TINY-SCALE ATOMIC STRUCTURE AND THE COLD NEUTRAL MEDIUM

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ABSTRACT

We consider the tiny-scale atomic structure (TSAS) on scales of tens of astronomical units, which has been detected by 21-cm absorption lines against quasars with VLBI techniques, against pulsars with time variability and against close binary stars in optical interstellar lines. The TSAS is associated with ordinary cold neutral medium (the CNM). Under the conventional interpretation, the thermal pressure of the TSAS gas is extremely high, some 44 times greater than the Galactic hydrostatic pressure at $z = 0$ and 4,300 times greater than the standard CNM thermal pressure. This is unacceptable because the TSAS is quiescent, ubiquitous, and appears to reside in all CNM clouds. Moreover, under the conventional interpretation, $H_2$ should be very abundant in the TSAS, thus exacerbating the pressure problem and also leading to very large extinctions.

We consider modifications in the conventional interpretation to ease these dilemmas. They can be eased if the TSAS temperatures are very low, $\sim 7.5$ K, but with conventional heating and cooling mechanisms this is impossible without large attenuation of the interstellar radiation field, rather, we estimate the TSAS temperature to be $\sim 15$ K. We settle on a geometric solution in which the CNM clouds contain two components: one is the TSAS gas, in the form of either cold, dense curved filaments or sheets; the other is the inter-TSAS gas, which is warmer and less dense. Recognizable TSAS occurs where these TSAS structures happen to line up along the line of sight, producing significant column densities and small transverse length scales even with relatively modest volume densities. We discuss these two-component CNM clouds as complete, integral units and consider the conditions required to simultaneously satisfy the observational constraints on both the standard CNM clouds and also the TSAS. The sheets or filaments occupy a few percent of the CNM cloud volume and contribute about 10% or 30% (respectively) of the total CNM column density. The sheets produce smaller thermal pressures than the cylinders; the sheet pressures can be as small as the standard CNM pressure. We provide suggestions for further observations that will confirm the geometric solution and possibly distinguish between filaments and sheets.

Subject headings: ISM: clouds — ISM: structure — turbulence
ADOPTED TSAS PROPERTIES (Stanimirovic et al 2007)

Column density (units $10^{18}$ cm$^{-2}$):

$$N(HI)_{TSAS,18} = 0.75 T_{15}$$ \hspace{1cm} (1)

Plane-of-the-sky scale length

$$L_{TSAS,\perp} = 30 \text{ AU}$$ \hspace{1cm} (2)

The line-of-sight scale length ($G$ is anisotropy factor)

$$L_{TSAS,\parallel} = GL_{TSAS,\perp}$$ \hspace{1cm} (3)

$N(HI)_{TSAS}$ and $L_{TSAS,\parallel}$ provide (units $100$ cm$^{-3}$)

$$n(HI)_{TSAS,2} = \frac{N(HI)_{TSAS}}{L_{\parallel}} = \frac{17 T_{15}}{G}$$ \hspace{1cm} (4)

And the pressure ($\tilde{P} = \frac{P}{k}$; units $4000$ cm$^{-3}$ K)

$$\tilde{P}_{TSAS,4K} = 6.25 \frac{T_{15}^2}{G}.$$ \hspace{1cm} (5)
CNM resides within a warmer phase.

If $P_{\text{CNM}} > \text{MAX}$, then the warmer phase cannot exist.

If $P_{\text{CNM}} < \text{MIN}$, then the CNM cannot exist—unless it is embedded in high-pressure HIM.

CONCLUSION: The CNM pressure must lie between MIN and MAX—a factor of only 2.5!

(from Wolfire et al 2003)
THERMAL EQUILIBRIUM?

WITH THERMAL AND PRESSURE EQUILIBRIUM:

We require $G \sim 6$; not too unreasonable

Time for equilibrium $\sim 10^5$ years; “too long”?  
Evaporation time if embedded in WNM $\sim 60$ years; “too short”?

WITHOUT EQUILIBRIUM—ASSUME 10 TIMES OVERPRESSURE:

Can be embedded ONLY in the HIM.  
In HIM, evaporation time is instantaneous. Too short!!  
Expansion at $\sim$Mach 10, $\sim 0.3$ km/s. 15 years to move 100 AU. “too short?”

Overpressure means overdensity and decreased time for equilibrium, making nonequilibrium less probable.
THERMAL EQUILIBRIUM?

Equilibrium: heating rate = cooling rate
Cooling: no molecules: it’s only CII excitation:

\[ n^2 \Lambda = 3 \times 10^{-27} n(HI)^2 \left[ 1 + 0.42 \frac{x}{10^{-3}} \right] e^{-92/T} \text{ erg cm}^{-3} \text{s}^{-1} . \]

(1)

First term: HI collisions; second, electron collisions.

Heating is another matter. We assume no PAHs; their heating gives \( T \sim 60 \text{ K} \), too high. This leaves:

1. Ionization of CI by starlight. This gives \( T = 16 \text{ K} \).

2. Ionization of HI by cosmic rays. This gives \( T = 33 \text{ K} \).

We observe the Knapp/Verschuur cloud with \( T=17 \text{ K} \). This argues CR heating is unimportant everywhere in the local neighborhood.
In the interiors of dense clouds, the opacity reduces the radiant energy density so sharply that optical pumping becomes unimportant, and \( \Lambda_{H_2} \) becomes positive. However, the kinetic temperature of such clouds is normally much less than \( E_{01}/k \), which equals 510 K, and the exponential factor in \( n(2) \) [see equation (2-27)] reduces \( n(2)/n_H \) in equation (6-14) so sharply that \( \Lambda_{H_2} \) is negligible. At low temperatures, HD radiates more strongly in the infrared than does \( H_2 \), since the HD transition from \( J = 1 \) to \( 0 \) is permitted, and \( E_{01}/k \) is only 130°. Thus even if \( n(1D)/n(1H) \) is as low as 1/20,000, HD will contribute more to \( \Lambda \) than will \( H_2 \) for \( T < 80° \) [6]. Cooling within dense clouds by line radiation from CO, CH, and CN molecules with even lower \( E_{01} \) can be important [6], but the high opacity in the lines must be considered. Cooling and heating of the gas by collisions with dust grains, whose temperature is determined primarily by radiative processes [59, 1a], can be a dominat element in the thermal equilibrium of dense clouds.

A general picture of the overall loss function in \( H I \) as well as in \( H II \) regions is provided [6] in Fig. 6.2. For \( T < 10,000°K \), curves are shown for several different values of \( x \), here defined as \( n_e/n_H \); when \( x \) drops to \( 10^{-3} \), collisional excitation of atoms and ions by neutral \( H \) atoms dominates \( \Lambda \). Cooling by \( H_2 \) molecules is ignored in Fig. 6.2. The steep rise in \( \Lambda \) at about 10,000° results in part from the collisional excitation of \( H \) [see equation (6-12)] and in part from the marked increase of \( n_e \) as the Hydrogen becomes ionized.

As in \( H II \) regions, we determine the cooling time \( t_\Lambda \) from Fig. 6.2 on the assumption that \( T > T_e \); then \( \Lambda \) is correspondingly much greater than \( \Gamma \) in equation (6-1). With \( x \) taken at its minimum value of about \( 5 \times 10^{-4} \), corresponding to full ionization of C, Fe, and Si, we obtain for no depletion and with \( H_2 \) cooling again ignored

\[
t_\Lambda = 2.4 \times 10^6 \frac{n_H}{n_e} \text{ years,} \tag{6-15}
\]

with an accuracy of roughly 30 percent for \( n_e \) between 1 and 300 cm\(^{-3}\) and for \( T \) between 50 and 600°K. Thus the cooling time in \( H I \) gas is about 10 times that in the \( H II \) region with the same \( n_H \), but with \( T \approx 10,000°K \). Since \( n_e \) is normally several orders of magnitude less than \( n_H \) in \( H I \) regions, the radiative recombination time \( t_\Lambda \), given in equation (6-11), is usually longer than \( t_\Lambda \), even if the radiating atoms are depleted while the ionized ones are not.

b. Heating Function \( \Gamma \)

Among the energy gain processes, the only significant one that is known with reasonable accuracy is \( \Gamma_{e\gamma} \), the gain corresponding to electron capture by C II and other ions, with subsequent photoionization. This quantity is given by the equations obtained previously [56, 1a]; for C II the functions \( \phi_e \) and \( \chi_e \) must be used in equation (6-9), since the \( n = 1 \) shell is occupied, and recaptures occur to the levels with \( n > 2 \). If only C II is considered and excitation of ions by neutral \( H \) atoms is ignored, equating \( \Lambda_{e\gamma} \) to \( \Gamma_{e\gamma} \) yields

\[
T_e = 16°K, \tag{6-16}
\]

independent of \( n_e, n_H \), or the lowest boundary of C II. To obtain this result we have assumed that \( E_{\gamma} \approx 2 \) eV. Allowance for \( \Lambda_{H_2} \) reduces \( T_e \) somewhat.
Knapp/Verschuur cloud: 17 K; a very thin sheet (0.03 pc).
OPTICAL LINES FROM MINORITY IONIZATION SPECIES

Common optical interstellar absorption lines like NaI are produced by minority ionization species (ion state \( r \)). We have

\[
\text{Abs line str } \propto \frac{n_r}{n_{r+1}} = \frac{\alpha n_e}{\Gamma},
\]

Generally \( \alpha \propto T^{-0.6} \). Also \( n_e \propto \frac{P}{T} \). We assume that all electrons come from Carbon, that Carbon is fully ionized, and that \( \frac{n_r}{n_{r+1}} \ll 1 \). We have

\[
\text{Abs line str } \propto P T^{-1.6}
\]

The total \( T \) dependence is quite steep, \( T^{-1.6} \)—even steeper than HI, which goes as \( T^{-1} \).

Cold TSAS should have stronger optical lines than standard CNM.
ENVIRONMENT AND EVAPORATION

CNM clouds are enveloped within another gas phase: warmer CNM, WNM, WIM, or HIM. Small clouds lose mass by evaporation; large clouds gain mass by condensation (Cowie & McKee 1977).

For CNM embedded in WNM, at $\tilde{P}_{4K} = 1$, $r_{crit} \sim 4000$ AU. TSAS is smaller than this so it should evaporate.

For CNM embedded in $10^6$ K HIM, $r_{crit} \sim 25$ pc; most CNM structures are smaller, so they all evaporate. Contrary to intuition, the mass evaporation rate $\dot{M} \propto R$, not $R^2$.

1. For a TSAS sphere with radius 30 AU embedded within the WNM at 8000 K, $t_{evap} \sim 60$ years—SHORT!!

2. Embedded in WIM, $t_{evap} \sim 2000$ years—still short!

3. For the HIM at $10^6$ K, evaporation is instantaneous.

To reduce evaporation rate we need an unsharp interface: TSAS embedded in standard CNM, embedded in WNM or perhaps WIM.
IF TSAS IS DISCRETE STRUCTURES...

- $P/k \sim 4000 \text{ cm}^{-3} \text{ K}$
- $T_{\text{low}}, \sim 18 \text{ K}$
- $L_{\perp} \sim 30 \text{ AU}$
- $L_{\parallel} = G L_{\perp} \sim 190 \text{ AU}$
- Strong optical absorption lines such as NaI
- Evaporation time $\sim 60 \text{ yr}$ unless the boundary is fuzzy (meaning: cold TSAS to warmer CNM to WNM and beyond)
- **BUT**…our 17 K cloud resides in HIM! (so much for theory!)