

THE FIRST STEP OF INTERSTELLAR CHEMISTRY REVEALED BY HERSCHEL/HIFI

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Abstract. Absorption spectroscopy performed with Herschel/HIFI in the direction of bright star-forming regions of the inner Galaxy provides a new probe of the interstellar medium. The ground-state transition of several light hydrides are found to have large optical depths and are therefore sensitive tracers of gas components that are poorly known such as gas of low density containing only a small fraction of molecular hydrogen. The large observed abundances of HF, CH⁺, OH⁺, H₂O⁺ among others, provide new clues on the processes leading to the incorporation of heavy elements into interstellar chemistry.

Keywords: astrochemistry, diffuse interstellar medium, hydrides, absorption spectroscopy, submillimeter and far infrared

1 Absorption spectroscopy with HIFI and the unique properties of light hydrides

The HIFI instrument aboard the Herschel satellite is an heterodyne instrument in the submillimeter range. The ground-state rotational transitions of light hydrides fall in this wavelength range because of the low reduced mass of these species. Their dipole moment is in general large, so the critical densities of these transitions are very high ($n_{\text{H}} > 10^7 \text{ cm}^{-3}$) and only the lowest level of the rotational ladder ($J=0$) is significantly populated in the low density, weakly irradiated, diffuse interstellar medium (ISM): the light hydrides are therefore expected to be detected via absorption lines against the strong dust continuum emission of massive star-forming regions. Absorption spectroscopy is very sensitive and reaches in the far-infrared the same range of column densities as in the visible or UV range for species that are accessible in the two wavelength ranges. The spectral resolution is high: HIFI observations reach 0.1 km s^{-1} . Last, hydrides form from reactions with molecular hydrogen and, depending on the species, they provide clues on the first steps of interstellar chemistry in gas containing only a low fraction of H₂. In absorption, they are valuable tracers of the diffuse gas (in space and velocity), independently of other tracers, such as CO or dust emission.

Figure 1 displays seven of the lines detected so far in absorption against the dust continuum emission of the remote star-forming region W31C (or G10.6-0.34). It shows the line-to-continuum ratio as a function of the LSR velocity, so that absorption ranges between 1 (continuum level) and 0 (saturated absorption). The different spectra are shifted for clarity but the scales remain the same (except for SH⁺ that is scaled by a factor 10). Two main results are immediately noticeable: (1) some of the lines are heavily saturated over most of the velocity range sampled by the line of sight, such as CH⁺(1-0), others such as water or HF are saturated over only restricted velocity intervals, while SH⁺ or H₂O⁺ have an optical depth clearly smaller than unity at all velocities, and (2) the similarity between the velocity profiles of HF and H₂O for instance is striking.

Several papers have already been published in the A&A Herschel and Herschel/HIFI Special Issues. Some of the most salient results obtained so far are summarized here. Additional results include CH (Gerin et al. 2010), H₂Cl⁺ (Lis et al. 2010), C₃ (Mookerjea et al. 2010) and nitrogen hydrides (Persson et al. 2010).

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1.1 HF

Although fluor is not an abundant element, the HF(1-0) transition is saturated because most of fluor available in the gas phase is in the form of HF that has a larger binding energy than H₂. The H₂ + F reaction is highly exothermic with a small activation energy barrier of 500 K. The comparison of the spectra of HF with para-water shows that in spite of the abundance ratio, [O]/[F] ~ 10⁴, the optical depth of HF(1-0) is larger than that of para-H₂O (Neufeld et al. 2010). The analysis of the optical depth of the different velocity components shows that at least 1/3 of gas-phase fluor is in the form of HF. HF is therefore a new tracer of H₂ since it is present as soon as H₂ is present (Neufeld et al. 2010, Sonnentrucker et al. 2010).

1.2 OH⁺ and H₂O⁺

The direct comparison of the absorption profiles of OH⁺ and H₂O⁺ (Figure 1) is not straightforward because of the hyperfine structure of the transitions (Gerin et al. 2010). Nevertheless, it is visible that the OH⁺ spectrum is more saturated than that of H₂O⁺. The ratios of the column densities inferred are significantly larger than unity. This is unexpected because the two species are closely linked: the oxygen chemistry in the ISM is initiated by cosmic-ray (or X-ray) ionization of hydrogen. Then the slightly endothermic charge exchange reaction H⁺ + O produces O⁺ which reacts rapidly with H₂ to form OH⁺. Subsequent rapid H-atom abstraction produces H₂O⁺ and H₃O⁺, opening the gas-phase route to H₂O. The large ratio of OH⁺ to H₂O⁺ column densities implies that the absorbing gas is weakly shielded from the ambient radiation field with only a low fraction of hydrogen in the molecular form (less than 10%). The large column densities in turn imply a large ionization rate, up to $\zeta = 2.4 \times 10^{-16} \text{ s}^{-1}$, a result similar to that inferred from the abundances of H₃⁺ observed in the diffuse ISM.

1.3 CH⁺ and SH⁺

These two radicals are different from all others because their formation proceeds via highly endothermic reactions of either C⁺ or S⁺ with H₂. It has been known since its first detection, four decades ago, that UV-driven chemistry in diffuse gas cannot reproduce the large abundances of CH⁺ that have been found in the Solar neighborhood. Since the CH⁺(1-0) line is so saturated, column densities are inferred from absorption lines of ¹³CH⁺(1-0) (Falgarone et al. 2010). The large abundances are confirmed along sight-lines crossing the Galaxy, with however a large scatter. A specific warm non-equilibrium chemistry activated by short bursts of turbulent dissipation (the so-called TDR model, for Turbulent Dissipation Regions, Godard et al. 2009, 2010) is able to reproduce the observed CH⁺ abundances in the diffuse medium. Interestingly, the CH⁺ abundance is proportional to the dissipation rate, which makes this radical a specific tracer of the dissipation of suprathermal energy in the ISM. SH⁺ is much less abundant than CH⁺ but they form a very unique couple for the study of turbulent dissipation in the diffuse ISM. The endothermicities of their formation pathways differ by a factor larger than 2, hence their abundance ratio is a unique tracer of the probability distribution of dissipated energy.

2 Perspectives

Absorption spectroscopy of light hydrides provides unique and versatile informations on a variety of processes in the ISM, as well as the first steps of interstellar chemistry. They specifically probe the least molecular regions of the diffuse ISM. The large opacities of the ground-state lines make them anticipated tracers of yet unseen gas components in external and high-z galaxies.

The results presented here have been (and are still being) obtained in the framework of the guaranteed time key-project PRISMAS (Probing interstellar molecules with absorption line spectroscopy, PI M. Gerin) of the Herschel/HIFI instrument.

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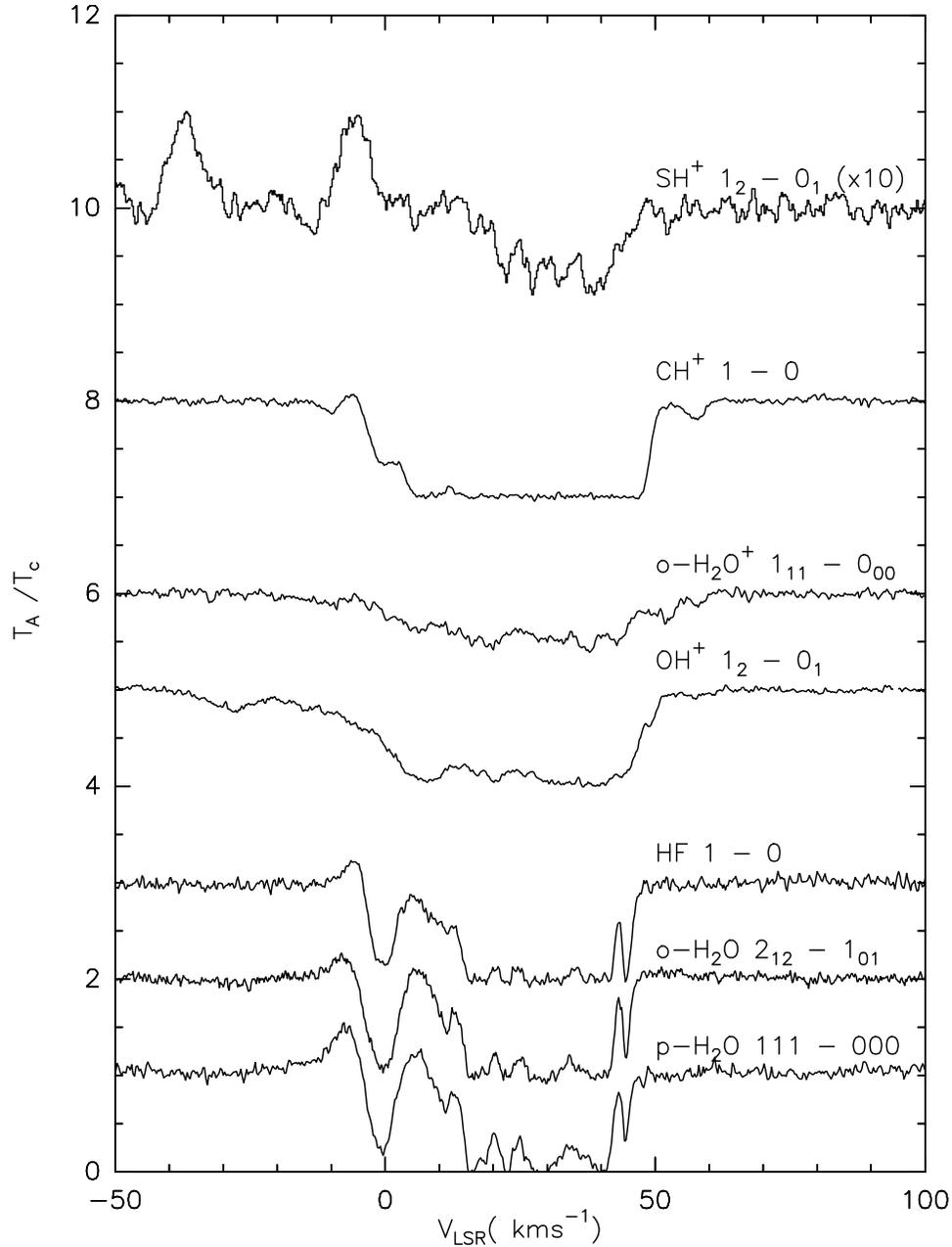


Fig. 1. Absorption of the ground-state rotational transitions of six light hydrides observed against the dust continuum emission of the bright star-forming region W31C (or G10.6-0.34) by Herschel/HIFI. The emission lines in the SH^+ spectrum are methanol lines from the star-forming region.

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