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Herschel observations of the hydroxyl radical (OH) in young stellar objects


(Affiliations are available on page 5 of the online edition)

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ABSTRACT

Aims. “Water In Star-forming regions with Herschel” (WISH) is a Herschel key program investigating the water chemistry in young stellar objects (YSOs) during protostellar evolution. Hydroxyl (OH) is one of the reactants in the chemical network most closely linked to the formation and destruction of H2O. High-temperature (T > 250 K) chemistry connects OH and H2O through the OH + H2 ↔ H2O + H reactions. Formation of H2O from OH is efficient in the high-temperature regime found in shocks and the innermost part of protostellar envelopes. Moreover, in the presence of UV photons, OH can be produced from the photo-dissociation of H2O through H2O + γν → OH + H +.

Methods. High-resolution spectroscopy of the 163.12 μm triplet of OH towards HH 46 and NGC 1333 IRAS 2A was carried out with the Heterodyne Instrument for the Far Infrared (HIFI) on board the Herschel Space Observatory. The low- and intermediate-mass protostars HH 46, TMR 1, IRAS 15398-3359, DK Cha, NGC 7129 FIRS 2, and NGC 1333 IRAS 2A were observed with the Photodetector Array Camera and Spectrometer (PACS) on Herschel in four transitions of OH and two [O I] lines.

Results. The OH transitions at 79, 84, 119, and 163 μm and [O I] emission at 63 and 145 μm were detected with PACS towards the class I low-mass YSOs as well as the intermediate-mass and class I Herbig Ae sources. No OH emission was detected from the class 0 YSO NGC 1333 IRAS 2A, though the 119 μm was detected in absorption. With HIFI, the 163.12 μm was not detected from HH 46 and only tentatively detected from NGC 1333 IRAS 2A. The combination of the PACS and HIFI results for HH 46 constrains the line width (FWHM ≥ 11 km s−1) and indicates that the OH emission likely originates from shocked gas. This scenario is supported by trends of the OH flux increasing with the bolometric luminosity, as found in our sample. Similar OH line ratios for most sources suggest that OH has comparable excitation temperatures despite the different physical properties of the sources.

Key words. astrophysics – stars: formation – ISM: molecules – ISM: jets and outflows – ISM: individual objects: HH 46

1. Introduction

The hydroxyl radical (OH) is a cornerstone species of the oxygen chemistry in dense clouds and is particularly important in the chemical reaction network of water. H2O and OH are closely linked through the OH + H2 ↔ H2O + H reactions. The formation path of H2O from OH is efficient at the high temperatures found in shocks or in the innermost parts of circumstellar envelopes (Kaufman & Neufeld 1996, Charnley 1997). Below about 250 K, standard gas-phase chemistry applies, in which H2O is formed and destroyed through ion-molecule reactions. In regions not completely shielded from UV radiation, photodissociation becomes a major destruction path of H2O, leaving OH as a byproduct. A better understanding of the OH emission will therefore help to constrain the water chemistry.

The observation of far-infrared (FIR) rotational OH lines by ground based facilities is severely limited by the Earth’s atmosphere. Previous studies of OH FIR emission with the ISO showed that OH is one of the major molecular coolants in star-forming regions (e.g. Giannini et al. 2001). However, with a large beam of 80″, ISO was unable to resolve the central source from the outflows, preventing an assessment of the origin of the OH emission. Interpretation of the ISO OH measurements thus relied mostly on the assumption that the OH emission arises from gas with the same temperature and density as the high-J CO FIR emission (e.g. Nisini et al. 1999, Ceccarelli et al. 1998). The Herschel Space Observatory permits observations of OH FIR transitions at both higher angular and spectral resolution and at higher sensitivity than ISO.

Observations of H2O, OH and related species towards a large set of young stellar objects over a wide range of luminosities and masses are being carried out in the ‘Water In Star-forming regions with Herschel’ (WISH) key program to trace the water chemistry during protostellar evolution (van Dishoeck et al. in prep). OH emission at 163.12 μm (1837.8 GHz) was detected with PACS towards the class I YSO HH 46
Because of spin-orbit interaction, the OH rotational levels are built within two ladders, $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$ (Offer & van Dishoeck 1992). Each level is further split by A doubling and hyperfine structure. A level diagram can be found in Fig. C.1 in the appendix. We use the molecular data from the Leiden atomic and molecular database LAMDA\(^1\) (Schöier et al. 2005).

High-resolution observations of the OH triplet at 163.12 $\mu$m (1837.747, 1837.817 and 1837.837 GHz) were performed with the Heterodyne Instrument for the Far-Infrared (HIFI, de Graauw et al. 2010) on board the ESA Herschel Space Observatory (Pilbratt et al. 2010) towards HH 46 and NGC 1333 IRAS 2A. HIFI data were stitched together using the Herschel interactive processing environment (HIPE v3.0.1, Ott 2010) and further analyzed using GILDAS-CLASS\(^2\) software. We removed standing waves after the subtraction of a low-order polynomial and calibrated to $T_{\text{mb}}$ scale using a main beam efficiency of 0.74. The H and V polarizations were combined.

HH 46, TMR 1, IRAS 15398-3359, and NGC 7129 FIRS 2 were observed with PACS (Poglitsch et al. 2010) in line spectroscopy mode around four OH doublets at 79, 84, 119, and 163 $\mu$m. The [O I] 63 and 145.5 $\mu$m lines were also observed except for TMR 1. Each segment at $\lambda < 100$ $\mu$m and $\lambda > 300$ $\mu$m was corrected for T$_{\text{mb}}$ scale using a main beam efficiency of 0.74. The H and V polarizations were combined.

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The observation of YSOs using OH transition with PACS and ISO spectra.

### Table 1. OH and [O I] line fluxes observed with PACS.

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\lambda$ (μm)</th>
<th>$\nu$ (GHz)</th>
<th>$E_0$ (K)</th>
<th>HH 46 Flux [10^{-18} W m^{-2}]</th>
<th>TMR 1 Flux [10^{-18} W m^{-2}]</th>
<th>IRAS 15398 Flux [10^{-18} W m^{-2}]</th>
<th>DK Cha Flux [10^{-18} W m^{-2}]</th>
<th>NGC 7129 Flux [10^{-18} W m^{-2}]</th>
<th>N 1333 I 2A Flux [10^{-18} W m^{-2}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH 1 0–1 1</td>
<td>79.12 3789.3</td>
<td>181.9</td>
<td>55 ± 7</td>
<td>128 ± 14</td>
<td>194 ± 29$^a$</td>
<td>351 ± 58</td>
<td>230 ± 39</td>
<td>&lt;350</td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>79.18 3763.3</td>
<td>181.7</td>
<td>38 ± 6</td>
<td>102 ± 14</td>
<td></td>
<td>215 ± 43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>84.60 3543.8</td>
<td>290.5</td>
<td>87 ± 6</td>
<td>170 ± 18</td>
<td>93 ± 16</td>
<td>347 ± 48</td>
<td>181 ± 28</td>
<td>&lt;165</td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>119.23 2514.3</td>
<td>120.7</td>
<td>38 ± 10</td>
<td>121 ± 17</td>
<td>95 ± 50$^b$</td>
<td>132 ± 39</td>
<td>absorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>119.44 2510.0</td>
<td>120.5</td>
<td>44 ± 7</td>
<td>101 ± 17</td>
<td></td>
<td>134 ± 59</td>
<td>absorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>163.12 1837.8</td>
<td>270.1</td>
<td>56 ± 8</td>
<td></td>
<td>47 ± 9</td>
<td>170 ± 69$^c$</td>
<td></td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>OH 1 0–1 1</td>
<td>163.40 1834.8</td>
<td>269.8</td>
<td>&lt;27</td>
<td>55 ± 7</td>
<td>54 ± 10</td>
<td>69 ± 26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[O I] 63–60</td>
<td>63.18 2474.8</td>
<td>227.7</td>
<td>1260 ± 54</td>
<td>–</td>
<td>1958 ± 197</td>
<td>3128 ± 333</td>
<td>1219 ± 130</td>
<td>&lt;320</td>
<td></td>
</tr>
<tr>
<td>[O I] 63–60</td>
<td>145.53 2650.1</td>
<td>326.6</td>
<td>82 ± 8</td>
<td>–</td>
<td>122 ± 17</td>
<td>170 ± 72</td>
<td>104 ± 35</td>
<td>&lt;180</td>
<td></td>
</tr>
</tbody>
</table>

Notes. $^a$ Doublet not resolved. Table lists the integrated flux over both components.

### Figure 2. PACS spectra of the observed OH doublets at 79, 84, 119, and 163 μm. Sources in the top panel were observed in line spectroscopy mode, those in the lower panel in range spectroscopy mode (different sampling). Dashed vertical lines indicate the OH frequencies, dotted lines show the position of CO lines.

### Figure 3. Observed OH line fluxes from PACS plotted versus the upper level energy of the transition. Ser SMM 1 and NGC 1333 IRAS 4 measured with ISO are included for comparison. Symbols correspond to different OH transitions: 79 μm as diamond, 84 μm as triangle, 119 μm as circle, and 163 μm as square. Fluxes of the doublet components are summed. The 84.60 μm flux multiplied by two is used for the 84 μm doublet because the 84 μm line is blended with CO(3–1).

### Figure 4. Observed OH line fluxes with increasing bolometric source luminosity $L_{bol}$ found in our source sample. We calculated the OH line luminosity $L_{OH}$ individually for each transition and source from the observed fluxes and found indications that the differences between the sources may depend on the individual $L_{bol}$. The correlation between $L_{OH}$ and $L_{bol}$ is reminiscent of that found for the CO outflow force with luminosity (Bontemps et al. 1996). The latter relation was taken as evidence that more massive envelopes have higher accretion rates and thus drive more powerful outflows. van Kempen et al. (2010b) speculate that the OH emission originates in the wake of the jet impinging on the dense, inner parts of the envelope, creating dissociative shocks in which [O I] is the dominant coolant, followed by OH (Neufeld & Dalgarno 1989). The relation between OH emission and luminosity supports this scenario.
Comparison of OH with [O i] emission shows that stronger OH emission coincides with higher [O i] intensities (Fig. 5) and also with increasing [O i] 63/145 μm line flux ratios. For HH 46, TMR 1, and NGC 7129 FIRS 2, the bulk of the [O i] and OH emission comes from close to the protostar where densities are on the order of 10^5 cm^{-3} or higher, as illustrated by the lack of extended OH emission in HH 46 (van Kempen et al. 2010b). Some spatially extended OH emission is detected from IRAS 15398-3359 and DK Cha, and is highly correlated with the spatial extent of [O i] emission. The correlation between the intensities (Fig. 5) suggests that the bulk of [O i] and OH emission originates in the same physical component in all sources. This argument, together with the OH – Lbol and OH – [O i] relations, supports the dissociative shock scenario. The [O i] 63 μm/145 μm line ratios are in the range of 13–19, also consistent with fast, dissociative J-type shocks (ν > 60 km s^{-1}, Neufeld & Dalgarno 1989). Note that an OH – [O i] relation can also be indicative of photo-dissociation, as argued for Sgr B2 by Giococeheaa et al. (2004).

Models of photon-dominated regions (Kaufman et al. 1999) predict similar [O i] 63 μm/145 μm line ratios, but those require ν < 10^7 km s^{-1}, which is inconsistent with an origin in the inner, dense envelope.

5. Conclusions

The OH hyperfine transition triplet at 163.12 μm (1837.8 GHz) was not detected above the noise level obtained with HIFI. Combined with the flux derived from the unresolved line observed with PACS, this constrains the line width to FWHM ≥ 11 km s^{-1}. This width is much broader than expected for the quiescent envelope from ground-based observations (van Kempen et al. 2009a) and indicates that the observed OH emission most likely stems from shocked gas in HH 46.

Herschel PACS observations of OH lines at 79, 84, 119, and 163 μm have been carried out for four low-mass YSOs, one intermediate-mass protostar and one class I Herbig Ae object. OH emission is detected in all sources except the class 0 YSO NGC 1333 IRAS 2A, where the OH 119 μm transitions are observed in absorption and only upper limits can be derived for the other lines. Sources with detected OH emission show surprisingly similar OH line ratios despite the large ranges of physical properties covered in this study, suggesting that OH emission might arise from gas at similar conditions in all sources. Furthermore, we find trends of correlations between OH integrated intensities and [O i] emission as well as bolometric luminosity, consistent with an origin in the wake of dissociative shocks. Given the low number of sources in the sample, confirmation from additional observations is needed. In a similar HIFI observation, OH emission was tentatively detected below the 5σ level for the strongest triplet component in NGC 1333 IRAS 2A, in agreement with the upper limits on OH emission in the PACS observation of the same source. Given the uncertain baseline, this needs to be treated with caution. Further OH observations and modeling should eventually allow the determination of the OH/H2O abundance ratio in shocks, which traces the UV field through its dependence on the fraction of atomic to molecular hydrogen.

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References


Fig. 4. Dependence of OH line luminosity on the bolometric luminosity of the source. Symbols and colors as in Fig. 3.

Fig. 5. Observed OH fluxes plotted against [O i] 63 μm flux (left panel) and 145 μm flux (right panel). Symbols and colors as in Fig. 3.
Appendix A: Observational details

Table A.1 lists the coordinates, observing dates, and the observation identity numbers of our sources along with the assumed distance, the bolometric luminosity, the envelope mass and the source type. For comparison, Ser SMM1 and NGC 1333 IRAS 4 observed with ISO are included as well. For Ser SMM1, we use the average values of the fluxes presented by Larsson et al. (2002). The data for NGC 1333 IRAS 4 are taken from Giannini et al. (2001). Note that for NGC 1333 IRAS 4, we use the luminosity and mass of NGC 1333 IRAS 4A.

Table A.1. Source properties and observational details.

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance [pc]</th>
<th>Luminosity [L_\odot]</th>
<th>Envelope Mass [M_\odot]</th>
<th>Type</th>
<th>RA [h m s]</th>
<th>Dec [\degree]</th>
<th>Obs. Date</th>
<th>Obs.id</th>
</tr>
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<tbody>
<tr>
<td>HH 46</td>
<td>450</td>
<td>16</td>
<td>5.1</td>
<td>Class I</td>
<td>08:25:43.9</td>
<td>51:00:36</td>
<td>2009-10-26</td>
<td>1342186315 (PACS)</td>
</tr>
<tr>
<td>TMR 1</td>
<td>140</td>
<td>3.7</td>
<td>0.12</td>
<td>Class I</td>
<td>04:39:13.7</td>
<td>25:53:21</td>
<td>2010-04-17</td>
<td>1342194783 (HIFI)</td>
</tr>
<tr>
<td>IRAS 15398-3359</td>
<td>130</td>
<td>0.92</td>
<td>0.53</td>
<td>Class I</td>
<td>15:43:01.3</td>
<td>34:09:15</td>
<td>2010-02-27</td>
<td>1342191302 (PACS)</td>
</tr>
<tr>
<td>DK Cha</td>
<td>178</td>
<td>29.4</td>
<td>0.03</td>
<td>Herbig Ae</td>
<td>12:53:17.2</td>
<td>77:07:10.6</td>
<td>2009-12-10</td>
<td>1342188039 (PACS)</td>
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<tr>
<td>NGC 7129 FIRS 2</td>
<td>1260</td>
<td>500</td>
<td>50.0</td>
<td>Intermed.-Mass</td>
<td>21:43:01.7</td>
<td>66:03:23.6</td>
<td>2010-02-13</td>
<td>1342190686 (PACS)</td>
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<tr>
<td>NGC 1333 I 2A</td>
<td>235</td>
<td>20</td>
<td>1.0</td>
<td>Class 0</td>
<td>03:28:55.6</td>
<td>31:14:37</td>
<td>2010-02-24</td>
<td>1342191149 (PACS)</td>
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<td></td>
<td>2010-03-08</td>
<td>1342191773 (HIFI)</td>
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<td>Serpens SMM1</td>
<td>415</td>
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<td>–</td>
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<tr>
<td>NGC 1333 I 4</td>
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<td>5.8</td>
<td>4.5</td>
<td>Class 0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>ISO</td>
</tr>
</tbody>
</table>

Notes. (a) Heathcote et al. (1996); (b) van Kempen et al. (2009a); (c) Motte et al. (1998); (d) Ohashi et al. (1996); (e) Jørgensen et al. (2002); (f) Murphy et al. (1986); (g) Froebrich (2005); (h) van Kempen et al. (2009b); (i) Whittet et al. (1997); (j) van Kempen et al. (2010a); (k) Shevchenko & Yakubov (1989); (l) Johnstone et al. (2010); (m) Crimier et al. (2010); (n) Hirota et al. (2008); (o) Jørgensen et al. (2009); (p) Dzib et al. (2010); (q) Hogerheijde et al. (1999) \(L_{bol}\) scaled to a distance of 415 pc; (r) Larsson et al. (2002); (s) Giannini et al. (2001).

Appendix B: OH line ratios

Fig. B.1. Ratios of the observed OH fluxes. The numbers denote the corresponding wavelengths. The symbols are: circle for HH 46, upward triangle for TMR 1, downward triangle for IRAS 15398-3359, squares for NGC 7129 FIRS 2, plus signs for DK Cha, crosses for Ser SMM1 and diamonds for NGC 1333 IRAS 4. The color coding is the same as in Fig. 3.

Appendix C: OH term diagram

Fig. C.1. Level diagram of the lowest excited states of OH up to \(E_{up} \approx 300\) K. Splitting of the levels because of A-doubling and hyperfine structure is not to scale. Transitions observed with PACS are shown in green, the high-resolution observations of the hyperfine transitions carried out with HIFI in red.