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HINSA as a tool for studying dark clouds and star formation

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Abstract. Traditionally it has been difficult to obtain estimates of the HI content of molecular clouds due to the sheer complexity of the galactic background HI emission. However, with the use of the recently discovered HINSA (HI Narrow Self-Absorption) features we are for the first time able to make direct measurements of the HI column density in cold molecular clouds with high extinction. This allows us to study a variety of properties in these clouds including the molecular to atomic hydrogen ratio. Measurements and understanding of this ratio can give us estimates of the chemical ages of these clouds, in turn providing us with constraints on star formation. More specifically we are able to place some constraints on the timescale over which a molecular cloud collapses from a diffuse ($A_v < 1$) to a compact star-forming state. Such constraints would have considerable impact on several disputed areas of star formation theory including the role of magnetic fields and ambipolar diffusion. With new observations at the Green Bank Telescope we have greatly increased the amount of available HINSA data previously obtained using the Arecibo telescope, and though our analysis is still very much preliminary, we are beginning to see that HINSA and its correlations with molecular, IR, and optical data may prove to be an even more useful tool in studying dark molecular clouds and other objects than previously anticipated.

Key words. molecular clouds – spectral lines

1. Introduction

The complex structure of the warm galactic HI background has made it nearly impossible to determine the HI content of diffuse objects within the galaxy. This is largely due to the difficulty in assigning a particular emission component or feature to any individual object. Through a new technique we have recently gained the ability to measure the HI content of dark clouds.

HI Narrow Self-Absorption (HINSA) has only recently been adapted as terminology, referring to 21cm HI self-absorption features with nonthermal linewidths comparable to associated molecular linewidths (Li & Goldsmith 2003). This rather innocuous definition hides an important implication. If the HI absorption features have comparable nonthermal line widths to those of molecular lines along the same line of sight, then the HI responsible for the absorption must be associated with molecular clouds. Furthermore, as confirmed by maps of four clouds by Goldsmith & Li (2005), the HI must occupy similar regions of the clouds as the molecules to which they are associated such as OH or ^{13}CO. In order for

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the HI to self-absorb it must have a sufficiently low temperature[1], which can only happen if the HI is shielded from external UV radiation, e.g. dust absorption. Therefore we are led to conclude that HINSA is caused by cold HI located within well shielded dark cloud cores that have not yet begun forming stars.

The ability to confidently measure the HI content of dark clouds opens up a new tool that is capable of yielding many significant insights into the nature of the interstellar medium. In this paper we will only briefly discuss two such uses for HINSA which we have recently begun to analyze. It should be noted however that this research is, at the time of writing, still in its early stages.

2. HINSA Observations

Li & Goldsmith (2003) completed a survey of 29 dark clouds in Taurus at the Arecibo Telescope in Puerto Rico. A sample of several spectra is included in Figure 1. They found HINSA in over 85% of the clouds surveyed. They also showed strong correlations between ^{13}CO, OH, and HINSA both spatially and spectroscopically. However all of their clouds were in Taurus which is a relatively nearby region. We performed a much larger survey using the Green Bank Telescope in 2004 which included over 70 clouds at distances of up to 700pc. We found HINSA in over 50% of our clouds which, in comparison with the previous survey, may imply that HINSA features in clouds at greater distances are washed out by foreground HI emission.

3. The Usefulness of HINSA

Here we discuss two fundamental questions on the evolution of the interstellar medium which we are currently working on that should be answered by using HINSA in order to measure the HI content of dark clouds.

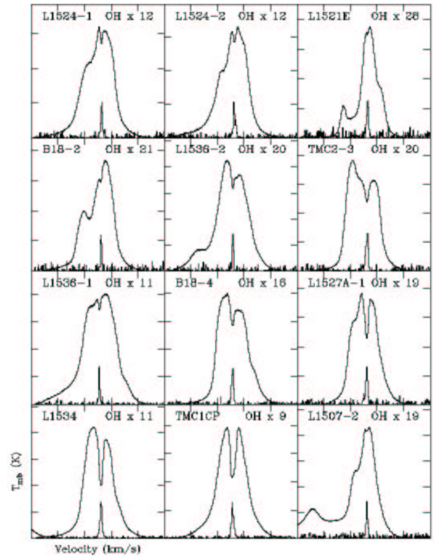

Fig. 1. A sample of 12 HI spectra and accompanying OH emission Li & Goldsmith (2003). The OH spectra are necessary in order to discern HINSA from other features of the background HI emission. The strong correlation in central velocity and line width between HINSA and OH are good indications of their association.

3.1. The Evolution of Molecular Clouds

The commonly accepted evolution of star forming regions can be crudely summarized as follows:

- A diffuse cloud is maintained in atomic form by the UV radiation field. At some point it is compressed by an outside influence (shockwave or collision).
- As the cloud is compressed its density and optical extinction increase. Once the optical extinction (A_V) reaches roughly 1 magnitude the cloud's core becomes sufficiently shielded to begin forming H_2 on dust grains (Bergin et al. 2004).
- The cloud (or a portion of it) may become gravitationally bound and thus continues to collapse and increase in density.
- The timescales for collapse from $A_V = 1$ is affected by many factors including the

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[1] In some cases there are indications of temperatures as low as 10K (Li & Goldsmith 2003)

coupling between the gas and the magnetic field, fragmentation, and rotation.

By properly extracting and interpreting the HINSA absorption we can determine the HI content of dark clouds. Comparison with the H_2 content [2] will through the use of our numerical models give us estimates of the chemical age. More explicitly, we are able to determine how long these clouds have had a high enough optical extinction (> 1 magnitude) to allow efficient conversion of atomic to molecular hydrogen. Even in steady state, there is an HI density of $\simeq 2$ cm^{-3} produced by cosmic ray ionization of H_2. For times earlier than the characteristic HI $\rightarrow H_2$ conversion time of $3{\times}10^9/\mathrm{n}_0$ yr (where n_0 is the proton density), the HI density will be higher. Thus, as described by Goldsmith & Li (2005), the time–dependent HI density is a robust tracer of the chemical "age" of a cloud, defined as the time since initiation of the atomic to molecular conversion process produced by an increase in the extinction. Figure 2 shows the results of such modeling for a small sample of the clouds observed thus far. Detailed modelling of all our HINSA sources will provide with the tools necessary to make a definitive statement on the timescales for star formation and the role of magnetic fields.

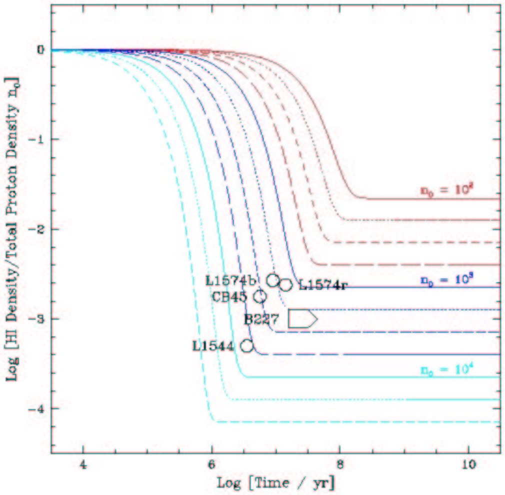

Fig. 2. A simple model of a uniform constant density cloud as it converts its atomic Hydrogen into molecular form over time. Different curves represent different total proton densities. Displayed are derived ages for a few HINSA clouds for which the analysis has been completed.

3.2. Structure and Formation of Filamentary Structures

One of the clouds mapped during the recent observations at Green Bank is L204[3]. It is a rather large filament located roughly 140 pc away in Ophiucus (McCutcheon et al. 1986). While such structures are prevalent in the ISM, their formation is poorly understood. Nakajima et al. (1996) developed a numerical model in which a pre-existing cloud is acted upon by an external magnetic field and through fragmentation forms filamentary structures like L204. Piontek et al. (2004) imply that such filaments are expressions of the galactic magnetic field acting on the diffuse ISM. This raises a fundamental question; are filaments formed by reshaping pre-existing clouds or are they formed ab initio from the diffuse ISM? We believe that we can answer that basic question through the use of HINSA features in L204.

Figure 3 shows the region of L204 mapped in HI along with the corresponding extinction obtained from 2MASS data using a method similar to Padoan et al. (2002). By using previously mentioned techniques we can obtain the chemical age of the filament. We can also obtain an upper limit on the dynamical age of L204 thanks to its filamentary structure. Figure 4 shows CO velocities across various points in the filament. If we take two points having a maximum velocity difference of about 2km/sec (+ 40 $\Delta\delta$) and 5 km/sec (-20 $\Delta\delta$) we get a velocity difference of 3km/sec across 1 degree of the sky (corresponding to roughly 3 pc). If we then make the assumption that the radial separation between those two points is at most equal to their transverse seperation we can get an upper limit on the dynamical age of that por-

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[2] Estimated from observations of H_2 tracers such as ^{13}CO

[3] Lynds catalog number 204

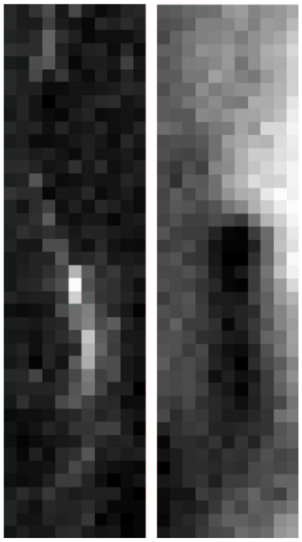

Fig. 3. Left: A map of extinction in L204 calculated from stellar reddening determined from 2MASS data. Brighter regions correspond to higher extinction. Right: HI integrated intensity map covering channels with HINSA. Dimmer regions correspond to greater HINSA absorption.

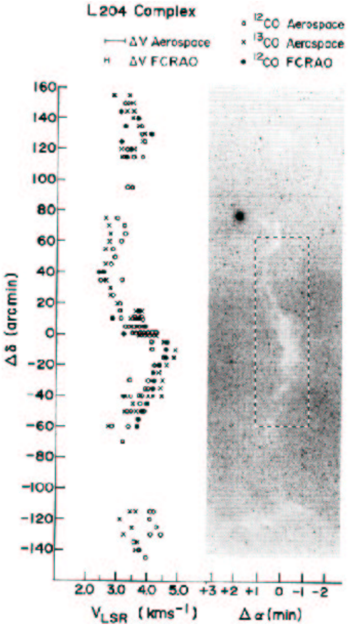

Fig. 4. CO velocity data and optical image of the entire L204 filament McCutcheon et al. (1986). The boxed region corresponds to the maps in Figure 3

tion of the cloud of roughly 1 million years[4]. This is comparable to the free-fall timescale.

If the chemical age of L204 is greater than its dynamical age it would be a strong indication that L204 was formed through the reshaping of a pre-existing cloud and not ab initio from diffuse gas. This information will be a vital clue in understanding filamentary structures and the nature of turbulence in the ISM in general. The very same kinematic structure which allows us to make this determination also necessitates an OH map of the region which is at the time of writing unavailable, but for which observing time on the Green Bank Telescope has been requested.

4. Conclusions

We are still only learning how to use and interpret HINSA absorption features, however they have already shown to be useful in answering two longstanding fundamental questions concerning the nature of the ISM and star formation. While our research has not yet fully matured it shows HINSA to be a useful tool with significant scientific merit.

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[4] Of course this assumes that the cloud is not composed of discontinuous clumps lined up along our line of sight, but this can be inferred from the continuity of the HINSA absorption