloud. A time exceeding $1 \times 10^{14}$ s ($3 \times 10^6$ yr) is required for the H → H₂ conversion to have proceeded sufficiently far to avoid obvious saturation in the single-dip absorption spectra. The exact depth of the absorption profile depends on the details of the cloud structure. Our conclusions here are consistent with observational results analyzed in terms of the fractional abundance of cold H in a cloud with a single uniform (average) density (Paper II). The present modeling results demand times $\sim 3 \times 10^{14}$ s ($1 \times 10^7$ yr), but since we have not fitted specific H i spectra and determined H i and H₂ column densities, it is not appropriate to give more precise values at this point.

Another manifestation of the drop in the atomic hydrogen density as the cloud evolves is the reduction of the apparent line width of the absorption profile, which continues through the later part of the time period considered here. Considering only the largely Gaussian pure absorption spectra, the line width decreases from 2.7 km s⁻¹ at time $1.4 \times 10^{14}$ s ($4.5 \times 10^6$ yr) to 1.4 km s⁻¹ at time $5.7 \times 10^{14}$ s ($1.8 \times 10^7$ yr). The line broadening at the earlier time is essentially a result of saturation. The width of the optical depth profile, defined as the width at half maximum, increases until time $1.4 \times 10^{14}$ s ($4.5 \times 10^6$ yr), and then decreases slightly, while the line width at 10% of maximum increases monotonically throughout the calculation. This is basically a result of the changing relative amount of H in regions having lower and greater velocity dispersion. At early times, the large column density of H in the dense, relatively quiescent core completely dominates the optical depth profile, but as time passes, the atomic hydrogen in the exterior layers of the cloud becomes relatively more important. The result is a FWHM line width of 1.6 km s⁻¹ compared to that of 1.05 km s⁻¹ (combined thermal and nonthermal) expected from the core of the cloud alone. Under close examination, the line profile is not accurately described by a Gaussian profile, since the velocity distribution within each layer of the cloud is a Gaussian, the variation of the line width as a function of position results in the line profile no longer being purely Gaussian.

The corresponding spectra for model 2 (having higher central density and smaller size) are shown in Figure 11. While the general behavior is similar to that for model 1, there are several noticeable differences. The early-time evolution of the line profile is similar to that for model 1, with very prominent, broad absorption evident, and structure from the temperature gradient clearly visible in terms of the central filling-in of the absorption profile. However, starting at about $5 \times 10^{13}$ s ($1.6 \times 10^6$ yr), it is evident that the drop in the column density in the higher density cloud is more dramatic that in the lower density cloud. By $\sim 1 \times 10^{14}$ s,
(3 × 10^6 yr), the model 2 profile has a single minimum, while that of model 1 still has a peak within the absorption feature. This is due to the smaller 21 cm optical depth (3.0 for model 2 compared to 6.8 for model 1) in the presence of the temperature gradient. The line profile for model 2 is broadened by saturation but narrows and weakens as the H I to H2 transformation is completed.

In steady state, both clouds have optically thin HINSA features, with /C28_max = 0.49 for model 2 compared to 0.71 for model 1. The weaker feature for the denser cloud is really a reflection of its smaller size and hence the shorter path with the steady state H I density given by equation (7). The optical depth in steady state for model 2 is closer to those determined from observations of HINSA clouds, typically a few tenths, although a few sources do have τ approaching unity.

4.2. Effect of Background Temperature

As a consequence of the complex temperature structure of the clouds modeled here, the antenna temperature of the background radiation can have a dramatic effect on the line profiles produced by the foreground cloud. The temperature of the atomic hydrogen in the well-shielded, cold portion of the cloud (≤20 K) is colder than the antenna temperature of any commonly encountered background signal. This is not the case for the atomic hydrogen in the warmer, outer portion of the cloud, which can produce line profiles in which the contribution of the cold HINSA feature is much less obvious than in the preceding discussion. In Figure 12 we show examples with the peak background temperature reduced from the 60 K used in Figures 10 and 11, to 45 and 35 K. The actual antenna temperature across the range of velocities of the absorbing cloud is lower than this and varies due to the 5 km s^{-1} velocity offset combined with the 30 km s^{-1} background line width. In each case the spectrum of the background source has been subtracted from the spectrum produced by the model cloud located in front of the background source. This allows details of the spectra, which would be lost were the entire background emission spectrum to be plotted, to be seen. The spectra in Figure 1, as well as those in Papers I and II, were all taken in total power (on-source-only) mode, and there is no danger of features being produced by small differences in the background spectrum on and off the foreground cloud. Recalling from Figures 2–4, the temperature is ~60 K in the outermost layer of the cloud, falls to ~20 K at the point where there is 1 mag of external dust extinction, and drops to 10 K in the central portion of the cloud. Thus, for T_A, bg = 52–58 K, as produced by a cloud with peak intensity T_A, bg at 5 km s^{-1} = 60 K, there is very little gas at temperatures comparable to that of the background, so one gets only absorption lines irrespective of the evolutionary state of the (foreground) cloud and the distribution of atomic hydrogen within it.

Once the background temperature falls to ~40 K (for T_A, bg at 5 km s^{-1} = 45 K), the situation is somewhat different, as seen in the right-hand panels of Figure 11. At early evolutionary times, the 21 cm line observed from the exterior of the cloud becomes...
optically thick at a depth where the temperature is greater than 40 K, and so the antenna temperature at the velocity of the center of the self-reversed absorption profile is slightly greater than that of the background. As one moves to the line wings, one sees deeper into the cloud, and \( C_2 \) occurs in colder gas, so one again sees absorption.\(^7\) As the cloud evolves, the hydrogen in the outer layers becomes optically thin, and the line profile is dominated by the absorption in the colder central region of the cloud. This remains somewhat optically thick, even until times \( \approx 10^{14} \) s \((3 \times 10^6 \) yr), as revealed by the asymmetry of the line minus background absorption spectra. At relatively late times, the 21 cm line is optically thin, but there is more atomic hydrogen in the cold core of the cloud than in its envelope, so the net effect at line center is absorption. As one looks at the wings of the line profile of the foreground cloud, since the line width in the outer portion of the cloud is broader, the emission is dominated by warm hydrogen in the outer part of the cloud, and is manifest as the small maxima offset by \( \pm 1 \) km s\(^{-1}\) from the foreground cloud centroid velocity. With a peak background antenna temperature of 45 K, this effect is quite modest, and there would not be much difficulty in identifying the absorption feature as due to cold gas, and obtaining a reasonably accurate determination of the column density of H\(_i\) in the core of the cloud.

\(^7\) The line profiles in Figs. 10 and 11 have absorption minima at early times that reach the same value of antenna temperature. In Fig. 12, which plots the line minus the background, the absorption minima appear to have different values due to the variation in the antenna temperature of the background across the velocity range of the foreground cloud.
dominated by a central emission feature that reaches 10 K above
the background antenna temperature at the cloud centroid veloc-
ity. As the H i density drops, the signature of the atomic gas in
the foreground cloud becomes much weaker, and during the
phase in which the 21 cm line is somewhat optically thick \((\tau \approx 10^{14} \text{ s} \text{ or } 3 \times 10^6 \text{ yr})\), the line profile is very complex. This results
from the inverted center of the absorption line profile reaching just
about to the level of the background, combined with weak net
absorption features at \(\pm 1 \text{ km s}^{-1}\) from line center together with
weak excess emission features at \(\approx 1.5 \text{ km s}^{-1}\) from line center.
This very complex undulatory line profile might easily escape
notice as being due to absorption by cold H i; the wiggles are
similar to those seen in the spectrum of B227 in Figure 1 at veloc-
ities between 4 and 14 km s\(^{-1}\), although the background tem-
perature of the B227 profile is much larger, with \(T_{\text{A, bg}} \approx 80\) K, than we
are considering here. At very late times, we are left with a central
absorption feature flanked by modest excess emission, which
again would be recognizable as a signature of cold H i.

The overall conclusion here is that while a narrow H i absorp-
tion profile at the centroid velocity of a dense cloud defined by
molecular tracers is always a signature of associated cold H i, the
absence of readily detectable H i absorption does not indicate
that there is no cold atomic hydrogen present. The availability of
a molecular tracer to determine the velocity and line width of the
relatively quiescent gas in the central portion of the cloud is highly
advantageous for interpreting the H i absorption spectra. A low
background temperature (or, equivalently, an enhanced tempera-
ture of the outer portion of the foreground cloud, as would be pro-
duced by being in a region of enhanced interstellar radiation field
intensity) can produce a line profile that disguises the contribution
of the cold absorbing gas.

5. DISCUSSION AND CONCLUSIONS

Understanding the processing of material in the interstellar
medium, its relationship to star formation, and the timescales for
different parts of the cycling between stars and gas is a complex
undertaking. In the present work we have investigated the trans-
formation of atomic to molecular hydrogen in a region contain-
ging gas and dust that has been compressed. The increased density
raises the rate of molecular formation and the larger column den-
sity of those clouds to their current average values of a few thousand
\(\text{cm}^{-2}\). Since the evolution of the H i and H2 densities depends on
both of these parameters, the present study was undertaken to
include realistic treatment of photodissociation as a function of po-
sition in a cloud with structure including density and temperature
gradients. We do not treat the time dependence of \(n\) and \(T\), but
rather fix them to conform with models representing centrally con-
densed, hot-edged, predominantly molecular clouds that are largely
consistent with observations.

The present work also attempts to make a closer connection with
HINSA observations by calculating the line profiles that
would be measured if the model cloud were observed in absorp-
tion against the bright, relatively uniform background provided
by general Galactic H i emission. We have considered two model
clouds, treated as slabs that vary in one dimension and are infinite
in the two other dimensions. Each cloud has a total proton column
density \(\approx 10^{22} \text{ cm}^{-2}\). The interstellar radiation field is assumed to
be incident on one side of the cloud, which is heated to 60 K. As
one moves away from this interface, the density increases, and the
temperature drops to 10 K. The difference between the two models
is the central density \((1.6, 7.4) \times 10^4 \text{ cm}^{-3}\) for models 1 and 2,
respectively, and the cloud size, which differs so as to result
in equal column densities. Each complete model cloud used to
calculate the HINSA spectra comprises two such slabs back to
back and is thus an approximation of a warm-edged cloud with
H i fractional abundance \(n_{\text{H}i}/n_{\text{H}_2} \approx 1\) in the outer layers and
\(\approx 10^{-4}\) in the center of the clouds in steady state.

The time dependence of the spectral signature of the H i seen
in absorption provides an important diagnostic of the evolution of
the H i distribution in the cloud. The timescale for the con-
version of H i to H2 in well-shielded cloud cores is inversely pro-
portional to the proton density. Thus, in the denser central portion
of the cloud, the timescale \(\tau_{\text{center}}\) for H i \(\rightarrow\) H2 conversion is
approximately \(10^{12} \text{ s} (3.2 \times 10^4 \text{ yr})\). However, during the course of
the evolution of the cloud, the H i density drops \(3-4\) orders of
magnitude, thus requiring time \(\approx 10^{13} \text{ s} (3.2 \times 10^5 \text{ yr})\).
If we consider that the central portion of the cloud is heated by the
energy released during the H i \(\rightarrow\) H2 conversion process, then
since the characteristic cooling time is much less than that of this
heating phase, we end up with a \(\approx 10^4 \text{ K}
\) cloud core with a very low
steady state value \(n(\text{H}) \approx 2 \text{ cm}^{-2}\) after a time equal to a few \(\times
10^{13} \text{ s} (\approx 10^6 \text{ yr})\)
following the initial cloud compression has
passed. The timescale in the outer layers of the cloud is far longer
due to the lower density there, with \(\tau_{\text{edge}} \approx 10^{14} \text{ s} (3 \times 10^6 \text{ yr})\).

The 21 cm spectra sample atomic hydrogen throughout the
evolving cloud. Since the optical depth in a given region of the
cloud varies inversely as its temperature, the optical depth per
hydrogen atom is considerably less in the outer portion than in
the central part of the cloud. The peak optical depth varies in-
versely as the line width, which being larger in the outer portion

\[n(\text{H}) \approx 2 \text{ cm}^{-2}\]

One apparently discrepant cloud is the globule studied by Klappa et al.
(2005) and found to have \(0.02 \leq N(\text{H} i)/N(\text{H}_2) \leq 0.25\). However, the con-
clusion that this 2 kpc distant cloud is gravitationally unbound suggests that it may
be nowhere near steady state and, consequently, has a much higher fractional
abundance of atomic hydrogen than the clouds studied in detail in Paper II, which
are close to virial equilibrium.
of the cloud than in the center, similarly results in a lower absorption per hydrogen atom in the periphery of the cloud than in the center. The combination of these two factors explains why the steady state \( \text{H} \) column density in the outer part of the cloud is almost invisible compared to that in the center.

The \( \text{H} \) density in the low- and moderate-density regions of the cloud takes the longest to approach its steady state value. The evolution of these regions of the cloud thus provides a strong observational constraint on the “age” of the cloud. At early times, the \( \text{H} \) in the low- and moderate-density regions of the cloud is so abundant that it overwhelms the atomic hydrogen in the cloud core. This situation is readily identifiable from the spectra produced; the large quantity of \( \text{H} \) produces (depending on details of the temperature structure) emission features or absorption features significantly broader and deeper than those observed. The fact that such spectra are not observed may in part be due to simplifying assumptions made about the time independence of the density and temperatures structure of our model clouds, but it is also the case that the agreement between \( ^{13}\text{CO} \) and HINSA line widths means that there cannot be significant saturation broadening taking place for the latter. This in turn implies that the \( \text{H} \) density must be within a factor of a few of the steady state value in order that the peak \( \text{H} \) absorption optical depths be less than or on the order of unity. In cases in which the background antenna temperature is lower than the temperature in the outer part of the foreground cloud, excess emission above the background results. In this situation, we see complex spectra, but it is always the case that a narrow absorption line traces the cold \( \text{H} \) in in the well-shielded cloud core within a cloud that has evolved to being fairly close to steady state. Based on general comparison with observed spectral lines, an interval of a few \( \times 10^{14} \) s \( (1 \times 10^{7} \) yr \) can be set as the minimum that must have passed between the initial cloud compression and the present state of clouds as traced by HINSA.

The heating of gas in the cloud by the interstellar radiation field becomes significant in the outer portion of the cloud defined by \( A_i \leq 1 \) mag (see e.g., Fig. 5 of Le Bourlot et al. [1993] for \( \chi = 1 \) as appropriate to a cloud in a low-mass star-forming region). It is not surprising that the sizes of regions defined by \( T < 12 \) K and \( A_i \leq 1 \) mag are quite similar. The absolute size does depend on the cloud model, being smaller by a factor \( <3.8 \) for model 2 compared to model 1, somewhat less than the factor 4.6 by which the central density is larger. Clouds with different density profiles will not follow this relationship, but in the context of understanding the close agreement of clouds sizes measured in \( ^{13}\text{CO} \), \( ^{12}\text{CO} \), and HINSA presented in detail in Paper II, it is important to realize that the “molecular cloud” size is effectively determined by the point where photochemistry of the trace species becomes dominant. This again is where the external dust extinction is \( \approx 1 \) to a few mag. We thus see a natural explanation of the clouds’ having a similar size in cold \( \text{H} \) and in carbon monoxide isotopologues. The detailed agreement is affected by self shielding in \( ^{13}\text{CO} \) and \( ^{12}\text{CO} \), which along with chemical isotopic fractionation explains why the cloud sizes are larger in \( ^{13}\text{CO} \) than \( ^{12}\text{CO} \) (Paper II).

The studies of HINSA directly probe the central regions of dark clouds, but from the perspective of what the spectra do not look like, the results are relevant to the issue of the extent of lower density halos around molecular clouds, which may contain atomic (Andersson et al. 1991, 1992) and molecular (Wannier et al. 1993) species. Studies of these regions are difficult, but as pointed out by Bensch (2006), these halos may have a significant effect on the interior regions of the clouds in terms of increasing the attenuation of the external radiation field as well as providing some pressure confinement of the molecular gas.

To interpret the observations of the cloud halos and cores in a unified manner will require combining realistic models of the cloud dynamics with accurate values for the rates of critical chemical reactions. Detailed investigation of spatial correlations between emission from cloud halos and absorption from cloud cores should be very valuable in assessing the evolutionary status of clouds. This requires at least two-dimensional models, including correction of the photodissociation rates for nonplanar geometry as discussed by Ford et al. (2003). More detailed treatment of the \( H \) \( \rightarrow \) \( H_2 \) conversion is also required, especially at late times, when the density of atomic hydrogen is low (Biham et al. 2001; Biham & Lipshtat 2002). With this improved modeling, observations of HINSA in molecular clouds should become an effective tool for obtaining constraints on the evolutionary history of clouds, their age, and the overall timescale for star formation.

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