Molecular content of the circumstellar disk in AB Aur
First detection of SO in a circumstellar disk

A. Fuente1, J. Cernicharo2, M. Agúndez3, O. Berné4, J. R. Goicoechea5, T. Alonso-Albi1, and N. Marcelino2

1 Observatorio Astronómico Nacional (OAN), Apdo. 112, 28803 Alcalá de Henares, Madrid, Spain
2 Departamento de Astrofísica, Centro de Astrobiología (CSIC-INTA), Ctra Ajalvir km 4, 28850 Madrid, Spain
3 LUTH, Observatoire de Paris-Meudon, 5 place Jules Janssen 92190 Meudon, France
4 Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

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ABSTRACT

Aims. Very few molecular species have been detected in circumstellar disks surrounding young stellar objects. We are carrying out an observational study of the chemistry of circumstellar disks surrounding T Tauri and Herbig Ae stars. First results of this study are presented in this note.

Methods. We used the EMIR receivers recently installed at the IRAM 30m telescope to carry a sensitive search for molecular lines in the disks surrounding AB Aur, DM Tau, and LkCa 15.

Results. We detected lines of the molecules HCO+, CN, H2CO, SO, CS, and HCN toward AB Aur. In addition, we tentatively detected DCO+ and H2S lines. The line profiles suggest that the CN, HCN, H2CO, CS and SO lines arise in the disk. This makes it the first detection of SO in a circumstellar disk. We have unsuccessfully searched for SO toward DM Tau and LkCa 15, and for c-C3H2 toward AB Aur, DM Tau, and LkCa 15. Our upper limits show that contrary to all the molecular species observed so far, SO is not as abundant in DM Tau as it is in AB Aur.

Conclusions. Our results demonstrate that the disk associated with AB Aur is rich in molecular species. Our chemical model shows that the detection of SO is consistent with that expected from a very young disk where the molecular adsorption onto grains does not yet dominate the chemistry.

Key words. stars:formation—stars: individual (AB Aur, DM Tau, LkCa 15)—stars: pre-main sequence, circumstellar matter—planetary systems: protoplanetary disks

1. Introduction

Circumstellar disks are complex systems in which essentially all the processes that play a role in the interstellar medium, UV radiation, X-rays, grain surface chemistry, molecular depletion, turbulent mixing, accretion flows and time dependency, are working. Chemical models with increasing complexity have been developed in the last decade (see e.g. Aikawa et al. 2000; Dutrey et al. 2007; Agúndez, Cernicharo & Goicoechea, 2008; Nomura et al. 2009), but the disk chemistry is a quite unexplored field from the observational point of view. Large millimeter telescopes have started to provide some insight into the chemistry of the cold gas toward the most massive nearby disks. Thus far, few molecules (CO, 13CO, CN, C2H, HCN, HNC, HCO+, H2CO) have been detected in circumstellar disks. This small molecular inventory is mainly due to the weakness of the molecular emission from circumstellar disks. Disks have small masses, lower than 0.1 M☉, small sizes, radii of a few 100 AU, and because of depletion in the midplane and/or photodissociation in the surface, the disk averaged abundances of most molecules (including CO and its isotopologues) are a factor of 5–10 lower than in the interstellar medium. High sensitivity is, therefore, required for an observational study. We have carried out a sensitive search for molecular lines mainly in the disk around the Herbig Ae star AB Aur using the IRAM 30m telescope. Some lines have also been searched toward DM Tau and LkCa 15. Our results show the rich molecular content in the disk around AB Aur.

AB Auriga is one of the nearest, brightest and best studied Herbig Ae stars. It has a spectral type A0–A1 (Hernández et al. 2004) and is located to the Southwest of the molecular cloud L1517 (Duvert et al. 1986), at a distance of 145 pc (van den Ancker et al. 1998). Interferometric observations at millimeter wavelengths detected the circumstellar disk around this star in the continuum and in the CO (and its isotopologues) lines (Piétu et al. 2005). Instead of being centrally peaked, the continuum emission is dominated by a bright, asymmetric (spiral-like) feature at about 140 AU from the central star.

The disk modeling of the continuum and molecular emission showed that the disk is warm and showed no evidence of CO depletion. Schreyer et al. (2008) searched for emission of the HCO+ 1→0, HCN 1→0, CS 2→1, C2H 1→0 and some CH3OH lines in this disk using the Plateau de Bure Interferometer (PdBI), but they only detected the HCO+ 1→0 line.

2. Observations

The list of observed lines and the telescope parameters are given in Table 1. The observations were done in two observing periods, September, 2009 and March, 2010, with the new EMIR receivers arranged to provide a bandwidth of 4 GHz in both, the 3mm and 1mm bands. As backends we used the wide bandwidth autocorrelator WILMA which provides a spectral resolution of 2 MHz and covers the whole band, and the narrow bandwidth correlator VESPA centered at the line frequency and providing...
a spectral resolution of 80 kHz at 1.3mm and 40 kHz at 2.7mm \((-0.1 \text{ km s}^{-1}\)). All the observations were done using the wobbler switching (WS) procedure with a throw of 120°. This procedure provides flat baselines which are essential for detecting weak and wide lines toward compact sources, which is the case for the lines arising in circumstellar disks. In the case of AB Aur, the disk is still immersed in the parent cloud whose emission extends farther than the wobbler throw (see Semenov et al. 2005). Then, at the velocities of the ambient cloud the detected emission is just the ON-OFF balance without any physical interpretation (remind that the OFF position is moving in the sky during the source tracking). For this reason, we have blanked the channels corresponding to the ambient cloud emission in the spectra toward AB Aur. We have searched for c-C_2H_6 and SO also toward DM Tau and LkCa15. In these cases, contamination from the ambient cloud is not expected. The observational results are shown in Table 2.

3. Results

Fig. 1 shows some of the spectra observed toward AB Aur. The lines from the molecular cloud are very narrow, \(\Delta v \sim 0.5 \text{ km s}^{-1}\), and centered at 5.9 km s\(^{-1}\) (Duvert et al. 1986 and Fig. 2a). The emission of the ambient cloud lies at the velocities [5.4,6.4] km s\(^{-1}\). The channels corresponding to these velocities are blanked in the spectra shown in Fig. 1.

After blanking the cloud velocities, we have detected emission at \(>3\sigma\) of the HCO\(^+\) 1→0, CN 1→0, H_2CO 3_0→2_0, SO 3→2_0, CS 3→2_0, and HCN 3→2_0. In addition, we have tentatively detected (\(>3\sigma\)) the DCO\(^+\) 2→1 and H_2S 1,0→1,0 lines. All the (\(>3\sigma\)) detected lines have the typical two-horn profile observed in the circumstellar disk, with two peaks centered at 4.8±0.25 km s\(^{-1}\) and 6.8±0.25 km s\(^{-1}\) (see Fig. 1 and Fig. 2b). This prompts us to interpret the emission of these lines as arising from the circumstellar disk. The only doubtful case is the CN 1→0 line in which the two-horn profile is not so clear. Since CN is one of the most abundant species in disks (Dutrey et al. 1997, Thi et al. 2004, Öberg et al. 2010), we decided to keep it in our list of detected species. The narrowness of the CN 1→0 line could be due to the fact that its emission is

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Table 1: List of targeted lines

| Line | Freq.(GHz) | HPBW(\(\) ) | \(\eta_a\) |
|------|-----------|-------------|----------|
| CO 2→1 | 230.538 | 10.0 | 0.63 |
| HCO\(^+\) 1→0 | 89.188 | 28.0 | 0.81 |
| HCO\(^+\) 3→2 | 267.558 | 9.0 | 0.53 |
| HCN 1→0 | 88.631 | 28.0 | 0.81 |
| HCN 3→2 | 265.886 | 9.0 | 0.53 |
| CN 2→1 | 113.490 | 22.0 | 0.81 |
| CS 2→1 | 97.981 | 25.0 | 0.81 |
| CS 3→2 | 146.969 | 16.0 | 0.74 |
| CS 3→2 | 262.004 | 9.0 | 0.53 |
| H_2CO 3_0→2_1 | 218.222 | 11.0 | 0.63 |
| SO 3→2 | 138.178 | 17.0 | 0.74 |
| SO\(^2\) 5→4 | 219.949 | 11.0 | 0.63 |
| c-C_2H_6 2_1→1_0 | 85.339 | 29.0 | 0.81 |
| c-C_2H_6 6_0→5_1 | 217.222 | 11.0 | 0.63 |
| c-C_2H_6 6_1→5_2 | 217.222 | 11.0 | 0.63 |
| DCO\(^+\) 2→1 | 144.077 | 16.0 | 0.74 |
| DCO\(^+\) 2→1 | 144.828 | 16.0 | 0.74 |
| SiO 2→1 | 86.847 | 29.0 | 0.81 |
| SiO 6→5 | 260.518 | 9.0 | 0.53 |
| HCO 1_0,3_2→1_0,1,2 | 86.671 | 29.0 | 0.81 |
| HCO 1_0,3_2→1_0,1,2 | 86.708 | 29.0 | 0.81 |
| HCO 1_0,3_1→1_0,1,2 | 86.777 | 29.0 | 0.81 |
| HCO 1_0,3_1→1_0,1,2 | 86.805 | 29.0 | 0.81 |
| H_2S 1_1→0_1 | 168.763 | 14.0 | 0.74 |

1 Observed with the wide band spectrometer WILMA in the HCN 3→2 tuning.
2 Observed with the wide band spectrometer WILMA in the c-C_2H_6 6_0→5_1 tuning.
coming from the outermost part of the disk. We would like to
remind, however, that this detection requires of further confir-
mation by interferometric observations.

The disk was previously detected in the HCO$^+$ 1→0 line us-
ing the PdBI by Schreyer et al. (2008). Therefore, we can use
this line to check the validity of our interpretation. In Fig. 3,
we compare our HCO$^+$ spectrum with that observed toward the
star position by Schreyer et al. (2008). Since the synthesized beam
of these observations was 5.2′′ × 4.8′′, this spectrum missed the
emission of the outer part of the disk (R > 378 AU). The emission
of this outer region is expected at velocities < 0.87 km s$^{-1}$
from the systemic velocity. We only consider velocities > 0.45 km s$^{-1}$
relative to the systemic velocity, therefore the outer part of
the disk is not relevant in our comparison. The integrated in-
tensity emission of the 30 m spectra in the velocity intervals
[4.2,5.4] km s$^{-1}$ and [6.4,7.25] km s$^{-1}$ is lower by a factor of
≈ 1.3 than the integrated emission of the HCO$^+$ 1→0 line as ob-
served with the PdBI (see Fig. 3). The agreement is acceptable
and we consider that our interpretation is valid.

In Table 2, we show the list of non-detections (in the consid-
ered velocity ranges). Our 3σ upper limit to the emission of CS
2→1 line improve by a factor of 2 the previous one obtained by
Schreyer et al. (2008) using the PdBI.

4. Averaged molecular abundances in the disk

In the following we derive approximated average column den-
sities in the disks assuming optically thin emission, a uniform
temperature of T$_d$ = 10 K and 20 K, and Local Thermodynamic
Equilibrium (LTE). The assumed disk sizes (diameters) are: 13″
for AB Aur (Piétu et al. 2005), 6" for LkCa15 (Thi et al. 2004)
and 13″ for DM Tau (Piétu et al. 2007). In Table 3 we compare
the obtained fractional abundances with those derived in other
disks following a similar procedure. The first result is that the
molecular abundances measured toward AB Aur are very similar
to those found toward other disks which reinforce our interpre-
tation of the disk origin for the observed lines.

The HCO$^+$ abundance in AB Aur is similar to those mea-
sured in the TT stars LkCa15 and TW Hya, and in the HAe stars
HD 163296 and MWC 480. Only DM Tau presents a signifi-
cantly larger (a factor of 10) HCO$^+$ abundance which suggests
that DM Tau is a special case among circumstellar disks. The
same remains true for CN and HCN. Both molecules present
abundances of $\sim 10^{-10}$ (CN) and $\sim 10^{-11}$ (HCN) in all the disks
except DM Tau in which the measured abundances are a fac-
tor of 10 larger. The case of H$_2$CO is a bit different. It is also
overabundant in DM Tau (5×10$^{-10}$) but it is underabundant in
TW Hya ($< 10^{-12}$). Our SO detection in AB Aur is the first one
in a circumstellar disk and ours, the first estimate of the SO abun-
dance in a circumstellar disk. We have unsuccessfully searched
for SO toward DM Tau and LkCa15. Our upper limit toward DM
Tau shows that in contrast with the behavior observed in the
other species, SO is not overabundant in DM Tau relative to
AB Aur. The abundance of C$_2$H in AB Aur is 1000 times lower
than in DM Tau. We have used the C$_2$H 3→2 line to derive the
upper limit to the C$_2$H abundance. Recent results by Henning et
al. (2010) show that the excitation temperature of C$_2$H could be
lower than 10 K in some disks. In this case, the value of the up-
per limit would increase. The searched c-C$_2$H$_2$ line has not been
detected in any of the observed disks. The obtained upper limit to
the [c-C$_2$H$_2$]/[HCO$^+$] ratio is still consistent with the observa-
tional results in PDRs (Fuente et al. 2003).

In Table 3, we also compare some representative column
density ratios. These ratios are meaningful providing that the
molecules arise in the same region that could not be the case.
The value of [CN]/[HCN] is fairly uniform (within a factor of 2)
among the observed disks. However, there are large variations,
more than an order of magnitude, in the values of [CS]/[SO],
[H$_2$CO]/[HCO$^+$] and [C$_2$H]/[HCO$^+$]. This suggests that these
column density ratios are more sensitive to the in most cases
poorly known disk structure and/or grain properties. One im-
portant parameter in disks is the deuteration degree. Qi et al.
(2008) derived a [DCO$^+$]/[HCO$^+$] ratio of ≈ 0.03 in TW Hya.
Our tentative detection of DCO$^+$ in AB Aur would imply a
[DCO$^+$]/[HCO$^+$] ratio of ≈ 0.03, similar to TW Hya.

Table 2: Observational results

| Line          | Detections | Non-detections |
|---------------|------------|----------------|
|               | Line       | Area$^1$      | rms$^2$ (mK) | Line       | Area$^1$      | rms$^2$ (mK) |
| HCO$^+$       | 1→0        | 47 ± 4        |              | CN        | 2→1         | 16 ± 4        |
| HCO$^+$       | 3→2        | 93 ± 3        |              | CS        | 2→1         | 4 ± 1         |
| CN            | 1→0        | 26 ± 6        |              | C$_2$H    | 3→2         | 7 ± 4         |
| CS            | 3→2        | 75 ± 7        |              | HCN       | 1→0         | 6 ± 2         |
| H$_2$CO       | 3$_{0,3}$→2$_{0,2}$ | 87 ± 5  |              | c-C$_2$H$_2$ | 2→1         | 4 ± 2         |
| SO            | 3$_1$→2$_1$ | 26 ± 4        |              | c-C$_2$H$_2$ | 6→5         | 4 ± 2         |
| SO            | 5$_3$→4$_3$ | 64 ± 2        |              | DCN       | 2→1         | 4 ± 2         |
| HCN           | 3→2        | 92 ± 6        |              | SiO       | 2→1         | 4 ± 2         |
| DCO$^+$       | 2→1        | 8 ± 2         |              | SiO       | 6→5         | 9 ± 3         |
| H$_2$S        | 1$_{1,0}$→0$_{0,1}$ | 69 ± 11 |              | HCO       | 1$_{0,1}$→0$_{0,0}$ | 4 ± 2         |
|               | 3→2        | 69 ± 11       |              | DM Tau    | 2→1         | 3 ± 2         |
|               | 6→5        | 6 ± 3         |              | LkCa15    | 2→1         | 3 ± 2         |
|               | 5$_3$→4$_3$ | 3 ± 3         |              | c-C$_2$H$_2$ | 6→5         | 9 ± 3         |

$^1$Sum of the integrated intensity area in the velocity intervals
[4.2,5.6],[6.4,7.25] km s$^{-1}$

$^2$ rms in a channel of 1 km s$^{-1}$

$^3$ Observed only with a velocity resolution of 2.7 km s$^{-1}$
We have taken advantage of the high sensitivity of the EMIR re-
sumed results and conclusions of Piéru et al. (2005), the intense stellar radiation makes 
the inner R<200 AU region of the disk. The SO abundance 
decrease rapidly with time because of the adsorption onto the grain surfaces. The youthness of the AB Aur disk could be key to have higher SO abundance.

6. Summary and conclusions

We have taken advantage of the high sensitivity of the EMIR receivers recently installed in the IRAM 30m telescope to make a sensitive search for molecular emission in three prototypical disks, AB Aur, DM Tau and LkCa 15. Our results and conclusions can be summarized as follows:

- We have detected the HCO$^+$ 1→0, CN 1→0, H$_2$CO $^{3,3}_0$→$^{2,2}_0$, SO $^{3,1}_3$→$^{2,2}_2$, CS 3→2, HCN 1→0 and HCN 3→2 lines toward AB Aur. In addition, we have tentatively detected the DCO$^+$ 2→1 and H$_2$S $^{1,0}_{1,0}$→$^{0,1}_{-0,1}$ lines. Based on the lines profiles, we interpret the emission of the CN 1→0, HCN 3→2, H$_2$CO $^{3,3}_0$→$^{2,2}_0$, CS 3→2, and the SO $^{3,1}_3$→$^{2,2}_2$ lines as arising from the disk. If confirmed, this is the first detection of SO in a circumstellar disk.

- We have unsuccessfully searched for SO toward DM Tau and LkCa 15. The obtained upper limits show that SO is under-abundant in DM Tau relative to AB Aur.

- We have searched for c-C$_3$H$_2$ toward AB Aur, DM Tau and LkCa 15. The obtained upper limits are still consistent with the [c-C$_3$H$_2$]/[HCO$^+$] values obtained in PDRs.

Our observational work has significantly increased (from 1 to 6) the number of species detected toward the disk in AB Aur. If confirmed by interferometric observations, the SO detection would be the first one in a circumstellar disk. Our chemical model suggests that the high SO abundance derived in AB Aur disk is consistent with that expected in a very

5. Discussion

In order to guide our interpretation of the observed features and provide additional support to their disk origin, we have performed a (preliminary) chemical model adopting the disk and stellar parameters from Schreyer et al. (2008) and the updated chemical network of Agúndez et al. (2008). Our aim is to investigate if detectable SO column densities can be produced in this disk. In Fig. 4 we show the radial distribution of the vertical column densities of some molecules as calculated at 2.5 Myr (the age of AB Aur). In agreement with the observational results of Piéru et al. (2005), the intense stellar radiation makes the disk to be moderately warm, with temperatures above 20 K even in the disk midplane so that volatile molecules such as CO are not severely depleted on grain surfaces. In our model, the major gas phase reservoir of sulphur are the CS and SO molecules, with high column densities of SO mainly present in the inner R<200 AU region of the disk. The SO abundance decrease rapidly with time because of the adsorption onto the grain surfaces. The youthness of the AB Aur disk could be key to have higher SO abundance.
young and warm disk where depletion of gas onto grains is not dominating the chemistry yet.

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