Astro2020 Science White Paper

Probing the Interstellar Medium in the 2020s and Beyond

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract (optional): In this Science White Paper we describe how a dedicated facility with a wide field of view, large aperture, and a highly multiplexed, multi-object, high spectral resolution spectrograph (hereafter DWFMOS) will allow us to unify our understanding of the gas structure in galaxies by placing measurements of interstellar absorption features routinely used to trace diffuse gas (simple atoms, simple molecules and the Diffuse Interstellar Bands – DIBs) on an equal footing with those of H I and CO emission. This proposed facility offers an unprecedented dynamical range that will allow us to investigate diffuse gas across the Galaxy and hence better understand the gas structure, its physical conditions and will allow mapping of the transition from molecular and atomic gas traced by CO and H I emission more thoroughly through comprehensive studies of diffuse atomic and diffuse molecular gas solely observable in the UV/visible and sub-mm.

1 Galactic structure

Interstellar matter is a key component of galaxies and significantly influences their evolution. Most of the mass of this material is in the form of neutral gas and the associated dust, and it is studied on global scales through measurements of atomic hydrogen emission at 21 cm and CO emission at 2.6 mm, with the CO data used as a proxy for gas that is mainly molecular hydrogen.

Relatively recent observations of gamma-rays produced by cosmic-ray interactions with the neutral gas (Grenier et al. 2005) and of infrared emission from dust (Planck Collaboration et al. 2015) have revealed the presence of gas not associated with H I or CO emission: the so-called CO-dark H_2 gas. The GOT C+ Key Programme with the *Herschel Space Telescope* surveyed [C II] emission at 158 μm and combined these data with H I and CO spectra (Langer et al. 2010). This effort (Pineda et al. 2013; Langer et al. 2014) found that about 30% of the molecular material in the Solar Neighborhood was in the form of CO-dark H_2 gas.

We have argued (Sheffer et al. 2008; Rice et al. 2018) that diffuse molecular gas observed in absorption at visible, UV and sub-mm wavelengths is the same material as that forming the CO-dark H_2 gas. Some of the strongest absorption features come from CH and CH^+ in the visible, and from H_2 and CO in the UV, and HF and H_2O in the sub-mm. Diffuse molecular clouds (see Snow & McCall 2006, for a review) are considered clouds in transition from mainly atomic to fully molecular gas, hence an important first step in star formation. As a result, they play a crucial role in the lifecycle of the interstellar medium (ISM), making their study critical in advancing our understanding of how molecular clouds form. Because of their relatively low densities ($n_{\rm H}$ $\leq$1000 cm^{-3}) and their low shielding from UV radiation compared to dense clouds, diffuse clouds were expected to be mostly devoid of molecules. However, the last four decades of UV to radio observations, from space and the ground, have demonstrated that diffuse clouds have a surprisingly rich chemistry. While great strides have been made in describing the chemical pathways and physical processes at play in the diffuse gas (Sonnentrucker et al. 2007; Sheffer et al. 2008; Liszt et al. 2010; Neufeld et al. 2012; Sonnentrucker et al. 2015), significant questions remain to be answered.

One of these is the long-standing mystery related to the nature and identity of the DIBs. The DIBs are absorption features detected mostly in visible and NIR observations of the ISM, whether Galactic or extragalactic. The DIB carriers are thought to be of molecular origin based on over 90 years of accumulated observational evidence, but their true nature remains largely unknown to this day, thus pointing at a (potentially significant) missing link in our understanding of ISM physics and chemistry. Regardless of their true nature, our understanding of the DIB behavior has matured to a point at which about a dozen (of $>$ 500 now known, Hobbs et al. 2008, 2009) DIBs can be used as diagnostics of the atomic and diffuse molecular phases of the ISM (e.g., Sonnentrucker 2014; Welty et al. 2014; Lan et al. 2015; Fan et al. 2017).

2 Need for a DWFMOS

To date, absorption-line studies of the ISM, however, face some limitations. First, the distance from the Sun to intervening absorption components is typically less than about 1 kpc in the UV and visible range because of interstellar extinction. Second, the dynamic range of studied angular scales (UV, visible, submm, radio) is narrow (either large angular scales are covered but with many degrees of angular separation between individual pointings or small individual clouds are covered with high angular density pointings). Such limitations hinder the ability to generate a unified understanding of the gas structure in the Galaxy. This is mostly due to the available facilities: MOS on large aperture telescopes are not easily accessible for large surveys, while MOS on small aperture telescopes can only observe background stars up to about V=10. To probe material toward objects with V approaching 20 over a high dynamic range of angular scales requires a DWFMOS. Such a dedicated facility will observe stars and galaxies across the entire sky, allowing for very diverse surveys (Galactic, extragalactic, cosmological) to be pursued, while providing the necessary data for the Galactic absorption line studies proposed here. Hereafter we describe more specifically how the studies of the diffuse ISM would greatly benefit from a DWFMOS facility. We first look at the diffuse gas in clouds and supernova remnants (SNRs). Then we discuss the gains for the specific field of astrochemistry and the study of DIBs.

3 Diffuse Gas in Molecular Clouds and near SNRs

The GOT C+ survey utilized data on emission from H I and CO isotopologues to seek the types of material probed by their [C II] observations. Rice et al. (2018) merged the picture from the $Herschel$ survey with that from Pan et al. (2005) based on kinematic associations of absorption features and inferred a combined view that had the following components.
• Diffuse atomic clouds have components seen in Ca II, Ca I, H I, and sometimes [C II].
• Diffuse molecular clouds, or equivalently CO-dark H_2 gas, have components in [C II], K I, CH^+, CH, or CN without ^{12}CO or ^{13}CO emission.
• Dense molecular cloud envelopes have components seen in ^{12}CO or ^{13}CO emission and any combination of the other species.

Comparisons of UV/visible molecular absorption-line studies with high-resolution studies using sub-mm data have also provided complementary information on the physics and chemistry of the absorbing gas, over a large range of opacities and at great distances in the Galactic disk. As a result, these clouds constitute "in-situ" laboratories in which a variety of physical and chemical processes of broad applicability in astrophysics can be studied. The *Herschel*/HIFI Key Program PRISMAS (Probing InterStellar Molecules with Absorption line Studies, Gerin et al. 2010) surveyed key hydrides within the Galaxy. Up to 22 small molecular species were specifically targeted with PRISMAS in order to probe the chemistry in diffuse molecular clouds and to constrain the physical processes at play in the Galactic diffuse ISM. These studies have demonstrated that non-equilibrium processes such as shocks and turbulence are ubiquitous in the Galactic volume (Godard et al. 2014; Neufeld & Wolfire 2016) and need to be taken into account in ISM cloud models in order to explain the observed molecular abundances and diversity. While most chemical pathways involve gas phase reactions alone in the diffuse ISM, Sonnentrucker et al. (2015) also confirmed that grain surface chemistry could play a significant role in the production of some molecular species, such as gas phase H_2O, in this low density environment.

With a DWFMOS, a sampling of sight lines considered by Rice et al. (2018) that include both more stars and stars at greater distances would become possible. It would in particular be trivial to probe the exact locations of the GOT C+ pointings. Such measurements will yield a more complete census of diffuse neutral gas in the Galaxy.

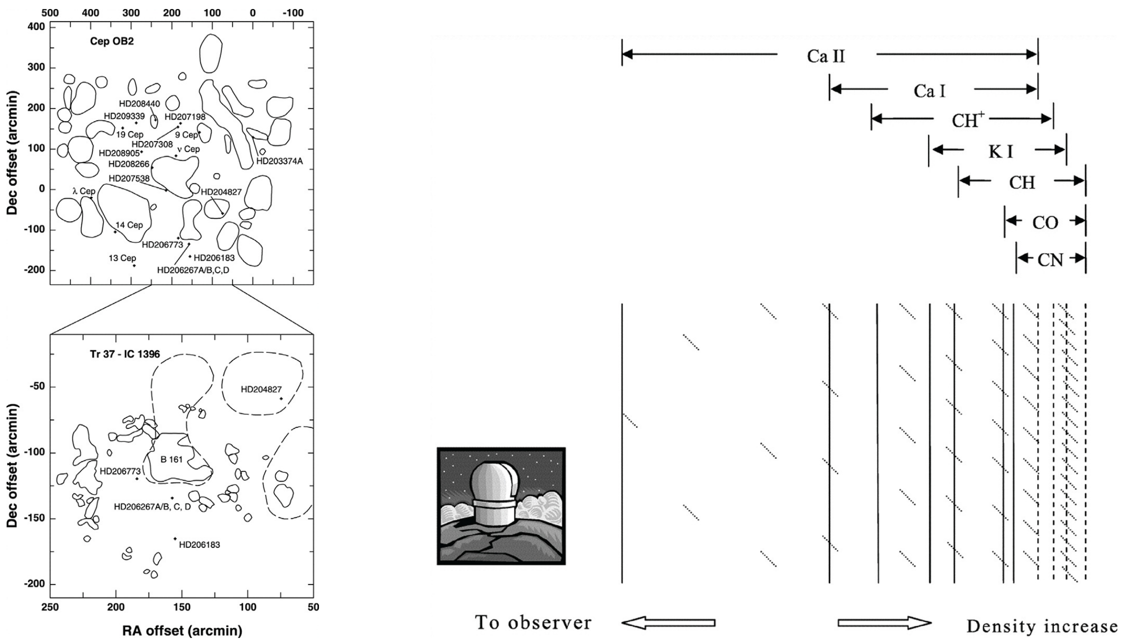

Figure 1: *(Left)*: Stars in Cep OB2 projected onto a map of CO emission from Pan et al. (2005). *(Right)*: Schematic from Pan et al. (2005) showing the distribution of atomic and molecular species in a plane-parallel diffuse cloud from the edge to the center. The spacing between hash-marks provides a sense of the density variation.

The published examples for this area of research relied on observations of single objects in samples ranging from a few stars to tens of stars. Welty et al. (1989) mainly measured Na I D absorption surrounding the small molecular clouds MBM 40 and MBM 53-55 as well as CH absorption toward a star that probes the envelope of MBM 53. Pan et al. (2005) searched for absorption from CH, CH^+, and CN molecules as well as from Ca I, Ca II, and K I toward stars in the Cep OB2 and Cep OB3 associations. Fig. 1 shows how the lines of sight to stars in Cep OB2 are distributed relative to the molecular gas seen in emission. This represents the sample in Pan et al. (2004) with high-resolution spectra; a comparable sample, given in their Appendix, was too faint to observe at high resolution. This highlights that much more extensive samples of stars can be included in surveys of molecular cloud envelopes, mimicking more closely emission-line maps. Observations with a DWFMOS at $\lesssim$10 km s^{-1} resolution ($R \gtrsim 30000$) will make this a reality. Through analyses of correlations involving the number of velocity components, their column densities, and their line widths, Pan et al. (2005) were able to describe the distribution of species along the line of sight (see Fig. 1). Such a schematic will aid in interpreting measurements with a DWFMOS.

The vast majority of the work on small-scale interstellar structure is based on pointings toward individual stars. The DensePak fiber optic array and the Hydra multi-object array on the WIYN telescope were used by Meyer & Lauroesch (1999) and Points et al. (2004), respectively, to observe Na I D toward stars in M15 and the h and χ Persei double cluster. Both arrays were able to observe about 100 targets at spectral resolutions about 12 to 14 km s^{-1}. Smoker et al. (2015) analyzed archival VLT/FLAMES spectra of interstellar Ca II absorption with comparable spectral resolution. However, focused observations of small-scale structure in diffuse molecular clouds are rare; Pan et al. (2001) examined atomic and molecular absorption toward the components of HD 206267 and HD 217035 and Pan et al. (2004) presented data for ρ Oph. Sonnentrucker et al. (2002, 2003) combined atomic and molecular absorption features to constrain the atomic/molecular gas structure toward HD 185418 and to the disentangle the quiescent gas from that tracing a SNR toward HD 192639.

These molecular studies were accomplished through separate pointings to each component or individual sight lines. The proposed DWFMOS facility will significantly expand on the results from the earlier studies thanks to greatly enlarged samples per pointing and significantly higher spectral resolution. It will also allow unprecedented studies of the interactions between SNRs and the surrounding neutral gas. The use of a DWFMOS will greatly expand the samples of Sallmen & Welsh (2004), who observed stars probing the Sh 147 SNR in absorption from Na I D and Ca II K, and of Hirschauer et al. (2009), who studied the IC 443 SNR in a large number of atomic and molecular species. In particular, a much finer mapping of the kinematics will be possible. In addition, a DWFMOS facility will easily monitor absorption features in front of faint high proper motion background stars (now available thanks to GAIA), thus revealing the very small scale structure (10–100 AU) in clouds and remnants, expanding the work of Dirks & Meyer (2016) to the entire Galaxy.

Münch (1968) used the Ca II survey of Adams (1949) acquired at about 5 km s^{-1} resolution to infer there are 5 diffuse interstellar clouds per kpc in the Solar neighborhood. Since 1990, several groups obtained ultra-high resolution spectra of interstellar species with resolutions between 0.5 and 1.0 km s^{-1}. Examples include measurements of atomic (Welty et al. 1994, 1996; Price et al. 2001) and molecular (Crawford et al. 1994; Crane et al. 1995) absorption. With such high spectral resolutions, the authors typically find Doppler broadening parameters, or b-values, of a few tenths km s^{-1}. These b-values are considerably smaller than those found by Pan et al. (2004) at somewhat coarser resolution (1.5 km s^{-1}). We suggest that measurements at the highest resolution sample turbulent substructure within diffuse interstellar clouds and that the picture of Münch (1968) is still appropriate for the kinds of surveys with the DWFMOS described in this White Paper.

4 Diffuse Interstellar Bands

The ISM is known to be a multi-phase environment. Its study requires disentangling the degeneracies between those multiple phases which is observationally very challenging as the instrumentation at hand often does not allow to fully resolve these degeneracies spatially. While the nature of the DIB carriers remains elusive to this day, with the potential exception of five DIBs that have been associated with C_{60}^{+} (Campbell et al. 2015; Walker et al. 2015, 2017; Galazutdinov et al. 2017; Cordiner et al. 2017; Spieler et al. 2017), our understanding of the DIB behavior has matured to a point at which about a dozen (of > 500 now known, Hobbs et al. 2008, 2009) DIBs can be used as diagnostics of the atomic and diffuse molecular phases of the ISM, regardless of their true nature (e.g., Welty et al. 2014; Lan et al. 2015; Fan et al. 2017).

All DIB surveys to date (see Sonnentrucker 2014, for a review) have shown that the DIB spectrum is overwhelmingly dominated by narrow features ($\sim 92\%$ with FWHM < 6 Å) absorbing primarily in the visible ($\lambda < 9000$ Å, e.g. Hobbs et al. 2008, 2009), with a small fraction ($\sim$2%) recently discovered in the NIR (e.g., Misawa et al. 2009; Geballe et al. 2011; Zasowski et al. 2015; Elyajouri et al. 2017). These surveys have now revealed that some DIBs correlate quite well with atomic H but poorly with H_2, making these particular features reliable surrogate tracers of the interstellar atomic gas in the Universe (Herbig 1993; Friedman et al. 2011; Vos et al. 2011; Ensor et al. 2017). A small group of DIBs, the C_2-DIBs, are preferentially detected in sight lines that exhibit enhanced absorption from interstellar molecular carbon (C_2), making these particular DIB features potential tracers of gas with significant molecular fraction (Thorburn et al. 2003).

It has also been observationally known for decades that the strength of the DIBs varies significantly with the physical conditions found in the gas local to the DIB carriers. These variations were analytically quantified as an ionization effect in Sonnentrucker et al. (1997), but a statistically significant sample of homogenous measurements was lacking to confirm (or not) the proposed theory. Vos et al. (2011) observed 89 B stars in the Upper Sco region, within an area of about 400 square degrees. Focusing on five strong and narrow DIBs near 6000 Å in addition to atomic and molecular features (CH, CH^{+}, CN, K I, Ca I), they inferred the intensity of the interstellar radiation field (ISRF) and the molecular hydrogen fraction, and revealed that several DIBs can be used to trace the density and exposure to the ISRF of the clouds. Fan et al. (2017) produced so far the largest homogenous, statistically significant sample of more than 100 DIB measurements in over 150 sight lines distributed over the entire northern Galactic plane ($d < 1.2$ kpc) and compared the DIBs' strength with measurements of the known atomic and molecular tracers of the diffuse gas (H I, H_2, C_2, CH, CH^{+}, CN, K I, Na I, etc.). Fan et al. not only confirmed the suspected trends in Sonnentrucker et al. (1997), but also clearly established for the first time, that there are two distinct classes of DIB carriers, the normal (atomic gas and dust tracing) DIBs and the C_2-DIBs, and that 6 of the best studied DIBs could be used to map any given sight line density structure (or cloud depth).

The DWFMOS we propose would provide many times the sample of Fan et al. (2017), enabling a more detailed understanding of the DIB's relationship with atomic and molecular tracers, and potentially revealing more DIB classes. Thousands to millions of sight lines spread across the Galaxy will allow us to constrain physical conditions and their variations from small to large angular scales, from individual clouds to giant complexes and even to the entire Galaxy. All of this will bring us closer to identifying DIB carriers.

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