New Temperature Ratios of Purely Interstellar Gas: Thermally Unstable Gas

1. INTRODUCTION

The formation and evolution of the interstellar medium (ISM) is a complex process involving various physical and chemical processes. These processes are influenced by the temperature and density of the gas and the presence of differentially ionized species. In this paper, we present new temperature ratios of purely interstellar gas, which are thermally unstable.

2. NEW DATA FOR THE INTERSTELLAR GAS

We have measured the temperature ratios of pure interstellar gas in several regions of the galaxy. Our results indicate that the gas is thermally unstable, with temperature ratios significantly higher than those observed in earlier studies.

3. CONCLUSION

Our new measurements provide important insights into the thermal properties of the interstellar gas. These findings have implications for our understanding of the formation and evolution of the ISM and the role of temperature ratios in determining the stability of the gas. Further studies are needed to fully understand the implications of these results.
2.1. Observations and reduction technique

Heiles and Troland (2001) are performing a survey of Zeeman splitting of HI absorption lines with the Arecibo telescope. These data have long integration times, which produces excellent signal/noise and makes them unsurpassed for obtaining temperatures. Our results are more accurate and cover more sources than the best previous surveys, which are the Arecibo work by DST2 and PST, and the Boun/NRAO work by MWKG. Here we report on 24 sightlines, 19 of which have [b] > 20° but otherwise are randomly selected within Arecibo’s declination range ~ 0° → 39°.

Each absorption spectrum consists of very obvious velocity components and we represent their optical depths by a set of N Gaussians. Thus we least squares fit the observed spectrum \( \frac{I_{\nu}}{I_0} = e^{-\tau} \), where

\[
\tau = \sum_{n=0}^{N-1} \tau_m e^{-\left(\frac{V-V_{0m}}{\delta V_n}\right)^2},
\]

(1)

here \( \tau_{\nu} = \) the absorption profile divided by the continuum source strength and \( (V_{0n}, \delta V_n) \) are (central velocity, FWHM) of component n. We assume that each component is an independent physical entity, and is isothermal. This is consistent with the findings of KSG.

Each HI emission spectrum contains structure but, also, is wider than its associated absorption spectrum, as is well known. We assume that the emission spectrum \( T_{\nu} = T_{C,\text{NM}} + T_{\text{WNM}} \), where \( T_{C,\text{NM}} \) is the contribution from the aforementioned CNM components. \( T_{\text{WNM}} \) is the contribution from K additional wide Gaussians to represent the WNM; K is small and often just one. The spin temperatures in these additional components are so high that they have negligible optical depth and produce no easily discernible features in the absorption spectrum.

In least-squares fitting the emission, we include the absorption of more distant CNM Gaussians by less distant ones. Letting \( T_n \) be the spin temperature of component n, which is also the kinetic temperature,

\[
T_{C,\text{NM}} = \sum_{n=0}^{N-1} T_n (1 - e^{-\tau_n}) e^{-\sum_{m \neq n} \tau_m},
\]

(2)

where the subscript m with its associated optical depth profile \( \tau_m \) represents each of the M CNM clouds that lie in front of cloud n. For multiple absorption components, we experiment with all possible orders along the line of sight and choose the one that yields the smallest residuals. We also include the absorption of each WNM component by the CNM by assuming that a fraction \( F_k \) lies in front of all the CNM and is unabsorbed, with the rest all lying behind; thus

\[
T_{\text{WNM}} = \sum_{k=0}^{K-1} [F_k + (1-F_k) e^{-\tau_k}] T_{\nu, k} e^{-\left(\frac{V-V_{0k}}{\delta V_k}\right)^2},
\]

(3)

where the subscript k represents each WNM component. Note that \( T_{\nu, k} \) is a brightness temperature, not a kinetic temperature. In most cases \( F_k \) is indeterminate and we can only distinguish between the two extremes \( F_k = (0, 1) \). The differences for different orderings are sometimes not statistically significant but nevertheless lead to differences in the derived CNM temperatures. These differences reflect the uncertainties in \( T_n \) more than the conventional errors derived from least squares fits. Additional uncertainties can occur if there are unresolved subcomponents. We defer discussion of these details to the more comprehensive paper (Heiles and Troland 2001).

Previous single-dish authors, in contrast, implicitly assume that clouds are not isothermal. They derive the spin temperature of a cloud at the peak of its absorption profile. Thus each point on their histograms represents the lowest derived temperature for that particular cloud. This temperature, however, is not the coldest temperature in the cloud, because the line of sight also passes through warmer gas.

2.2. Sample result: 3C18

Figure 1 exhibits the results for 3C18 [located at (\( \ell, b \)) = (119°, −53°)], which is a simple profile and good for an illustrative example. In the top panel the solid line is the observed absorption spectrum \( \frac{I_{\nu}}{I_0} \), which we fit with the three CNM components whose depths and halfwidths are indicated; the dash-dot line is the fit. In the bottom panel the solid line is the observed emission spectrum \( T_{\nu} \). The dashed curve is \( T_{C,\text{NM}} \); the dotted is \( T_{\text{WNM}} \) fit with \( K = 1 \), which is unabsorbed by the CNM because the lowest residuals are obtained with \( F = 1 \). The full fitted curve is the sum, shown as dash-dot, which is a good fit except in the extreme line wings where stray radiation makes the data suspect (e.g. Hartmann & Burton 1997).

For 3C18, the WNM component has halfwidth 10.0 km s\(^{-1}\), which corresponds to purely thermal broadening at \( T = 2200 \) K; this is an upper limit on the kinetic temperature \( T_{K} \). For the three CNM components, left-to-right on Figure 1, the halfwidths are (2.5±0.03, 6.3±0.07, 11±0.15) km s\(^{-1}\) and spin temperatures are 32±1, 43±6, and 46±9 K. The ratio of total linewidth to thermal linewidth are (2.04 ± 0.07, 4.50 ± 0.63, 0.75 ± 0.18); the 1σ uncertainty on the last ratio is statistically consistent with a ratio \( \geq 1 \), as it must be. The (WNM, CNM) components contribute \( \delta N \left( H \right) = (3.2, 1.8) \times 10^{20} \) cm\(^{-2}\), respectively. The WNM/CNM ratio is \( \approx 1.8 \), which is close to our global average.

2.3. The ensemble of WNM temperatures

Our 49 WNM components have linewidths that correspond to upper limits on the kinetic temperature. The top two panels of Figure 2 exhibit histograms of these limits, one for number of components and one for column density. Not included on these histograms is one absorption component for which the spin temperature was derived:

\[
T_{\nu, spin} = 725 \text{ K}, \quad \delta N \left( H \right) = 1.4 \times 10^{20} \text{ cm}^{-2}.
\]

Including this, 20 of the WNM components (40%) have \( T_{K} = 500 \to 5000 \) K. These contain > 47% of the total WNM column density; this is a lower limit because the WNM temperatures are upper limits. Because these components are not visible in absorption, their spin temperatures exceed ~ 500 K. This range, \( 500 \to 5000 \) K, is approximately the thermally unstable range that separates CNM from WNM.

1 The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

2 We find about half the DST absorption profiles to exhibit large differences from ours, with DST components being wider and multiply-peaked; some of DST’s profiles were corrupted by local oscillator stability problems (Dickey, private communication). This completely explains the disagreement of Greisen and List (1990) with DST for 3C348.
2.4. Our ensemble of CNM temperatures

Our 86 CNM temperatures are derived from absorption/emission data and are values, not upper or lower limits. The bottom two panels of Figure 2 exhibit histograms of these temperatures. The two histograms exhibit broad peaks in the range $T = 25 \rightarrow 75$ K. 47 of the CNM components (54%) have temperatures in this range; these contain 61% of the total CNM column density. We also see colder gas: 10 components (11%) containing 5% of the mass have $T = 10 \rightarrow 25$ K. We discount the four small $N(HI)$ components having $T < 10$ K; they are weak and the temperatures have large errors. We find no support for the weakly significant $T = \tau$ relation reviewed by KH.

2.5. Ratio of CNM and WNM components and mass

For WNM gas ($T \geq 500$ K), we found 49 components with total $N(HI) = 107 \times 10^{20}$ cm$^{-2}$. For CNM gas ($T \leq 200$ K) we found 80 components having a total $N(HI) = 65 \times 10^{20}$ cm$^{-2}$. In the mildly ambiguous range $T = 200 \rightarrow 500$ K we found 6 components with total $N(HI) = 7.5 \times 10^{20}$ cm$^{-2}$. Thus, the ratio of CNM to WNM is, in terms of number of components, 1.6; in terms of mass, 0.60. Overall, our results indicate that about 60% of the neutral atomic ISM is WNM, with $T > 500$ K.

2.6. Temperatures from optical/UV absorption line observations

To derive kinetic temperatures from an atomic optical/UV absorption line, one decomposes it into Gaussian components. Then one does the same with the 21-cm emission line toward the star, fixing the central velocities to be the same. The comparison of line widths separates the thermal and turbulent broadening. The derived temperatures are upper limits because the HI line comes from a much larger angular area so the nonthermal component of its width may be larger than that of the heavy element lines. Such temperatures are probably the best one can do for the WNM, but for CNM gas they are much less accurate than those derived from 21-cm absorption/emission line data.

Spitzer & Fitzpatrick (1995) and Fitzpatrick & Spitzer (1997) use this technique towards two high-latitude stars and derive temperatures and column densities for 21 diffuse neutral components. Of this total, 3 components have $T > 5000$ K, 13 have $T < 500$ K, and 5 have $T$ in the unstable $500 \rightarrow 5000$ K range; thus, 24% of the components are thermally unstable; these contain 63% of the mass.

One can derive excitation temperatures of the low-J states of H$_2$ using UV absorption lines (Shull et al 2000; Spitzer, Cochran, & Hirshfeld 1974). These tend to agree with previous 21-cm line temperatures and are systematically higher than ours. If our temperatures are correct, then the low-J states are nonthermally populated, as are the high-J ones.

3. Discussion and comparison with theory

3.1. The WNM

Both our new HI and the optical/UV observations show that much of the WNM—at least 47%—lies at temperatures that are unstable to isobaric perturbations. Our Arecibo data show this departure from thermal stability in a statistically convincing manner. Previous 21-cm line studies have hinted at this result. In emission/absorption studies, MWKG decomposed emission line profiles into Gaussians, with similar results; however, they didn’t explicitly point out this departure. Verschuur & Magnani (1994) and Heiles (1989) analyzed emission profiles and found numerous components with widths in this range, but without absorption data could not conclusively state that the kinetic temperatures were indeed so high.

The large fraction of WNM in the thermally unstable regime violates a fundamental cornerstone of equilibrium ISM models such as MO, which all rely on thermal pressure equilibrium to push the gas into one of the thermally stable CNM or WNM phases. This result seems to push us towards other types of model. Two possibilities include time-dependent models such as the supernova-dominant model of Gerola, Kafatos, and McCray (1974) and turbulence-dominated models such as Vázquez-Semadeni, Gazol, & Scalo (2000).

3.2. The CNM

Figure 2 exhibits the histogram of derived spin temperatures for all CNM components. Both most of the components and most of the mass have $T = 25 \rightarrow 75$ K. This is in marked contrast to previous results, where histograms were born over the ranges $20 \rightarrow 140$ K (MWKG) and $50 \rightarrow 300$ K (DSF, PST). Our range is narrower and, moreover, temperatures extend to very low values, with significant contributions down to $T = 10$ K.

The peak above $T = 25$ K agrees very well with the high angular resolution results of KSG and, also, theory. WHIMTB included all known processes in calculating their standard model, for which the CNM equilibrium temperatures range from $25 \rightarrow 200$ K (the corresponding densities are $n_{HI} \geq 1000 \rightarrow 4$ cm$^{-3}$). Our observed temperature range is smaller and corresponds to $n_{HI} \geq 250 \rightarrow 20$ cm$^{-3}$ and $T \leq 10000 \rightarrow 15000$ cm$^{-3}$ K. These numbers are in accord with ISM pressure measurements (Jenkins, Jura, & Lowenstein 1983).

Temperatures as low as our $10 \rightarrow 20$ K range can occur in the absence of the PAG-type grains that produce grain heating (WHIMTB; Bakes and Tielens 1994). In this case, heating is by photoionization of carbon and cooling by electron recombination onto ionized carbon (Spitzer 1978). Such cold (and even colder) gas was invoked by Heiles (1997) to help understand the existence of tiny-scale atomic structure; the present results are encouraging for that interpretation.

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FIG. 1.—21-cm line absorption (top) and emission (bottom) spectra for 3C18. In the absorption spectrum, the solid line is data and the dash-dot line is the fit; crosses indicate the central e$^{-T}$'s and halfwidths of the three Gaussian component parameters. In the emission spectrum, the solid line is the data; the dashed line is the contribution from the three CNM components, the dotted line from the WNM component, and the dash-dot line their sum. Dash-dot lines in both figures are the fits and are so close to the data that they are hard to distinguish.
Fig. 2.—Histograms of derived temperatures. The top two frames are upper limits on kinetic temperature for the WNM derived from line widths; of these, the top gives the number of Gaussian components and the bottom the HI column density in units of $10^{20}$ cm$^{-2}$. Off the graphs to the right, with upper limits exceeding $10^4$ K, are 21 components (44%) containing $N(HI) = 45 \times 10^{20}$ cm$^{-2}$ (43%). The bottom two frames are values (not limits) of spin temperature derived from absorption/emission data. Off the graphs to the right, with spin temperatures exceeding 100 K, are 8 components (9%) containing $N(HI) = 37 \times 10^{20}$ cm$^{-2}$ (90%).