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LETTER TO THE EDITOR

Herschel observations of the hydroxyl radical (OH) in young stellar objects^{★,★★}

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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 ($T \gtrsim 250$ K) chemistry connects OH and H₂O through the $\text{OH} + \text{H}_2 \rightleftharpoons \text{H}_2\text{O} + \text{H}$ 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 $\text{H}_2\text{O} + \gamma_{\text{UV}} \rightarrow \text{OH} + \text{H}$.

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 [OI] lines.

Results. The OH transitions at 79, 84, 119, and 163 μm and [OI] 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 ($\text{FWHM} \gtrsim 11 \text{ km s}^{-1}$) and indicates that the OH emission likely originates from shocked gas. This scenario is supported by trends of the OH flux increasing with the [OI] flux and 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. astrochemistry – 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 $\text{OH} + \text{H}_2 \rightleftharpoons \text{H}_2\text{O} + \text{H}$ 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, photo-dissociation 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

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

** Appendices (page 6) are only available in electronic form at <http://www.aanda.org>

(van Kempen et al. 2010b), but the triplet, split by 90 MHz, could not be resolved. Based on modeling results, the OH emission was attributed to a J -type shock and not to the quiescent envelope. We carried out high-resolution spectroscopy with HIFI to test whether the detected OH emission is dominated by shock contribution by resolving the line profiles. This paper presents the HIFI observations in HH 46 as well as the class 0 object NGC 1333 IRAS 2A. New PACS observations of OH and [O I] are reported for the low-mass protostars IRAS 15398-3359, NGC 1333 IRAS 2A, and TMR 1.

2. Observations and data reduction

Because of spin-orbit interaction, the OH rotational levels are built within two ladders, ${}^2\Pi_{3/2}$ and ${}^2\Pi_{1/2}$ (Offer & van Dishoeck 1992). Each level is further split by Λ 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 LAMDA¹ (Schöier et al. 2005).

High-resolution observations of the OH triplet at $163.12\ \mu\text{m}$ (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-CLASS² software. We removed standing waves after the subtraction of a low-order polynomial and calibrated to T_{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 $163\ \mu\text{m}$. The [O I] 63 and $145.5\ \mu\text{m}$ lines were also observed except for TMR 1. Each segment at $\lambda < 100\ \mu\text{m}$ and $\lambda > 100\ \mu\text{m}$ covers 1 and $2\ \mu\text{m}$ at $R \sim 3000$ and $R \sim 1500$, respectively. In addition, DK Cha and NGC 1333 IRAS 2A were observed with PACS from 55–210 μm at $R \sim 1000$ in range spectroscopy mode. Details of the PACS observations of HH 46, NGC 7129 FIRS 2, and DK Cha are described in van Kempen et al. (2010b), Fich et al. (2010), and van Kempen et al. (2010a), respectively. All spectra were reduced with HIPE v2.9. PACS spectra are recorded in a 5×5 array of $9''.4$ square spatial pixels (spaxels). The observations of IRAS 15398-3359, TMR 1, NGC1333 IRAS 2A, and DK Cha were mispointed sufficiently in a way that the peak of the continuum emission differs from the central spaxel.

The line and continuum emission seen by PACS is spatially extended in most cases. Spectra were extracted from the spaxels that include OH emission. The wavelength-dependent point-spread function was roughly corrected by comparing the amount of continuum emission in the summed spaxels to that in the total array. Most integrated line intensities were derived from Gaussian fits to the unresolved lines. In a few cases, the OH doublets could not be resolved and the intensities were then derived by simple integration over the spectrum. The absolute flux calibration below and above $100\ \mu\text{m}$ was separately determined from in-flight observations of (point) calibration sources. The relative spectral response function within each band was determined from ground calibration prior to launch. The uncertainty in absolute and relative fluxes is estimated to be 30–50%. Additional details on the observations can be found in the appendix.

¹ <http://www.strw.leidenuniv.nl/~moldata/>

² <http://www.iram.fr/IRAMFR/GILDAS>

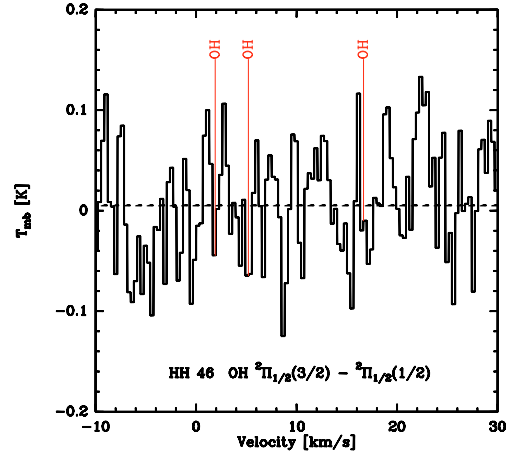


Fig. 1. HIFI spectrum at $163.12\ \mu\text{m}$ ($1837.8\ \text{GHz}$) towards the low-mass YSO HH 46 ($v_{\text{lsr}} = 5.2\ \text{km s}^{-1}$). OH lines were not detected in 34 min of on source integration time (polarizations combined).

3. Results

HIFI did not detect the $163.12\ \mu\text{m}$ OH hyperfine triplet at the noise level of $T_{\text{rms}} \approx 70\ \text{mK}$ on T_{mb} scale for the nominal WBS resolution of about $1.1\ \text{MHz}$ ($0.163\ \text{km s}^{-1}$). The spectrum is presented in Fig. 1. Combining the HIFI and PACS observations constrains the line width (see Sect. 4).

PACS detected OH emission at 79, 84, 119, and $163\ \mu\text{m}$ towards the class I sources HH 46, TMR 1 and IRAS 15398-3359 as well as the class I Herbig Ae star DK Cha and the intermediate-mass source NGC 7129 FIRS 2 (Fig. 2). An exception is the $163.40\ \mu\text{m}$ line of HH 46, where we only have an upper limit because of the uncertain baseline towards the end of the spectral window where the line is located. The [O I] $63\ \mu\text{m}$ and $145\ \mu\text{m}$ lines were also detected. An overview of the results is given in Table 1. The 1σ errors listed in Table 1 do not include the systematic error of 30–50% from uncertainty in the calibration. Because of blending with CO(31–30), the $84.42\ \mu\text{m}$ doublet component of OH is not listed. For the analysis, we assumed the flux to be identical to the $84.60\ \mu\text{m}$ OH flux because all observed doublets show comparable fluxes of the components within the calibration uncertainty.

The only class 0 YSO in the sample, NGC 1333 IRAS 2A, is fundamentally different from all other sources in the sample. The OH $119\ \mu\text{m}$ doublet is seen in absorption, with an equivalent width of about $7.5\ \text{km s}^{-1}$ for each component. No other OH lines were detected at the noise level obtained after removal of the fringing effects. However, the upper limits are larger than the fluxes detected from the class I sources. On the other hand, the upper limit on the [O I] $63\ \mu\text{m}$ emission is at least a factor of four lower than the weakest [O I] $63\ \mu\text{m}$ line found in our sample.

4. Analysis

To constrain the line width of the $163.12\ \mu\text{m}$ OH triplet from HH 46, the HIFI non-detection is combined with the flux ($22 \times 10^{-18}\ \text{W m}^{-2}$) of the unresolved lines measured with the high-sensitivity PACS instrument. The expected integrated intensity for HIFI is $\sim 1.1\ \text{K km s}^{-1}$ for the triplet in total, as calculated from the PACS observation. This value was derived for a $13''$ beam under the assumption that the source is unresolved, because the OH emission from HH 46 appears to be centrally concentrated (van Kempen et al. 2010b). Assuming LTE ratios ($\sim A_{ul}g_u$) for the three components, the strongest transition has an integrated intensity of $0.66\ \text{K km s}^{-1}$. An upper limit on the integrated intensity is calculated from the HIFI observation using

Table 1. OH and [OI] line fluxes observed with PACS.

Transition	λ [μm]	ν [GHz]	E_{up} [K]	HH 46	TMR 1	IRAS 15398	DK Cha	NGC 7129	N 1333 I 2A
				Flux [$10^{-18} \text{ W m}^{-2}$]	Flux [$10^{-18} \text{ W m}^{-2}$]	Flux [$10^{-18} \text{ W m}^{-2}$]	Flux [$10^{-18} \text{ W m}^{-2}$]	Flux [$10^{-18} \text{ W m}^{-2}$]	Flux [$10^{-18} \text{ W m}^{-2}$]
OH $_{1,1}^2-_{1,0}^3$	79.12	3789.3	181.9	55 ± 7	128 ± 14	194 ± 29^a	360 ± 87	229 ± 33	<350
OH $_{2,2}^3-_{2,1}^3$	79.18	3786.3	181.7	38 ± 5	102 ± 14	— ^a	315 ± 58	230 ± 39	—
OH $_{3,3}^4-_{3,2}^4$	84.60	3543.8	290.5	87 ± 6	170 ± 18	93 ± 16	347 ± 48	181 ± 28	<165
OH $_{4,4}^5-_{4,3}^5$	119.23	2514.3	120.7	38 ± 9	83 ± 10	121 ± 17	95 ± 50^a	132 ± 39	absorption
OH $_{5,5}^6-_{5,4}^6$	119.44	2510.0	120.5	44 ± 7	101 ± 11	130 ± 17	— ^a	134 ± 59	absorption
OH $_{6,6}^7-_{6,5}^7$	163.12	1837.8	270.1	22 ± 4	56 ± 8	47 ± 9	170 ± 60^a	116 ± 45	<100
OH $_{7,7}^8-_{7,6}^8$	163.40	1834.7	269.8	<27	55 ± 7	54 ± 10	— ^a	69 ± 26	—
[OI] $^3P_1-^3P_2$	63.18	4744.8	227.7	1260 ± 54	—	1958 ± 197	3128 ± 333	1219 ± 130	<320
[OI] $^3P_0-^3P_2$	145.53	2060.1	326.6	82 ± 8	—	122 ± 17	170 ± 72	104 ± 35	<180

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

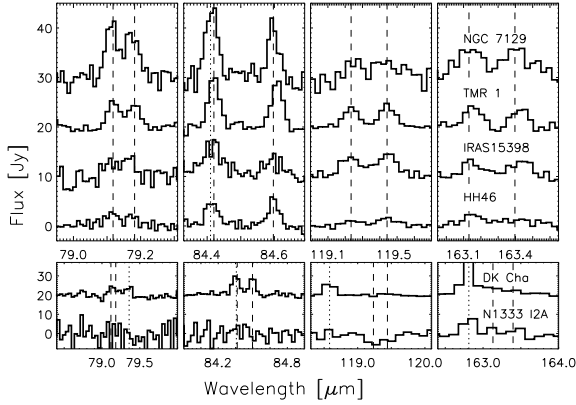


Fig. 2. PACS spectra of the observed OH doublets at 79, 84, 119, and 163 μm . Sources in the *top panel* were observed in line spectroscopy mode, those in the *lower panel* in range spectroscopy mode (different sampling). Dashed vertical lines indicate the OH frequencies, dotted lines show the position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

$\sigma = 1.3 \sqrt{\delta\nu \Delta\nu} T_{\text{rms}}$ with $\delta\nu$ the velocity resolution, $\Delta\nu$ the expected line width and an assumed 30% calibration uncertainty. Rebinning the spectrum to a resolution of 16 MHz (2.6 km s^{-1}) yields an rms of 31 mK and would therefore allow 5σ (3σ) detections for Gaussian lines with $FWHM \leq 4 \text{ km s}^{-1}$ ($FWHM \leq 11 \text{ km s}^{-1}$). From the non-detection we conclude that the flux observed with PACS is likely to be emitted from lines with $FWHM \geq 11 \text{ km s}^{-1}$. For comparison, the $FWHM$ of the $\text{H}_2\text{O } 1_{10-1_{01}}$ transition derived from recent unpublished HIFI observations is about 16 km s^{-1} . The $\text{CO}(6-5)$ and $\text{CO}(7-6)$ lines observed with APEX by van Kempen et al. (2009a) are narrower. 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.

Figure 3 compares the OH fluxes from YSOs as measured here with PACS and in ISO observations of two additional sources, Ser SMM1 (Larsson et al. 2002) and NGC 1333 IRAS 4 (Giannini et al. 2001). Despite the wide range of luminosities and masses covered in our sample, the sources show surprisingly similar characteristics in terms of their OH emission: the OH 84 μm doublet is generally the strongest of the four, while the integrated intensity of the weakest doublet at 163 μm is roughly a factor of three lower. The 119 μm flux can vary compared to higher excitation lines because this line, which is connected to the ground state level, becomes more easily optically thick. It can also be affected by absorption against the continuum by cold gas layers lying in front of the source. The 79 μm doublet links the lowest energy states of both rotational ladders, but because of the smaller Einstein A coefficients of the cross-ladder transitions, these lines are less affected by optical depth than the

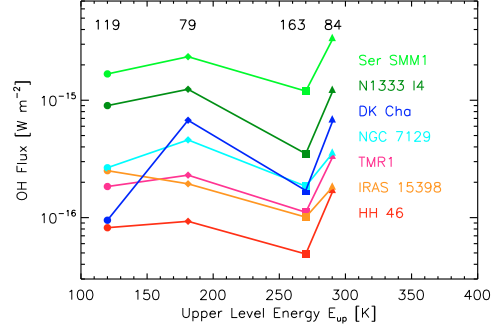


Fig. 3. Observed OH line fluxes from PACS plotted versus the upper level energy of the transition. Ser SMM 1 and NGC 1333 IRAS 4 measured with ISO are included for comparison. Symbols correspond to different OH transitions: 79 μm as diamond, 84 μm as triangle, 119 μm as circle, and 163 μm as square. Fluxes of the doublet components are summed. The 84.60 μm flux multiplied by two is used for the 84 μm doublet because the 84.42 μm line is blended with $\text{CO}(31-30)$.

119 μm lines. The 79 μm fluxes are lower than those at 84 μm for most sources, but higher than at 119 μm .

Flux ratios of the observed OH lines were calculated from the summed doublet components to compare the excitation of the involved energy levels among the sources. The line ratios of different sources agree within a factor of two except when the 119 μm transition is involved (Fig. B.1 in the appendix) and are consistent with the results from ISO observations from the class 0 sources NGC 1333 IRAS 4 and Ser SMM1.

Emission in the 84 μm transition, which has $E_{\text{up}}/k_B \approx 300 \text{ K}$, indicates that OH is tracing the warm ($T \geq 100 \text{ K}$) and dense ($n \geq 10^5 \text{ cm}^{-3}$) gas in our sources. Modeling results show that transitions in the $^2\Pi_{3/2}$ ladder are mostly excited by collisions while the population of the $^2\Pi_{1/2}$ levels is dominated by radiative pumping via the cross-ladder transitions. The weak 163 μm lines and emission at 79 μm indicate that FIR pumping is less important than collisional excitation in our sources.

Figure 4 shows the trend of stronger OH emission 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 [OI] is the dominant coolant, followed by OH (Neufeld & Dalgarno 1989). The relation between OH emission and luminosity supports this scenario.

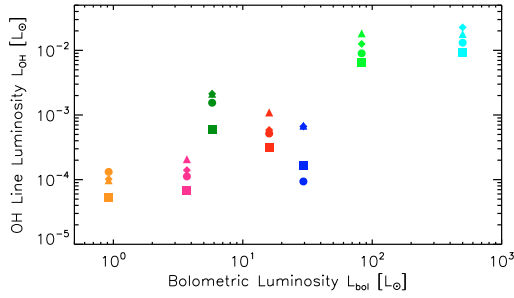


Fig. 4. Dependence of OH line luminosity on the bolometric luminosity of the source. Symbols and colors as in Fig. 3.

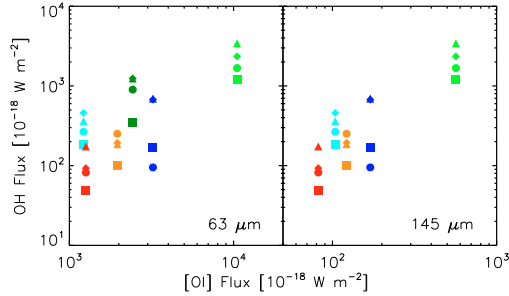


Fig. 5. Observed OH fluxes plotted against [OI] 63 μm flux (left panel) and 145 μm flux (right panel). Symbols and colors as in Fig. 3.

Comparison of OH with [OI] emission shows that stronger OH emission coincides with higher [OI] intensities (Fig. 5) and also with increasing [OI] 63/145 μm line flux ratios. For HH 46, TMR 1, and NGC 7129 FIRS 2, the bulk of the [OI] 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 [OI] emission. The correlation between the intensities (Fig. 5) suggests that the bulk of [OI] and OH emission originates in the same physical component in all sources. This argument, together with the OH – L_{bol} and OH – [OI] relations, supports the dissociative shock scenario. The [OI] 63 μm /145 μm line ratios are in the range of 13–19, also consistent with fast, dissociative J-type shocks ($v > 60 \text{ km s}^{-1}$, Neufeld & Dalgarno 1989). Note that an OH – [OI] relation can also be indicative of photo-dissociation, as argued for Sgr B2 by Goicoechea et al. (2004). Models of photon-dominated regions (Kaufman et al. 1999) predict similar [OI] 63 μm /145 μm line ratios, but those require $n < 10^5 \text{ cm}^{-3}$, 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 $FWHM \geq 11 \text{ km s}^{-1}$. 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 [OI] 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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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.

Source	Distance [pc]	Luminosity [L_{\odot}]	Envelope Mass [M_{\odot}]	Type	RA [h m s]	Dec [$^{\circ}$ ' '']	Obs. Date	Obs.id
HH 46	450 ^a	16 ^b	5.1 ^b	Class I	08:25:43.9	-51:00:36	2009-10-26	1342186315 (PACS)
TMR 1	140 ^c	3.7 ^d	0.12 ^e	Class I	04:39:13.7	+25:53:21	2010-04-17	1342194783 (HIFI)
IRAS 15398-3359	130 ^f	0.92 ^g	0.5 ^h	Class I	15:43:01.3	-34:09:15	2010-03-29	1342192984 (PACS)
DK Cha	178 ⁱ	29.4 ^j	0.03 ^j	Herbig Ae	12:53:17.2	-77:07:10.6	2010-02-27	1342191302 (PACS)
NGC 7129 FIRS 2	1260 ^k	500 ^l	50 ^m	Intermed.-Mass	21:43:01.7	+66:03:23.6	2009-12-10	1342188039 (PACS)
NGC 1333 I 2A	235 ⁿ	20 ^o	1.0 ^o	Class 0	03:28:55.6	+31:14:37	2009-12-10	1342188040 (PACS)
							2009-10-26	1342186321 (PACS)
							2010-02-13	1342190686 (PACS)
							2010-02-24	1342191149 (PACS)
							2010-03-08	1342191773 (HIFI)
Serpens SMM1	415 ^p	82.9 ^q	8.7 ^q	Class 0			–	ISO ^r
NGC 1333 I 4	235 ⁿ	5.8 ^o	4.5 ^o	Class 0			–	ISO ^s

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

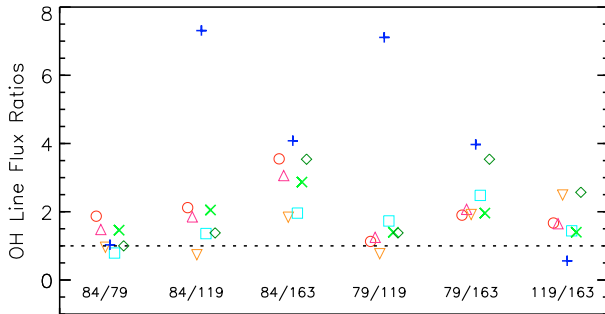


Fig. B.1. Ratios of the observed OH fluxes. The numbers denote the corresponding wavelengths. The symbols are: circle for HH 46, upward triangle for TMR 1, downward triangle for IRAS 15398-3359, squares for NGC 7129 FIRS 2, plus signs for DK Cha, crosses for Ser SMM1 and diamonds for NGC 1333 IRAS 4.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

Appendix C: OH term diagram

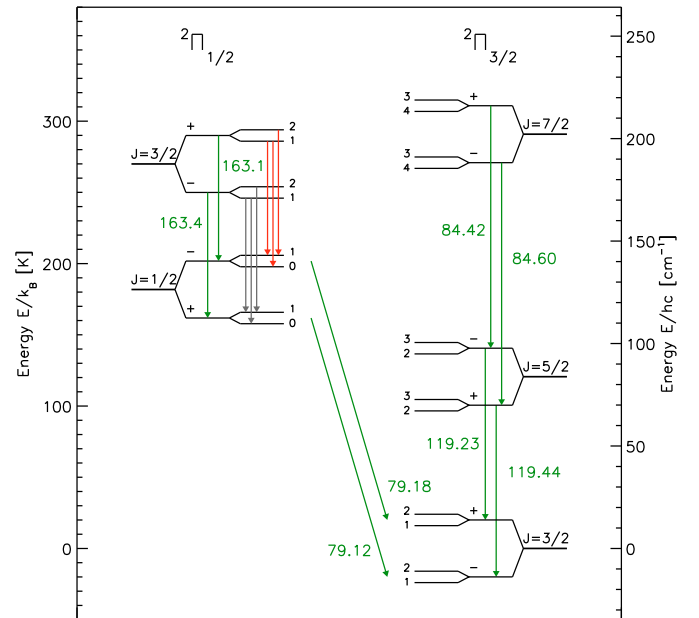


Fig. C.1. Level diagram of the lowest excited states of OH up to $E_{\text{up}} \approx 300$ K. Splitting of the levels because of Λ -doubling and hyperfine structure is not to scale. Transitions observed with PACS are shown in green, the high-resolution observations of the hyperfine transitions carried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