Highlights of Astronomy, Volume 16
XXVIIIth IAU General Assembly, August 2012
T. Montmerle, ed.

doi:10.1017/S174392131401237X

Observational constraints on the multiphase ISM

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Abstract. In recent years we have seen a wealth of new observations and analysis that sheds light on the distribution and physical properties of various ISM phases. In particular the thermal pressure from C I (Jenkins & Tripp 2011) shows the bulk of the CNM phase with a log normal pressure distribution. It appears that thermal instability is important for phase separation, but with with a thermal pressure variation about the mean driven by turbulence. In additional, there is evidence from C I, H_2, and complex molecules, of both higher and lower pressure environments. An additional "phase" that is of increasing interest for high z, low metallicity galaxies is the C^+/H_2 gas that is not traced by H I or CO. This review presents the observational evidence for the existence and physical properties of these various ISM phases.

Keywords. ISM: general, ISM: clouds, ISM: structure

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1. The cold and warm neutral gas phases

1.1. *Thermal pressure*

The term "phase" generally refers to gas within a distinct temperature regime. The cold neutral atomic gas or CNM is at about 100 K, and the warm neutral atomic gas or WNM is about 8000 K. The thermal pressure in the CNM has recently been re-evaluated by Jenkins & Tripp (2011; hereafter JT) using UV absorption spectroscopy of C I. In a mass-weighted PDF they find a median thermal pressure of about $P/k \approx 3800$ K cm^{-3}. The distribution is fit by a log-normal distribution between $\log P/k$ 3.2 and 4. A log-log plot of the PDF shows deviations from the log-normal distribution at low column densities. There is both a high pressure wing (up to $\log P/k \sim 4.6$) and low pressure wing (down to $\log P/k \sim 2.0$). By estimating the UV radiation field along each line of sight, JT argue that the high pressure clouds are close to massive stars and the pressures are affected by mechanical processes such as winds and shocks. The higher pressure clouds are not characteristic of the diffuse ISM. For the low pressure clouds JT suggest that at sizes < 1000 AU the eddy turnover times are shorter that the radiative cooling times and thus the gas is acting closer to adiabatically or $\gamma > 1$. Passot & Vázquez-Semadeni (1998) found that for adiabatic indexes greater than 1, the distribution will be skewed towards lower values. similar to that found by JT.

The width and shape of the pressure distribution is produced by turbulence but what sets the median thermal pressure? Kim *et al.* (2011) have carried out simulations of a multiphase galactic disk. In a thermal pressure versus density (phase) diagram, most of the mass lies along the thermal equilibrium curve. They find a distinct CNM phase and a distinct WNM phase with some mass at thermally unstable temperatures. The median pressure is close to the "two phase" pressure $P_{2p} = \sqrt{P_{\min} P_{\max}}$ where $P_{\min}$ and $P_{\max}$ are the minimum and maximum pressures allowed for two phases (Wolfire *et al.* 2003). Thus, the distribution of thermal pressures in the CNM appear to be set by turbulence with a median pressure set by the two phase pressure.

There are also constraints on the CNM gas temperature from UV absorption studies of the ground state H_2 Ortho and Para column densities. For diffuse gas ($A_V < 1$) the mean temperature is about 80 K (Rachford *et al.* 2009).

1.2. *Hot pockets*

In addition to the log-normal distribution in thermal pressures JT required a small (0.05%) mass of gas at high pressure ($P/k \sim 3 \times 10^5$ K cm^{-3}) along each line of sight. This could be a manifestation of small scale turbulence or turbulent dissipation. Additional observations have inferred pockets of small scale heating or density enhancements. For example 1)warm cloud chemistry that might produce HCO^+ and CH^+ (Godard *et al.* 2009; Falgarone *et al.* 2010), 2)Tiny Scale Atomic structure TSAS that appears in H I absorption on 10s of AU scales (Heiles 1997). 3)Warm diffuse H_2 seen in emission (Falgarone *et al.* 2005). 4)High H_2/PAH emission ratios seen in high latitude clouds (Ingalls *et al.* 2011), and 5)warm H_2 seen towards molecular cloud surfaces illuminated by low UV fields (Goldsmith *et al.* 2010; Habart *et al.* 2011).

There are plenty of H_2 observations, however, that can be fit with grain photoelectric heating that do not require mechanical heating. For example, Sheffer *et al.* (2011) fit the observed H_2 rotational line emission from NGC2023 with a PDR model with $n = 10^5$ cm^{-3} and $\chi = 4 \times 10^3$. In this high radiation field intensity, grain photoelectric heating is sufficient to reproduce the line emission.

1.3. *Thermally unstable gas*

There is some disagreement over the fraction of warm neutral medium that is thermally unstable. Based on the results by Heiles & Troland (2003) it is often "quoted" that 50% of the gas mass is in thermally unstable temperatures. First note that they found that locally 60% of the gas is WNM and 40% CNM (by mass). The fraction of thermally unstable gas applies to the WNM (60%) portion, and not the total. Note also that their Figure 2 shows two different distributions: in plane ($|b| < 10$) and out of plane ($|b| > 10$). For the in-plane distribution only $\sim$ 25% of the warm gas is outside the $7000 - 9000$ K range expected for thermally stable gas. Thus the thermally unstable gas is only about 15% of the the total in-plane gas mass when the cold phase is included. The out-of-plane distribution is quite odd with very little gas at $7000 - 9000$ K. It would appear that the in-plane gas is dominated by thermal instability plus turbulence while the out-of-plane gas is dominated by dynamical processes. Note also that the in-plane uncertainties are large and the statistics are poor. The in-plane results are based on only 8 lines of sight while the out-of-plane results are based on 79 lines of sight. Current (GALFA; Peek *et al.* 2010) and future (GASKAP; Dickey *et al.* 2012) H I surveys will certainly improve the statistics.

1.4. *Phase distribution*

Dickey *et al.*(2009) used an H I emission/absorption technique to measure the mean H I emission per unit length, the mean absorption per unit length, and the ratio of the two. They find that the ratio is nearly constant from the solar circle out to 25 kpc. This means that the ratio of CNM to WNM is nearly constant to 25 kpc. They also find that the volume averaged density and thus the thermal pressure drops by about a factor of $\sim$ 30 from the solar circle to 20 kpc. Wolfire *et al.* (2003) calculated a phase diagram for 18 kpc and found a $P_{\rm min}$ of about 10 lower than at the solar circle. Thus the inferred thermal pressure from H I observations is much lower than the calculated $P_{\rm min}$. How can the CNM/WNM fraction stay constant if the thermal pressure is less than $P_{\rm min}$? One way this might happen is if turbulence bumps up the pressure above $P_{\rm min}$ to maintain CNM gas. The constant ratio of CNM/WNM to large Galactic radii provides a strict model test.

2. Power spectrum of diffuse and dense gas

There are a number of Herschel PACS and SPIRE key projects that examine the structure and power spectrum of diffuse and dense gas. Miville-Deschênes et al. (2010) presented a SPIRE map at 250 μm of the Polaris Flare region. At $25''$ beam size numerous clumps and filaments are seen in this high latitude translucent cloud. The power spectrum was measured with a slope -2.7 from $\sim$ 0.8 pc down to 0.01 pc. The turbulent cascade extends to quite small sizes at least in these high latitude clouds. Filamentary structure is also seen in the Hi-Gal survey (Molinari *et al.* 2010). Image processing highlights the filamentary structure revealing star formation occurring along the filaments. What forms the filaments and clumps? Probably gravity, turbulence, and magnetic fields all play a role in creating filaments followed by fragment into cores via gravitational instability.

3. OVI column density

Another constraint on phase distributions comes from OVI column densities and mean abundances derived from FUV (FUSE) absorption line spectroscopy (Bowen *et al.* 2008). In collisional ionization equilibrium, the OVI abundance peaks at about 3×10^5 K. This is cooler than X-ray emitting material but warmer than WNM. The OVI comes from conductive interfaces or turbulent mixing layers. As Don Cox has pointed out many times, the line-of-sight averaged OVI is only a few 10^{-8} cm^{-3}, so there cannot be too many interfaces or else the abundance will be higher than observed. The FUSE observations are fit with 1.3×10^{-8} cm^{-3} . The emerging picture of a turbulent ISM is more complicated than having cold clouds embedded in either a hot or warm medium. Recent hydrodynamic modeling by de Avillez & Breitschwerdt (2005) have taken the OVI constrain into account.

4. Dark molecular gas

Dark molecular gas is is gas that has C^+ and H_2 but no or very little CO (Grenier *et al.* 2005; Wolfire *et al.* 2010). Of course it is not really dark but emits in C^+, CI, and IR continuum. The model calculation by Wolfire *et al.* (2010) find about 30% dark gas fraction over a range of giant molecular cloud masses - a value consistent with the gamma-ray observations reported in Grenier *et al.* (2005). More recent gamma-ray observations using FERMI Abdo *et al.* 2010) and IR observations from *Planck* (Planck collaboration 2011) find slightly higher fractions ($\sim 50\%$) but with large cloud-to-cloud variations. The dark gas may in fact not be molecular depending on optical depth effects in H I (Braun *et al.* 2009). Hydrodynamic models may account for the cloud-to-cloud variation and constrain the atomic fraction of dark gas.

Acknowledgements

M.G.W would like to acknowledge partial support for this work provided by NASA through awards issued by JPL/Caltech 1426973 and 1457797.

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https://doi.org/10.1017/S174392131401237X Published online by Cambridge University Press