

Upper limits to the water abundance in starburst galaxies[★]

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ABSTRACT

Aims. We have searched for emission from the 557 GHz *ortho*-water line in the interstellar medium of six nearby starburst galaxies.

Methods. We used the Odin satellite to observe the $1_{10}-1_{01}$ transition of *o*-H₂O in the galaxies NGC 253, IC 342, M 82, NGC 4258, CenA, and M 51. None of the galaxies in our sample was detected.

Results. We derive three sigma upper limits to the H₂O abundance relative to H₂ ranging from 2×10^{-9} to 1×10^{-8} . The best of these upper limits are comparable to the measured abundance of H₂O in the Galactic star forming region W3. However, if only 10% of the molecular gas is in very dense cores, then the water abundance limits in the cores themselves would be larger by a factor of 10 i.e. 2×10^{-8} to 1×10^{-7} .

Conclusions. These observations suggest that detections of H₂O emission in galaxies with the upcoming Herschel Space Observatory are likely to require on-source integration times of an hour or more except in the very brightest extragalactic targets such as M 82 and NGC 253.

Key words. galaxies: starburst – galaxies: general – ISM: molecules – astrochemistry

1. Introduction

Recent space-based observations by SWAS (Melnick et al. 2000) and Odin (Frisk et al. 2003) have revealed a low gas-phase abundance of water under most conditions in the interstellar medium (e.g. Snell et al. 2000a; Olofsson et al. 2003). This low abundance is most likely due to the water molecules freezing out to form water ice on dust grains (e.g. Bergin et al. 2000). However, gas phase water abundances 100 to 10 000 times larger than the typical ambient cloud value have been seen toward hot cores with ISO (e.g. van Dishoeck & Helmich 1996) and in shock-heated outflows (Bergin et al. 2003) and supernova remnants (Snell et al. 2005). The significant dependence of the gas-phase water abundance on environment makes it interesting to search for water emission lines in even more extreme environments, namely the nuclei of nearby starburst galaxies.

In this paper, we present sensitive upper limits to the $1_{10}-1_{01}$ emission line of *ortho*-H₂O at 556.936 GHz in six nearby starburst galaxies. The observations and data

reduction are discussed in Sect. 2. We combine the H₂O upper limits with published CO $J = 1-0$ data to derive upper limits to the H₂O abundance relative to H₂, $x(o\text{-H}_2\text{O})$, in Sect. 3. We summarize and discuss the possibilities for future H₂O detections with the Herschel Space Observatory in Sect. 4.

2. Observations and analysis

We observed the central regions of six nearby starburst galaxies (NGC 253, IC 342, M 82, NGC 4258, CenA, and M 51) with Odin between 2002 November 22 and 2005 June 17 with on-source integration times ranging from 17 to 25 h. Odin's 1.1 m telescope has a beam diameter of 2.1' at the 556.936 GHz frequency of the $1_{10}-1_{01}$ transition of *ortho*-H₂O and a main beam efficiency of 0.9 (Frisk et al. 2003). Details of the observations for each galaxy are given in Table 1. The observations were made in position switching mode; the off positions were located 850'' to the south-east for NGC 253, IC 342, M 82, and NGC 4258, 280'' to the south-east for CenA, and 900'' to the east for M 51. The backend for all observations was an acousto-optic spectrometer with a spectral resolution of 1 MHz (0.5 km s^{-1}) and a total bandwidth of 1.1 GHz ($\sim 600 \text{ km s}^{-1}$). Odin's pointing is estimated to be accurate to 15''. However, for M 82, maps of Jupiter made after the data were obtained suggest that the pointing for

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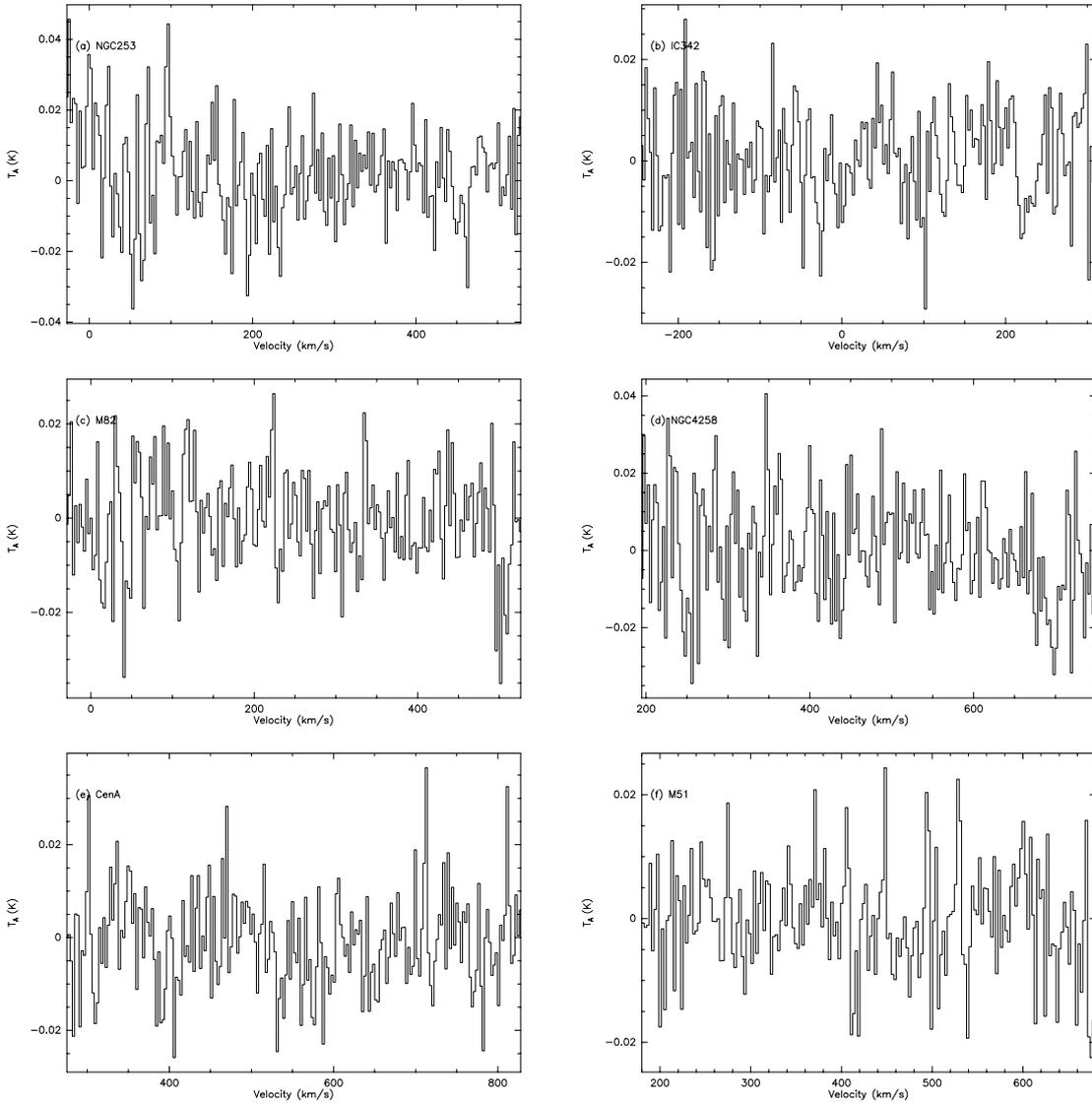


Fig. 1. Spectra of nearby starburst galaxies tuned to the $1_{10}-1_{01}$ transition of *ortho*- H_2O at 556.936 GHz. The velocity scale is V_{LSR} . No broad line (consistent with the observed CO $J = 1-0$ emission from these sources) is seen in any of the spectra. **a)** NGC 253 ($V_{\text{LSR}} = 249 \text{ km s}^{-1}$). The spectrum was obtained toward coordinates 00:47:35.2 –25:17:20 (J2000); this position is $28''$ from the starburst nucleus. **b)** IC 342 ($V_{\text{LSR}} = 32 \text{ km s}^{-1}$). **c)** M 82 ($V_{\text{LSR}} = 250 \text{ km s}^{-1}$). Due to drifts in Odin’s pointing model with time, this spectrum was obtained at an offset of $\sim 55''$ from the center of M 82, which is at 09:55:54.0 +69:40:57 (J2000). **d)** NGC 4258 ($V_{\text{LSR}} = 472 \text{ km s}^{-1}$). **e)** Cen A ($V_{\text{LSR}} = 550 \text{ km s}^{-1}$). **f)** M 51 ($V_{\text{LSR}} = 460 \text{ km s}^{-1}$).

this galaxy was in error by $\sim 55''$. We take this pointing error into account in our analysis below.

The data reduction followed the methods described in Wilson et al. (2003) to identify and remove individual spectra with anomalous system temperatures or contamination by the Earth’s atmosphere. The individual spectra were averaged and the resulting spectrum was binned to a spectral resolution of 2.7 km s^{-1} for the final analysis. The summed spectra were fit with a 0–2 order polynomial baseline excluding the expected velocity range of the H_2O emission; typically a velocity range of $200\text{--}400 \text{ km s}^{-1}$ was excluded from the baseline fit. The resulting spectra are shown in Fig. 1.

Upper limits (3σ) to the integrated intensity of the H_2O line were calculated using the width of the CO $J = 1-0$ line observed over the same area as the Odin beam. The upper limits to the H_2O integrated intensity and the CO line widths are given in Table 1. CO line widths (full width at zero intensity) appropriate to the Odin beam were calculated for three galaxies from the

data in the BIMA SONG survey (Helfer et al. 2003). For Cen A and M 82, the emission in the maps of Eckart et al. (1990) and Walter et al. (2002), respectively, lies almost entirely within the Odin beam and so we used all the emission to estimate the line width. For NGC 253, the full width of the CO line is defined by the spectrum at the starburst nucleus (Sorai et al. 2000). For M 82, the integrated intensity is corrected for the pointing error assuming a compact source and an Odin primary beam of $2.1'$ (full width at half maximum). For NGC 253, the observed coordinates are $28''$ from the peak emission in the galaxy, and so we also correct the integrated intensity upper limit for this offset.

3. Upper limits to the $\text{H}_2\text{O}/\text{H}_2$ abundance ratio

We can use the upper limits to the H_2O integrated intensity to calculate upper limits for the H_2O abundance within the Odin beam using the formula given by Snell et al. (2000b). We adopt an H_2 volume density of $1 \times 10^6 \text{ cm}^{-3}$ and a temperature of

Table 1. H₂O Observations and abundance limits.

Source	Coordinates (J2000)	T_{sys} (K)	t_{int} (hr)	rms ^a (mK)	$\Delta V(\text{CO})$ (km s ⁻¹)	$I(\text{H}_2\text{O})^b$ (K km s ⁻¹)	D (Mpc)	$M_{\text{H}_2}^c$ (10 ⁹ M _⊙)	$x(o\text{-H}_2\text{O})^d$	CO Reference
NGC 253	00:47:35.2 -25:17:20	4100	18.5	13	450	1.6	2.5	0.60	$<2.0 \times 10^{-9}$	Sorai et al. (2000)
IC 342	03:46:49.6 +68:05:45	3700	25.0	10	130	0.56	3.9	0.39	$<2.6 \times 10^{-9}$	Helfer et al. (2003)
M 82	09:55:54.0 +69:40:57	3400	20.1	10	400	1.9	3.9	1.56	$<1.7 \times 10^{-9}$	Walter et al. (2002)
N4258	12:18:57.5 +47:18:14	4300	17.4	13	450	1.4	8.1	0.81	$<1.3 \times 10^{-8}$	Helfer et al. (2003)
CenA	13:25:27.6 -43:01:08	4500	17.2	10	600	1.2	4.0	0.29	$<7.8 \times 10^{-9}$	Eckart et al. (1990)
M 51	13:29:53.1 +47:11:48	3900	23.7	8	200	0.56	7.7	1.64	$<2.4 \times 10^{-9}$	Helfer et al. (2003)

^a Rms noise at a resolution of 2.7 km s⁻¹. ^b Three sigma upper limit integrated over $\Delta V(\text{CO})$; values for M 82 and NGC 253 include scaling by 1.61 and 1.15, respectively, to account for pointing errors; see text. ^c Assumes $X_{\text{CO}} = 2 \times 10^{20}$ H₂ cm⁻² (K km s⁻¹)⁻¹. ^d Three sigma upper limit assuming $n_{\text{H}_2} = 10^6$ cm⁻³ and $T_K = 40$ K. Depending on the average density of the molecular gas on large scales and the mass fraction in dense cores, these abundance limits could be larger by a factor of ~ 10 or more (see text).

40 K to calculate the H₂O column density upper limits. We adopt a relatively high H₂ volume density in these calculations because the H₂O emission most likely originates in the densest parts of the interstellar medium.

We use published CO $J = 1-0$ data to calculate the mass of molecular hydrogen within the Odin beam. For IC 342, NGC 4258, and M 51, we integrated the CO flux within the Odin beam from the publicly available BIMA SONG data (Helfer et al. 2003). We adopt a CO-to-H₂ conversion factor $X_{\text{CO}} = 2 \times 10^{20}$ H₂ cm⁻² (K km s⁻¹)⁻¹ (Strong et al. 1988) and use the formula in Wilson & Scoville (1990) to calculate the molecular gas mass. For CenA, we take the molecular gas mass from Eckart et al. (1990) and rescale it to our adopted conversion factor and distance. For M 82, we take the molecular gas mass from Walter et al. (2002) but adjust the mass in the streamers to our adopted conversion factor. For NGC 253, we adopt the mass in the bar plus the “nuclear bar” from Sakai et al. 2000 and scale it to our adopted distance and conversion factor. The molecular hydrogen gas masses and distances are given in Table 1, along with the resulting upper limits for the *ortho*-H₂O abundance, $x(o\text{-H}_2\text{O})$.

Our limits on the *ortho*-H₂O abundance range from 2×10^{-9} to 1×10^{-8} . Note that these estimated abundance limits are inversely proportional to our assumed value of 10^6 cm⁻³ for the H₂ volume density. The tightest constraints are for the four nearest and/or most gas-rich galaxies: NGC 253, IC 342, M 82, and M 51. For NGC 4258, its larger distance is the primary reason why the abundance limit is larger than the other five galaxies, since its molecular hydrogen mass translates into a smaller average column density in the Odin beam. For CenA, the smaller molecular hydrogen column density is also the primary reason for its larger abundance limit.

Goicoechea et al. (2005) have detected H₂O in absorption towards NGC 253 using the Infrared Space Observatory (ISO). They derive a lower limit to the H₂O column density of $\geq 1 \times 10^{15}$ cm⁻². This limit is significantly larger than the 3σ upper limit to the H₂O column density derived from our Odin data, which is $<4 \times 10^{13}$ cm⁻². This apparent discrepancy can be understood by examining the regions probed by the two instruments: the Odin upper limit is an average over a 2.1' region, while the ISO absorption spectrum probes the much smaller region of the central continuum source. The central source has a size of $\sim 12''$ at mid-infrared wavelengths (Förster Schreiber et al. 2003) while examining archival 850 μm continuum images from the James Clerk Maxwell Telescope suggests the size of the central submillimeter source is no more than $30''$. These sizes correspond to filling factors of 0.01–0.06 in the larger Odin beam, which are sufficient to bring the two column density limits into agreement. Alternatively, assuming a density of

10^4 cm⁻³ (Bayet et al. 2004; Güsten et al. 2006) would also bring the two abundance estimates into good agreement (see below).

These water abundance upper limits correspond to values averaged over kiloparsec scales that, in our own Galaxy, would include many giant molecular clouds. If we were to picture the molecular interstellar medium in these starburst galaxies as being similar in structure to normal spiral galaxies, then only a fraction of the molecular gas would be contained in cores that are dense enough to produce significant H₂O emission. In this situation, the upper limit to the water abundance in the cores themselves would be larger than the values given in Table 1, perhaps by factors of 10–50 depending on the exact fraction of gas in dense cores¹. Alternatively, the molecular interstellar medium of starburst galaxies is likely to have considerably higher average densities than those of normal galaxies. If water emission arises from an extended medium with a uniform density of 10^4 – 10^5 cm⁻³ (Bayet et al. 2004; Güsten et al. 2006), the upper limits on large scales given in Table 1 would increase by factors of 10–100.

It is interesting to compare these upper limits to the H₂O abundance in starburst galaxies with the H₂O abundance estimated for Galactic star forming regions. Snell et al. (2000a) estimate H₂O abundances ranging from 6×10^{-10} to 1×10^{-8} for eight giant molecular cloud cores. (They also obtain upper limits for the H₂O abundance in dark clouds, with the most stringent upper limit of 7×10^{-8} being obtained for TMC-1.) Wilson et al. (2003) obtain an H₂O abundance for the W3 IRS5 region of 2×10^{-9} . Olofsson et al. (2003) used Odin to detect H₂¹⁸O at two positions in Orion and derive an H₂O abundance of $\sim 10^{-5}$ toward the outflow associated with Orion BN-KL and $(1-8) \times 10^{-8}$ in the ambient cloud 2' to the south. More recently, Wiström et al. (2006) have used C¹⁸O $J = 5-4$ and H₂O observations from Odin to measure a water abundance of $\geq 8 \times 10^{-8}$ in the Orion photon-dominated region. Plume et al. (2004) have used absorption line measurements toward W49A to obtain H₂O abundances of 8×10^{-8} to 4×10^{-7} toward three foreground clouds. Bergin et al. (2003) found much higher abundances of $>10^{-6}$ toward three outflows in the NGC 1333 molecular cloud core. Snell et al. (2005) have detected H₂O emission in the supernova remnant IC 443 with abundances (assuming [CO]/[H₂] = 10^{-4}) between 2×10^{-8} and 3×10^{-7} . They suggest that both photodissociation

¹ For example, the W3 cloud contains a total of 10^5 M_⊙ (Lada et al. 1978), of which 1900 M_⊙ (Tieftrunk et al. 1995) is contained within the single core studied in H₂O emission by Wilson et al. (2003). Depending on the masses of the three other large cores in W3(OH) and W3 Main (Tieftrunk et al. 1995, 1998), this cloud likely contains 2–8% of its mass with densities high enough to excite water emission.

of H₂O in post-shock gas and freeze-out of H₂O in the ambient gas are needed to explain the weakness of the H₂O lines.

The above discussion shows that the Odin upper limits for the H₂O abundance averaged over kiloparsec scales are comparable to the lowest abundances obtained in the cores of Galactic giant molecular clouds. Naively, one might expect the interstellar medium in intense starburst galaxies like M 82 to have similar physical conditions to high-mass star forming cores but with those conditions now present on kiloparsec scales. The H₂O upper limits obtained here suggest that this naive picture is not correct, and that even in intense starburst galaxies there is a substantial mass of molecular gas that is not in the warm dense conditions appropriate to produce H₂O emission. This conclusion is consistent with recent estimates of the average gas density of 10⁴–10⁵ cm⁻³ in some nearby starburst galaxies (Bayet et al. 2004; Güsten et al. 2006). It is also possible that the intense ultraviolet radiation fields produced in starburst galaxies photo-dissociate more of the H₂O molecules than is the case for individual high-mass cores like W3. Melnick et al. (2005) suggest that H₂O in the gas phase is restricted to a thin layer of gas in molecular cloud cores, deep enough that it is shielded from the ambient ultraviolet radiation field but not so deep that the molecules freeze out onto dust grains. The stronger ultraviolet radiation fields in starburst galaxies might conceivably alter this delicate balance and make H₂O an even rarer molecule in the gas phase than it is in our own Galaxy. Finally, dramatic H₂O absorption features are seen in observations toward Sgr A (Sandqvist et al. 2003) and Sgr B2 (Neufeld et al. 2003) in the Galactic Center region. These observations may imply that self-absorption of the H₂O line could make it very difficult to detect emission in regions such as starburst nuclei with warm dense gas containing multiple outflows and shocks from supernova remnants. All these effects may conspire to make the emission lines of H₂O very difficult to detect even in the brightest and closest starburst galaxies.

4. Conclusions and future prospects

We have obtained long integrations with the Odin satellite in an attempt to detect the emission line of *ortho*-water in six nearby starburst galaxies. None of the galaxies were detected, with upper limits to the H₂O integrated intensity ranging from 0.6 to 1.9 K km s⁻¹. We have combined these upper limits with published CO data to derive upper limits to the H₂O abundance in each galaxy. Our 3σ upper limits to [H₂O]/[H₂] range from 2 × 10⁻⁹ to 1 × 10⁻⁸. The most sensitive limits are comparable to the measured abundance of H₂O in the Galactic star forming region W3 (Wilson et al. 2003). However, if only 10% of the molecular gas is in very dense cores, then the water abundance limits in the cores would be larger by a factor of 10 i.e. 2 × 10⁻⁸ to 1 × 10⁻⁷. Similarly, if the average density in these starburst galaxies is 10⁴–10⁵ cm⁻³, the abundance limits would be larger by factors of 10–100.

These observations can provide useful guidance for planning additional searches for H₂O emission with future space missions. The most sensitive 3σ upper limit to the H₂O emission obtained with Odin is 0.5 K km s⁻¹ (for IC 342 and M 51), which corresponds to 1600 Jy km s⁻¹ or 3 × 10⁻¹⁷ W m⁻². The currently quoted sensitivity for the HIFI 460–680 GHz heterodyne spectrometer² on the Herschel Space Observatory corresponds to a 3σ upper limit of 1.4 × 10⁻¹⁸ W m⁻² for a spectral

line of width 130 km s⁻¹ for one hour of dual beam switched observations, or about twenty times more sensitive than our existing Odin data. Thus, to obtain H₂O spectra of these galaxies which are ten times more sensitive than the Odin spectra presented here will require integration times with Herschel of only 5–20 min per source.

Alternatively, we can estimate what integration time will be needed to reach an H₂O abundance limit of 2 × 10⁻¹⁰, e.g., a factor of 10 lower than the abundance of water in W3 (Wilson et al. 2003). For NGC 253 and M 82, this limit is reached in 3–6 min, while IC 342 and M 51 would require ~30 min of integration. However, CenA and NGC 4258 require 3.5 and 5.1 h, respectively, to reach this abundance limit. These longer integration times are primarily due to the lower surface density of molecular gas in these two galaxies. This analysis suggests that significant integration times may be required to detect H₂O in emission even with Herschel, and that the best targets for the initial searches will be the most gas-rich, nearby starburst galaxies. If deep searches are not successful in detecting H₂O in emission, it may have interesting implications for the astrochemistry of starburst galaxies. However, the recent ISO results on H₂O absorption lines in starburst galaxies (Goicoechea et al. 2005; Gonzalez-Alfonso et al. 2004) suggest that absorption line searches with Herschel may be very fruitful, especially given its much improved angular resolution compared to Odin.

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References

- Bayet, E., Gerin, M., Phillips, T. G., & Contursi, A. 2004, *A&A*, 427, 45
 Bergin, E. A., Melnick, G. J., Stauffer, J. R., et al. 2000, *ApJ*, 539, L129
 Bergin, E. A., Kaufman, M. J., Melnick, G. J., Snell, R. L., & Howe, J. E. 2003, *ApJ*, 582, 830
 Eckart, A., Cameron, M., Rothermel, H., et al. 1990, *ApJ*, 363, 451
 Förster Schreiber, N. M., Sauvage, M., Charmandaris, V., et al. 2003, *A&A*, 399, 833
 Frisk, U., Hagström, M., Ala-Laurinaho, J., et al. 2003, *A&A*, 402, L27
 Goicoechea, J. R., Martin-Pintado, J., & Cernicharo, J. 2005, *ApJ*, 619, 291
 Gonzalez-Alfonso, E., Smith, H. A., Fischer, J., & Cernicharo, J. 2004, *ApJ*, 613, 247
 Güsten, R., Philipp, S. D., Weiss, A., & Klein, B. 2006, *A&A*, 454, L115
 Helfer, T. T., Thornley, M. D., Regan, M. W., et al. 2003, *ApJS*, 145, 259
 Lada, C. J., Elmegreen, B. G., Cong, H.-L., & Thaddeus, P. 1978, *ApJ*, 226, L39
 Melnick, G. J., Stauffer, J. R., Ashby, M. L. N., et al. 2000, *ApJ*, 539, L77
 Melnick, G. J., Bergin, E. A., Hollenbach, D., et al. 2005, in *Astrochemistry Throughout the Universe: Recent Successes and Current Challenges*, ed. D. C. Lis, G. A. Blake, & E. Herbst, IAU Symp., 231, 108
 Neufeld, D. A., Bergin, E. A., Melnick, G. J., & Goldsmith, P. F. 2003, *ApJ*, 590, 882
 Olofsson, A. O. H., Olofsson, G., Hjalmarsen, Å., et al. 2003, *A&A*, 402, L47
 Plume, R., Kaufman, M. J., Neufeld, D. A., et al. 2004, *ApJ*, 605, 247
 Sandqvist, A., Bergman, P., Black, J. H., et al. 2003, *A&A*, 402, L63
 Snell, R. L., Howe, J. E., Ashby, M. L. N., et al. 2000a, *ApJ*, 539, L101
 Snell, R. L., Howe, J. E., Ashby, M. L. N., et al. 2000b, *ApJ*, 539, L93
 Snell, R. L., Hollenbach, D., Howe, J. E., et al. 2005, *ApJ*, 620, 758
 Sorai, K., Nakai, N., Kuno, N., et al. 2000, *PASJ*, 52, 785
 Strong, A. W., Bloemen, J. B. G. M., Dame, T. M., et al. 1988, *A&A*, 207, 1
 Tieftrunk, A. R., Wilson, T. L., Steppe, H., et al. 1995, *A&A*, 303, 901
 Tieftrunk, A. R., Megeath, S. T., Wilson, T. L., & Rayner, J. T. 1998, *A&A*, 336, 991
 van Dishoeck, E. F., & Helmich, F. P. 1996, *A&A*, 315, L177
 Walter, F., Weiss, A., & Scoville, N. 2002, *ApJ*, 580, L21
 Wilson, C. D., & Scoville, N. Z. 1990, *ApJ*, 363, 435
 Wilson, C. D., Mason, A., Gregersen, E., et al. 2003, *A&A*, 402, L59
 Wirstrom, E., Bergman, P., Olofsson, A. O. H., et al. 2006, *A&A*, 453, 979

² Calculated using HSPOT V2.0.0 and assuming an aperture efficiency of 70%.