The molecular content of the diffuse ISM

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1 Scientific context

1.1 Characterizing the diffuse ISM with absorption line spectroscopy

The past decade has seen huge advances in our understanding of the diffuse interstellar medium, driven observationally by absorption line spectroscopy performed at millimeter and submillimeter wavelengths towards background continuum sources. The diffuse ISM is of central importance to the emergence of H_2 and the formation of the molecular clouds, the sites of star formation.

At submillimeter wavelengths, observations performed using Herschel/HIFI, APEX, and SOFIA/GREAT have allowed the ground-state rotational transitions of several interstellar hydrides to be observed for the first time at high spectral resolution: these comprise OH (e.g. Wiesemeyer et al. 2016), OH^+, H_2O^+ (e.g. Wyrowski et al. 2010; Ossenkopf et al. 2010; Gerin et al. 2010a; Neufeld et al. 2010a), CH (e.g. Gerin et al. 2010b, Wiesemeyer et al.), CH^+(Falgarone et al. 2010), ArH^+ (Schilke et al. 2014), SH^+ (Menten et al. 2011), SH (Neufeld et al. 2012a, 2015), HF (Neufeld et al. 2010b; Sonnentrucker et al. 2010), H_2Cl^+ (Lis et al. 2010; Neufeld et al. 2012b), and HCl^+ (de Luca et al. 2012.)

At the same time, millimeter wave observations have characterized the abundances of heavier species in diffuse clouds along multiple sight-lines to mm-wave continuum sources: these include C_2H (Gerin et al. 2011), HCO^+, HCN, HNC (Godard et al. 2010), CS, SO, and H_2S (Neufeld et al. 2015).

1.2 Interstellar molecules as diagnostic probes

Interpreted in the context of detailed astrochemical models for the turbulent ISM, the observations of these molecules provide a wealth of information about the environment in which they are found.

(1) Molecules such as HF, CH, C_2H and HCO^+ provide excellent tracers of H_2 (Sheffer et al. 2008; Gerin et al. 2019), which is not directly detectable except through UV observations of the nearest hot stars. At millimeter and submillimeter wavelengths, where such observations are unaffected by dust absorption, background sources (and foreground clouds) can be observed at large distances within the Galactic plane.

(2) The OH^+, H_2O^+, and ArH^+ molecular ions, which are formed in reaction sequences initiated by cosmic-rays, have been used to probe the cosmic-ray ionization rate (CRIR) and its variation within the Galaxy (Neufeld & Wolfire 2016, 2017).

(3) Several other molecules – including CH^+, SH, H_2S, SH^+, CS, and SO – probe a "warm chemistry" that is driven by the dissipation of interstellar turbulence (e.g. Godard et al. 2014). In observations performed in 2014 using the IRAM 30 m telescope, we observed the H_2S $1_{10} - 1_{01}$ (169 GHz), CS $J = 2-1$ (98 GHz) and SO 3_2-2_1 (99 GHz) transitions toward five bright continuum sources: W31C, G29.96-0.02, G34.3+0.1, W49N and W51. All three transitions were detected in absorption toward all five sources, as was the SH 1383 GHz $^2\Pi_{3/2} J = 5/2 - 3/2$ transition observed with the GREAT spectrometer on SOFIA (Neufeld et al. 2015; see Fig. 1 below). The observed abundances of these sulphur-bearing molecules greatly exceeded those predicted by standard models of cold diffuse molecular clouds, providing further evidence for the enhancement of endothermic reaction rates by elevated temperatures or ion-neutral drift. These observations provided important constraints on shock and turbulent dissipation region (TDR) models.

(4) By combining observations of multiple species, examining correlations and measuring abundance ratios, it has been possible to determine the distribution function for the H_2 fraction within the diffuse ISM; this provides an important constraint on global models for the formation and destruction of molecular hydrogen in a turbulent medium (e.g. Bialy et al. 2019).

1.3 HyGAL: an approved SOFIA Legacy Program

Thus far, the absorption line observations described above have been performed toward relatively small sample of the brightest, most well-studied sources. Motivated by the advances thereby obtained, and with the goal of broadening the sample size and Galactic coverage obtained to date, we are carrying out a Joint (i.e. US - German) SOFIA Legacy Program, "HyGAL," over the next two years. This 82-hour program, which was approved in full last December, will conduct absorption line observations of six hydride molecules (ArH^+, OH^+, H_2O^+, SH, CH and OH) plus [OI] and [CII] toward twenty-five THz continuum sources in the Galactic plane. HyGAL will take advantage of the GREAT spectrometer to achieve the high resolution needed to spectrally resolve individual clouds along each sight-line. This program will greatly expand the sample of diffuse clouds that have been studied intensively through absorption line spectroscopy, providing significantly better coverage of the Galactic disk.

2 Planned observations

In the IRAM 30m program proposed here, and in a associated program that we will propose to the ALMA Compact Array, we will observe foreground absorption by eight additional molecules along these same 25 sight-lines – H_2S, C_2H, HCO^+, HCN, HOC+, HNC, CS, and SO – providing a critical synergy with HyGAL and leveraging a large commitment of SOFIA time. Thanks to the large bandwidth of the EMIR receiver, the observations we propose can be performed very efficiently. Thus, we will observe eight key constituents of the diffuse ISM with two frequency settings: seven with the E090 receiver (C_2H, HCN, HCO^+, HOC+, HNC, HCO^+, CS and SO); and one (H_2S) with the E150 receiver. We will target all nine HyGAL sources at a declination greater than –10 deg: G29.96-0.02, W43 MM1, G31.41+0.3, G32.80+0.19, G45.07+0.13, DR21, NGC 7538 IRS 1, W3 IRS 5, W3(OH). (We will propose ALMA compact array observations of the other 16 more southerly sources.)

The resultant data will be analyzed in combination with the HyGAL observations to be performed with SOFIA. The full dataset will yield robust estimates of the column densities of 14 diffuse cloud species in of order 100 diffuse clouds. Correlations between the various species will be intially investigated with the use of Principal Component Analysis (e.g. Neufeld et al. 2015). Detailed abundance ratios will be confronted with diffuse cloud and TDR models. The H_2S: SH: CS: SO ratios have been previously shown to characterize a "warm chemistry" that is driven by the dissipation of interstellar turbulence. Our observations of HCO^+, C_2H, and HCN will improve the calibration of these molecules as tracers of the H_2 column. Moreover, the observed HCO^+/CH and HCO^+/HOC^+ ratios will provide an important constraint on the chemistry carbon-bearing species in the interstellar gas and – because HCO^+ is a precursor to CO – may have implications for the C^+/C/CO transition in clouds of increasing total column density.

3 Technical justification

We propose to observe in Wobbler switching mode, as we are mainly expecting to observe absorption lines. The continuum brightness temperatures (T_a^*) of the background sources are expected to range from $\sim 0.25 - 1.2$ K at 168.763 GHz, the frequency of the H_2S line that dominates the time estimate. For a source with a continuum brightness temperature 0.25 K, we require a signal-to-noise ratio on the continuum of at least 20 in a 1 km/s bandwidth, corresponding to a noise level of $\sim$ 20 mK at a frequency resolution of 200 kHz (0.36 km/s). This signal-to-noise ratio will allow a 25% absorption feature of width 1 km/s to be detected at the 5σ level. The H_2S line will be targeted in the USB of E150, simultaneously with the CS and SO lines in the USB of E090, in observations of duration 2 hr per source. In addition, we will observe each source for 30 minutes in a second setup that will target the C_2H, HCN, HCO^+, HOC+, and HNC lines in the LSB of E090, and SO in the USB of E090. This will achieve a comparable S/N ratio for those lines. Including the time needed for retuning the receivers, the total required time is 3 hours per source for all targets except G29.96-0.02. (Because H_2S, CS and SO were observed previously toward G29.96-0.02 (Neufeld et al. 2015), only 1 hr is needed for that source. The total time request is therefore 25 hr.

While many of the target sources have a larger flux than that assumed above, our strategy is to spend the same time on each source and to accept a variable signal-to-noise ratio. In our experience with Herschel, we found that this strategy is superior to one in which the integration time is varied to provide a constant signal-to-noise ratio. (In practice, the latter strategy requires one to spend a large fraction of the available time on the very weakest sources.)

We propose to observe during the summer season with EMIR using the tracked PSW observing mode. For a typical elevation of 45^0, an observing frequency of 168.763 GHz and a spectrometer resolution of 200.0 kHz, the sensitivity estimator tells us that we will reach a sensitivity of 20.5 mK [T_a^*] in 2.0 hr with average conditions (7.0 mm PWV, $T_{\rm sys}$ 337.7 K [T_a^*] mean per pixel). The total time required is 25 hr.

4 Supporting material

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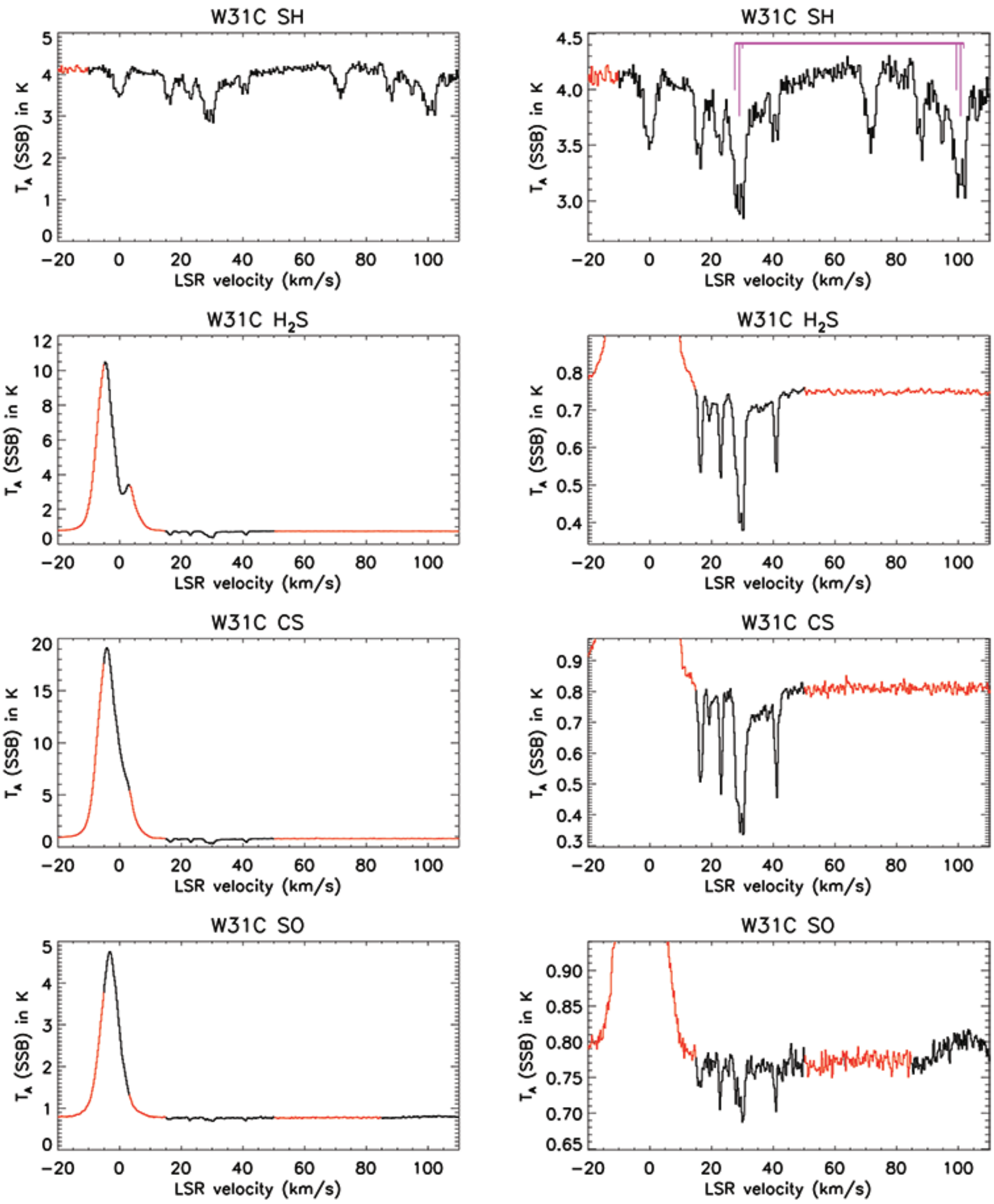

Figure 1: Spectra obtained toward W31C using SOFIA/GREAT (top panels) and the IRAM 30m telescope (other panels), from Neufeld et al. 2015. Red sections of each plot indicate spectral regions assumed devoid of absorption for the purpose of fitting a continuum with emission lines. The right panels are zoomed versions of the left panels, with the scaling chosen to reveal weak absorption features. Magenta lines indicate the lambda doubling and hyperfine splittings for SH.