**Letter to the Editor**

**Herschel observations of EXtra-Ordinary Sources (HEXOS): Detection of hydrogen fluoride in absorption towards Orion KL**


(Affiliations are available in the online edition)

Received 30 March 2010 / Accepted 20 April 2010

**ABSTRACT**

We report a detection of the fundamental rotational transition of hydrogen fluoride in absorption towards Orion KL using Herschel/HIFI. After the removal of contaminating features associated with common molecules (“weeds”), the HF spectrum shows a P-Cygni profile, with weak redshifted emission and strong blue-shifted absorption, associated with the low-velocity molecular outflow. We derive an estimate of $2.9 \times 10^{13}$ cm$^{-2}$ for the HF column density responsible for the broad absorption component. Using our best estimate of the H$_2$ column density within the low-velocity $\sim 6 \pm 3$ km s$^{-1}$ molecular outflow, we obtain a lower limit of $\sim 6 \times 10^{-9}$ derived by Neufeld et al. for cold, foreground clouds on the line of sight towards G10.6-0.4.

**Key words.** ISM: abundances – ISM: molecules – submillimeter: ISM – star-forming regions (HEXOS). With a strong continuum, it might be expected that Orion would exhibit numerous absorption lines; however it is well known to exhibit no absorption lines at mm wavelengths. For instance even CO $J = 1-0$, which is seen with self-reversals towards many star-forming regions, has a smooth emission line profile with no self-absorption (e.g. Tauber et al. 1991). The lack of absorption has been attributed to competing excitation gradients (external heating from $\theta C$ and internal heating from the embedded massive protostars), the location of the HII region on the front of the cloud, and the presence of numerous unresolved dense ($n_{H_2} > 10^5$ cm$^{-3}$) clumps along the line of sight (Tauber et al. 1991). At shorter wavelengths some evidence for absorption is found. Betz & Boreiko (1989) find that the blue side of the fundamental rotational transition of OH is completely absorbed, with only a red-shifted emission component. The far-infrared survey of Lerate et al. (2000) using ISO-SWS. With the shapes of water and OH lines gradually change from pure emission at the longest wavelengths to mostly P-Cygni profiles at the shortest wavelengths.

**1. Introduction**

Hydrogen fluoride (HF) is expected to be the main reservoir of fluorine in the interstellar medium because it is easily produced by the exothermic reaction of F with H$_2$ (Neufeld et al. 2005; Neufeld & Wolfire 2009) and its very strong chemical bond makes this molecule relatively insensitive to UV photodissociation. Interstellar HF was first detected by Neufeld et al. (1997) with ISO. The $J = 2-1$ rotational transition was observed in absorption towards Sgr B2, at a low spectral resolution using the ISO long-wavelength spectrometer (LWS). The HIFI instrument (de Graauw et al. 2010) aboard the Herschel Space Observatory (Filbratt et al. 2010) has allowed observations of the ground state rotational transition of HF at 1.232 THz to be performed for the first time, at high spectral resolution. This transition is expected to be generally observed in absorption because of the very large A coefficient (e.g. Neufeld et al. 2010). Only extremely dense regions could possibly generate enough collisional excitation to yield an HF feature with a positive frequency-integrated flux.

A full HIFI spectral scan of band 5a, with frequency coverage from 1.109 to 1.239 THz, was carried out as part of the guaranteed time key program Herschel observations of EXtra-Ordinary Sources: The Orion and Sagittarius B2 (Herschel) is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
have obtained spectra of the R-branch of the $v = 1-0$ band of both $^{13}$CO and $^{12}$CO toward the BN object and “source n” within Orion KL. These spectra, which are consistent with earlier spectra obtained at lower resolution and signal-to-noise ratio by Scoville et al. (1983), also show strong absorption at velocities about $-25$ and $12$ km s$^{-1}$. As we will discuss below, the particular excitation of these lines (ground rotational state HF and ground vibrational state CO) makes them strong candidates to be seen in absorption, provided favorable geometry and strong background continuum exist. Ground state rotational lines of water isotopologues have similar excitation requirements and HIFI observations of para-H$^{18}$O and para-H$_2^{12}$O, observed separately in band 4b, are also discussed here.

2. Observations

HIFI observations presented here were carried out on March 6, 2010 using the dual beam switch (DBS) mode pointed towards the Orion Hot Core at $\alpha_{J2000} = 5^h35m14.s$ and $\delta_{J2000} = -5^\circ22'36.7''$. The DBS reference beams lie approximately 3' east and west (i.e. perpendicular to the orientation of the Orion Molecular Ridge; e.g. Ungerechts et al. 1997). We used the Wide Band Spectrometer providing a spectral resolution of 1.1 MHz (0.26 km s$^{-1}$) over a 4 GHz IF bandwidth. Although both H and V polarization data were obtained, we only present here data from the H polarization, reduced using HIPE (Ott 2010) with pipeline version 2.4.

The band 4b and 5a spectral scans consist of double sideband spectra with a redundancy of 6, which gives observations of a lower or upper sideband frequency, DFS applied for the deconvolution and isolation of a single sideband spectrum (Comito & Schilke 2002). We applied the standard HIFI deconvolution using the doDeconvolution task within HIPE. All data presented here are deconvolved single sideband spectra, including the continuum. Regions of the spectrum free of lines were isolated and give a deconvolved single sideband spectrum (Comito & Schilke 2002). This allows for the deconvolution of the local oscillator. This allows for the deconvolution of a lower or upper sideband frequency with 6 di

3. Results

3.1. First detection of submm absorption towards Orion

Figure 1 shows the detection of HF $J = 1-0$ and para-H$^{18}$O $J = 1-0$ in emission and absorption towards Orion BN/KL (blue and red histograms, respectively). Both lines show high-velocity emission line wings on the red side of the systemic velocity of 9 km s$^{-1}$, a sharp drop near the systemic velocity, and broad absorption extending towards lower (blue) velocities. In contrast, $^{13}$CO $J = 2-1$ emission (black histogram) shows broad line wings superposed on a narrow feature at 9 km s$^{-1}$, but no evidence for absorption.

There are a number of issues which must be addressed. First these data were obtained using DBS which places the reference beams 3’ away from the central hot core. This is large enough to avoid any reference position contamination from the hot core and shock, but might encompass emission from the extended molecular ridge. Both HF and para-H$^{18}$O have high dipole moments and fast (>10$^{-2}$ s$^{-1}$) spontaneous de-excitation rates leading to critical densities in excess of 10$^8$ cm$^{-3}$ (Reese et al. 2005; Groosjean et al. 2003). Beyond the hot core, the density is well below this value (Bergin et al. 1996) and, for HF, extended emission is unlikely. This may not be the case for para-H$^{18}$O, as the ground state emission of ortho-H$_2$O is strong and extended (Snell et al. 2000; Olofsson et al. 2003). Because the DBS mode alternates between two reference positions, we have used the Level 1 data to compute a difference spectrum between the two reference positions; we see no evidence for emission or absorption in such a difference spectrum for either line. It is very unlikely that the same level of emission or absorption would be present in the two reference beams, separated by 6’ on the sky. In addition, the extended emission component in Orion is centered at 9 km s$^{-1}$ and has a narrow line width of 2–5 km s$^{-1}$. For HF we do see absorption at the systemic velocity, but also a broad blue-shifted absorption. We thus conclude that the observed absorption is real, and not an artifact of the observing mode employed.

3.2. Contamination by interfering lines

In the case of HF there is an additional complication in that the low-velocity blue absorption is blended with emission from CH$_3$OH ($\sim-10$ km s$^{-1}$) and SO$_2$ ($\sim-20$ and $-65$ km s$^{-1}$), shown in green. Subtraction of these contaminating lines results in the dark blue HF spectrum.

Fig. 1. HIFI detection of interstellar HF $J = 1-0$ (rest frequency 1232.46727 GHz; Noit et al. 1987) and para-H$^{18}$O $J = 1-0$ (at 1101.698256 GHz) towards Orion BN/KL (blue and red, respectively). The region of low-velocity HF absorption is highlighted in grey. Both observations are from HIFI band 5a and are referenced to the temperature scale on the left. The HF absorption is blended with the emission of CH$_3$OH ($\sim-10$ km s$^{-1}$) and SO$_2$ ($\sim-20$ and $-65$ km s$^{-1}$), shown in green. Subtraction of these contaminating lines results in the dark blue HF spectrum.
observations of molecular hot core sources and modeling tools are being developed to deal with this problem. The two SO$_2$ lines in the spectrum have been removed using such a model.\footnote{We made use of the myXCLASS program (http://www.astro.uni-koeln.de/projects/schilke/XCLASS), which accesses the CDMS (Müller et al. 2001, 2005; http://www.cdms.de) and JPL (Pickett et al. 1998; http://spec.jpl.nasa.gov) molecular data bases.} In the case of CH$_3$OH, the LTE model is not accurate enough to deal with the problem and we removed the interfering line by fitting a single-component gaussian and subtracting the emission. The emission fit and the final HF absorption spectrum are shown in Fig. 3. This spectrum is then used for the analysis in Sect. 4. The HF absorption full-width at zero intensity (FWZI) is $\sim 50$ km s$^{-1}$, which is less than that of para-H$_2$H$_2$O (FWZI $\sim 80$ km s$^{-1}$). For completeness, in the computation of the line-to-continuum ratio, we also explored the possibility that the CH$_3$OH and SO$_2$ lines contribute to the background emission for the absorbing HF gas. This will be reflected in our error analysis.

The analysis is simpler for H$_2$H$_2$O, which shows no evidence for any contamination within the absorption velocity range. For this line we have assumed a continuum value based on the level measured at frequencies adjacent to the water line.

4. Discussion

After the removal of features attributed to CH$_3$OH and SO$_2$, the HF $J = 1$–0 spectrum shows a P-Cygni profile with a broad, blueshifted absorption at LSR velocities between about $-45$ and $9$ km s$^{-1}$ and a redshifted emission component at LSR velocities in the range 12 to 50 km s$^{-1}$. The analysis of the HF emission, along with other spectral lines detected in Orion, will be discussed in a future paper. The HF spectrum is strikingly similar to that of another transition with an extremely high critical density: the CO fundamental vibrational band (Beuther et al. 2010) which shows an absorption feature that is stronger than the emission feature – is that the outflowing material is not entirely encompassed by the beam so that part of the emission flux is unobserved; this explanation could be tested by means of mapping observations.

Most of the material appears to have an outflow velocity $\leq 20$ km s$^{-1}$ and is likely associated with the “Low Velocity Flow” (e.g. Genzel & Stutzki 1989). The para-H$_2$H$_2$O and para-H$_2$H$_2$O $J=1_{11}$–0$_{00}$ (not shown) lines also show absorption at negative LSR velocities, although the absorption extends further, to LSR velocities as negative as $\sim -80$ km s$^{-1}$. This behavior may reflect the presence of enhanced water abundances in the High Velocity Flow (Franklin et al. 2008). The para-H$_2$H$_2$O (and para-H$_2$H$_2$O $J=1_{11}$–0$_{00}$) line profiles are also different from HF in exhibiting an emission feature that is stronger than the absorption feature. This behavior must imply that collisional excitation provides an additional excitation mechanism, and may suggest that the rate coefficients for excitation of the para-water transition are significantly larger than those for excitation of the HF transition. To date, the collisional excitation of HF has been computed only in the case where He is the collision partner (Reese et al. 2005); the rate coefficients thereby derived are indeed an order of magnitude smaller than those computed for the excitation of para-water by H$_2$ (Grosjean et al. 2003), but the rate coefficients for excitation of HF by H$_2$ might be expected to be larger than those for excitation by He.

We have determined the column density of absorbing molecules responsible for the broad blueshifted absorption features. If the absorbing material is assumed to cover the continuum source, we estimate the velocity-integrated optical depth HF $J = 1$–0 as 11.8 km s$^{-1}$, which implies an HF column density of $2.9 \times 10^{13}$ cm$^{-2}$ if all molecules are in the ground-state. Uncertainties introduced by the need to correct for the SO$_2$ and CH$_3$OH emission features result in possible errors that we estimate as about $\pm 25\%$. Derived under the same set of assumptions, the column densities of absorbing para-H$_2$H$_2$O and para-H$_2$H$_2$O are $1.3 \times 10^{13}$ cm$^{-2}$ and $7 \times 10^{12}$ cm$^{-2}$, respectively. Strictly,
these values are all lower limits, because the source could be partially-covered by clumps of arbitrarily large optical depth and the strong continuum could lead to some excitation. In addition, the water lines have strong emission which might lie behind the absorbing material. However, the fact that all three spectral lines show absorption profiles of similar shapes but different depths, suggests that the optical depths are not extremely large.

In order to estimate the molecular abundances implied by these column densities, we require an estimate of the total column density of H2. Beuther et al. (2010) used the observed strength of the 13CO v = 1 transition against the sight-line to Sgr B2 (Neufeld et al. 1997). Since the density in the Low Velocity Flow, n = 100 K kinetic temperature, an H2 density of 1 × 10^5 cm^-2 for the outflowing absorbing gas. An alternative estimate has been obtained by Persson et al. (2007) from observations of emission from C17O pure rotational lines; this yields a value 3 × 10^5 cm^-2 for the total H2 column density. By comparison, this would be associated with the blue outflow lobe. We have estimated the H2 column density independently from the range of redshifts accessible from ground-based submillimeter telescopes is indicated by Neufeld et al. (2005, see their Fig. 11).

Acknowledgements. HIFI has been designed and built by a consortium of institutes and university departments from across Europe, Canada and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands and with major contributions from Germany, France and the US. The Consortium members are: Canada: CSA, U.Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfP, MPS; Ireland, NUI Maynooth; Italy: ASI, IFAS-IAF, Osservatorio Astrofisico di Arcetri - INAF; Netherlands: SRON, TUD, Poland: CAMK, CBK, Spain: Observatorio Astronómico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology – M2C, RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University – Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC. Support for this work was provided by NASA through an award issued by JPL-Caltech. CSO is supported by the NSF, award AST-0540882.

References


5. Conclusions

Our observations of hydrogen fluoride toward Orion-KL have revealed an unusual absorption feature in the spectrum of this source. To our knowledge, this is the first report of a submillimeter spectral line with a net negative flux in this archetypical emission line source. The unusual behavior of the HF J = 1–0 transition is a consequence of its extremely large critical density, and is mirrored by mid-infrared observations of the CO v = 1–0 band. Thanks to the high spectral resolution achievable with HIFI, the HF J = 1–0 line promises to provide a unique probe of the kinematics of – and depletion within – absorbing material along the sight-line to bright continuum sources, and one that is uncomplicated by the collisionally-excited line emission that is usually present in the spectra of other transitions. Redshifted HF J = 1–0 absorption may also prove to be an excellent tracer of the interstellar medium in the high-redshift Universe; the range of redshifts accessible from ground-based submillimeter telescopes is indicated by Neufeld et al. (2005, see their Fig. 11).