The Astrophysical Journal, 651: L41–L44, 2006 November 1

METHANOL IN THE L1551 CIRCUMBINARY TORUS

Glenn J. White,[1,2] C. W. M. Fridlund,[3] P. Bergman,[4] A. Beardsmore,[5] René Liseau,[6] M. Price,[5] and R. R. Phillips[7]

Received 2006 June 22; accepted 2006 September 19; published 2006 October 17

ABSTRACT

We report observations of gaseous methanol in an edge-on torus surrounding the young stellar object L1551 IRS 5. The peaks in the torus are separated by ∼10,000 AU from L1551 IRS 5 and contain ∼0.03 $M_\oplus$ of cold CH_3OH. We infer that the CH_3OH abundance increases in the outer part of the torus, probably as a result of methanol evaporation from dust grain surfaces heated by the shock luminosity associated with the shocks associated with the jets of an externally located X-ray source. Any methanol released in such a cold environment will rapidly freeze again, spreading CH_3OH throughout the circumbinary torus to nascent dust grains, planetesimals, and primitive bodies. These observations probe the initial chemical conditions of matter infalling onto the disk.

Subject headings: ISM: general — ISM: individual (HH 154, L1551, L1551 IRS 5) — ISM: jets and outflows

1. INTRODUCTION

In the earliest stages of their formation, low-mass young stellar objects are embedded in flattened gaseous envelopes. Surrounding these nascent protostars, planetary systems, primitive bodies, and their attendant dust grains will condense from the infalling material. In this Letter, we study the distribution of the organic molecule methanol around a protostellar core, as it is an important constituent of the young material in the disk. The L1551 molecular core (distance 140 pc) contains a young binary system (seen as an infrared and radio source, L1551 IRS 5) hidden inside a dense envelope providing ∼150 mag of visual extinction (Stocke et al. 1988; White et al. 2000; Fridlund et al. 2005). A molecular outflow emanates from the center of the disk (Snell et al. 1980; Kaifu et al. 1984; Fridlund & White 1989; Rainey et al. 1987; Parker et al. 1991), with atomic jet(s) associated with an X-ray–emitting region being observed to the southwest (Fridlund & Liseau 1998; Favata et al. 2002, 2003; Bally et al. 2003; Fridlund et al. 2005). The protostellar disk is surrounded by a massive (radius ∼ 20,000 AU) cool envelope that exhibits both rotational and infall motions (Takakuwa et al. 2004; Moriarty-Schieven et al. 2006). Fridlund et al. (2002) used HCO^+, $H^{13}CO^+$, and ^{13}CO $J = 1$–0 observations to estimate that the mass of the disk is ∼2.5 ± 1.5 $M_\odot$.

2. OBSERVATIONS

Observations of CH_3OH (96 GHz 2_k–1_k and 242 GHz 5_k–4_k), HCN ($J = 1$–0), and CO ($J = 1$–0) were obtained using the Onsala 20 m and the James Clerk Maxwell Telescope (JCMT) 15 m telescopes in 2004 February and 2005 January/April. The Onsala observations used a single-sideband SIS receiver, with a 1600 channel × 25 kHz autocorrelator back end. The JCMT observations of a higher CH_3OH transition (241 GHz 5_k–4_k) were made using the standard facility RxA2 receiver. All lines were corrected to a common main-beam brightness, T_{mb}, scale. Additional data for CS and $C^{34}S$ ($J = 2$–1) are taken from Fridlund et al. (2002).

3. METHANOL

Methanol plays a key part in the chemistry leading to the production of biogenic molecules and is an important constituent of icy grain mantles and comets. Thermally excited gas-phase CH_3OH has previously been observed from warm inner envelopes surrounding just a few Class 0 protostars, where it is evaporated from warm dust grains heated by the central protostar or by an accretion shock at the edge of an infalling envelope (Goldsmith et al. 1999; Velusamy et al. 2002; Maret et al. 2005).

Maps showing the distribution of CH_3OH, HCN, and CO toward L1551 observed from Onsala are shown in Figure 1, and velocity channel maps for the 96 GHz CH_3OH and CS $J =$ 2–1 lines in Figure 2. The methanol has three peaks located ∼6500–12,000 AU from IRS 5 along a southeast-northwest line. The high-density tracer, HCN, is centrally peaked and marginally resolved, located between the two inner methanol peaks. CO emission, which traces low-density material, streams orthogonally away to the northeast and southwest. The methanol appears as an edge-on torus surrounding the HCN core and is oriented orthogonally to the CO outflow. The velocity shift between the two CH_3OH peaks is 0.07 km s^{-1}—which, *if* indicative of rotation, would imply a rotational period ∼6.5 × 10^5 yr. Spectra toward L1551 IRS 5 and at the two main methanol peaks are shown in Figure 3, along with the model fits described next.

We have modeled the CH_3OH line intensities using an accelerated lambda iteration radiative transfer technique for a spherical-core envelope (Phillips & Little 2000), with an assumed core radius of 5000 AU; envelope radius of 12,500 AU; and turbulent velocity of 0.45 km s^{-1} (from the $H^{13}CO^+$ line width; Fridlund et al. 2002). The *A* and *E* symmetry states of CH_3OH were calculated separately using collisional rates, energy levels, and Einstein rates from Müller et al. (2001) and Pottage et al. (2004), and convolved to the Onsala and JCMT beamwidths. A number of models were run spanning a range of temperature, density, and abundance gradients to simultaneously match both the relative and absolute spectral line intensities, and the observed morphology of the torus. The observations unfortunately do not provide strong constraints on the CH_3OH kinetic temperature, and so the temperature and density gradients used in the model

[1] Department of Physics and Astronomy, Open University, Venables Building, Room N1072, Walton Hall, Milton Keynes MK6 7AA, England; g.j.white@open.ac.uk.

[2] Space Physics Division, Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, England.

[3] ESTEC, P.O. Box 299, NL-2200AG Noordwijk, Netherlands; malcolm.fridlund@esa.int.

[4] Onsala Space Observatory, SE-439 92 Onsala, Sweden; bergman@oso.chalmers.se.

[5] School for Physics and Astronomy, University of Kent, Canterbury CT2 7NR, England; mcp2@star.kent.ac.uk, ab75@star.kent.ac.uk.

[6] Stockholm Observatory, 106 91 Stockholm, Sweden; rene@astro.su.se.

[7] Department of Physics, University of Lethbridge, 4401 University Drive, Lethbridge, AB T1K 3M4, Canada; robin.phillips@uleth.ca.

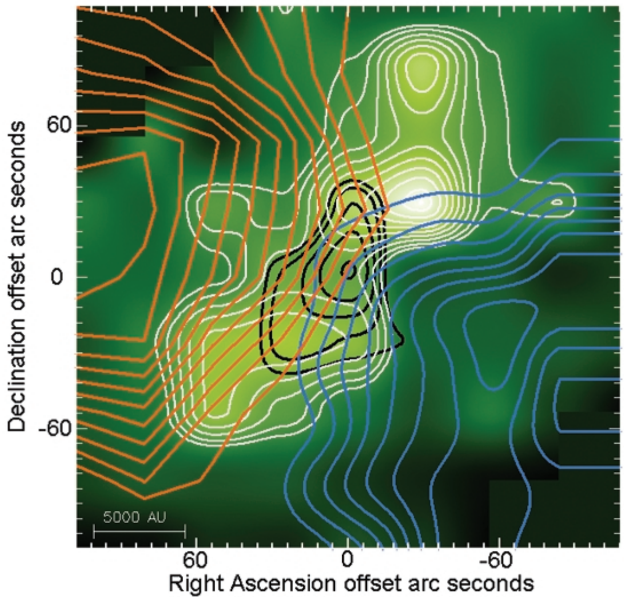

FIG. 1.—CH_3OH 2_0–$1_0(A)$ line map (Onsala data at 96.7414 GHz; *green image with white contours*) superimposed with contours of the HCN J = 1–0 (Onsala data shown as black contours), and red- and blueshifted CO J = 1–0 outflows (shown as red and blue contour lines, respectively) from the data shown in Fridlund et al. (2002). West is on the left, and north is at the top. The bottom left bar shows the size scale for a distance of 140 pc.

were chosen to match those of White et al. (2000) derived from dust continuum measurements.

When we use this model, the best fit suggests a central hydrogen gas density (at the position of L1551 IRS 5) $n(H_2) = 7.5 \times 10^5$ cm^{-3} and a methanol abundance $X = 8 \times 10^{-10}$ relative to H_2. Since the temperature and density are known to decline away from L1551 IRS 5 (see Fig. 4 [*left*], which is derived from White et al. 2000), the observed torus structure then requires that the methanol abundance increases to $\sim 4 \times 10^{-9}$ at the inner edge of the methanol ring and to 10^{-8} in the outer envelope, as shown in Figure 4 (*right*). The abundance increase is needed since the H_2 density is ~20 times lower at the edge of the CH_3OH peaks than toward the source center at L1551 IRS 5. In this best-fit model, the torus contains 0.03 $M_\oplus$ of CH_3OH. Models run with CH_3OH kinetic temperatures in the torus ≥20 K failed to reproduce the observed disk structure while simultaneously matching the absolute and relative line temperatures. Since the gas and dust should be well thermalized at the estimated densities, it is reasonable to assume that the kinetic temperature of the CH_3OH will be close to the dust temperature (13 K from White et al. 2000). The models underestimate the observed line width toward IRS 5, which we believe is affected by additional dynamics and/or turbulence/outflow activity near L1551 IRS 5, which is not modeled here.

4. OTHER SPECIES IN THE CIRCUMBINARY TORUS

The integrated HCN, CS, $C^{34}S$, HCO^+, and $H^{13}CO^+$ distributions peak close to L1551 IRS 5 (Fridlund et al. 2002), whereas the CH_3OH map appears as an edge-on torus surrounding the HCN core. The CS and HCO^+ channel maps show a faint signature of this torus structure but at low levels not contributing significantly to their integrated emission maps (C. W. M. Fridlund et al. 2006, in preparation).

Van der Tak et al. (2000) suggest that gas-phase production

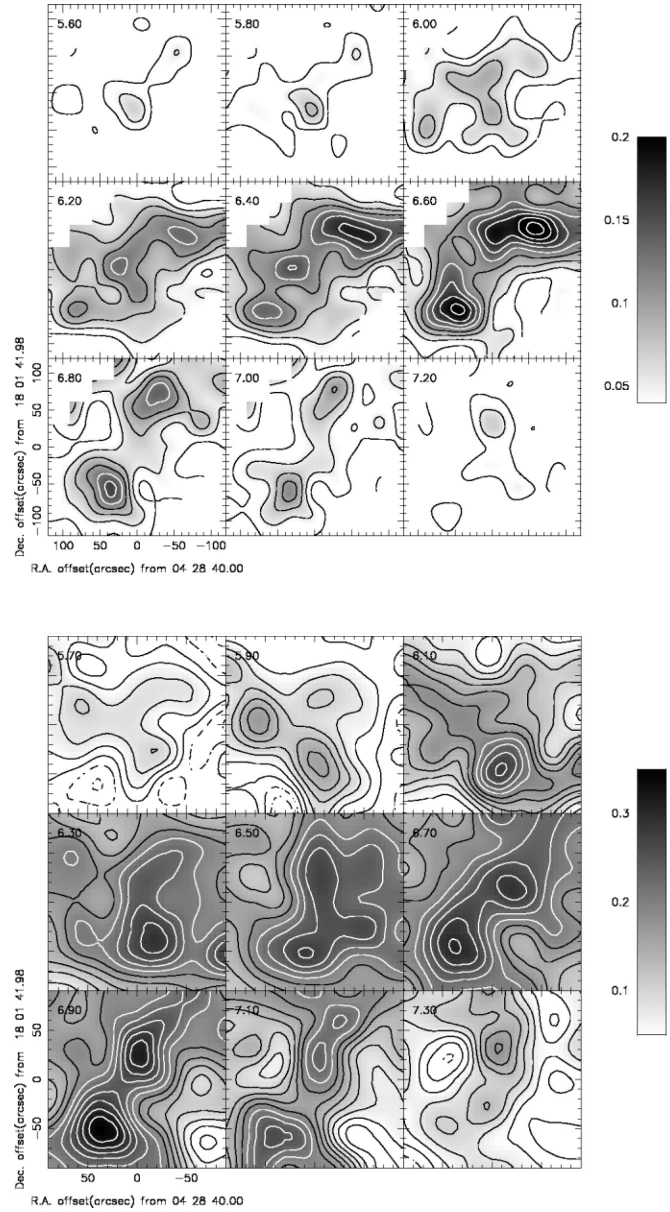

FIG. 2.—*Top*: Channel maps in the 2_0–$1_0(A)$ CH_3OH line. The lowest contour level is 0.15 K km s^{-1}, and contour intervals are at 0.1 K km s^{-1}. *Bottom*: Channel maps in the CS J = 2–1 line with the lowest contour at the 0.375 K km s^{-1} channel and subsequent contour intervals increasing by 0.125 K km s^{-1}. The central (0, 0) position of the maps and spectra is that of L1551 IRS 5 at R.A.(2000.0) = $04^h31^m34^s.13$, decl.(2000.0) = 18°08′04″.95.

of CH_3OH at temperatures ≤100 K follows the radiative association of H_2O and CH_3^+. However, the relative inefficiency of the process would result in low abundances, $\sim 10^{-11}$ relative to H_2. Recent storage ring measurements (Geppert et al. 2006) of the dissociative recombination of $CH_3OH_2^+$ with electrons indicate extensive C−O bond fragmentation, emphasizing the difficulty for ion-molecule reactions to form CH_3OH, which will preferentially be destroyed via an $H_3^+ + CH_3OH \rightarrow CH_3OH_2^+ + e^+$ reaction. It is increasingly difficult to reconcile observed CH_3OH abundances with ion-molecule chemical production. Solid-phase reactions, including cosmic-ray irradiation processes therefore likely are important for CH_3OH formation on grain surfaces (Wada et al. 2006). Observations in dark clouds, where grain chemistry operates, indicate higher abundances of $\sim 10^{-9}$ (Takakuwa et al. 1998; Turner 1998), and

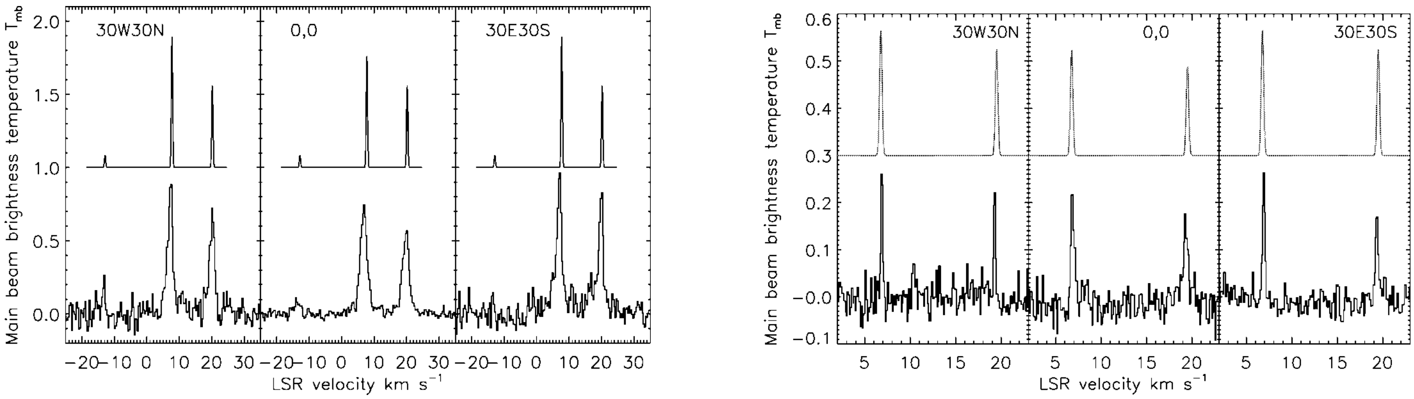

FIG. 3.—CH_3OH data and model fits for the (*left to right*) 2_{-1}–$1_{-1}(E)$, 2_0–$1_0(A)$, and 2_0–$1_0(E)$ lines at 96.7394, 96.7414, and 96.7446 GHz, and the 5_{-1}–$4_{-1}(E)$, and 5_0–$4_0(A)$ lines at 241.7672 and 241.7914 GHz, respectively, toward the central IRS 5 position and at the two peaks in the 96 GHz CH_3OH line. The frequency scales assume $v_{lsr} = 6.5$ km s^{-1} (Fridlund et al. 2002).

toward hot cores, where CH_3OH is evaporated off grain surfaces, abundances $\gtrsim 10^{-7}$ (Blake et al. 1987) have been reported. Grain temperatures would need to be $\gtrsim$120 K for methanol to be efficiently released from icy or clathrate mixtures on dust grain surfaces (Blake et al. 1987; Sandford & Allamandola 1993).

4.1. *Heating of Grains*

Our model suggests that gas-phase methanol in the envelope is sufficiently cold to rapidly freeze back onto dust grains and solid surfaces, which will occur on a timescale $t \sim 3 \times 10^9/n(\mathrm{H}) \sim 4000$ yr, where n(H) is the hydrogen density cm^{-3}. Shocks and direct heating could reevaporate the icy mantles, although the liberated CH_3OH will rapidly cool again. The midplane dust temperature, T_{dust}, due to L1551 IRS 5 will be (Fridlund et al. 2002)

$$\mathrm{T_{dust}} \approx 38 \left(\frac{r}{100\ \mathrm{AU}}\right)^{-0.4} \left(\frac{L}{L_\odot}\right)^{0.2}\ \mathrm{K}. \qquad (1)$$

At the CH_3OH peaks, $T_{dust} \sim 13$ K (White et al. 2000), which is inadequate for CH_3OH to be evaporated. Methanol has been observed toward the L1157 molecular disk (Velusamy et al. 2002), and higher mass protostellar cores (van der Tak et al. 2000), where direct heating could directly evaporate the CH_3OH—but it does not appear that this mechanism could drive off significant amounts of CH_3OH at the distance of the L1551 CH_3OH peaks.

An alternative source of heating is suggested by the presence of a Herbig-Haro jet (HH 154) emanating from L1551 IRS 5 and terminating in a working surface—presently located ∼15″ away from the IRS 5 binary (Fridlund et al. 2005). This jet is one of the few X-ray sources associated with low-mass stellar jets and has four separate shock interactions—two detected in X-rays (Favata et al. 2002, 2006; Bally et al. 2003) and two seen in [O III] λ5007 and Hα (Fridlund et al. 2005). If we assume a clear line of sight to the surface of the flared disk/envelope/torus surface, the temperatures of icy grains heated by the jet luminosity would be (Hollenbach & McKee 1979)

$$T_{\mathrm{grain}} = 47\,\frac{J_{\mathrm{UV}}}{a_\mu C_1}\ \mathrm{K} \qquad (2)$$

for ice, where C_1 is 2, the grain radius, a_μ, is assumed to be 0.15 μm (Brown 1990), and the mean intensity is J_{UV}. The shock luminosity is then

$$F_S = 5.8 \times 10^{-4} n_0 v_{s7}^3\ \mathrm{ergs\ cm^{-2}\ s^{-1}}. \qquad (3)$$

The projected distance of the methanol peaks from the shocks is ≈6000 AU. If we assume this flux is dominated by X-rays, extreme-ultraviolet (EUV), and far-UV emission (Hollenbach & McKee 1979; Hartigan et al. 1987), T_{grain} will reach 100–150 K—which is adequate to liberate CH_3OH. The grains would, however, rapidly cool again, with the evaporated gas becoming thermally well coupled with the grains. The infall of material would naturally move grains initially at the edge of the torus from the zone exposed to X-rays and EUV/vacuum-UV photons to cooler shielded regions of the torus.

The gas-phase CH_3OH abundance in L1551's outer molecular envelope will depend on the balance between several processes, including (1) freezeout onto dust grains; (2) destruction by ion-molecule reactions, since enhanced ion densities will be induced by the X-ray irradiation forming CH_3OH on a similar timescale to grain surface reactions (Wada et al. 2006); and (3) evaporation or release from dust grains following grain heating, or vaporization by an accretion shock (Velusamy et al. 2002).

To test the importance of process 2 above, a chemical model was kindly run for us by S. Viti (C. Lintott & S. Viti 2006, in preparation) for a molecular cloud having solar metallicity and a high (100 × standard) ionization rate, with the same temperature and density as those we infer. This suggests that a high methanol abundance could survive against ion-molecule reactions for at least 10^4 yr, i.e., similar to or greater than the

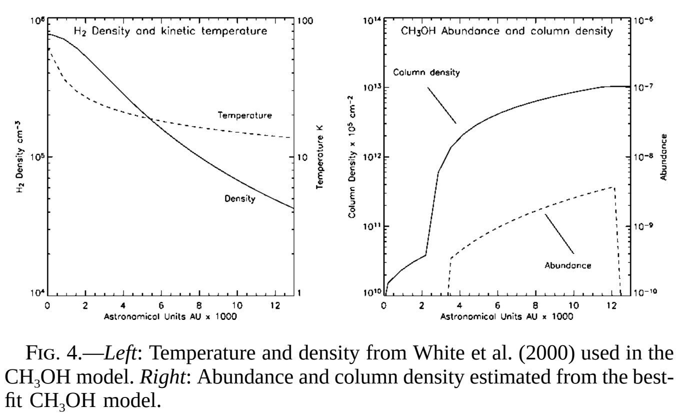

FIG. 4.—*Left*: Temperature and density from White et al. (2000) used in the CH_3OH model. *Right*: Abundance and column density estimated from the best-fit CH_3OH model.

freezeout timescale. For process 3, we favor release from heated grains over the accretion shock scenario on the basis of the narrow CH_3OH line widths that are observed in the outer L1551 molecular envelope (∼0.6 km s^{-1} compared to several kilometers per second in the L1157 inner core) and the distance of the CH_3OH peaks from L1551 IRS 5. There is no compelling evidence to suggest the CH_3OH abundance in the outer L1551 torus is significantly influenced by an accretion shock: the narrow CH_3OH line center lies within 0.1 km s^{-1} of the systemic velocity inferred from many other lines (∼6.5 km s^{-1}; Fridlund et al. 2002).

4.2. *Discussion and Conclusions*

Star formation occurs in the dense cores of molecular clouds. If we assume that comet formation occurs as an adjunct to this process, information about the primordial chemical abundances should be locked into the dust grains and comets, which are the main repositories of primitive material left over from the solar protostellar disk. The molecular inventory of protostellar envelope material has been discussed by White et al. (2003), with CH_3OH commonly being found in comets (Mumma et al. 2003), along with other organic molecules. Our detection of methanol in a region at a similar distance from L1551 IRS 5 as that of the Oort Cloud from our own Sun suggests that the CH_3OH may be able to accrete to and spread throughout the outer L1551 protostellar envelope, seeding dust grains and primitive bodies with chemical precursor material that could contribute to the synthesis of more complex molecules. This detection of methanol in the L1551 circumbinary torus provides a first glimpse into the initial chemical conditions of matter infalling onto protostellar disks, and future determinations of the abundances of other molecules in the X-ray/EUV illuminated zone could therefore provide a interesting test of the "interstellar" versus "nebular" aspects of cometary and planetesimal chemistry.

In summary: (1) we have detected a massive (0.03 $M_\oplus$), and most likely cold (≤20 K—based on dust continuum measurements), toroidal shaped ring of methanol surrounding the L1551 IRS 5 protobinary system; (2) we propose a new mechanism where shock luminosity heating by the jets associated with an externally located X-ray source—these have a direct line of sight to the torus surface—could raise the dust temperature sufficiently to liberate CH_3OH; (3) we suggest that the luminosity from the jet/X-ray source located just above the L1551 torus is able to heat the dust grains sufficiently to liberate a substantial amount of gaseous CH_3OH in the outer disk of L1551; and (4) we speculate that the methanol released will rapidly freeze back onto solid material in the outer envelope, spreading CH_3OH to the surfaces of dust grains and primitive bodies—and potentially modifying the primitive surfaces of solid material in L1551's outer molecular envelope. The observations give indications of the initial chemical conditions of matter infalling onto the disks.

We acknowledge discussions with B. Davidson, G. Moriarty-Schieven, V. Ossenkopf, R. Nelson, H. Rickman, F. van der Tak, M. Walmsley, D. Williams, and S. Viti, and thank D. Clements and H. Butner for help in obtaining the JCMT service observations, and an anonymous referee for helpful comments.

REFERENCES

Bally, J., Feigelson, E., & Reipurth, B. 2003, ApJ, 584, 843
Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987, ApJ, 315, 621
Brown, P. D. 1990, MNRAS, 243, 65
Favata, F., Bonito, R., Micela, G., Fridlund, M., Orlando, S., Sciortino, S., & Peres, G. 2006, A&A, 450, L17
Favata, F., Fridlund, C. V. M., Micela, G., Sciortino, S., & Kaas, A. A. 2002, A&A, 386, 204
Favata, F., Giardino, G., Micela, G., Sciortino, S., & Damiani, F. 2003, A&A, 403, 187
Fridlund, C. V. M., Bergman, P., White, G. J., Pilbratt, G. L., & Tauber, J. A. 2002, A&A, 382, 573
Fridlund, C. V. M., & Liseau, R. 1998, ApJ, 499, L75
Fridlund, C. V. M., Liseau, R., Djupvik, A. A., Huldtgren, M., White, G. J., Favata, F., & Giardino, G. 2005, A&A, 436, 983
Fridlund, C. V. M., & White, G. J. 1989, A&A, 223, L13
Geppert, W., et al. 2006, Faraday Discuss., in press
Goldsmith, P. F., Langer, W. D., & Velusamy, T. 1999, ApJ, 519, L173
Hartigan, P., Raymond, J., & Hartmann, L. 1987, ApJ, 316, 323
Hollenbach, D., & McKee, C. F. 1979, ApJS, 41, 555
Kaifu, N., et al. 1984, A&A, 134, 7
Maret, S., Ceccarelli, C., Tielens, A. G. G. M., Caux, E., Lefloch, B., Faure, A., Castets, A., & Flower, D. R. 2005, A&A, 442, 527
Moriarty-Schieven, G. H., Johnstone, D., Bally, J., & Jenness, T. 2006, ApJ, 645, 357
Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, A&A, 370, L49
Mumma, M. J., DiSanti, M. A., dello Russo, N., Magee-Sauer, K., Gibb, E., & Novak, R. 2003, Adv. Space Res., 31, 2563
Parker, N., White, G. J., Williams, P. G., & Hayashi, S. S. 1991, A&A, 250, 134
Phillips, R. R., & Little, L. T. 2000, MNRAS, 317, 179
Pottage, J. T., Flower, D. R., & Davis, S. L. 2004, MNRAS, 352, 39
Rainey, R., White, G. J., Richardson, K. J., Griffin, M. J., Cronin, N. J., Monteiro, T. S., & Hilton, J. 1987, A&A, 179, 237
Sandford, S. A., & Allamandola, L. J. 1993, ApJ, 417, 815
Snell, R. L., Loren, R. B., & Plambeck, R. L. 1980, ApJ, 239, L17
Stocke, J. T., Hartigan, P. M., Strom, S. E., Strom, K. M., Anderson, E. R., Hartmann, L. W., & Kenyon, S. J. 1988, ApJS, 68, 229
Takakuwa, S., Mikami, H., & Saito, M. 1998, ApJ, 501, 723
Takakuwa, S., et al. 2004, ApJ, 616, L15
Turner, B. E. 1998, ApJ, 501, 731
van der Tak, F. F. S., van Dishoeck, E. F., & Caselli, P. 2000, A&A, 361, 327
Velusamy, T., Langer, W. D., & Goldsmith, P. F. 2002, ApJ, 565, L43
Wada, A., Mochizuki, N., & Hiraoka, K. 2006, ApJ, 644, 300
White, G. J., Thompson, M. A., Fridlund, C. V. M., & Huldtgren White, M. 2003, in Towards Other Earths: *DARWIN*/*TPF* and the Search for Extrasolar Terrestrial Planets, ed. M. Fridlund & T. Henning (ESA SP-539; Noordwijk: ESA), 653
White, G. J., et al. 2000, A&A, 364, 741