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The methanol lines and hot core of OMC2-FIR4, an intermediate-mass protostar, with Herschel/HIFI*


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ABSTRACT

In contrast with numerous studies on the physical and chemical structure of low- and high-mass protostars, much less is known about their intermediate-mass counterparts, a class of objects that could help to elucidate the mechanisms of star formation on both ends of the mass range. We present the first results from a rich HIFI spectral dataset on an intermediate-mass protostar, OMC2-FIR4, obtained in the CHESS (Chemical Herschel Survey of Star forming regions) key programme. The more than 100 methanol lines detected between 554 and 961 GHz cover a range in upper level energy of 40 to 540 K. Our physical interpretation focusses on the hot core, but likely the cold envelope and shocked regions also play a role in reality, because an analysis of the line profiles suggests the presence of multiple emission components. An upper limit of 10−6 is placed on the methanol abundance in the hot core, using a population diagram, large-scale source model and other considerations. This value is consistent with abundances previously seen in low-mass hot cores. Furthermore, the highest energy lines at the highest frequencies display asymmetric profiles, which may arise from infall around the hot core.

Key words. stars: formation – ISM: abundances – ISM: kinematics and dynamics – ISM: molecules

1. Introduction

Intermediate-mass, and therefore intermediate-luminosity protostars offer insights into the physical and chemical differences between the formation of low- and high-mass stars, but questions about their chemistry and dominant gas-heating mechanisms remain only partly answered.

Deep in the interior of a protostellar core, energy is released by a forming protostar. This energy heats the surrounding gas by dust-mediated and UV photon heating, as well as through shocks caused by protostellar outflows. The respective roles of these mechanisms as a function of protostar luminosity and the effects of heating on protostar evolution, are under intense study (e.g. Spaans et al. 1995; Doty et al. 2006; Bruderer et al. 2009), with the role of shocks and UV photons in low- and intermediate-luminosity sources emphasized by recent Herschel Space Observatory results (Fich et al. 2010; van Kempen et al. 2010). Sub-millimeter molecular line emission is a versatile probe of the physical and chemical conditions in these heated regions, the hot cores, revealing the initial conditions for forming stars and planetary systems. Hot cores are compact (sizes <0.1 pc), warm (T > 100 K), and show evidence of complex chemistry (Kurtz et al. 2000; Ceccarelli et al. 2007). The two main paths to this complexity are gas-phase and grain-surface reactions (e.g. Garrod et al. 2008). During the gradual warm-up of grains in a hot core, species formed on them in earlier evolutionary phases react and the products are later released into the gas phase. Observable chemical differences include a methanol–formaldehyde abundance ratio, which increases with decreasing protostar luminosity (Cazaux et al. 2003; Bottinelli et al. 2004, 2007).

We present Herschel/HIFI sub-millimeter observations of methanol line emission toward the intermediate-mass protostar OMC2-FIR41, attributing part of the emission to a hot core. With a luminosity of 1000 L⊙ (Crimier et al. 2009, hereafter Crim09) and a distance of only 440 pc (Hirota et al. 2007), the protostar OMC2-FIR4 is an excellent laboratory to study hot core chemistry in the intermediate mass regime. A structure model, constrained by 7.5′′ to 14.8′′ resolution dust-continuum maps and the broadband spectral energy distribution, was made for OMC2-FIR4 by Crim09.

* Herschel is an ESA space observatory with science instruments provided by European-led principal Investigator consortia and with important participation from NASA.

1 SIMBAD entry: [MWZ90] OMC-2 FIR 4.
The uncertainties in the properties of the central component are large, but the model suggests a hot core radius of $R_{\text{core}} = 440$ AU and densities above $\sim 5 \times 10^{10}$ cm$^{-3}$. At $\sim 1''$ resolution, FIR4 is seen to consist of several clumps, which may be forming a cluster of protostars (Shimajiri et al. 2008, hereafter Shim08). Some of this activity may be triggered by an outflow from the nearby source OMC2-FIR3.

Methanol is a powerful diagnostic of the physical and chemical conditions in protostellar sources (van der Tak et al. 2000; Leurini et al. 2004, 2007; Maret et al. 2005; Wang et al. 2010), and is used to that end here. A careful analysis of methanol is also important for recovering the other species which CH$_3$OH lines often blend with.

2. Observations

The source OMC2-FIR4 was observed with the HIFI spectrograph on the ESA Herschel Space Observatory (Pilbratt et al. 2010), using only the wide band spectrometer (WBS) (de Graauw et al. 2010), covering bands 1b (554.5 to 636.5 GHz), 2b (714.1 to 801 GHz), and 3b (858.0 to 961.0 GHz). The WBS native resolution is 1.1 MHz. The data were taken in dual beam switch (DBS) spectral scan mode with a redundancy of four. More observations, expected later in 2010, will cover most of HIFI’s frequency range. Median baseline subtraction and sideband deconvolution were performed with the HIPE 2 software (Ott 2010). A frequency-dependent main beam efficiency within three percent of 0.70 and a calibration uncertainty of 15% were used in calculating line fluxes. For a detailed review of HIFI’s in-orbit performance, see Roelfsema et al. (2010).

The data quality in 1b is superb, whereas 2b and 3b are significantly influenced by spurious features, “spurs”, introduced by the local oscillator electronics, which act to increase noise in the single-sideband spectra and can damage spectral line profiles. Combining the H and V polarizations, the rms outside the bright lines is $T^*_b = 10$ mK in 1b, 21 mK in 2b, and 26 mK in 3b.

3. Results

Preliminary data processing reveals 91 lines from 17 species in band 1b, and similar numbers in 2b and 3b, establishing OMC2-FIR4 as a relatively line-rich protostar (see also the review by Ceccarelli et al. 2010). Methanol lines are advantageous to study in OMC2-FIR4 because they are abundant, cover a large range of excitation conditions, and are straightforward to measure because the spectrum is less crowded than in higher luminosity hot sources, in which more levels of more species can be significantly excited. Out of the hundreds of CH$_3$OH transitions in each band, we detect 46 lines in band 1b, 46 in 2b, and 40 in 3b, with a range of 40 $K \lesssim E_u \lesssim 540$ K in excitation energy. Identification made use of the JPL database, with methanol data by Xu et al. (2008). This paper discusses lines detected with $>4\sigma$ confidence and not blended or damaged by spurs.

3.1. Line profiles

Average line profiles were calculated in two energy ranges, $E_u \lesssim 200$ K and $E_u \gtrsim 200$ K, for each observed band. These six average profiles are presented in Fig. 1, with the number of lines and relevant beam sizes given. Before averaging, each line profile was resampled to an 0.2 km s$^{-1}$ resolution grid with origin at the rest frequency, fitted by a single Gaussian and normalized by the intensity at the fit center. Distinguishing between the core ($|v| < 2$ km s$^{-1}$) and wings ($|v| > 2$ km s$^{-1}$) of a profile, we

\[ \Delta \ln \frac{N_i}{g_i} \lesssim 0.37. \]

Another factor is beam dilution, which contributes up to $\Delta \ln \left( \frac{N_i}{g_i} \right) \approx 2 \ln \left( \frac{37/25}{\sigma} \right) \approx 0.8$ for a point source observed

![Fig. 1. Averaged CH$_3$OH line profiles in the $E_u \lesssim 200$ K (left) and $E_u \gtrsim 200$ K (right) ranges, for bands 1b (top), 2b (middle) and 3b (bottom). The gray area marks the biased weighted standard deviation of the sample of normalized profiles. The two fitted Gaussians (blue, green) and their sum (dashed red line) are given.

<table>
<thead>
<tr>
<th>$E_u$ range</th>
<th>Fit</th>
<th>FWHM [km s$^{-1}$] (bands 1b, 2b, 3b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lesssim 200$ K</td>
<td>1</td>
<td>(1.52, 1.84, 1.72) ± (0.01, 0.08, 0.08)</td>
</tr>
<tr>
<td>2</td>
<td>(4.84, 5.16, 5.62) ± (0.03, 0.11, 0.07)</td>
<td></td>
</tr>
<tr>
<td>$\gtrsim 200$ K</td>
<td>1</td>
<td>(2.22, 2.08, 2.06) ± (0.04, 0.11, 0.28)</td>
</tr>
<tr>
<td>2</td>
<td>(5.68, 5.16, 4.44) ± (0.13, 0.13, 0.24)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_u$ range</th>
<th>Fit</th>
<th>Gaussian centre [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lesssim 200$ K</td>
<td>1</td>
<td>(0.02, –0.02, –0.06) ± (0.01, 0.03, 0.04)</td>
</tr>
<tr>
<td>2</td>
<td>(–0.04, 0.03, –0.38) ± (0.01, 0.04, 0.04)</td>
<td></td>
</tr>
<tr>
<td>$\gtrsim 200$ K</td>
<td>1</td>
<td>(0.05, 0.05, –0.22) ± (0.02, 0.04, 0.10)</td>
</tr>
<tr>
<td>2</td>
<td>(0.39, 0.23, 0.04) ± (0.05, 0.05, 0.10)</td>
<td></td>
</tr>
</tbody>
</table>

note that the cores of the average line profiles seem to show a broadening trend with decreasing beam size and increasing $E_u$. Also, the wings are weaker in the higher energy regime than in the lower.

Two-component blind Gaussian fits were made for the average profiles in each energy range and band. The fits systematically separate into a narrow and broad component, the widths and central locations of which are given in Table 1. The superiority of a two-Gaussian fit to that of a single Gaussian, as well as the trends mentioned in the previous paragraph, strongly suggest the presence of at least two physical emission components with different beam filling factors, as discussed in Sect. 4.

3.2. Population diagram and LTE modelling

The detection of 132 CH$_3$OH lines covering 500 K in upper level energy presents an excellent opportunity to perform a population diagram analysis (Goldsmith & Langer 1999) to study the excitation conditions. In Fig. 2 we present the population diagram for the observed methanol lines. Line fluxes were obtained from single-Gaussian fits.

Part of the vertical scatter in Fig. 2 is due to optical depth, estimated from LTE modelling to contribute $\Delta \ln (N_i/g_i) \lesssim 0.37$. Another factor is beam dilution, which contributes up to $\Delta \ln (N_i/g_i) \approx 2 \ln \left( \frac{37/25}{\sigma} \right) \approx 0.8$ for a point source observed.
The source OMC2-FIR4 is a line-rich protostar with a high degree of chemical and physical complexity. The hundreds of CH$_3$OH transitions that are detectable with HIFI cover a wide range of excitation conditions and offer unprecedented spectral constraints on the structure of protostellar cores.

Previous knowledge (Jørgensen et al. 2006, Shim08, Crim09) suggests OMC2-FIR4 is dominated by three components: a large-scale, cool envelope $\sim 10^2$ AU across; a compact hot core $\sim 10^2$ AU across; and the outflow from FIR3, in particular a suspected blue-shifted spot resulting from its interaction with the FIR4 envelope. The hot core gives rise to a dominant part of the emission in all lines in our LTE model, but the changes in line profiles through Fig. 1 imply reality is more complex. The envelope may contribute significantly to the lowest excitation lines, and shocks from regions such as where the FIR3 outflow strikes FIR4 (Shim08) are likely to be important.

The effects of the hot core radius and H$_2$ column density on the line fluxes are degenerate if the lines are optically thin, as they are in our LTE model. Thus, an upper limit on the former and lower limit on the latter will result in an upper limit on the methanol abundance. Attributing the luminosity of FIR4, $10^{5} L_{\odot}$ to the central protostar and assuming grain mantle evaporation at 100 K, one finds an upper limit of $R_{\text{core}} \approx 760$ AU for 0.1 $\mu$m olivine grains. More realistic radiative transfer would decrease this value. At 440 pc, 760 AU extends $\sim 1.75''$ on the sky, which is adopted as the core radius in the model.

To reproduce the observed $K_0 = 0$ line fluxes with LTE at an assumed $T_{\text{exc}} = 120$ K, we need a column density of $N(\text{CH}_3\text{OH}) = 6 \times 10^{16}$ cm$^{-2}$ in the model hot core. Integrating the Crim09 H$_2$ density distribution from 100 to $R_{\text{crim}} \approx 440$ AU, one obtains $N(\text{H}_2) \approx 6 \times 10^{22}$ cm$^{-2}$. The source model was based on low-resolution maps, and the core is poorly constrained and excludes the inner 100 AU. We thus take the H$_2$ column density as a lower limit and, adopting it in the LTE model, conclude that the obtained CH$_3$OH abundance $X_{\text{core}} = 10^{-6}$ is a conservative upper limit. The highest abundance seen in low-mass hot cores is $2 \times 10^{-6}$ (Jørgensen et al. 2005). If the hot core does not

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**Table 2. Excitation temperature and column densities.**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Component</th>
<th>$T$ [K] (type)</th>
<th>$N_{\text{meth}}$ [cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>$K_u = 0(A)$</td>
<td>$145 \pm 12$ (rot)</td>
<td>$(2.2 \pm 0.5) \times 10^{14}$</td>
</tr>
<tr>
<td>diagram</td>
<td>$K_u = 0(E)$</td>
<td>$120 \pm 8$ (rot)</td>
<td>$(1.4 \pm 0.3) \times 10^{14}$</td>
</tr>
<tr>
<td>LTE model</td>
<td>Envelope</td>
<td>$40$ (exc)</td>
<td>$2 \times 10^{14}$</td>
</tr>
<tr>
<td>input</td>
<td>Hot core</td>
<td>$120$ (exc)</td>
<td>$6 \times 10^{16}$</td>
</tr>
<tr>
<td>LTE simu-</td>
<td>$K_u = 0(A)$</td>
<td>$164$ (rot)</td>
<td>$1.4 \times 10^{14}$</td>
</tr>
<tr>
<td>lated obs.</td>
<td>$K_u = 0(E)$</td>
<td>$168$ (rot)</td>
<td>$1.7 \times 10^{14}$</td>
</tr>
</tbody>
</table>

**Notes.** From the top: the rotational temperatures and methanol column densities derived from the observed population diagram; the input excitation temperatures and column densities of the LTE model; the rotational temperatures and column densities derived from the modelled population diagram.

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$^3$ CASSIS has been developed by CESR-UPS/CNRS (http://cassis.cesr.fr).
dominate the line emission in reality, smaller hot core sizes and methanol column densities, as well as higher rotational temperatures, may be consistent with the data. Presently, the abundance of methanol in the envelope is very poorly constrained. We set it to $2 \times 10^{-9}$ in the LTE model, consistent with the factor $10^2 - 10^{5}$ abundance jump seen in hot cores (van der Tak et al. 2000; Maret et al. 2005).

The hot core density is broadly constrained to be between $10^4$ and $10^5$ cm$^{-3}$ by this early analysis. Lower and higher values would be difficult to reconcile with the large-scale density profile, furthermore the population diagram suggests the $K$ ladders with the lowest $n_K$ may approach LTE while those with the highest $n_K$ clearly deviate from it. Typical kinetic temperatures well in the $\approx 100$ K hot core regime are implied by the obtained rotational temperatures of $T_{rot} \approx (120 \ldots 145)$ K. Shock contributions from the FIR3-FIR4 interaction spot as well as the hot core itself need to be considered before drawing further conclusions about the temperature structure.

An intriguing feature is the appearance of an asymmetry in the $E_u \geq 200$ K lines, as seen in Fig. 1. Because these lines should be dominated by the hot core emission, the profiles observed could represent the blue asymmetric profile expected for infalling gas (e.g. Walker et al. 1994), implying we may be seeing collapse in the central regions. To clarify whether infall, shocks, or other phenomena are responsible for the asymmetry, interferometry as well as further analysis of the Herschel/HIFI data, in particular the $^{13}$CH$_3$OH lines, will be employed.

We note the difference in column density of the $K_0 = 0$ transitions of the $A$ and $E$ states in Table 2. Whether it is truly significant will be explored in a future paper. Also, early results from an analysis of formaldehyde in OMC2-FIR4 will be presented in a companion paper (Crimier et al., in prep.).

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