Evidence and Implications of Pressure Fluctuations in the ISM

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Abstract. A recent survey of the fine-structure excitation of neutral carbon reveals that the interstellar medium in the Galactic plane exhibits a thermal pressure, \( nT/k \), that ranges from about \( 10^3 \) to \( 10^4 \) cm\(^{-3}\)K from one location to the next, with occasional excursions in excess of about \( 10^5 \) cm\(^{-3}\)K. The large excitations for small amounts of gas indicate that some regions are either subjected to shocks or must be pressurized within time scales much shorter than the time needed to reach thermal equilibrium. These rapid fluctuations probably arise from the cascade of macroscopic mechanical energy to small scales through a turbulent cascade. One consequence of this effect is that changes in gas temperature can arise from near adiabatic compressions and expansions, and this may explain why investigations of 21-cm emission and absorption reveal the presence of hydrogen at temperatures well below the expected values derived from the balance of various known heating and cooling processes.

Keywords: Dynamics, Thermal Pressure, Gas Phases, Turbulence, Structure

Abbreviations: ISM – Interstellar Medium

1. Introduction

While gases within the Milky Way show enormous ranges in density and temperature, the simplest, most general picture is that variations in the product of these two quantities, the thermal pressure, are very much smaller by comparison. This may be true at the most superficial level, and indeed a convincing theory (at the time) of the ISM (Field, Goldsmith & Habing 1969) was built upon the premise that the observable phases of the ISM arise simply from a thermal instability (Field 1965) with uniform heating at a nearly constant pressure. In this picture, the cool phase is reasonably static and confined by a uniform external pressure from a surrounding warm medium. It is now more apparent that this tranquil picture of the ISM is probably unjustified since we have known for some time that disturbances over macroscopic scales arising from supernova explosions, newly formed H II regions, stellar mass loss, bipolar flows, infalling gas from the halo and Galactic density wave shocks can all inject significant mechanical energy in various locations and disrupt the medium.
A major refinement in the theory of the ISM was created by McKee & Ostriker (1977), who recognized some important global consequences of energetic phenomena, which can lead to the creation of large filling factors for material at high temperatures and low densities [see also (Cox & Smith 1974; Cox 1979, 1981)]. An often overlooked property of the McKee & Ostriker model [e.g., (Cox 1995)] is that the pressures should vary by significant amounts from one location to the next (Jenkins, Jura & Loewenstein 1983). Ultimately, we should expect that large-scale enhancements and rarefactions in the pressures should become more widespread and chaotic as they propagate to different locations and migrate to smaller scales through the creation of a turbulent cascade (Mac Low et al. 2001).

Thermal pressures are a minor component of the total ISM pressure, which also includes magnetic, dynamical (i.e., turbulent) and cosmic ray components. Boulares & Cox (1990) estimated that the weight of material on either side of the Galactic plane should balanced by a total pressure $p/k = 2.5 \times 10^4$ cm$^{-3}$ K. Inasmuch as typical thermal pressures are about a factor 10 lower and thus seemingly of little importance dynamically, one might wonder why we are interested in their average value and distribution over different volumes of space. The answer arises from several considerations: first, thermal pressure values are molded by processes arising from the other forms of pressure and thus convey important information, second, they reflect the physical state of the gas at the atomic scale and thus have an influence on various reaction rates and equilibria, such as those pertaining to ionization, heating, cooling and chemistry. Finally, thermal pressures are easy to measure.

There are various ways to determine thermal pressures, but probably the most straightforward one is by measuring the relative populations of atoms in the excited fine-structure levels of their ground electronic states. This can be done by observing absorption lines of the atomic multiplets, seen in the uv spectra of hot background stars. The fine-structure levels are populated by collisions with other atoms, ions, molecules, and electrons. The excitations (and de-excitations) occur at rates proportional to the local densities of these collision partners, and a balance between these processes and the spontaneous radiative decay of the upper levels establishes an equilibrium (with a very short time constant) determined by the local density and temperature of the gas.
2. Thermal Pressures from C I Fine-structure Excitation

Of the various species that have ground electronic states with two or more fine-structure levels, in most circumstances neutral carbon seems to be the most useful one for indicating local conditions. While one is not able to determine unique values for either temperature or density, Jenkins & Shaya (1979) showed that under the most common conditions in the ISM their product was reasonably well defined from the two population ratios of the upper levels with respect to the total in all three states. Moreover, since the problem is over-determined by having more than one ratio, it is possible to differentiate between a uniform, medium pressure and an admixture of two or more regions having low and high pressures, even if they have the same radial velocity. The latter property was exploited by Jenkins & Tripp (2001) (hereafter JT01) to show that there was pervasive evidence for a small amount of gas at \( p/k > 10^5 \text{ cm}^{-3} \text{ K} \), some two orders of magnitude above the general average pressure.

Figure 1 shows the amounts of C I within different pressure intervals that were found in a survey of 21 stars by JT01, who used the highest resolution mode (E140H with the narrowest entrance slit, yielding \( R = 200,000 \)) of the \textit{Space Telescope Imaging Spectrograph} on HST. The pressure distributions show a clear link to the kinematical properties of the gas: disturbed material outside the range of normally allowed radial velocities are dominant at high pressures, while the lowest extremes in pressure appear to be quiescent. From this it seems clear that the thermal pressures are responding to dynamical processes, as we would expect. The preponderance of negative velocity gas at high pressures probably arises from material compressed by mass flows from the target stars or their neighbors in the early-type stellar associations.

As we consider the evidence from C I, we must acknowledge that the distribution of pressures reflects material weighted by the respective abundances of C I, which in turn are governed by the ionization equilibrium of C I with the more common form of carbon, C II. This effect exaggerates the amount of high-pressure material because there is a shift toward greater C I/C II at high densities. If the gas can be characterized with an equation of state (see §3) \( p \propto n^{\gamma_{\text{eff}}} \), where \( \gamma_{\text{eff}} \) is the barytropic index,

\[
n(\text{H I}) \propto p^{0.324 - 1.622/\gamma_{\text{eff}}} n(\text{C I}) \ .
\]

Eq. 1 shows the correction\(^1\) that must be applied to the C I pressure distribution function to obtain an even-handed representation for all

\(^1\) The coefficients in the exponent of \( p \) are derived from the calculations of carbon ionization equilibria by Jenkins (2002) which include not only recombinations of ions
Figure 1. A histogram indicating the relative amounts of C I in different logarithmic intervals found by Jenkins & Tripp (2001), with the gas segregated according to whether the radial velocity is below, within, or above the allowed range of velocities between the observer and the star, as determined from estimates for the effects of differential Galactic rotation along the respective sight lines.

of the neutral gas. The transformations of the distributions for three different values of $\gamma_{\text{eff}}$ are shown in Fig. 2.

3. The Effects of Changes in Pressure

We now imagine what happens when the ISM is in a chaotic state where dynamical processes force the pressures to vary with position and time on either side of some mean value. In this picture, we may characterize the pressure fluctuations as random. Even though temperatures and with free electrons but also their neutralization by very small, negatively-charged dust grains (Weingartner & Draine 2001).
Figure 2. Transformations of the original C I pressure distribution (top panel: sum of all velocity intervals depicted in Fig. 1) to the total amounts of gas for 3 values of the barytropic index $\gamma_{\text{eff}}$ (lower 3 panels), derived by applying Eq. 1 to each pressure interval. The three values of $\gamma_{\text{eff}}$ represent (1) 0.72: approximate slope of the thermal equilibrium relation, 1.00: isothermal gas, 1.67 purely adiabatic behavior.

Densities may vary, we must still insist that a balance between heating and cooling is maintained over a time interval much longer than the characteristic thermal time scales. Of course, our assumption about randomness is an idealization: in large part the real data will reflect this condition, but from time to time coherent effects (pressurizations) from specific sources are bound to manifest themselves and distort the results.

Wolfire et al. (1995) have calculated thermal equilibria of the ISM using recent refinements in the estimates for various processes that contribute to the heating and cooling. Two of their equilibrium curves are shown in the three panels showing $\log(p/k)$ vs. $\log n$ of Figure 3. If we propose that pressure changes are very slow compared to the thermal equilibration time, then the gas will adjust its temperature to agree with the equilibrium line as the pressure changes from one extreme to another (solid curve). This condition is shown in the top.
panel of the figure. However, the results of JT01 indicate that such slow changes for the more extreme excursions are not realistic, since large positive pressures would cause the temperature to drop to the point that the CI excitations become very small, contrary to what is observed. JT01 found that $\gamma_{\text{eff}} > 0.90$, i.e., measurably larger than $\gamma_{\text{eff}} \approx 0.72$ for the equilibrium curve.

At the opposite extreme, very rapid fluctuations in pressure will cause the gas to move along an adiabat, where $\gamma_{\text{eff}}$ becomes the real value of $\gamma$, $c_p/c_v = 5/3$, as is illustrated in the middle panel of Fig. 3. Also, if the gas is subjected to supersonic turbulence, shocks will form and cause momentary excursions of the temperatures up to about 1000 K for Mach numbers $M \approx 10$.

Finally, we may consider a contrived but pedagogically useful situation where the pressure driving function is approximately a square wave. Here, a cycle may be established where rapid adiabatic expansions and compressions have interludes where the gas may approach its thermal equilibrium for the given pressure. In this last case, somewhat larger extremes in temperature may be achieved. The significance of this possibility is discussed in the next section.

4. The Puzzle of Cold HI

Recent surveys of 21-cm emission and absorption are providing convincing evidence that temperatures of neutral hydrogen in the ISM in many cases deviate substantially from the values expected from thermal equilibrium (Gibson et al. 2000; Heiles 2001; Knee & Brunt 2001; Dickey et al. 2002; Heiles & Troland 2002). [The part of the equilibrium curve with a negative slope in Fig. 3 is unstable to bifurcation into separate warmer and cooler phases (Field 1965; Shull 1987; Begelman 1990).] In a chaotic medium, one can understand why temperatures that are intermediate between the two principal stable phases may be present. It is easy to imagine that mixing of warm and cool phases can operate over timescales shorter than the time needed to segregate the gas into stable high and low temperature branches of the equilibrium curve (Vázquez-Semadeni, Gazol & Scalo 2000; Gazol et al. 2001). However, HI temperatures below a value of about 30 K are more difficult to accept. Occasionally, temperatures as low as 10 K have been recorded.

One initially might propose that the very cold temperatures imply simply a diminution of the heating rate or enhancement of the cooling rate. For instance, perhaps there is a deficit of small grains that are responsible for photoelectric heating. While this may sound like an attractive solution, Wolfire et al (1995) show that the dust-to-gas ratio
Figure 3. Three schematic illustrations of how the logarithms of the ISM pressures (ordinates) and densities (abscissae) could change for different hypothetical driving functions of pressure as a function of time (three periodic waves on the left). The dashed curves inside the panels show the thermal equilibrium curves of Wolfire et al (1995) for column densities \(N(\text{HI}) = 10^{19}\) cm\(^{-2}\) (lower curve) and \(10^{18}\) cm\(^{-2}\) (upper curve) for shielding against external EUV radiation. Top panel: Very slow changes in pressure (shown to the left of the panel) result in the gas conditions moving up and down the thermal equilibrium curve with a slope in the log \(p\) – log \(n\) plane of \(\gamma_{\text{eff}} \approx 0.72\). The temperature extremes (heavy dots) for pressures ranging from \(10^3\) to \(10^4\) cm\(^{-3}\) K are 166 and 30 K. Middle panel: Very rapid changes in pressure will cause the gas to move on an adiabatic track (\(\gamma_{\text{eff}} = 5/3\)) with temperature extremes of 30 and 76 K for the same pressure differences. Bottom panel: A square-wave driving function can achieve larger temperature extremes of 12 and 76 K, as the gas is forced to move on the parallelogram track in a clockwise fashion.
must be lower than one-tenth the normal value to have temperatures as low as 15 K, a value that is still above that of some of the 21-cm absorbing clouds. Many of the cold clouds seem not to be identified with regions containing molecules which could add to the cooling rate (Gibson et al. 2000).

A possible solution to the cold H I problem could arise from the existence of mechanical cooling due to rapid pressure fluctuations. A single cycle of pressure changes, perhaps one that somewhat approximates the square-wave idealization shown in the bottom panel of Fig. 3, could achieve a temperature as low as 12 K soon after a rapid expansion from a thermally stabilized condition starting at \( p/k = 10^4 \text{ cm}^{-3} \text{ K} \).

However, in order for decompressions to drive the gas along an adiabat, they must occur over a time scale\(^2\) that is much shorter than the heating time,

\[
t_{\text{heat}} = \frac{(5/2) kT}{\Gamma} \tag{2}
\]

\( \approx 5500 \text{ yr} \) at \( T = 30 \text{ K} \) if the heating rate \( \Gamma = 6 \times 10^{-26} \text{ erg s}^{-1} \text{ atom}^{-1} \) that is typical for the cold, neutral medium (Wolfire et al. 1995). A cloud that is suddenly relieved of an external confining pressure will expand only at its sound speed,

\[
c_s = (\gamma p/\rho)^{1/2} \tag{3}
\]

which equals 0.54 km s\(^{-1}\) for \( T = 30 \text{ K} \). If the cloud’s shape is a sheet, then the factor of 4 drop in \( n(\text{H}) \) shown in Fig. 3 could be accomplished in less than 5500 yr if the thickness were less than about \( 10^{-3} \text{ pc} \) (cylindrical or spherical clouds could satisfy this condition if they had diameters larger by factors of \( 3^{1/2} \) and \( 3^{2/3} \), respectively). However, in a medium where there is supersonic turbulence, random inertial forces in the fluid can create large positive mass divergences and drag a dense region apart at an expansion rate comparable to the random velocities present, which may exceed the sound speed by a large factor. Thus, roughly speaking, if the average Mach number of the turbulence is 10, we may expect an increase of the limiting size for nearly adiabatic cooling to \( \sim 0.01 \text{ pc} \).

Over recent years, new findings from optical absorption lines (Meyer & Lauroesch 1999; Lauroesch, Meyer & Blades 2000; Andrews, Meyer & Lauroesch 2001) and 21-cm line absorption (Dieter, Welch & Romney 1976; Diamond et al. 1989; Frail et al. 1994; Davis, Diamond & Goss 1996; Faison et al. 1998; Faison & Goss 2001) have shown unmistakable

\(^2\) The arguments presented here apply to gas that is mostly in atomic form. See Ballesteros-Paredes, Vázquez-Semadeni & Scalo (1999) for a similar discussion that applies to dense, molecular clouds.
evidence that in almost any viewing direction the ISM exhibits large contrasts in density\(^3\) over scales ranging from \(2 \times 10^{-5}\) to 0.03 pc. These observations provide strong support for the pervasive character of small structures, a conclusion that is consistent with their being shaped by the action of turbulence.

5. Final Remarks

A major theme advanced in this paper is that the pressures and hence structure of the ISM change rapidly and are probably molded by chaotic velocity fields that converge and diverge. This is a significant departure from the picture that high densities arise simply from static “clouds” that are stabilized by a uniform external pressure. The notion that such clouds may be an oversimplification is not new: the nondiscrete character of ISM phases was imagined by Chandrasekhar & Münch (1952) when they stated, “. . . the distribution of density is considered to be continuous but exhibiting fluctuations of a statistical character.” This outlook was formed long before interstellar turbulence was a fashionable topic.

An important consideration that arises from the dominant role of interstellar turbulence is that under many circumstances the density condensations are ephemeral (unless gravitational binding or the coherent, large-scale dynamical processes listed in §1 become important). As a consequence, pressure enhancements of very short duration may allow some of the more rapid atomic and chemical processes to take place, but other reactions may not achieve an equilibrium state. For instance, the time needed to adjust the rotational temperatures of H\(_2\) range from 7000 yr for moderate \(J\) levels to change by 2 as they collide with H, to about 90,000 yr for transitions between ortho and para hydrogen caused by collisions with protons. The equilibrium between molecular and atomic hydrogen in the general ISM has a time constant that ranges from about 600 yr for unshielded regions to over \(10^7\) yr for shielded regions. In view of the strong indications that pressures can change over time scales intermediate between these extremes, we must view with caution any interpretations that assume that these phenomena have advanced uniformly to an equilibrium state.

\(^3\) In interpreting raw information from either the visible absorption line or 21-cm absorption results, one must acknowledge that they have temperature dependences \(T^{-0.62}\) and \(T^{-1.00}\), respectively.
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