

Properties of the Thinnest Cold HI clouds in the Diffuse Interstellar Medium

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Abstract. We have obtained deep HI observations in the direction of 22 continuum sources without previously detected cold neutral medium (CNM). 18 CNM clouds were detected with a typical HI column density of $3 \times 10^{18} \text{ cm}^{-2}$. Our surprisingly high detection rate suggests that clouds with low HI column densities are quite common in the interstellar medium. These clouds appear to represent an extension of the traditional CNM cloud population, yet have sizes in hundreds to thousands of AUs. We present properties of the newly-detected CNM sample, and discuss several theoretical avenues important for understanding the production mechanisms of these clouds.

1. Introduction

While properties and origin of the AU-scale structure in the cold neutral medium (CNM) are still under debate, a possibly related new population of CNM clouds has been discovered recently. Using the Westerbork radio telescope, Braun & Kanekar (2005) detected very weak HI absorption lines toward three high-latitude sources. Along each line of sight multiple absorption lines were detected, with the peak optical depth of only 0.1 to 2%. Stanimirović & Heiles (2005) used the Arecibo telescope to confirm the existence of these low-optical-depth CNM clouds in directions of two of the sources. They also emphasized that these clouds have HI column densities among the lowest ever detected for the CNM, $\sim 10^{18} \text{ cm}^{-2}$. We will therefore call these clouds the ‘low- $N(\text{HI})$ ’ clouds.

How atypical are low- $N(\text{HI})$ clouds? From the theoretical point of view, the traditional CNM clouds have a typical size of 2 pc and $N(\text{HI}) \sim 3 \times 10^{20} \text{ cm}^{-2}$, the lowest expected column density being $6 \times 10^{19} \text{ cm}^{-2}$ (McKee & Ostriker 1977). From an observational point of view, the recent survey by Heiles & Troland (2003, HT03) suggested a typical $N(\text{HI}) = 0.5 \times 10^{20} \text{ cm}^{-2}$ for CNM clouds. While column densities of low- $N(\text{HI})$ clouds are 30–50 times lower than theoretical and observational expectations, these densities are close to what is

measured for the tiny scale atomic structure (TSAS), $N(\text{HI}) \sim \text{a few} \times 10^{18}$ to 10^{19} cm^{-2} (Heiles, SINS). In Figure 1 we illustrate graphically how low- $N(\text{HI})$ clouds compare with TSAS and CNM clouds by plotting the typical linear size and HI volume density for these three types of objects. Low- $N(\text{HI})$ clouds occupy the region in this diagram between TSAS and CNM clouds, the regime that is currently observationally probed only with optical observations of globular clusters (e.g. Meyer & Lauroesch 1993).

In this contribution we focus on two particular questions regarding the low- $N(\text{HI})$ clouds: (1) how common are these clouds in the ISM, and (2) how are these clouds related to the traditional spectrum of CNM clouds? In Section 2. we summarize our recent search for the low- $N(\text{HI})$ clouds with the Arecibo telescope. We describe our results in Section 3. and discuss physical mechanisms responsible for the production of low- $N(\text{HI})$ clouds in Section 4.

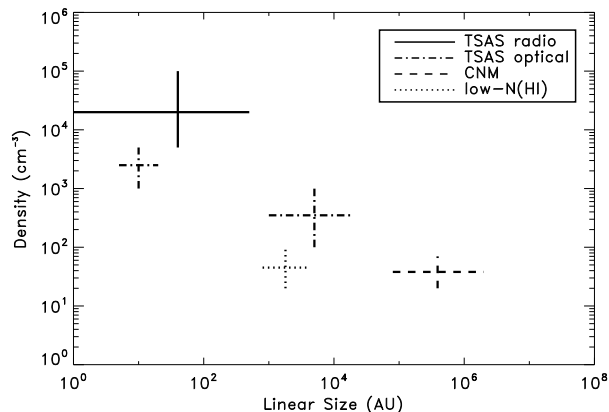


Figure 1. Typical linear size and HI volume density of TSAS, traditional CNM clouds (dashed line), and the low- $N(\text{HI})$ clouds (dotted line; based on data from Stanimirović & Heiles 2005). In the case of TSAS, the radio measurements are shown with a solid line (from Heiles, SINS), while optical measurements of double stars and stars in globular and open clusters (probing scales of hundreds of AU), as well as from temporal variability (probing scales of tens of AU), are shown with dot-dashed lines (from Lauroesch, SINS).

2. Recent Search for Low- $N(\text{HI})$ Clouds with the Arecibo Telescope

To search for new low- $N(\text{HI})$ clouds we have recently obtained HI emission and absorption spectra in the direction of 22 continuum sources with the Arecibo radio telescope. About half of the sources were chosen from HT03 as being without detectable CNM after ~ 15 minutes of integration, the remaining sources were selected from catalogs by Dickey et al. (1978) and Crovisier et al. (1980). None of the sources in our sample had previously detected CNM. The observing strategy was the same as in HT03 and Stanimirović & Heiles (2005), however the integration time per source was significantly longer (1 to 4.5 hours). The final velocity resolution of HI spectra is 0.16 km s^{-1} . The final rms noise level in the absorption spectra is $\sim 5 \times 10^{-4}$ over 0.5 km s^{-1} channels. For sources with newly-detected CNM, we used the technique developed by HT03 to estimate

the spin temperature. However, this technique turns out to be unreliable for our data as most of the CNM clouds have a very low optical depth and occupy a solid angle significantly smaller than the Arecibo beam. For CNM features presented in this paper, we have chosen $T_{\text{sp}} = T_{\text{k}}/2$. This is a safe assumption that probably over-estimates our $N(\text{HI})$ as HT03 found that majority of their CNM clouds had $T_{\text{sp}} = T_{\text{k}}/3$.

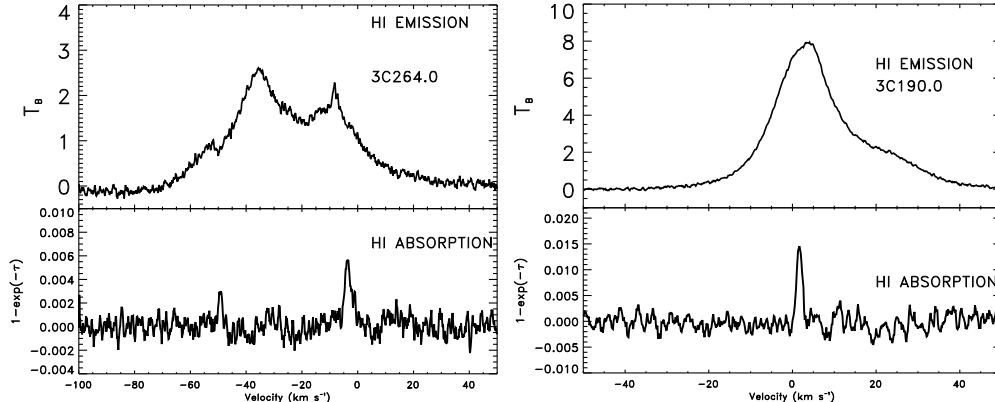


Figure 2. HI emission and absorption spectra for 3C264 (left) and 3C190.0 (right) obtained with the Arecibo telescope. Two new CNM components were detected for 3C264, and one for 3C190.0.

3. Properties of Low- $N(\text{HI})$ Clouds

Out of 22 sources in this study, ten show clear CNM features, and in many cases multiple lines along the line of sight were detected. In total, we have detected at least 18 new CNM features with the peak HI optical depth in the range 2×10^{-3} to 2×10^{-2} . *The detection rate in this experiment is surprisingly high, suggesting that clouds with low optical depth are quite common in the ISM.*

Figure 2 shows HI emission and absorption spectra for two sources in our survey, 3C264.0 (left) and 3C190.0 (right). For each source, the top and bottom panels show the HI emission and absorption spectra. We detected two CNM clouds in the case of 3C264.0 and one cloud in the case of 3C190.0. The peak optical depth is 5×10^{-3} and 3×10^{-3} for clouds in the direction of 3C264.0, and 2×10^{-2} for the cloud in the direction of 3C190.0. The velocity FWHM for the three clouds is 3.5, 1.5, and 1.4 km s^{-1} , respectively. Clearly, these are cold HI clouds, with $N(\text{HI}) \sim 5 \times 10^{18}$, 2×10^{17} , and $1 \times 10^{18} \text{ cm}^{-2}$, respectively. The HI peak brightness temperature in these directions is only about 2.5 K and ~ 8 K, with the total $N(\text{HI})$ being $2 \times 10^{20} \text{ cm}^{-2}$ and $3.3 \times 10^{20} \text{ cm}^{-2}$, respectively. The ratio of the CNM to total HI column density, $R = N(\text{HI})_{\text{CNM}}/N(\text{HI})_{\text{TOT}}$ is only about 5% and $\sim 1\%$, respectively.

In total, our current sample has 21 low- $N(\text{HI})$ clouds: 18 from this study, and three from Stanimirović & Heiles (2005). Two thirds of the clouds have $N(\text{HI}) < 10^{19} \text{ cm}^{-2}$. In comparison, HT03 had 20 clouds with $N(\text{HI}) < 10^{19} \text{ cm}^{-2}$ out of 143 CNM components. In comparison to the Millennium Survey

by HT03, we have almost doubled the number of clouds in the lowest column density bin. $\tau_{\max} = 10^{-2}$, $\text{FWHM} = 2.4 \text{ km s}^{-1}$, and $N(\text{HI}) = 3 \times 10^{18} \text{ cm}^{-2}$.

The next obvious question to ask is how do low- $N(\text{HI})$ clouds relate to CNM clouds with higher column densities? Heiles & Troland (2005) investigated statistical properties of the CNM components detected in their Millennium Survey and found that the probability distribution of the CNM column density closely follows $\Phi(N) \propto N^{-1}$ over two orders of magnitude, from $N_{\min} = 2.6 \times 10^{18} \text{ cm}^{-2}$ to $N_{\max} = 2.6 \times 10^{20} \text{ cm}^{-2}$. We have added column densities of our 21 low- $N(\text{HI})$ clouds to $\Phi(N)$ from Heiles & Troland (2005) and the resultant histogram is shown in Figure 3. The solid line in this figure represents the $\Phi(N) \propto N^{-1}$ fit obtained by slightly extending the lower limit to $N_{\min} = 2 \times 10^{18} \text{ cm}^{-2}$. Surprisingly, a single function fits well both sets of objects. This suggests that low- $N(\text{HI})$ clouds may not belong to a separate class of interstellar clouds, but could simply be *the low column density extension of the CNM population*.

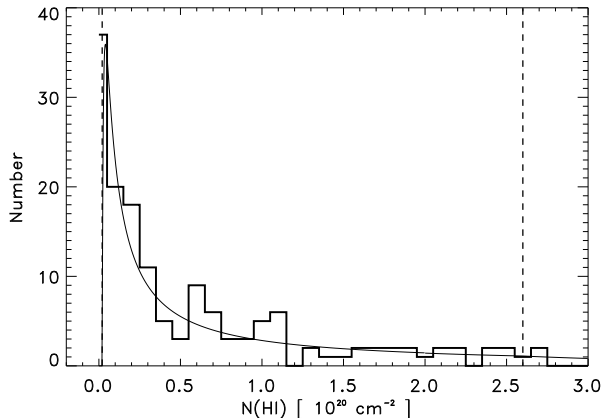


Figure 3. The observed distribution of $N(\text{HI})$ derived by combining the CNM components from HT03 with low- $N(\text{HI})$ clouds. The solid line represents the curve N^{-1} defined over the range of column densities from 2×10^{18} to $2.6 \times 10^{20} \text{ cm}^{-2}$. The minimum and maximum column densities are shown with dashed lines.

In Figure 4 we show R vs $N(\text{HI})_{\text{TOT}}$ for all CNM components found in the HT03 survey (shown with triangles and crosses) and in our survey (circles). HT03 noticed that CNM clouds in their survey followed almost a linear trend up to about $N(\text{HI})_{\text{TOT}} \sim 12 \times 10^{20} \text{ cm}^{-2}$, while sources without the CNM clearly stood out as a potentially distinct class of objects. Most low- $N(\text{HI})$ clouds have $R < 5\%$ which is suggestive that the CNM is embedded in large warmer envelopes containing most of the HI, also providing protection against evaporation.

If we assume that low- $N(\text{HI})$ clouds are at the standard ISM pressure of $n(\text{HI})T \sim 3000 \text{ K cm}^{-3}$, then their estimated HI volume density is $n(\text{HI}) \sim 20\text{--}100 \text{ cm}^{-3}$. The line-of-sight size of these clouds is then given by $L(\parallel) = N(\text{HI})/n(\text{HI}) \sim 800\text{--}4000 \text{ AU}$. If the clouds are however overpressured and $n(\text{HI})T > 3000 \text{ K}$, then $L(\parallel) < 800\text{--}4000 \text{ AU}$, even closer to the traditional TSAS. In any case, low- $N(\text{HI})$ clouds are most likely small, with sizes in the range of a few hundreds to a few thousands of AUs. This is larger than the ‘canonical’ TSAS but still significantly smaller than the traditional pc-size CNM

clouds. Another constraint on cloud sizes comes from direct interferometric imaging by Braun & Kanekar (2005) who reported HI emission clumps with sizes of 3×10^3 AU. In any case, it appears that low- $N(\text{HI})$ clouds could be an extension of the traditional population of CNM clouds, bridging the gap between CNM clouds and TSAS.

4. Discussion

Physical mechanisms responsible for the production of cold clouds with very low column densities are not well understood. There are three potentially interesting theoretical avenues that await a closer comparison with observations.

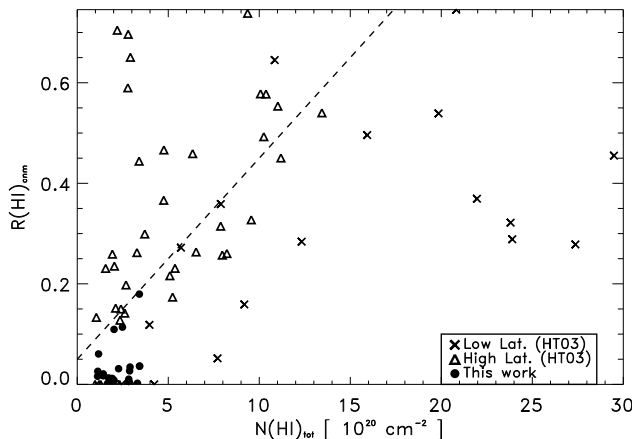


Figure 4. CNM fraction $R = N(\text{HI})_{\text{CNM}}/N(\text{HI})_{\text{TOT}}$ vs $N(\text{HI})_{\text{TOT}}$ for clouds from HT03, shown with crosses for latitudes between 10 and 30 degrees and with diamonds for latitudes higher than 30 degrees. Low- $N(\text{HI})$ clouds are shown as filled circles. The dashed line represents the trend noted by HT03.

Conductive heat transfer occurs between the CNM and their surrounding warmer medium, forming an interface region through which heat flows between the two phases. In the case of the least intrusive interface, CNM to WNM with the intercloud temperature of $10^2 - 10^4$ K, the expected lower limit on the column density of the interface region is quite low, $N(\text{HI}) \sim 3 \times 10^{17} \text{ cm}^{-2}$ (McKee & Cowie 1977). In this case the expected critical radius for CNM clouds (at which clouds are stable and neither evaporate nor condense) is $R_{\text{rad}} \sim 6 \times 10^3$ AU. CNM clouds smaller than R_{rad} evaporate but are surprisingly long-lived, their typical evaporation timescale is of order of 10^6 yr (see Stanimirović & Heiles 2005 for details). Similar timescales were reached recently by Nagashima, Inutsuka, & Koyama (2006) based on 1-D numerical simulations. Our low- $N(\text{HI})$ clouds have sizes below the critical cloud radius even in the case of the least-intrusive WNM. These CNM clouds, protected from ionization by large WNM envelopes, should be evaporating but over long timescales, and hence could be common in the ISM.

Condensation of WNM into CNM triggered by the collision of turbulent flows is capable of producing a large number of small CNM clouds with low column densities, as seen in simulations by Audit & Hennebelle (2005) and Hen-

nebelles (2006, SINS). The CNM clouds produced in simulations are thermally stable and embedded in large, unstable WNM filaments, their typical properties are: $n \sim 50 \text{ cm}^{-3}$, $T \sim 80 \text{ K}$, $R \sim 0.1 \text{ pc}$. The number of cold clouds, as well as their properties, depend heavily on the properties of the underlying turbulent flows.

General ISM turbulence envisions interstellar clouds as dynamic entities that are constantly changing in response to the turbulent “weather”, a picture very different from the traditional approach. Numerical simulations of turbulent ISM, for example Vázquez-Semadeni, Ballesteros-Paredes, & Rodríguez (1997) show many clouds with very small sizes and low column densities ($< 10^{19} \text{ cm}^{-2}$). These clouds are out of dynamical equilibrium and probably very transient.

CNM destruction by shocks in simulations by Nakamura et al. (2005) can also produce a spray of small HI shreds that could be related to low- $N(\text{HI})$ clouds. These shreds have large aspect ratios, up to 2000, but further comparison with observations awaits inclusion of a magnetic field.

5. Summary

The CNM clouds with $N(\text{HI}) \sim 10^{18} \text{ cm}^{-2}$ are easily and frequently detected with deep radio integrations. These clouds are very thin along the line of sight, $L(\parallel) \sim 800\text{--}4000 \text{ AU}$, and could be related to TSAS. They are evaporating very fast, unless being surrounded by a lot of mild WNM, $T \sim 10^2 - 10^4 \text{ K}$, in which case they could last for up to $\sim 1 \text{ Myr}$. The CNM fraction relative to the total HI column density also supports the existence of large WNM envelopes which contribute up to 95-99% of the total $N(\text{HI})$. The combined histogram of $N(\text{HI})$ for ‘classic’ CNM clouds and low- $N(\text{HI})$ clouds can be fitted with a single function, $\Phi(N) \propto N^{-1}$. This suggests that low- $N(\text{HI})$ clouds are, most likely, a low column density extension of the CNM cloud population.

Acknowledgments. SS and CH acknowledge support by NSF grants AST-0097417 and AST-9981308. We would also like to thank the NRAO for hosting this highly stimulating and enjoyable conference. NK acknowledges support from the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

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