Astrochemistry at work in the L1157–B1 shock: acetaldehyde formation

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1 INTRODUCTION

Complex organic molecules (COMs) have a key role among the many molecules so far detected in space: since they follow the same chemical rules of carbon-based chemistry, which terrestrial life is based on, they may give us an insight into the universality of life. Of course, large biotic molecules are not detectable in space, certainly not via (sub)millimeter observations. However, to determine whether pre-biotic molecules may form in space, we first need to understand the basic mechanisms that form smaller COMs. There is an extensive literature on the subject and still much debate on how COMs may form in space (e.g. Herbst & van Dishoeck 2009; Caselli & Ceccarelli 2012; Bergin 2013). Two basic processes are, in principle, possible: COMs may form on the grain surfaces or in gas phase. It is possible and even probable that the two processes are both important in different conditions for different molecules.

Acetaldehyde (CH3CHO) has been detected in a large range of interstellar conditions and with different abundances, namely in hot cores (Blake et al. 1986), hot coronas (Cazaux et al. 2003), cold envelopes (Jaber et al. 2014), Galactic Center clouds (Requena-Torres et al. 2006) and prestellar cores (Öberg et al. 2010). Grain surface models predict that CH3CHO is one of the simplest COMs and can be formed either by the combination of two radicals on the grain surface, CH3 and HCO, which become mobile when the grain temperature reaches ~30 K (Garrods & Herbst 2006), or by irradiation of iced CH4, CO2 and other iced species (Bennett et al. 2005). For the former route, the two radicals are predicted to be formed either because of the photolysis of more complex molecules on the grain mantles or, more simply, because of the partial hydrogenation of simple biatomic molecules on the grain mantles (Taquet et al. 2014).
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2012). Conversely, gas phase models claim that acetaldehyde is easily formed by the oxidation of hydrocarbons, which are produced by the hydrogenation of carbon chain on the grain mantles (Charnley et al. 1992, 2004). Finally, a further possible mechanism involving formation in the very high density gas-phase immediately after ice mantles are sublimated has been proposed by Rawlings et al. (2013).

In general, it is very difficult to distinguish which of these three mechanisms are at work and, consequently, their relative importance. The chemically rich shocked region L1157-B1 offers a unique possibility to test these theories, as it is a place where the dust is not heated by the protostar, but some of the grain mantles are sputtered/injected in the gas phase because of the passage of a shock (see e.g. Fontani et al. 2014). The L1157-mm protostar ($d = 250$ pc) drives a chemically rich outflow (Bachiller et al. 2001), associated with molecular clumpy cavities (Gueth et al. 1996), created by episodic events in a precessing jet. Located at the apex of the more recent cavity, the bright bow shock called B1 has a kinematical age of 2000 years. This shock spot has been the target of several studies (e.g. the Large Programs Herschel/CHESs (Chemical Herschel Surveys of Star forming regions); Ceccarelli et al. 2010; and IRAM-30m/ASAI (Astrochemical Survey At IRAM). In this Letter we report high spatial resolution observations of acetaldehyde, with the aim to constrain and quantify the contribution of gas phase chemistry to the CH$_3$CHO formation.

2 OBSERVATIONS

L1157-B1 was observed with the IRAM Plateau de Bure (PdB) 6-element array in April–May 2013 using both the C and D configurations, with 21–176 m baselines, filtering out structures $\geq 20''$, and providing an angular resolution of $2'' \times 2''$ (PA = $90^\circ$). The primary HPBW is $\sim 37''$. The observed CH$_3$CHO lines (see Table 1) at $\sim 134$–136 GHz were detected using the WideX backend which covers a 4 GHz spectral window at a 2 MHz ($\sim 4.4$ km s$^{-1}$) spectral resolution. The system temperature was 100–200 K in all tracks, and the amount of precipitable water vapor was generally $\sim 5$ mm. Calibration was carried out following standard procedures, using GILDAS-CLIC. Calibration was performed on 2C270 (bandpass), 1926+611, and 1928+738 (phase and amplitude). The absolute flux scale was set by observing 3C279 (bandpass), 1926+611, and 1928+738 (phase and amplitude). The primary HPBW is $\sim 37''$. The observed CH$_3$CHO lines (see Table 1) at $\sim 134$–136 GHz were detected using the WideX backend which covers a 4 GHz spectral window at a 2 MHz ($\sim 4.4$ km s$^{-1}$) spectral resolution. The system temperature was 100–200 K in all tracks, and the amount of precipitable water vapor was generally $\sim 5$ mm. Calibration was carried out following standard procedures, using GILDAS-CLIC. Calibration was performed on 2C270 (bandpass), 1926+611, and 1928+738 (phase and amplitude). The absolute flux scale was set by observing 3C279 (bandpass), 1926+611, and 1928+738 (phase and amplitude). The absolute flux scale was set by observing 3C279 (bandpass), 1926+611, and 1928+738 (phase and amplitude). The absolute flux scale was set by observing 3C279 (bandpass), 1926+611, and 1928+738 (phase and amplitude).

3 RESULTS: IMAGES AND SPECTRA

Acetaldehyde emission has been clearly (S/N $\geq 10$) detected towards L1157–B1. Fig. 1 shows the map of the CH$_3$CHO(7$_0.7$–6$_0.6$) E and A lines integrated emission. In order to verify whether the present CH$_3$CHO image is altered by filtering of large-scale emission, we produced the CH$_3$CHO(7$_0.7$–6$_0.6$) E+A spectrum summing the emission measured at PdB in a circle of diameter equal to the half-power beam width (HPBW) of the IRAM-30m telescope (17''). We evaluated the missing flux by comparing such emission with the spectrum directly measured with the single-dish (from the ASAI spectral survey, Lefloch et al., in preparation). As already found for HDCO by Fontani et al. (2014), with the PdB we recover more than 80% of the flux, indicating that both tracers do not have significant extended structures. The spatial distribution reported in Fig. 1 shows that CH$_3$CHO is mainly associated with two regions: (i) the eastern B0-B1 cavity opened by the precessing jet (called ‘E-wall’, see Fig. 1 in Fontani et al. 2014), and (ii) the arch-like structure composed by the B1a-e-f-b clumps identified by CH$_3$CN (called ‘arch’). The red, turquoise, and magenta polygons shown in Fig. 1 sketch out these two regions, intersecting at the position of the B1a clump. Note that B1a is in turn located where the precessing jet is expected to impact the cavity producing a dissociative J-shock (traced by high velocity SiO, H$_2$O, [FeII], [OI], and high-J CO emission: e.g. Gueth et al. 1998, Benedettini et al. 2012).

Table 1. List of CH$_3$CHO transitions detected towards L1157-B1

| Transition | $\nu^a$ (GHz) | $E_a^a$ (K) | $S^b_a$ (D$^2$) | $\log(\text{A}/\text{s}^{-1})^a$ |
|------------|---------------|-------------|-----------------|-----------------------------|
| (7$_0.7$–6$_0.6$)E | 133.830 | 26 | 88.5 | -4.04 |
| (7$_0.7$–6$_0.6$)A | 133.854 | 26 | 88.4 | -4.08 |
| (7$_2.6$–6$_2.5$)A | 134.694 | 35 | 81.3 | -4.11 |
| (7$_2.6$–6$_2.5$)E | 135.685 | 35 | 81.3 | -4.10 |

$^a$ From the Jet Propulsion Laboratory database (Pickett et al. 1998).

Figure 2 shows the CH$_3$CHO line spectrum observed with the 3.6 GHz WideX bandwidth towards the brightest clump, B1a. Up to six lines ($E_u = 26$–35 K, see Table 1) are detected with a S/N $> 3$. Using the GILDAS-Weeds package (Maret et al. 2011) and assuming optically thin emission and LTE conditions, we produced the synthetic spectrum (red line in Fig. 2) that best fits the observed one. Note that the CH$_3$CHO lines are blue-shifted, by 2 km s$^{-1}$, with respect to the cloud systemic velocity (+2.6 km s$^{-1}$; Bachiller & Peréz Gutierrez 1997), and have linewidths of 8 km s$^{-1}$. Similarly, we extracted the CH$_3$CHO line spectrum towards the three B1 zones, ‘E-wall’, ‘arch’, and ‘head’, shown in Fig. 1. Table 2 reports the measured peak velocities, intensities (in $T_B$ scale), FWHM linewidths, and integrated intensities, for each of the three zones.

4 CH$_3$CHO ABUNDANCE

Figure 1 compares the CH$_3$CHO distribution with that of HDCO (Fontani et al. 2014), showing an excellent agreement, with weak or no emission at the head of the bow B1 structure (called ‘head’). The acetaldehyde emission is concentrated towards the ‘E-wall’ and ‘arch’ zones, namely the part of B1 associated with the most recent shocked material, as probed by the HDCO emission. This is further supported by the fact that the brightest acetaldehyde emission comes where also CH$_3$OH, another dust mantle product, and CH$_3$CN, a 6-atoms COM, emission peak (Codella et al. 2012). Conversely, gas phase models claim that acetaldehyde is easily formed by the oxidation of hydrocarbons, which are produced by the hydrogenation of carbon chain on the grain mantles (Charnley et al. 1992, 2004). Finally, a further possible mechanism involving formation in the very high density gas-phase immediately after ice mantles are sublimated has been proposed by Rawlings et al. (2013).
et al. 2009, Benedettini et al. 2013). Finally, the CH$_3$CHO observed emission is also confined in the low-velocity range ($FWHM \sim 8$ km s$^{-1}$) of the L1157-B1 outflow, which is dominated by the extended B1 bow-cavity, according to Lefloch et al. (2012) and Busquet et al. (2014). In summary, similarly to HDCO, CH$_3$CHO traces the extended interface between the shock and the ambient gas, which is chemically enriched by the sputtering of the dust mantles.

To derive the column density, we used the LTE populated and optically thin assumption and best fitted the six detected lines of Tables 1–2. Towards the B1a peak, we find $N_{\text{CH}_3\text{CHO}} = 9 \times 10^{13}$ cm$^{-2}$, and a rotational temperature of $T_{\text{rot}} = 15$ K, in agreement with the value derived for the molecular core from single-dish CO and HDCO measurements (10–70 K; Lefloch et al. 2012, Codella et al. 2012). Assuming rotational temperatures between 10 and 70 K (Table 2) we derived a column density of $5 \times 30 \times 10^{12}$ cm$^{-2}$ in the ‘E-wall’ and ‘arch’ regions, and $\sim 2 \times 3 \times 10^{12}$ cm$^{-2}$ in the ‘head’. The size of the regions (at 3σ level) is 9″ (‘E-wall’), 7″ (‘arch’), and 8″ (‘head’). An estimate of the CH$_3$CHO abundance can be derived using the CO column density $\approx 10^{17}$ cm$^{-2}$ derived by Lefloch et al. (2012) on a 20″ scale. We derived $N_{\text{CH}_3\text{CHO}}$ using the CH$_3$CO spectrum extracted on the same scale and assuming 10–70 K. We find $N_{\text{CH}_3\text{CHO}} \approx 0.9 \sim 1.6 \times 10^{13}$ cm$^{-2}$, which implies a high abundance, $X$(CH$_3$CHO) $\approx 2 \sim 3 \times 10^{-8}$, similar to what has been measured in hot-corinos ($\approx 2 \sim 6 \times 10^{-9}$, Caux et al. 2003), and larger than that measured in prestellar cores ($\approx 10^{-11}$, Vastel et al. 2014) and towards high-mass star forming regions ($\approx 10^{-11}$–$10^{-9}$, Caux et al. 2003; Charnley 2004).

5 GAS PHASE FORMATION OF CH$_3$CHO

The ratio between $N_{\text{CH}_3\text{CHO}}$ and the column density of HDCO, i.e. a molecule which in L1157-B1 is predominantly released by grain mantles (Fontani et al. 2014), is higher (even if we consider the uncertainties, see Table 2) in the ‘arch’ with respect to the ‘E-wall’ by a factor $\sim 2$–8. Assuming the same grain mantle composition and release mechanism, this difference suggests that, in the ‘arch’, a significant fraction of the observed CH$_3$CHO is formed in the gas phase. In the gas phase, the injection from grain mantles of ethane (C$_2$H$_6$) is expected to drive first C$_2$H$_5$ and successively acetaldehyde (e.g. Charnley 2004; Vasyunin & Herbst 2013): the overlap between the HDCO (Fontani et al. 2014) and CH$_3$CHO emitting regions supports this scenario. We can, therefore, use the measured CH$_3$CHO abundance to constrain the quantity of C$_2$H$_5$ that has to be present in the gas phase in order to produce the observed quantity of CH$_3$CHO. To this end, we use the chemical code ASTROCHEM4, a pseudo time dependent model that follows the evolution of a gas cloud with a fixed temperature and density considering a network of chemical reactions in the gas phase. We followed the same 2-steps procedure adopted in Podio et al. (2014) and Mendoza et al. (2014), to first compute the steady-state abundances in the cloud (i.e. $T_{\text{kin}}=10$ K, $n_{\text{H}_2}=10^{4}$ cm$^{-3}$, $\zeta=3 \times 10^{-16}$ s$^{-1}$); and then we followed the gas evolution over 2000 yr at the shocked conditions (i.e. $T_{\text{kin}}=70$ K and $n_{\text{H}_2}=10^{5}$ cm$^{-3}$). To estimate the influence of a possibly larger gas $T_{\text{kin}}$ during the passage of the shock, we also run cases with temperatures up to 1000 K. We adopt the OSUL$^5$ chemical network and assume visual extinction of $A_V=10$ mag and grain size of 0.1 μm. We assume that the abundances of OCS and CO$_2$ are also enhanced by the passage of the shock, namely their abundance in step 2 is $X$(CO$_2$) = 6 $\times 10^{-5}$ and $X$(OCS) = 6 $\times 10^{-6}$. Similarly, we assume that the abundance of methanol in step 2 is 2 $\times 10^{-6}$, in agreement with the most recent determination in L1157-B1 by Mendoza et al. (2014). Finally, we varied the C$_2$H$_5$ abundance from $2 \times 10^{-7}$ to $2 \times 10^{-5}$. As expected, the predicted steady-state abundance of acetaldehyde in the cloud is very low ($1.5 \times 10^{-15}$). However, once C$_2$H$_5$ is in the gas phase, it rapidly reacts with oxygen forming abundant acetaldehyde on timescale shorter than 100 years (Fig. 3). The CH$_3$CHO abundance reaches the observed value, $\approx 2 \sim 3 \times 10^{-8}$, at the shock age (2000 years), for C$_2$H$_5 \sim 2 \sim 6 \times 10^{-7}$. Note that

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Table 2. Observed parameters (in $T_B$ scale) of the CH$_2$CHO/$\nu_{0,% 60,0}$ E and A emission, and acetaldehyde column densities $N_{\text{CH}_3\text{CHO}}$ derived in the 3 regions identified in Fig. 1 (E-wall, arch, and head) following Fontani et al. (2014), see Sect. 3. The (range of) excitation temperatures ($T_{\text{ex}}$) used to derive $N_{\text{CH}_3\text{CHO}}$ have been assumed equal to the rotation temperatures derived in Codella et al. (2012), Lefloch et al. (2012), and Fontani et al. (2014). The last columns report the X(CH$_3$CHO)/X(CH$_2$OH) and X(CH$_3$CHO)/X(HDCO) abundance ratios using the CH$_2$OH and HDCO data (and similar beams) by Benedettini et al. (2013) and Fontani et al. (2014).

| Transition | $T_{\text{peak}}$ | $V_{\text{peak}}$ | $FWHM$ | $N_{\text{CH}_3\text{CHO}}$ | CH$_3$CHO/CH$_2$OH | CH$_3$CHO/HDCO |
|------------|-----------------|-----------------|--------|-----------------|-------------------|---------------|
|            | (mK)            | (km s$^{-1}$)   | (mK km s$^{-1}$) | (10$^{12}$ cm$^{-2}$) | 10 K – 70 K | 10 K – 70 K |
| $7_{0,7}$–$6_{0,6}$ E | 30(3) | +0.4(0.4) | 8.2(1.0) | 264(28) | 5.0(0.3)–9.2(0.5) | 1.7(0.1)–11.0(0.6) | 1.9(0.2)–0.9(0.1) |
| $7_{0,7}$–$6_{0,6}$ A | 29(3) | +0.5(0.5) | 8.6(1.3) | 263(31) | 15.9(0.1)–29.4(0.1) | 0.6(0.1)–4.2(0.1) | 7.6(1.1)–3.7(0.5) |
| $7_{0,7}$–$6_{0,6}$ E | 71(7) | −0.9(0.3) | 9.2(0.8) | 748(54) | 1.7(0.3)–3.1(0.5) | 0.2(0.1)–0.7(0.1) | $\geq 1.5$ |
| $7_{0,7}$–$6_{0,6}$ A | 76(7) | −0.2(0.9) | 8.0(0.5) | 608(42) | 8.2(3) +0.4(0.4) | 8.0(1.0) | 8.2(1.0) |

$^a$ The errors are the gaussian fit uncertainties. The spectral resolution is 4.4 km s$^{-1}$. $^b$ Derived using the ($7_{0,7}$–$6_{0,6}$) E and A emissions.
Chemical differentiation in L1157–B1: the maps are centred at: i.e. at $\Delta \alpha = +21\,\text{h}$ and $\Delta \delta = -64\,\text{arcmin}$ from the driving protostar. Upper panel: CH$_3$CHO($J=7_0-6_0$) E+A integrated emission (green colour, black contours) on top of the HDCO($J=1-0$, $K_a=1$; $K_b=1$) line (white contours; Fontani et al. 2014). First contour and steps of the CH$_3$ line (white contours; Benedettini et al. 2013). The HPBWs are: $3\,\text{arcsec} = 10\,\text{yr}$ and $10\,\text{arcsec} = 100\,\text{yr}$. $\sigma$ contours indicate the L1157-B1 clumps identified using the CH$_3$CN image (Codella et al. 2009). The red, turquoise, and magenta polygons called ‘E-wall’, ‘arch’, and ‘head’ indicate the 3 portions of L1157-B1 selected by Fontani et al. (2014) to investigate H$_2$CO deuteration. Bottom panel: CH$_3$CN($8K-7K$) emission (green colour, black contours; Codella et al. 2009) on top of the CH$_3$OH($3J-2J$) emission (white; Benedettini et al. 2013). The HPBWs are: $3\,\text{arcsec} = 10^5\,\text{yr}$ for CH$_3$CN and $3\,\text{arcsec} = 10^7\,\text{yr}$ for CH$_3$OH. The labels indicate the L1157-B1 clumps identified using the CH$_3$CN image (Codella et al. 2009).

Figure 1. Chemical differentiation in L1157–B1: the maps are centred at: $\alpha(J2000) = 20^h 30^m 09\fs5, \delta(J2000) = +68\degr 01\arcmin 00\arcsec$, i.e. at $\Delta \alpha = +21\,\text{h}$ and $\Delta \delta = -64\,\text{arcmin}$ from the driving protostar. Upper panel: CH$_3$CHO($J=7_0-6_0$) E+A integrated emission (green colour, black contours) on top of the HDCO($J=1-0$, $K_a=1$; $K_b=1$) line (white contours; Fontani et al. 2014). First contour and steps of the CH$_3$ line (white contours; Benedettini et al. 2013). The HPBWs are: $3\,\text{arcsec} = 10\,\text{yr}$ and $10\,\text{arcsec} = 100\,\text{yr}$. $\sigma$ contours indicate the L1157-B1 clumps identified using the CH$_3$CN image (Codella et al. 2009). The red, turquoise, and magenta polygons called ‘E-wall’, ‘arch’, and ‘head’ indicate the 3 portions of L1157-B1 selected by Fontani et al. (2014) to investigate H$_2$CO deuteration. Bottom panel: CH$_3$CN($8K-7K$) emission (green colour, black contours; Codella et al. 2009) on top of the CH$_3$OH($3J-2J$) emission (white; Benedettini et al. 2013). The HPBWs are: $3\,\text{arcsec} = 10^5\,\text{yr}$ for CH$_3$CN and $3\,\text{arcsec} = 10^7\,\text{yr}$ for CH$_3$OH. The labels indicate the L1157-B1 clumps identified using the CH$_3$CN image (Codella et al. 2009).

6 DISCUSSION AND CONCLUSIONS

We have shown that acetaldehyde is abundant, $X$ (CH$_3$CHO) $\approx 2 \times 10^{-5}$, in the gas associated with the passage of a shock and enriched by iced species sputtered from grain mantles and injected into the gas phase. The measured acetaldehyde abundance could be consistent with the scenario of oxidation of gaseous hydrocarbons formed in a previous phase and released by the grain mantles. However, the abundance of the C$_2$H$_2$ required to reproduce the measured CH$_3$CHO is very high, $\sim 2 \times 10^{-7}$, namely less than 0.6% the elemental gaseous carbon. There are no observations of C$_2$H$_2$, hence it is impossible to compare with direct estimates of the abundance of this molecule. However, it has been argued that large quantities of frozen methane, of a few % of iced mantle water, is found around the L1527-mm protostar, where the detection of CH$_3$D (Sakai et al. 2012) indicates $X$(CH$_4$) $\approx 0.4-1.5 \times 10^{-5}$. This large abundance has been attributed to a low density of the pre-collapse core from which L1527-mm originated (Aikawa et al. 2008). Interestingly, the analysis of the deuteration of water, methanol and formaldehyde in L1157-B1 led Codella et al. (2012) to conclude that also the mantles of L1157-B1 were formed in relatively low density ($\sim 10^3\,\text{cm}^{-3}$) conditions.

To conclude, in the specific case of L1157-B1, gas phase reactions can produce the observed quantity of acetaldehyde only if a large fraction of carbon, of the order of 0.1%, is locked into iced hydrocarbons. Further observations of the hydrocarbons abundance in L1557-B1 are needed to confirm or dismiss our hypothesis.

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REFERENCES

Aikawa Y., Wakelam V., Garrod R.T., & Herbst E. 2008, ApJ 674, 993
Bachiller R., & Peréz Gutiérrez M. 1997, ApJ 487, L93
Benedettini, M., Busquet, B., Lefloch, B., et al. 2012, A&A 539, L3
Bennett C.J., Osamira Y., Lebar M.D., & KAiser R.I. 2005, ApJ 634, 968
Bergin, E.A. 2013, XVII Special Courses at the National Observatory of Rio de Janeiro. AIP Conference Proceedings [arXiv:1309.4720]
Blake G.A., Masson C.R., Phillips T.G., & Sutton E.C. 1986, ApJS 60, 357

© 2011 RAS, MNRAS 000, L9
Figure 2. CH$_3$CHO emission (in $T_B$ scale) extracted at the B1a position ($\alpha$(J2000) = 20° 39′ 10″2, $\delta$(J2000) = +68° 01′ 12″0), the three panels show the frequency intervals of the 4 GHz wide WideX where the six CH$_3$CHO lines with S/N $\geq$ 3σ (33 mK) are located (see Table 1). The red line shows the synthetic spectra which better reproduce the observations: it has been obtained with the GILDAS–Weeds package (Maret et al. 2011) assuming optically thin emission and LTE conditions with $N_{\text{CH}_3\text{CHO}}$ = 9 $\times$ 10$^{13}$ cm$^{-2}$, $T_{\text{ex}}$ = 15 K, $v_{\text{LSR}}$ = +0.6 km s$^{-1}$, and FWHM linewidth = 8.0 km s$^{-1}$.

Busquet G., Lefloch B., Benedettini, M., et al. 2014, A&A 561, 120
Benedettini, M., Viti, S., Codella, C., et al. 2013, MNRAS 436, 179
Caselli, P. & Ceccarelli, C. 2012, A&ARv, 20, 56
Cazaux S., Tielens A.G.G.M., Ceccarelli C., et al. 2003, ApJ 593, L51
Ceccarelli C., Bacmann A., Boogert A., et al. 2010, A&A 521, L22
Charnley S.B., 2004, Adv. Space Res. 33, 23
Charnley S.B., Tielens A.G.G.M., & Millar T.J. 1992, ApJ 399, L71
Codella C., Benedettini M., Beltrán M.T., et al. 2009, A&A 507, L25
Codella C., Ceccarelli C., Lefloch B., et al. 2012, ApJ, 757, L9
Fontani F., Codella C., Ceccarelli C., et al. 2014, ApJ 788, L43
Garrod R.T., & Herbst E. 2006, A&A 457, 927

Garrod R.T., Wakelam V., & Herbst E. 2007, A&A 467, 1103
Garrod R.T., Weaver S.L.W., & Herbst E. 2008, ApJ 682, 283
Garrod R.T., Vasyunin A.I., Semenov D.A., Wiebe D.S., & Henning Th. 2009, ApJ 700, L43
Gueth F., Guilloteau S., & Bachiller R. 1996, A&A 307, 891
Gueth F., Guilloteau S., & Bachiller R. 1998, A&A 333, 287
Herbst E., & van Dishoeck E.F. 2000, ARA&A 47, 427
Jaber A.A., Ceccarelli C., Kahane C., & Caux E. 2014, ApJ 791, 29
Lefloch B., Cabrit S., Busquet G., et al. 2012, ApJ, 757, L25
Maret S., Hily-Blant P., Pety J., et al., A&A 526, A47
Öberg K.I., Bottinelli S., Jørgensen J.K., van Dishoeck E.F. 2010, ApJ 716, 825
Occhiogrosso A., Vasyunin A., Herbst E., et al. 2014, A&A 564, 123
Pickett H.M., Poynter R.L., Cohen E.A., et al. 1998, J. Quant. Spectrosc. & Rad. Transfer 60, 883
Podio L., Lefloch B., Ceccarelli C., Codella C., & Bachiller R. 2014, A&A 565, 64
Requena-Torres M.A.; Martín-Pintado J., Rodríguez-Franco A., et al. 2006, A&A 455, 971
Rawlings J.M.C., Williams D.A., Viti S., & Cecchi-Pestellini C. 2013, MNRAS 430, 264
Sakai N., Shirley Y.L., Sakai T., et al. 2012, ApJ 758, L4
Taquet, V., Ceccarelli, C., & Kahane, C. 2012, ApJ 784, L3
Vastel C., Ceccarelli C., Lefloch B., & Bachiller R. 2014, ApJ 795, L2
Vasyunin A.I., & Herbst E. 2013, ApJ 769, 34

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