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THz Observations of the Cool Neutral Medium

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Abstract. The astrophysical drivers for far-infrared spectroscopy of the Galactic interstellar medium using a 15m class telescope on Dome A are compelling. For the diffuse, atomic phase, the most important lines in the far-IR spectrum are OI at 63μm and CII at 158μm. These are the dominant cooling lines of the cool, neutral medium, and they show rich spectral structure in Herschel observations at low latitudes. But theory predicts that they should both be highly sub-thermal in excitation, so that the level populations are not in equilibrium with the kinetic temperature of the gas. A large single dish telescope or an interferometer may be able to study the absorption and emission to determine the optical depth and column density of atoms and the physical conditions in the emission regions. Comparison of Herschel CII spectra with 21-cm absorption spectra indicates that a significant fraction of the 158μm flux may be coming from the atomic rather than the molecular phase.

Keywords. line: profiles, ISM: clouds, ISM: atoms, ISM: structure, Galaxy: disk, infrared: ISM

1. Introduction

Unlike oxygen and nitrogen, the ionization potential of carbon is slightly less than that of hydrogen, 11.26 vs. 13.59 eV. These 2 eV make a huge difference to the energy balance of the interstellar medium (ISM), because photons that can ionize carbon fly freely through most of the volume of the Galactic disk, and are only blocked by the high column densities of dense, cool clouds. So C^+ is the dominant ionization state of carbon in the diffuse phases of the ISM, including most cool, neutral medium clouds (see Draine 2011 §31.7 and fig. 31.2). Observing the boundary between CII and CI is an effective way to trace the interface between the atomic and molecular phases of the medium. In a classical photo-dissociation region (PDR, Hollenback & Tielens, 1997), the neutral, atomic carbon is in a thin layer somewhat deeper inside the molecular cloud than the photodissociation front where hydrogen goes from atomic to molecular. But in the general ISM, different conditions may cause these two layers to reverse their order. This is important to find out, because CII is such an efficient coolant for the atomic medium.

2. The Fine Structure Lines

Studying the aggregate spectrum of the interstellar radiation field in the Milky Way and other spiral galaxies shows that a significant fraction of the total luminosity (0.1 to 1% of the far-IR continuum flux) comes out in the 158μm line (Stacey *et al.* 2010). Studies of cooling processes in the diffuse molecular and atomic phases of the ISM show that this line carries away most of the kinetic energy of the medium, since it is easily excited at kinetic temperatures of a few tens to hundreds of K (Wolfire *et al.* 1995, Draine 2011 §30.3 and Figure 30.1). The 63μm line of OI is the second most important coolant,

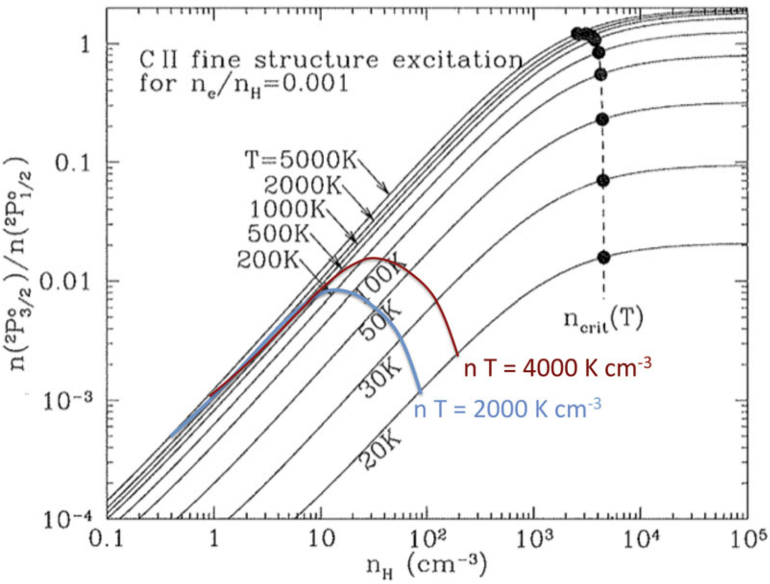

Figure 1. Level populations for the 158μm transition from Draine (2011, fig. 17.4). A typical range of kinetic pressures in the CNM and WNM are plotted. The implication is that the line will have very sub-thermal excitation, so that there may be a large reservoir of C^+ in the ground state, untraced by emission in the line.

and between them these two lines account for the most of the energy flow through the atomic ISM, at temperatures less than 10^4 K. So mapping the emission in these lines from the atomic medium is an important astrophysical diagnostic of conditions in the warm, neutral atomic medium (WNM) and the cool, neutral atomic medium (CNM), even though the total luminosity of the Galaxy in the lines may be dominated by HII regions and their nearby PDRs. In particular, the ratio of the strengths of the two lines is a sensitive diagnostic of the transition between the WNM and CNM, which is hard to trace by other means.

An important consideration for the far-IR fine-structure lines is their excitation temperature, i.e. the ratio of the populations of the upper and lower quantum levels expressed as a temperature through the Boltzmann equation. Figure 1 (taken from Draine 2011 fig. 17.4) shows the ratio of the level populations for the 158μm line as a function of density, with typical kinetic pressures for the CNM and WNM superposed. The density is two to three orders of magnitude below the critical density, n_{crit}, so the vast majority of the atoms are in the lower level. This means that observing the line in emission misses a huge reservoir of C^+ atoms that stay in their ground state. The 63μm OI line is similarly sub-thermally excited. Thus collisional deexcitation is very rare, and almost every collisional excitation of these two lines results in emission of a photon that carries energy away. But the long column densities of atoms in the ground state suggest that the optical depth of the line could be significant. Developing a way to measure the absorption in the line would be helpful. This technical challenge is a driver for future THz telescope design and construction. The Herschel and SOFIA observatories can begin the search for absorption in the 158μm line, but ultimately a large single dish telescope or an interferometer at the Antarctic Dome A site may be needed.

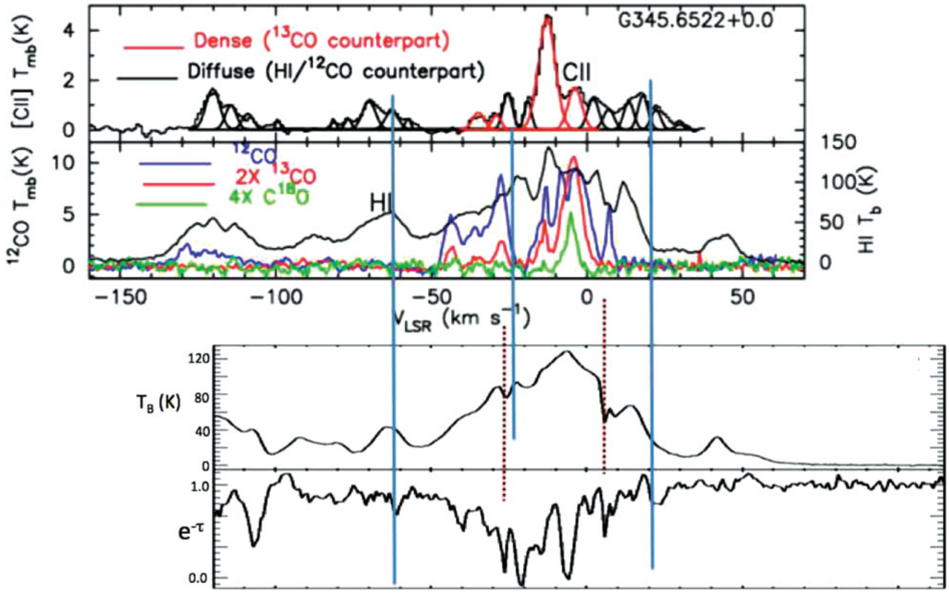

Figure 2. Spectra from Langer *et al.* (2010) showing the 158μm line (top panel) with comparison emission spectra in the 21-cm line (HI, and three CO isotopic species with different optical depths (^{12}CO, ^{13}CO, and C^{18}O) in the second panel. For comparison, the lower two panels show the 21-cm line emission and absorption toward a nearby continuum source, from Strasser (2006). Many of the CII line components show 21-cm absorption but no CO emission at all.

3. Molecular and Atomic Clouds

One of the most detailed studies of the 158μm line in the Galactic plane is that of Langer *et al.* (2010) made using the Herschel telescope. A typical line of sight, at (ℓ,b)=(345.65,0.0), is shown in Figure 2 (based on Langer *et al.*, 2010 fig. 3). Superposed on Figure 2, with the same velocity scales, are HI spectra from Strasser (2006). These show the 21-cm line of atomic hydrogen in emission (third panel) and absorption (bottom panel) in the nearby direction of a bright continuum background source at (ℓ,b)=(345.4,+0.2), taken from the Southern Galactic Plane Survey (McClure-Griffiths *et al.* 2005). As indicated by the vertical solid lines, there is good correspondence between the velocities of the molecule-free CII lines and the 21-cm absorption lines. Absorption in the 21-cm line occurs only in the CNM; the WNM contributes to the emission but not significantly to the optical depth (Dickey *et al.* 2003). Overall, the correspondence of the feature strengths in the CII spectrum with the 21-cm absorption is at least as good as with the ^{12}CO emission, and better than with the ^{13}CO and C^{18}O features.

Two interesting features of the 21-cm absorption spectrum are the deep but very narrow lines at v_{LSR} = -27 and +8 km s^{-1}. These components show corresponding dips in the 21-cm emission spectrum, indicating that the clouds are cold, so that they absorb the emission from gas at the same velocity in the background. Such features are common at low latitudes, and are often called HI self-absorption (HISA). HISA clouds may contain a significant fraction of the HI mass of the ISM (Gibson *et al.* 2005). They can be nearly invisible in 21-cm emission line surveys, but they appear clearly in absorption toward background continuum sources. Studying such clouds is one of the main goals of the GASKAP survey, planned for the Australian Square Kilometre Array Prototype telescope (Dickey *et al.* 2013).

4. Astronomy from Kunlun Station

The valiant work done by Chinese Antarctic explorers to develop and test the astronomical potential of the Dome A site is the foundation for several future telescopes that will operate at the Kunlun Observatory. Among the planned telescopes is the 5m diameter DATE5 THz/far-IR telescope. At $\lambda 158 \mu$m the beam size will be about $7''$. This small beam will allow on-minus-off observations toward bright continuum sources that can resolve away the confusion due to spatial variations in the emission, leading to very precise absorption spectra. If the 158μm line is optically thick in one or more phases of the ISM, the Kunlun Observatory may be the first to map the optical depth of the transition, throughout the inner Galaxy. This would be a breakthrough in ISM astrophysics. In addition to the possibility of detecting absorption at $\lambda\lambda 158$ and 63μm, the ratio of the emission brightness in these two lines will be a powerful diagnostic for distinguishing the different phases in the atomic and diffuse molecular ISM. Although the atmosphere will be a severe limitation on observing at these wavelengths, for some fraction of the time the lines may be accessible from Dome A, unlike any other site on the surface of the Earth. It is therefore well worth the attempt to study them from Kunlun Observatory.

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