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Simple Hydrides (OH and CH) Trace the Dark Molecular Gas

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Abstract. Emission lines from CO and HI are the standard tracers of molecular and atomic interstellar medium, respectively. In the past two decades, a consensus has formed that a substantial fraction of Galactic molecular gas evades detection by these two tracers, thus giving rise to the empirical concept of dark molecular gas (DMG). Largely based on the experience and evidence garnered from the Arecibo Millennium survey, we have formed an international consortium, the Pacific Rim Interstellar Matter Observers (PRIMO), to pursue alternative tracers of DMG, particularly absorption against background radio sources (quasars). PRIMO have carried out observing programs at Arecibo, JVLA, Delingha 13.7m, ATCA and ALMA, among others. Our observations reveal abundant hydrides, namely OH and CH, in DMG clouds. The historical difficulty of mapping OH can be explained by the measured OH excitation temperature

$$f(T_{\rm ex}^{\rm OH}) \propto \frac{1}{\sqrt{2\pi}\sigma}\exp[-(\ln(\mathrm{T}_{\rm ex}^{\rm OH}) - \ln(3.4\ \mathrm{K}))^2/(2\sigma^2)],$$

which is a modified log-normal function peaking close to the numerical value of the L-band Galactic continuum background (synchrotron + CMB). Both OH and CH are shown to be better tracers of molecular hydrogen than CO, particularly in the intermediate extinction regions ($\mathrm{A}_v \sim$ 0.05-2 magnitude), where DMG dominates.

Keywords. astrochemistry, ISM: atoms, ISM: molecules, Galaxy: abundances, radio lines: ISM

1. Overview

Hydrogen is the most abundant element in the universe. The atomic (HI) and molecular (H_2) form of hydrogen are key ingredients of the interstellar medium (ISM). Discovered in 1951, the λ21cm hyperfine structure transition of HI traces the total quantity of atomic ISM reasonably well, owing to its low opacity and commonly achievable excitation conditions. H_2, however, is illusive due to its low mass and lack of permanent dipole, which means that its lowest rotational levels are both forbidden and lie too high above ground state to be readily excited in molecular clouds. The discovery of CO, combining the third- (oxygen) and fourth- (carbon) most abundant elements, was considered a major

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astronomical discovery of the 20th century. A key caveat of using CO to trace H_2 is its large opacity; the widely used empirical CO intensity to H_2 column density conversion factor, the X-factor, faces the intrinsic challenge of relating surface brightness to total quantities summed over the full depth of a cloud. The viral argument (Solomon *et al.* 1987) has to be invoked. It is thus not surprising to see variation and uncertainty in the X-factor, and voluminous literature exists on this topic (e.g. Genzel *et al.* 2015).

A growing consensus is the underestimation of the total neutral gas mass as estimated from $N_{\rm HI}+XW_{\rm CO}$ (where $N_{\rm HI}$ is the atomic column density under the optically thin assumption, $W_{\rm CO}$ is the velocity-integrated CO intensity and X is the X-factor). Grenier *et al.* (2005) analyzed diffuse γ-ray emission from EGRET attributable to cosmic-ray interactions with hydrogen nuclei. Compared to the total hydrogen estimated from $N_{\rm HI}+XW_{\rm CO}$, wide-spread gamma-ray-derived hydrogen excess was found and dubbed 'dark gas'. Planck Collaboration *et al.* (2011) later showed an apparent excess in dust opacity in multiple Planck bands for gas with intermediate extinction. The self-shielding threshold of H_2 is about a decade smaller than that of CO (van Dishoeck & Black 1988). A natural expectation from PDR models is thus a layer of H_2 gas without stable CO, the canonical abundance of which is $[\rm CO]/[\rm H_2]\sim 10^{-4}$, meaning all carbon is tied in this molecule. We believe that the 'missing' molecular gas in this intermediate extinction layer ($\rm A_v \sim 0.05$-2 magnitude) is composed largely of dark molecular gas (DMG).

2. Hydrides Trace DMG

CH was the first interstellar molecule ever discovered; OH was the first discovered in the radio band. These simple hydrides are expected to be abundant in DMG. Despite their importance, however, large scale mapping of the extended ISM in either is rare. While the Λ-doubling transitions of OH and CH in L- and C-bands are accessible, the lines tend to be extremely weak compared to (say) CO. The complexity of their excitation is also an issue: their level populations are strongly affected by the rotational levels in the IR bands (Fig. 1). In cold gas or star forming regions, the molecules can be readily 'pumped' to IR levels, then decay readily into preferred sub-levels of the ground state, making excitation states of Λ-doubling transitions non-thermal. This was recognized immediately after the discovery of OH (Cook 1966), and to-date most studies of OH have been focussed on bright, compact OH maser sources. While masing in the DMG is much weaker, without the validity of LTE assumptions, converting flux to column density is challenging.

We tackle the excitation of hydrides from two angles. First, we utilize the quasar absorption analysis procedures developed by Heiles & Troland (2003). In their Arecibo Millennium survey, multiple off-source (OFF) positions were observed in addition to each on-souce (ON) sightline with a bright quasar in the beam. An international consortium, the Pacific Rim Interstellar Matter Observers (PRIMO), were formed in 2013 to expand such absorption studies to multiple bands. PRIMO has managed to obtain time from Arecibo, JVLA, ATCA, Delingha 13.7m, ALMA, and others, and has confirmed the abundant existence of OH in DMG. Based on OH absorption measurements, Planck dust opacities, and optical dust reddening, Nguyen *et al.* (2018) published systematic measurements of OH abundance across randomly sampled sightlines in the Arecibo sky, finding $[\rm OH]/[\rm H_2]\sim 10^{-7}$, which was stable (to within the uncertainties) in the range $\rm N(H_2)\sim$ 0.1–10 $\times 10^{21}$ cm^{-2}. Li *et al.* (2018) measured main-line OH excitation temperatures, finding an empirical trend,

$$\rm f(T_{ex}^{OH}) \propto \frac{1}{\sqrt{2\pi}\sigma} exp\left[-(ln(T_{ex}^{OH}) - ln(3.4\ K))^2/(2\sigma^2)\right]. \qquad (2.1)$$

The OH excitation temperature $\rm T_{ex}^{OH}$ peaks close to the Galactic emission background, providing a natural explanation for the difficulty of mapping OH in emission.

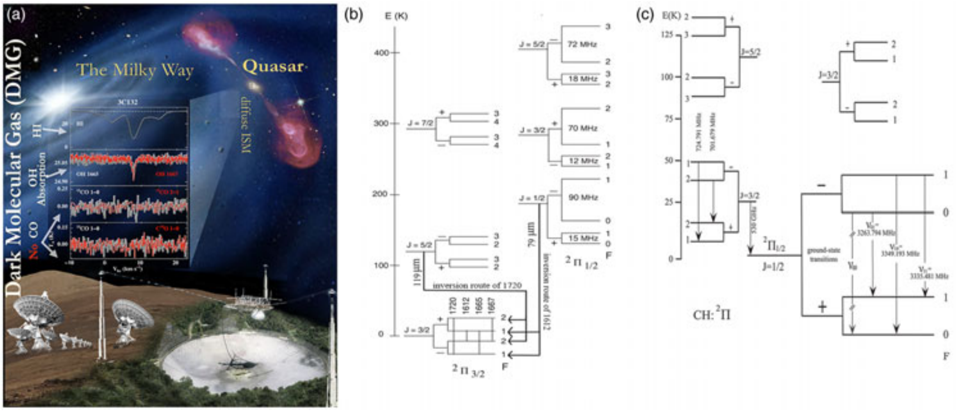

Figure 1. (a): Illustration of the absorption concept toward continuum sources. The spectra of DMG toward 3C132 are shown. The energy structures of OH and CH are shown in (b) and (c), respectively.

Second, we model the emission/absorption of hydrides in regions with other, independent constraints on their physical and chemical conditions, where the excitation problem can be solved by generating profiles under specific assumptions, made consistent with all available data sets, including other spectral species, 2MASS extinction, etc. Through a combined analysis of HI narrow self-absorption (HINSA), C^+, and OH, Tang *et al.* (2017) revealed a correlation between C^+ and OH in DMG clouds. A target with better constraints is the apparent transition edge in the Taurus molecular cloud (Goldsmith *et al.* 2008). Orr *et al.* (2014) published a self-consistent geometry and chemistry model of the regions, relying largely on CI and C^+ observations. We carried out Arecibo L- and C-band observations of the same region, and utilizing Orr's model, fitted to the excitation and abundance of OH and CH throughout the transition zone ($A_v \sim 0.2$–2). Xu *et al.* (2016) found an evolution in OH abundance from 8×10^{-7} to 1×10^{-7} with increasing extinction in the DMG (transition) region, while the fraction of DMG (DGF) was found to decrease with increasing extinction as

$$\mathrm{DGF} = 0.9 \times \exp\left[-\left(\frac{A_v - 0.79}{0.71}\right)^2\right]. \tag{2.2}$$

These trends are borne out by recent analysis of diffuse γ-ray data from Fermi (Remy *et al.* 2018). Xu & Li (2016) also compared the X-factors of hydrides with that of CO. The measured X-factors of OH and CH have much less scatter than that of CO in the transition zone, consistent with the fact that CO is evolving more dramatically in this intermediate extinction (below its self-shielding threshold) region.

In summary, simple hydrides such as OH and CH are better tracers of H_2 than CO in regions with dark molecular gas. Quasar absorption measurements have been demonstrated to provide an accurate handle of the excitation conditions of hydride transitions in radio bands. The upcoming, significantly more sensitive radio telescopes, FAST and SKA in particular (Li *et al.* 2018; McClure-Griffiths *et al.* 2015), will enable systematic measurement of hydrides throughout the Galactic ISM, thus quantify the so-called dark molecular gas.

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