ACTA ASTRONOMICA
Vol. **62** (2012) pp. 313–321

A Comparison of c-C_3H_2 and l-C_3H_2 in the Spiral Arm Clouds

M. Kulczak-Jastrzębska[1], D. Lis[2] and M. Gerin[3]

[1] Astronomical Observatory of the Jagiellonian University, 30-244 Orla 171, Kraków, Poland
e-mail:kulczak@oa.uj.edu.pl
[2] California Institute of Technology, Cahill Center for Astronomy and Astrophysics 301-17, Pasadena, CA 91125, USA
e-mail:dcl@caltech.edu
[3] LERMA, UMR 8112 du CNRS, École Normale Supérieure and Observatoire de Paris, 24 Rue Lhomond, 75231 Paris cedex 05, France
e-mail:maryvonne.gerin@lra.ens.fr

Received August 29, 2012

ABSTRACT

Using the IRAM 30-m telescope, we observed molecular absorption lines from c-C_3H_2 produced in diffuse clouds toward the high-mass star forming regions W51 e1/e2 and W49N to determine the abundance ratio between the cyclic and linear isomers of C_3H_2 (N_c/N_l). The abundance ratio is found to be 3–5 in the sources where l-C_3H_2 was previously detected. A possible source of uncertainty in the determination of N_c/N_l is related to the estimate of N(c-C_3H_2). The main goal of this paper is verification of this hypothesis.

Key words: *Radio lines: ISM – ISM: molecules – ISM: abundances*

1. Introduction

Carbon is the fourth most abundant element in the interstellar medium (ISM), and also the most versatile for building molecules. Carbon participates in numerous chemical reactions at any temperature, from the very cold dense cores, to warm and hot gas. Of the over 150 molecules detected in interstellar and circumstellar environments about 75% have at least one carbon atom, while one fourth are hydrocarbons. Moreover the heaviest and most complex molecules are organic molecules with carbon. This statistic does not take into account the Polycyclic Aromatic Hydrocarbons (PAHs), nor the Diffuse Infrared Band (DIB) carriers, which are more likely large organic molecules (Herbig 1995). While CH, CH^+ and CN have been known in the ISM since the 1940, the detection of other molecules in the diffuse gas has decreased afterwords. However recent, deep observations have revealed and confirmed the presence of diatomic, triatomic and even more complex molecules in the diffuse gas. Recent studies have shown that the C-rich diffuse interstellar medium is more chemically active than previously thought, with molecules as large as C_3 (Goicoechea *et al.* 2004, Oka *et al.* 2003) and c-C_3H_2 (Lucas and Liszt 2000, Gerin *et al.* 2011) (c-C_3H_2 is the most widespread interstellar ring molecule). The abundances of polyatomic molecules, such as c-C_3H_2, HCO^+, HCN and C_2H are somewhat higher than can be explained by conventional chemical models (van Dishoeck and Black 1986). Small carbon containing molecules, with a total of about 1 to 3 carbon atoms have several interesting properties: they show a widespread spatial distribution in the interstellar medium, they likely participate in the formation of long carbon molecules and are involved in photo-fragmentation process of larger species, such as PAHs. It is widely believed that carbon chain or ring species might be candidates for the Diffuse Interstellar Bands (Herbig 1975, 1995).

2. Observations

Absorption line studies toward strong background continuum sources are of interest because they allow probing diffuse, low-density clouds. The determination of the line opacity is independent of the excitation temperature if $T_{\rm ex} \ll T_{\rm c}$, where $T_{\rm c}$ is the brightness temperature of the continuum source. Such absorption line observations also allow measurements of column densities one or two orders of magnitude lower than those obtained through emission line studies.

2.1. Cyclic and Linear Forms of C_3H_2

Cyclopropelidene c-C_3H_2 was the first cyclic molecule to be detected in the ISM (Thaddeus *et al.* 1985, Vrtilek *et al.* 1990) and subsequently found to be ubiquitous throughout the Galaxy, even in the diffuse gas (Cox *et al.* 1988). Its linear isomer propadienlidene, H_2CCC, is the first stable member of the cumulene carbon chains, characterized by double bonds between the carbons and terminal non-bonded electrons. Propadienlidene has also been observed in a number of sources, albeit at a lower abundance. It was first detected by Cernicharo (1991) in the cold dark cloud TMC1. The observed abundance ratio between cyclic and linear C_3H_2 in TCM1 is 70 (Cernicharo *et al.* 1991). In the IRC+10216 circumstellar envelope this ratio has a value of at least 30, whereas for the diffuse gas values lower typically by a factor of ten have been derived.

2.2. Spiral-Arm Clouds

Cernicharo *et al.* (1999) detected linear C_3H_2 in absorption from the spiral-arm clouds seen on the lines of sight toward giant HII regions in the Galactic plane (W49N, W51, Sgr B2). We have also studied some of these sources (Table 1). Physical conditions in the spiral-arm clouds are supposed to overlap with those we inferred for the diffuse and translucent gas occulting extragalactic continuum sources. For the spiral-arm clouds ^{13}CO emission is relatively strong and we conclude that they are more akin to the denser, darker, translucent objects studied by Turner (1998). So the spiral-arm clouds toward W49 are at least 3–4 times higher in column density than the most opaque of the clouds studied by Lucas (2000).

Table 1

Coordinates and distances of the target sources

Source name	α (J2000)	δ (J2000)	D [kpc]	$v_{\rm LSR}$ [km/s]
W51e_1/e_2	$19^{\rm h}23^{\rm m}43\overset{\rm s}{.}9$	$+14°30'25\overset{''}{.}9$	7.0	56.0
W49N	$19^{\rm h}10^{\rm m}13\overset{\rm s}{.}2$	$+09°06'12''$	11.4	8.4

2.3. Data Analysis and Processing

The observations were performed with the IRAM 30-m telescope in 2006 August and December. We used the A100 and B100 receivers simultaneously with either the A230, B230 or the C150, D150 receivers. All receivers were operated in the single sideband mode, with a rejection of the image sideband better than a factor of 20. The observations were performed using the wobbling secondary reflector to obtain flat and stable baselines and an accurate measurement of the 3 mm radio continuum intensity. The wobbler throw was 240$''$and the switching rate 0.5 Hz. The weather conditions were average, with 5–10 mm of precipitable water vapor in August 2006 and less than 3 mm in December 2006. The pointing was checked on nearby planets and continuum sources, and was found accurate to within 5$''$. Spectra were recorded with the flexible, high spectral resolution back-end VESPA, tuned to the spectral resolution of 40 kHz and the spectral bandpass of 120 MHz, covering a velocity range of 400 km/s. We also used the 1 MHz filterbank to obtain broad-band spectra. We searched for the $2_{1,2}-1_{0,1}$ transition of ortho c-C_3H_2 at 85.338 GHz. The data processing was done using the IRAM GILDAS software package (Pety 2005). The resulting IRAM 30-m spectra are shown in Figs. 1, 2 and 3.

The data were first calibrated to the T_A^* scale using the chopper wheel method (Penzias and Burrus 1973), and subsequently converted to the main beam brightness temperature scale using efficiencies appropriate for 85 GHz: $F_{\rm eff} = 0.95$ and $B_{\rm eff} = 0.75$. The continuum intensity $T_{\rm mb(c)}$ was measured by fitting flat baselines to the spectra. Line parameters of the detected absorption features: central opacity τ, velocity v and line width ΔV, were derived by fitting Gaussian absorption

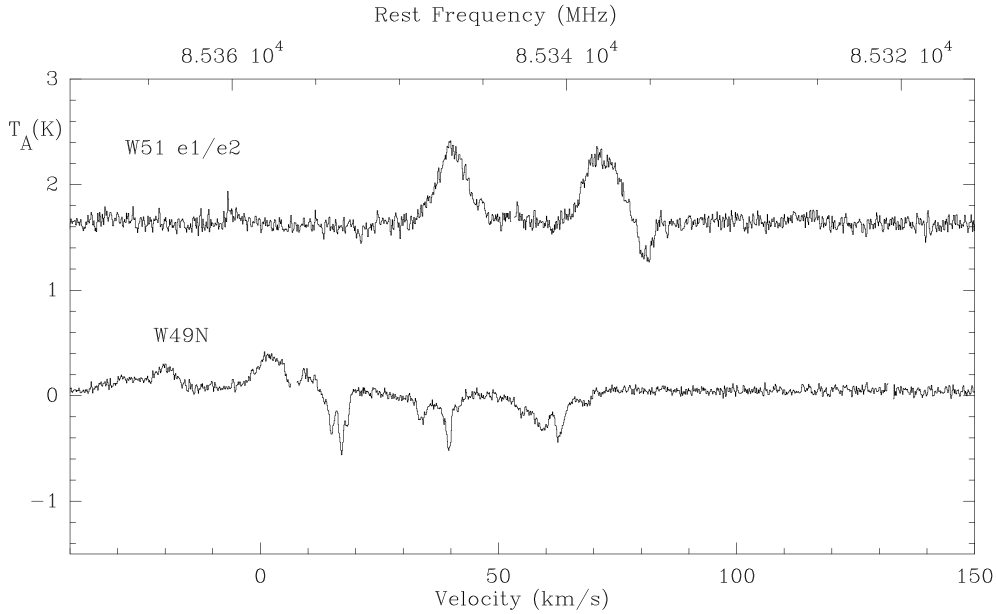

Fig. 1. Spectra of c-C_3H_2 toward W51 and W49N obtained with the IRAM 30-m telescope. The velocity scale is given relative to the Local Standard of Rest (LSR). The spectra have been offset for clarity

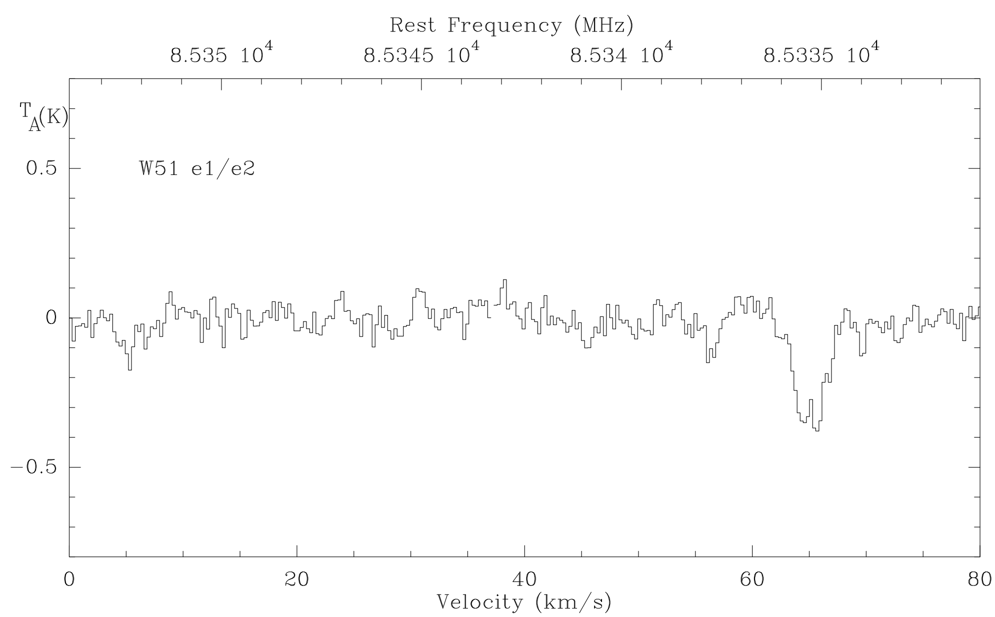

Fig. 2. Absorption spectra of c-C_3H_2 toward W51 (the emission lines were removed). The source continuum temperature was about 0.95 K

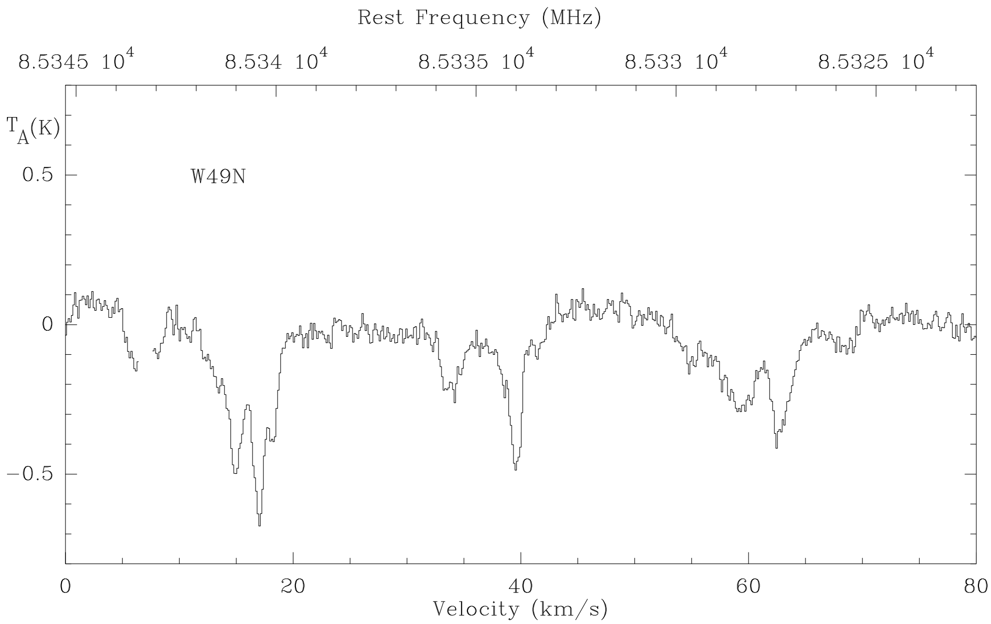

Fig. 3. Absorption spectra of c-C_3H_2 toward W49N (the emission lines were removed). The source continuum temperature was about 1.95 K

Table 2

Line Gaussian parameters of the c-C_3H_2 absorption components toward W51e_1e_2 and W49

Source name	v_{LSR} [km/s]	ΔV [km/s]	T_{mb} [K]	$T_{mb(c)}$ [K]	τ
W51e_1e_2	5.6	3.36 ± 0.48	-0.13	1.16	0.12 ± 0.04
	45.6	1.06 ± 0.14	-0.11	1.16	0.10 ± 0.04
	65.1	2.89 ± 0.14	-0.43	1.16	0.46 ± 0.06
W49N	15.2	1.54 ± 0.14	-0.48	2.34	0.22 ± 0.02
	34.1	3.36 ± 0.14	-0.24	2.34	0.11 ± 0.02
	39.5	2.38 ± 0.14	-0.50	2.34	0.24 ± 0.02
	59.5	3.18 ± 0.17	-0.35	2.34	0.16 ± 0.02
	62.9	2.54 ± 0.13	-0.49	2.34	0.23 ± 0.02

profiles to the spectra. The central opacity is defined as:

$$\tau = -\ln\left(1 - \frac{T_{mb}}{J(T_{ex}) - J(T_{cmb}) - T_{mb(c)}}\right) \tag{1}$$

where T_{mb} is the line temperature with respect to the continuum, $J(T)$ is the black body function $(\frac{h\nu}{k})/(e^{\frac{h\nu}{kT}} - 1)$. The excitation temperature (T_{ex}) of the transition is typically not much higher then 2.7 K (the cosmic background radiation temperature $T_{\rm cmb}$), since the densities of the regions where the lines formed are so low that the molecules are not collisionally excited. Under this assumption the optical depth of absorption line will be given directly from line to continuum intensity ratio as:

$$\tau = -\ln\left(1+\frac{T_{\rm mb}}{T_{\rm mb(c)}}\right). \qquad (2)$$

The line parameters derived from the IRAM observation of the c-C_3H_2 transition are listed in Table 2.

3. Results

We compute molecular column densities using the relation:

$$N_{\rm tot} = Z(T_{\rm ex})\cdot N_{\rm u}\cdot\frac{e^{E_{\rm u}/kT_{\rm ex}}}{g_{\rm u}} = Z(T_{\rm ex})\frac{8\pi\nu^3}{c^3}\cdot\frac{e^{E_{\rm u}/kT_{\rm ex}}}{g_{\rm u}A_{\rm ul}\cdot e^{h\nu/kT_{\rm ex}-1}}\int\tau\cdot d\upsilon \qquad (3)$$

where $Z(T_{\rm ex})$ is the partition function computed at the excitation temperature $T_{\rm ex}$, $N_{\rm tot}$ and $N_{\rm u}$ are the total column density and the column density in the upper state of the transition, respectively, $g_{\rm u}$ is the statistical weight of the upper level, $A_{\rm ul}$ is the Einstein spontaneous emission coefficient, ν is the line frequency and $\int\tau\cdot d\upsilon$ is the line opacity integrated over the line profiles. For a Gaussian line profile the integrated line opacity is proportional to the product of the line full width at half maximum $\Delta V\cdot\tau$ and the central opacity τ. The factor is very close to unity, and can be written as $\sqrt{\pi/4\ln 2}\simeq 1.065$. The ortho c-$C_3H_2$ column densities were derived from relation of Lucas and Liszt (2000):

$$N(\text{c-C}_3\text{H}_2) = 4.36\cdot 10^{12}\cdot 1.065\cdot\Delta V\cdot\tau \quad [\text{cm}^{-2}]. \qquad (4)$$

The results of calculation are shown in Table 3. We compare our estimates of the abundance ratio between the cyclic and linear isomer of C_3H_2 with those found by Cernicharo *et al.* (1991).

4. Discussion

Cernicharo *et al.* (1999) compared their column densities of l-C_3H_2 with the Madden *et al.* (1989) measurements of the $(1_{1,0}-1_{0,1})$ ortho c-C_3H_2 rotational transition at 18.343 GHz (excitation energy E/k of 0.9 K) toward high mass star forming regions (W51e_1e_2, W49N, W51D and Sgr B2). In W51e_1e_2 and W49N, the $1_{1,0}-1_{0,1}$ transition shows complex emission/absorption profiles where the emission corresponds in velocity with the HII region itself, and absorption appears at velocities corresponding to intervening cold clouds. Toward W51e_1e_2, a narrow absorption feature at 66 km/s is contaminated by a broad emission feature ($\Delta V = 12$ km/s) of the same molecule at the source velocity. A similarly

Table 3

Results

Source name	v^{*}_{LSR} [km/s]	v_{LSR} [km/s]	$N(l\text{-}C_3H_2)$ [cm^{-2}]	$N(c\text{-}C_3H_2)^{*}$ [cm^{-2}]	$N(c\text{-}C_3H_2)$ [cm^{-2}]	N_c/N_l^{*}	N_c/N_l
W51e$_1$e$_2$	6.0	5.6	$<$ 4.0E11	1.7E12	1.92E12	$>$ 4.25	$>$ 4.80
	45.5	45.6	$<$ 1.0E11	0.5E12	0.5E12	$>$ 5.0	$>$ 5.0
	66.3	65.12	4.7E11	1.6E12	6.17E12	3.4	13.1
W49N	15.8	15.2	4.0E11	3.0E12	1.60E12	7.5	4.00
	34.1	34.1	$<$ 4.5E11	3.5E12	1.69E12	$>$ 7.8	$>$ 3.84
	39.1	39.5	$<$ 2.6E11	3.5E12	2.61E12	$>$ 12.3	$>$ 10.0
	60.0	59.6	$<$ 2.9E11	2.5E12	2.38E12	$>$ 8.6	$>$ 8.20
	63.0	62.9	$<$ 2.2E11	2.8E12	2.71E12	$>$ 12.7	$>$ 12.3

*Cernicharo 1999

complicated spectrum of c-C_3H_2 at 18.343 GHz is observed between 0–20 km/s toward W49N region. The line absorption profile contaminated by the emission feature could be a source of error because the contamination would increase the value N_c/N_l. This explains some of the differences between column densities calculated in our work and those reported in Cernicharo *et al.* (1999) especially toward W51e$_1$e$_2$, at 66 km/s. The $2_{1,2}-1_{0,1}$ transition of ortho c-C_3H_2 at 85.338 GHz (excitation energy E/k of 4.1 K) is free of this problem because it shows only absorption profiles at velocities where the $1_{1,0}-1_{0,1}$ spectrum is contaminated by the emission from the background source.

Fossé *et al.* (2001) mapped in detail the region around the cyanopolyyene peak (hereafter CP) in TCM-1 in both l-C_3H_2 and c-C_3H_2. They compared two positions separated by 40″(which corresponds to 0.02 pc for the adopted distance of 100 pc to TCM-1; (Cernicharo 1987) and derived the following N_c/N_l ratios: at CP(0,0) 28 ± 6, and at the edge of the TCM-1 filament $(-40,0)$ 10 ± 3. These authors used the total column density (ortho + para) of c-C_3H_2, but if only the ortho c-C_3H_2 transition is used, assuming an ortho/para ratio of 3, a ratio $N_c/N_l = 7.5 \pm 2$. Fossé *et al.* (2001) used the UMIST95 chemical network (Millar *et al.* 1997) in a pure gas-phase scheme to model their observations. The general trend is that N_c/N_l increases with increasing visual extinction. This agrees with observations, since the ratio is lower in the diffuse medium than in the TCM-1 dark cloud. The cyclic-over-linear ratio can be separated into two regimes: "low" $(1 \leq A_V \leq 2)$ and "high" $(5 \leq A_V \leq 10)$, $A_V = 3$ being an intermediate case. In the low extinction regime (diffuse and translucent clouds) N_c/N_l strongly depends on the electron abundance. Why is the cyclic over linear ratio sensitive to ionization fractionation? In the UMIST95 chemistry C^+ can destroy both l-C_3H_2 and c-C_3H_2, whereas C reacts only with the linear isomer. The abundance ratio of 3–5 derived by Cernicharo *et al.* (1999) in the diffuse medium corresponds, as expected, to a high electron abundance and moderate visual extinction. In the high extinction regime, N_c/N_l is independent of the C^+/C ratio, while it is sensitive to the $(H_3^+ + C^+)/O$ ratio. Indeed, in the UMIST95 database, the atomic oxygen reacts only with l-C_3H_2. This reaction is negligible compared to other destruction reactions (in particular, the reactions with C^+ which affects both isomers) until all carbon is locked into CO. It is thus inefficient in low visual extinction regions where the abundances C and C^+ remain high. On the other hand, it becomes the principal destruction channel of l-C_3H_2 at high visual extinction. The variation of the cyclic-over-linear abundance ratio of C_3H_2 can be understood as a consequence of the competition between neutral-neutral and ion-neutral reactions in the interstellar medium. We can say that low ratios are indicative of a high electron abundance, while high ratios indicate a low electron abundance. In a more general way, isomeric ratios can be used to probe physical conditions in different media from the diffuse gas to dark clouds. The detection of l-C_3H_2 in the diffuse gas is important, because the cumulene carbon chains (H_2C_n) could contribute through their electronic transitions, to the DIBs. However, the results of Cernicharo *et al.* (1999) indicate a low abundance of C_nH radicals in the diffuse interstellar medium. These results were based on an old quantum chemical prediction of the electronic dipole moment, 4.1 Debye (which did not take into account electron correlation effects). However recent computations carried out by Wu *et al.* (2010) yield an almost identical value of 4.162 Debye. Indeed column densities of l-C_3H_2 needed to explain the diffuse interstellar band should be some three orders of magnitude higher than what is observed (Liszt *et al.* 2012).

5. Conclusion

Madden *et al.* (1989) calculated column densities of ortho c-C_3H_2 toward several strong Galactic background continuum sources. These data were used by Cernicharo *et al.* (1999) to determine the ratio N_c/N_l in the spiral-arm clouds on the line-of-sight toward: W51e_1e_2, W49N, W51D and Sgr B2. We have presented new data for W51e_1e_2, W49N and have calculated revised N(c-C_3H_2) values. The values of the cyclic-over-linear abundance ratio are low, 3–5, for diffuse and translucent cloud ($1 \leq A_V \leq 3$), and higher, 8–13, for spiral-arm clouds ($5 \leq A_V \leq 10$) (denser, darker, translucent objects). A high value is also derived for the edge of the TCM-1 filament (Fossé *et al.* 2001). In the low-A_V regime, the abundance ratio is sensitive to the C^+/C ratio and the second regime to the $(H_3^+ + C^+)/O$ ratio (Fossé *et al.* 2001). Isomeric ratios can be used to probe physical conditions in different environments from the diffuse gas to dark clouds. Our results are in agreement with the predictions of Cernicharo *et al.* (1999) that the difference in N_c/N_l ratio between different environments is probably a consequence of the distinct mechanisms leading to the destruction of the cyclic and linear isomers or their progenitors.

REFERENCES

Cernicharo, J., and Guelin, M. 1987, *A&A*, **176**, 299.
Cernicharo, J., Gottlieb, C.A., and Guelin, M., Killian, T.C., Paubert, G., Thaddeus, P., and Vrtilek, J.M. 1991, *ApJ*, **368**, L39.
Cernicharo, J., Cox, P., Fosse, D., and Gusten, R. 1999, *A&A*, **351**, 341.
Cox, P., Gusten, R., and Henkel, C. 1988, *A&A*, **206**, 108.
Fossé, D., Cernicharo, J., Gerin, M., and Cox, P. 2001, *ApJ*, **552**, 168.
Gerin, M., Kaźmierczak, M., and Jastrzebska, M. 2011, *A&A*, **525**, A116.
Goicoechea, J.R., Rodriguez-Fernandes, N.J., and Cernicharno, J. 2004, *ApJ*, **600**, 214.
Herbig, G.H. 1975, *ApJ*, **196**, 129.
Herbig, G.H. 1995, *Ann.Rev.A&A*, **33**, 19.
Liszt, H., Sonnentrucker, P., Cordirer, M., and Gein, M. 2012, *ApJ*, **753**, 28.
Lucas, R., and Liszt, H. 2000, *A&A*, **358**, 1069.
Madden, S.C., Irvine, W.M., and Matthews, H.E., and Friberg, P. 1989, *AJ*, **97**, 1403.
Millar, T.J., Farguhar, P.R. A., and Willacy, K. 1997, *A&AS*, **121**, 139.
Oka, T., Thoburn, J.M., McCall, B.J., Friedman, S.D., Hobbs, L.M., Sonnentrucker, P., Welty, D.E., and York, D.G. 2003, *ApJ*, **582**, 823.
Penzias, A.A., and Burrus, C.A. 1973, *Ann. Rev. Astron. Astrophys.*, **11**, 51.
Pety, J., Teyssier, D., Fossé, D., Gerin, M., Roueff, E., Abergel, A., Habart, E., and Cernicharo, J. 2005, *A&A*, **435**, 885.
Thaddeus, P., Vrtilek, J.M., and Gottlieb, C.A. 1985, *ApJ*, **299**, L63.
Wu,Q., Cheng, Q., Yamaguchi, Y., Li, Q., and Schaefer, H.F. 2010, *J. Chem. Phys.*, **132**, 44308.
van Dishoeck, E.,F., and Black, J.H. 1986, *ApJS*, **62**, 109.
Vrtilek, J.M., Gottlieb, C.A., Gottlieb, E.W., Killian, E.W., and Thaddeus, P. 1990, *ApJ*, **364**, L53.