DETECTION OF FORMAMIDE, THE SIMPLEST BUT CRUCIAL AMIDE, IN A SOLAR-TYPE PROTOSTAR

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ABSTRACT

Formamide (NH₂CHO), the simplest possible amide, has recently been suggested to be a central species in the synthesis of metabolic and genetic molecules, the chemical basis of life. In this Letter, we report the first detection of formamide in a protostar, IRAS 16293–2422, which may be similar to the Sun and solar system progenitor. The data combine spectra from the millimeter and submillimeter TIMASSS survey with recent, more sensitive observations at the IRAM 30 m telescope. With an abundance relative to H₂ of $\sim 10^{-10}$, formamide appears as abundant in this solar-type protostar as in the two high-mass star-forming regions, Orion-KL and SgrB2, where this species has previously been detected. Given the largely different UV-illuminated environments of the three sources, the relevance of UV photolysis of interstellar ices in the synthesis of formamide is therefore questionable. Assuming that this species is formed in the gas phase via the neutral–neutral reaction between the radical NH₂ and H₂CO, we predict an abundance in good agreement with the value derived from our observations. The comparison of the relative abundance [NH₂CHO]/[H₂O] in IRAS 16293–2422 and in the coma of the comet Hale-Bopp supports the similarity between interstellar and cometary chemistry. Our results thus suggest that the abundance of some cometary organic volatiles could reflect gas phase rather than grain-surface interstellar chemistry.

Key words: astrobiology – astrochemistry – ISM: abundances – ISM: individual objects (IRAS 16293-2422) – ISM: molecules – stars: formation

1. INTRODUCTION

The origin of life on Earth is obviously one of the most important open questions of modern science. Finding the answer implies putting together and solving a plethora of riddles. Many of them have one word in common: chemistry. What was the basic chemical mechanism that led atoms from molecules to life? Was it the first step connected to the metabolism, conversion of energy, or to the genetic passage of information? Or both? Is there a molecule which may have been the key to both of them? A recent study by Saladino et al. (2012) argues that formamide (NH₂CHO) may have been the starting point for the prebiotic synthesis of both metabolic and genetic species: amino acids, nucleic acid bases, acyclonucleosides, sugars, amino sugars, and carboxylic acids. This is because formamide is the simplest possible amide, and contains within its diverse chemistry the functional groups and chemical bonds of central biomolecule and is a versatile solvent and a reactant.

Although the chemistry in the interstellar medium (ISM) is clearly different from that on Earth and that the conditions are obviously not appropriate for life, how complex the interstellar chemistry is and what prebiotic molecules are synthesized in space are long-standing and important questions that have always raised the curiosity of even non-specialized researchers. As an example, the discovery of highly deuterated amino acids in meteoritic material has led to the hypothesis that amino acids are also synthesized in the harsh ISM conditions, in particular during the Sun protostellar phase (Pizzarello & Huang 2005; see also the recent review by Caselli & Ceccarelli 2012). Regardless of whether or not amino acids may have had a role in the terrestrial life appearance, the presence of important prebiotic molecules in space deserves our attention. In this context, whether formamide is synthesized in regions that will give birth to planetary systems like our own is of the greatest interest.

Before this work, formamide was detected toward only two interstellar sources, in the direction of the two galactic brightest millimeter sources: Orion-KL and SgrB2 (Turner 1989; Nummelin et al. 1998; Halfen et al. 2011). Both regions are active sites of massive star formation and present environmental conditions (strong UV emission, intense X-ray irradiation, violent shocks, ...) very different from those existing in regions giving birth to solar-type stars and planetary systems like the solar system. The examples of the molecular deuteration or the abundance of organic molecules make this point very clearly. In Orion-KL and SgrB2, the molecular deuteration is several orders of magnitude lower than in solar-type protostars (Ceccarelli et al. 2007). For example, while doubly deuterated water has been measured to be $\sim 10^{-3}$ with respect to the hydrogenated water toward the solar-type protostar IRAS 16293-2422 (Butner et al. 2007; Vastel et al. 2010), it remains undetected toward SgrB2 and Orion-KL. We know how important water and deuterated water are for understanding the origin of terrestrial oceans (e.g., Hartogh et al. 2011). On the same vein, the abundance (normalized to methanol) of several complex organic molecules (COMs) is larger by more than one order of magnitude in solar-type protostars than massive star-forming regions such as SgrB2 and Ori-KL (e.g., Bottinelli et al. 2007; Taquet et al. 2012).

When it comes to the specific case of formamide, various laboratory experiments have shown that, as for other prebiotic molecules, it can be synthesized in UV and energetic particle irradiated ices (e.g., Danger et al. 2011; Jones et al. 2011 and references therein), so that the origin of formamide in Orion-KL and SgrB2 may reflect the importance of these energetic processes. On the contrary, the environments of solar-type forming stars are much less exposed to those energetic processes. Therefore, before the present work, it remained to be proven that formamide can be synthesized in the more quiescent and colder gas surrounding solar-type protostars.



Figure 1. Representative spectra of formamide lines obtained toward IRAS16293 with the IRAM 30 m telescope. Spectra (a) and (f) are from the TIMASSS survey, whereas spectra (b)–(e) were obtained in 2012 March (see the text). Line frequencies and upper energy levels are indicated at the top on each line panel. The model profiles (in red) are LTE model predictions obtained with the CASSIS software for a 1"5 source, assuming uniform line widths and central velocities equal to the average values given by the Gaussian fits: $\langle V_{lsr} \rangle = 2.4 \text{ km s}^{-1}$ and $\langle FWHM \rangle = 4.2 \text{ km s}^{-1}$ (see the text). The lines denoted by "U" do not correspond to any obvious identification from the CDMS database (http://www.ph1.uni-koeln.de/cdms/) and the JPL database (http://spec.jpl.nasa.gov/). Intensities are in main-beam temperatures.

In this Letter, we report the successful search of formamide in one of such sources, IRAS 16293–2422 (hereinafter IRAS16293). Located in the L1689N cloud (d = 120 pc; Loinard et al. 2008), IRAS16293 hosts, in a common colder envelope, two hot corinos, A (south-east) and B (north-west), separated by about 4". Despite its relatively complex structure at arcsecond scales, IRAS16293 is the brightest and thus most appropriate source to carry out the search for new species in low-mass star-forming regions, as proven by the numerous new detections toward this source (e.g., Ceccarelli et al. 2000).

In addition, formamide has been detected in the comet Hale-Bopp (Bockelee-Morvan et al. 2000) whose chemical composition is suspected to be representative of the chemical composition of the primitive Solar Nebula. Thus, the comparison of the formamide abundance in Hale-Bopp with that of a solartype protostar can contribute to our understanding of the solar system astrochemical heritage.

2. OBSERVATIONS

The data presented here combine IRAM 30 m spectra from the TIMASSS survey (Caux et al. 2011) with more recent observations, performed in 2012 March, in four selected frequency ranges at 3, 2, and 1 mm, with the new broadband EMIR receivers at the IRAM 30 m telescope. Both sets of observations were centered on the B (northwest) source at $\alpha(2000.0) =$ $16^{h}32^{m}22^{s}.6, \delta(2000.0) = -24^{\circ}28'33'$. Note, however, that the A and B sources, separated by 4", are encompassed by the beam of our observations, even at the highest frequencies. All observations were performed in double-beam-switch (DBS) observing mode with a 90" throw. The pointing and focus were checked every two hours on planets or on continuum radio sources (1741-038 or 1730-130). Both sets of spectra were resampled at the same frequency resolution and averaged using the "stitch" command of the IRAM data reduction package CLASS⁴ to carefully check the coherence of the data in terms of line positions, shapes, and intensities. Comparison of the line intensities in

Table 1						
Observational Parameter	rs					

Frequency (GHz)	HPBW (arcsec)	Spectral Resolution (MHz)	rms ^a (mK)	Observations	
80-100.5	30-25	0.32	7	TIMASSS	
100.5-109.8	23	0.195	3	2012 Mar	
146.7-150.8	16	0.195	6	2012 Mar	
165.7–169.8	14	0.195	9–16	2012 Mar	
209.5-218.8	12	0.195	9	2012 Mar	
218.8–280	11–9	1.00	12-20	TIMASSS	

Note. ^a Expressed in $T_{\rm mb}$ units.

both sets of data shows that the calibration is accurate within 15%. Table 1 summarizes the observed bands and the details of the observations. Several representative spectra are plotted in Figure 1.

3. RESULTS: FORMAMIDE IDENTIFICATION

The new IRAM 30 m observations obtained in 2012 March present a systematically better spectral resolution and an rms in most cases comparable to or better than the TIMASSS spectra (see Table 1). Line identification was checked separately on both sets of data, based on the line frequencies given in the CDMS database (Müller et al. 2005). To limit our search to the lines expected to be the most intense, we have looked for transitions with an Einstein coefficient $A_{ij} \ge 3 \times 10^{-5} \text{ s}^{-1}$ and an upper energy $E_{up} \le 250 \text{ K}$ using the CASSIS software.⁵ With these criteria, 115 transitions lie in the (80–280 GHz) TIMASSS survey frequency range and a total of 39 lines were detected at the expected frequencies. In the frequency range covered by the 2012 March observations, we have detected 21 lines among the 37 transitions corresponding to the search criteria.

To verify whether the lines attributed to formamide constitute a reliable identification, we have performed the following tests.

⁴ http://www.iram.fr/IRAMFR/GILDAS

⁵ CASSIS has been developed by IRAP-UPS/CNRS (http://cassis.irap.omp.eu).



Figure 2. Histograms of the line distribution according to the four categories defined in the text: detected and isolated lines (DI), detected and blended lines (DB), undetected, weak or severely blended lines (N), and "missing" lines (M). The left panels refer to the formamide. The central and right panels refer to methyl formate (HCOOCH₃) and glycine (NH₂CH₂COOH) for a comparison with two other important COMs. The upper panels refer to the TIMASSS survey, whereas the bottom panels refer to the 2012 March observations (see the text).

- 1. We have built an LTE model reproducing the fluxes of the detected lines (see Section 4.1) and verified that it does not predict detectable but not detected lines in the observed bands (see also point 2).
- We have classified the formamide lines filling the abovementioned search criteria into four categories: (1) the detected and isolated lines; (2) the detected but blended lines;
 (3) the undetected, weak, or severely blended lines; and
 (4) the "missing" lines, i.e., those for which the predicted line is more than 50% brighter than the observed one. The histograms plotted in Figure 2 show the distribution of the lines in the four categories.
- 3. We have applied the same method to two other important COMs: (1) methyl formate (HCOOCH₃), firmly detected, and (2) glycine (NH₂CH₂COOH), a long searched for and not yet detected COM. The results are also shown in Figure 2.

A comparison of these distributions shows that in contrast to glycine, neither methyl formate nor formamide shows the "missing" lines (M). When all the spectra of the TIMASS survey are included, the formamide and the glycine line distributions have a large fraction of undetected lines (N). However, when the noise decreases and the spectral resolution increases, as in the 2012 March observations, both distributions evolve in opposite ways: many undetected lines (N) of glycine become "missing" lines (M) and, in contrast, they become detected (isolated, DI or blended, DB) lines in the case of formamide. With the improved 2012 March data, the formamide line distribution appears similar to that of the methyl formate. We are thus confident that our new observations confirm the detection of formamide in IRAS16293.

4. DISCUSSION

4.1. Formamide Abundance

The formamide lines thought to be free enough from nearby line blending have been fitted by Gaussian profiles. The fit parameters are given in Table 2 and some representative spectra are plotted in Figure 1.

Assuming that the lines are optically thin and LTE populated, we estimated the formamide column density from the line rotational diagram. In IRAS16293, emission from COMs is known to come from the protostellar sources A and B (in some cases predominantly from one of them), and not from the more extended envelope (see, for instance, the interferometric maps by Bottinelli et al. 2004; Chandler et al. 2005, and Bisschop et al. 2008). As explained before, our observations encompass both A and B. The formamide line emission observed with the IRAM 30 m telescope is thus most likely strongly beam diluted. Existing interferometric maps show that molecular emission from source A has a typical extent of 1".5 whereas emission from source B is unresolved, ≤ 0 ?8. Assuming a source size of 1",5, an LTE modeling of the detected lines leads to a rotational temperature of 47(-15, +43) K and a column density of 4.4 $(-1.9, +3.0) \times 10^{14} \text{ cm}^{-2}$. The line profiles predicted by this LTE model are superposed to the observed lines in Figure 1. With an H₂ column density of 3.5×10^{24} cm⁻², as derived by Bottinelli et al. (2004) for source A, we obtain a formamide abundance relative to H₂ of 1.3 (-0.6, +0.8) $\times 10^{-10}$.

Using the frequencies given in Halfen et al. (2011), we have also searched for acetamide, another simple species bearing a peptide bond (CH₃CONH₂) with transitions in the observed spectra. No line could be detected and, based on the same LTE modeling as for formamide, we obtain a 3σ upper limit to the acetamide abundance of $\sim 2.5 \times 10^{-10}$.

4.2. Chemistry

Several reaction pathways have been previously proposed to explain the abundance of gas-phase formamide in the interstellar medium: formamide might form either in the icy mantles of irradiated dust grains and then be released in the gas phase or formamide could be produced directly in the gas phase. The pioneering work of Hagen et al. (1979) had shown that formamide was formed by vacuum ultraviolet (VUV) irradiation of the ice mixture CO:NH₃:H₂O:CO₂. More recently, formamide was identified by Raunier et al. (2004) as one of the products formed by VUV photolysis of solid isocyanic acid (HNCO) at 10 K. These authors were also able to tentatively assign solid

$\overline{J'K_a'K_c'}$	\rightarrow	JK _a K _c	Frequency (GHz)	<i>E</i> _{up} (K)	A_{ij} (s ⁻¹)	$\int T_{\rm mb} dv^{\rm a}$ (mK km s ⁻¹)	$V_{\rm lsr}$ (km s ⁻¹)	FWHM (km s ⁻¹)
	,							
404	\rightarrow	303	84542.33	10.16	4.09E-5	157 (50)	3.6	7.4
422	\rightarrow	321	85093.27	22.13	3.13E-5	42(29)	2.8	3.0
413	\rightarrow	312	87848.87	13.53	4.30E-5	62(16)	2.5	3.4
505	\rightarrow	404	105464.22	15.23	8.11E-5	74(24)	3.2	6.4
532	\rightarrow	431	106141.40	42.13	5.29E-5	66(17)	3.6	6.7
523	\rightarrow	422	106541.68	27.25	7.03E-5	23(4)	2.2	1.4
514	\rightarrow	413	109753.50	18.80	8.78E-5	75(12)	2.7	4.4
726	\rightarrow	625	148223.14	40.43	2.12E-4	164 (65)	2.4	4.6
744	\rightarrow	643	148598.97	76.24	1.57E-4	155 (83)	2.8	3.4
734	\rightarrow	633	148709.02	55.39	1.91E-4	82(24)	1.6	3.4
725	\rightarrow	624	149792.57	40.60	2.19E-4	174 (27)	2.3	5.8
809	\rightarrow	707	167320.70	36.38	3.35E-4	119 (53)	2.1	3.2
835	\rightarrow	734	170039.07	63.56	3.03E-4	137 (80)	2.7	2.1
1029	\rightarrow	928	211328.96	67.80	6.56E-4	586 (106)	2.0	6.0
1019	\rightarrow	918	218459.21	60.86	7.48E-4	316 (166)	2.1	6.9
11210	\rightarrow	1029	232273.65	79.01	8.82E-4	174 (115)	1.4	4.9
1129	\rightarrow	1028	237896.68	79.93	9.48E-4	244 (84)	2.6	3.3
1258	\rightarrow	1157	254876.33	154.04	1.00E-3	196 (54)	1.2	1.8

 Table 2

 Parameters of the Detected and Resolved Lines

Notes. ^a The intensity scale is main-beam temperature. Errors include the 15% calibration uncertainty.

formamide in the ISO-SWS infrared spectra of massive protostellar sources, an identification never confirmed. Very recently, Jones et al. (2011) experimentally produced formamide by electron irradiating ice mixtures CO:NH₃. Energetic processing of icy mantles can thus be at least partially responsible for the presence of formamide in the gas phase. It is, however, very difficult to quantify to what extent (Jones et al. 2011). In the gas phase, to our knowledge there is no available measurements but a possible route is via the exothermic neutral–radical reaction between H₂CO and NH₂⁶:

$$H_2CO + NH_2 \rightarrow NH_2CHO + H.$$
 (1)

Indeed, both NH₂ and H₂CO have high abundances in protostellar sources. In fact, the abundance of formaldehyde is ~ 10^{-7} in the inner region of the envelope of IRAS 16293–2422 (Ceccarelli et al. 2000) while the abundance of NH₂ is ~ 10^{-9} in the cold outer envelope (Hily-Blant et al. 2010). If we assume that NH₂CHO is removed by the primary molecular ion HCO⁺, whose abundance is ~ 10^{-8} (Jorgensen et al. 2004), by the reaction

$$NH_2CHO + HCO^+ \rightarrow CO + NH_2CH_2O^+$$
, (2)

then the formamide abundance at steady state is

$$[NH_2CHO] = \frac{k_1(T)}{k_2(T)} \frac{[NH_2][H_2CO]}{[HCO^+]},$$
 (3)

where $k_1(T)$ and $k_2(T)$ are the rate coefficient of reactions (1) and (2). These rate coefficients are unknown but if the reactions are barrierless, standard values at 100 K are $k_1 \sim 10^{-10}$ for a neutral-radical reaction and $k_2 \sim 5 \times 10^{-9}$ for a ion-dipole reaction.⁷ We thus obtain a formamide abundance of $\sim 2 \times 10^{-10}$, in good agreement with the present determination in the hot corino of IRAS16293. Of course, rate measurements or calculations are necessary to confirm our estimates (especially for reaction (1)) but it is interesting to note that invoking grain-surface chemistry is not necessary to explain the gasphase abundance of formamide. The situation is different for acetamide (not detected in this work) because there is no obvious exothermic gas-phase formation route. Thus, the high abundance of acetamide in massive star-forming regions (Halfen et al. 2011) and its non-detection in IRAS16293 are consistent with a synthesis in irradiated ices.

To compare the formamide abundance found in IRAS16293 with that in the comet Hale-Bopp, we have used the formamide abundance relative to H₂O. According to the recent measurements by Coutens et al. (2012), the abundance of water in the IRAS16293 hot corino is about 5×10^{-6} so that the abundance ratio $[NH_2CHO]/[H_2O]$ is 2.5 (-2, +6) ×10⁻⁵. In Hale-Bopp, this ratio is ~ 6 times larger (0.01%–0.02%). We have plotted in Figure 3 the abundance of formamide relative to H_2 in the three interstellar sources SgrB2, Orion-KL, and IRAS16293 as well as its abundance relative to H₂O in the three same sources and in the comet Hale-Bopp. First, it is striking that the formamide abundance with respect to H_2 in the three interstellar sources agree within a factor of two. This result suggests that the presence of highly energetic radiative processes in massive star-forming regions does not play a dominant role in the synthesis of formamide. Second, the formamide abundance with respect to water in the three interstellar sources is similar (within a factor of 10) to that in Hale-Bopp, providing new evidence for the similarity between interstellar and cometary chemistry (see the discussion in Bockelee-Morvan et al. 2000 and Caselli & Ceccarelli 2012). Our results thus suggest that the abundances of cometary organic volatiles could reflect not only the grain-surface chemistry, as it is generally assumed, but also the gas-phase chemistry of the interstellar medium.

Finally, the singly deuterated isotopologues of formamide (NHDCHO and NH₂CDO) have been searched but not detected (millimeter frequencies will be published elsewhere by Margules et al.), which is consistent with the observed relatively low abundance of the main isotopologue.

⁶ We note that ab initio calculations (Li & Lü 2002) have shown that there is a large barrier (\sim 3000 K) for the other exothermic channel H₂CO + NH₂ \rightarrow HCO + NH₃.

⁷ The value of k_2 was obtained using the averaged dipole orientation (ADO) approximation which was shown to be accurate for, e.g., HCO⁺+HCN (Clary et al. 1985).



Figure 3. Abundance of formamide relative to H_2 (left) and to H_2O (right) in the three interstellar sources where it has been detected, the solar-type protostar IRAS16293 (IRAS), the two high-mass star-forming regions, Sgr B2 (Sgr) and Orion-KL (Ori), and in the comet Hale-Bopp (H-B).

5. CONCLUSIONS

We have reported the first detection of formamide, the simplest molecule with a peptide-like bond, in the hot corino of the solar-type protostar IRAS16293. The millimeter data combine spectra from the TIMASS survey and more recent observations performed at the IRAM 30 m telescope. The abundance of formamide with respect to H₂ is $\sim 1.3 \times 10^{-10}$, which is similar to that found in the massive star-forming regions SgrB2 and Orion-KL. This result questions the relevance of photolysis processes in the synthesis of formamide and possibly argues in favor of a gas-phase synthesis. Assuming that the neutral-neutral reaction between the abundant NH₂ and H₂CO molecules has no barrier, we predict a gas-phase abundance of $\sim 2 \times 10^{-10}$, in good agreement with the observations. The abundance of formamide with respect to H₂O is, within a factor six, similar to the abundance observed in the comet Hale-Bopp. Assuming that the formamide abundance measured in the coma of Hale-Bopp is representative of cometary ices, our results provide a new evidence for a possible direct link between cometary and interstellar chemistry.

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REFERENCES

Bernstein, M. P., Allamandola, L. J., & Sandford, S. A. 1997, AdSpR., 19, 991 Bisschop, S. E., Jørgensen, J. K., Bourke, T. L., Bottinelli, S., & van Dishoeck, E. F. 2008, A&A, 488, 959

- Bockelee-Morvan, D., Lis, D. C., Wink, J. E., et al. 2000, A&A, 353, 1101
- Bottinelli, S., Ceccarelli, C., Neri, R., et al. 2004, ApJL, 617, 69
- Bottinelli, S., Ceccarelli, C., Williams, J. P., & Lefloch, B. 2007, A&A, 463, 601
- Brucato, J. R., Baratta, G. A., & Strazzulla, G. 2006, A&A, 455, 395
- Butner, H. M., Charnley, S. B., Ceccarelli, C., et al. 2007, ApJL, 659, 137
- Caselli, P., & Ceccarelli, C. 2012, A&ARv, 20, 56
- Caux, E., Kahane, C., Castets, A., Coutens, A., & Ceccarelli, C. 2011, A&A, 532, A23
- Ceccarelli, C., Caselli, P., Herbst, E., Tielens, A. G. G. M., & Caux, E. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 47
- Ceccarelli, C., Loinard, L., Castets, A., Tielens, A. G. G. M., & Caux, E. 2000, A&A, 357, L9
- Chandler, C. J., Brogan, C. L., Shirley, Y. L., & Loinard, L. 2005, ApJ, 632, 371
- Clary, D. C., Smith, D., & Adams, N. G. 1985, CPL, 119, 320
- Coutens, A., Vastel, C., Caux, E., et al. 2012, A&A, 539, 132
- Danger, G., Bossa, J.-B., de Marcellus, P., et al. 2011, A&A, 525, 30
- Gerakines, P. A., Moore, M. H., & Hudson, R. L. 2004, Icar, 170, 202
- Hagen, W., Allamandola, L. J., & Greenberg, J. M. 1979, Ap&SS, 65, 215
- Halfen, D. T., Ilyushin, V., & Ziurys, L. M. 2011, ApJ, 743, 60
- Hartogh, P., Lis, D. C., Bockelée-Morvan, D., et al. 2011, Natur, 478, 218
- Hily-Blant, P., Maret, S., Bacmann, A., et al. 2010, A&A, 521, L52
- Jones, B. M., Bennett, C. J., & Kaiser, R. I. 2011, ApJ, 734, 78
- Jorgensen, J. K., Schöier, F. L., & van Dishoeck, E. F. 2004, A&A, 416, 603
- Li, Q. S., & Lü, R. H. 2002, JPCA, 106, 9446
- Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodriguez, L. F. 2008, ApJL, 675, 29
- Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, JMoSt, 742, 215
- Nummelin, A., Bergman, P., Hjalmarson, A., et al. 1998, ApJS, 117, 427
- Pizzarello, S., & Huang, Y. 2005, GeCoA, 69, 599
- Raunier, S., Chiavassa, T., Duvernay, F., et al. 2004, A&A, 416, 165
- Saladino, R., Botta, G., Pino, S., Costanzoc, G., & Di Mauro, E. 2012, Chem. Soc. Rev., 41, 5526
- Taquet, V., Ceccarelli, C., & Kahane, C. 2012, A&A, 538, A42
- Turner, B. E. 1991, ApJS, 76, 617
- Vastel, C., Ceccarelli, C., Caux, E., et al. 2010, A&A, 521, L31