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Evidence for a hot dust-free inner disk around 51 Oph

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Abstract. We report on the observation of CO bandhead emission around 51 Oph ($\Delta v = 2$). A high resolving power ($R \simeq 10000$) spectrum was obtained with the infrared spectrometer ISAAC mounted on VLT – ANTU. Modeling of the profile suggests that the hot ($T_{\text{gas}} = 2000 - 4000$ K) and dense ($n_{\text{H}} > 10^{10}$ cm$^{-3}$) molecular material as probed by the CO bandhead is located in the inner AU of a Keplerian disk viewed almost edge-on. Combined with the observation of cooler gas ($T_{\text{gas}} = 500 - 900$ K) by ISO-SWS and the lack of cold material, our data suggest that the disk around 51 Oph is essentially warm and small. We demonstrate the presence of a dust-free inner disk that extents from the inner truncation radius until the dust sublimation radius. The disk around 51 Oph may be in a rare transition state toward a small debris disk object.

Key words. stars: formation – accretion disks – planetary systems: protoplanetary disks

1. Introduction

Disks are commonly found around low- and intermediate-mass pre-main-sequence stars and are understood as natural by products of the conservation of angular momentum during star formation. The structure of the inner few Astronomical Units (AU) of protoplanetary disks plays an important role in the transfer of matter onto the star and the formation of terrestrial planets. The temperature in the inner AU of disks can attain a few thousand Kelvin and the density can be greater than $10^{12}$ cm$^{-3}$. Those conditions are required for CO bandheads ($\Delta v = 2$) to emit. Indeed, CO bandhead emission has been detected around objects such as the Be star$eta$ Pic (see also Roberge et al. 2002). Nevertheless, all studies suggest that the circumstellar matter is most likely in the form of a Keplerian disk rather than in a spherical shell. Finally, the fractional excess IR luminosities $L_{\text{IR}}/L_{\odot}$ of 51 Oph is 0.028, a value between the younger Herbig Ae stars ($>0.1$) and the Vega-like objects ($10^{-3} - 10^{-5}$). We obtained a high resolution $K$-band spectrum of 51 Oph centered around the position of a CO bandhead emission in order to clarify the detection of large amount of CO ($N(\text{CO}) = (0.1-10) \times 10^{21}$ cm$^{-2}$) by ISO and to characterize the structure of the inner dust-poor molecular disk. After describing the observation and data reduction in Sect. 2, a fit by a synthetic spectrum emitted by a Keplerian disk is shown in

* Based on observations collected at the European Southern Observatory at La Silla and Paranal, Chile (ESO Programme 68-C-0474).
Sect. 3. The discussion in Sect. 4 focuses on the structure of the inner disk around 51 Oph.

2. Observation and data reduction

The K-band spectrum was obtained with the near-infrared facility ISAAC mounted on the Very Large Telescope (VLT-ANTU) on March 15th 2002 at resolving power of 10000 (slit width of 0.3") in Service mode. The spectrum toward 51 Oph is part of a survey of CO bandhead in Herbig Ae stars. The data were reduced in a standard way using IRAF. We made use of flatfield and arc frames taken by the ESO staff during the day. Standard stars of spectral type A observed at the same day. The observation of CO bandhead confirms the large column density of CO seen by ISO-SWS. Moreover, at high-temperature and density the rapid formation of CO molecules to self-photodissociation by stellar ultraviolet photons. However, the CO column densities ($10^{20} – 10^{21} \text{ cm}^{-2}$) are well above the required value for the CO molecules to self-shield ($N(\text{CO}) \sim 10^{15} \text{ cm}^{-2}$, van Dishoeck & Black 1988). Moreover, at high-temperature and density the rapid formation of CO molecules by the neutral-neutral reaction $\text{C} + \text{OH} \rightarrow \text{CO} + \text{H}$ can easily compensate for the photodestruction.

4. Discussion

The observation of CO bandhead confirms the large column density of CO seen by ISO-SWS. Moreover, the profile of the emission lines indicates that the gas is seen almost edge-on. If the disk around 51 Oph is seen with an inclination of $88^\circ$ and the disk is geometrical thin (flat disk), then the ISO-SWS and the FUSE data can be reconciled. In the FUSE absorption study, the line-of-sight does not intercept the major part of the disk while emission studies with ISO or ISAAC are not sensitive to the actual projection angle $i$. On the other hand, hot gas of N I, S II and Fe III can be detected in absorption against the stellar photospheric emission because the evaporating bodies may follow a trajectory that is inclined with respect to the equatorial plane (Beust et al. 2001).

In the absence of extinction by dust grains, the principal destruction agent of CO is photodissociation by stellar ultraviolet photons. However, the CO column densities ($10^{20} – 10^{21} \text{ cm}^{-2}$) are well above the required value for the CO molecules to self-shield ($N(\text{CO}) \sim 10^{15} \text{ cm}^{-2}$, van Dishoeck & Black 1988). Moreover, at high-temperature and density the rapid formation of CO molecules by the neutral-neutral reaction $\text{C} + \text{OH} \rightarrow \text{CO} + \text{H}$ can easily compensate for the photodestruction.
Table 1. Best fit parameters. $i$ is the inclination, $R_{\text{min}}$ and $R_{\text{max}}$ are the emission area inner and outer radius, $T_{\nu}$(CO) is the gas temperature at $R_{\text{min}}$ and $N_{\nu}$(CO) is the column density of CO at $R_{\text{min}}$.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$R_{\text{min}}$</th>
<th>$R_{\text{max}}$</th>
<th>$T_{\nu}$(CO)</th>
<th>$N_{\nu}$(CO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>($^\circ$)</td>
<td>(AU)</td>
<td>(AU)</td>
<td>(K)</td>
<td>(cm$^{-2}$)</td>
</tr>
<tr>
<td>88$^\circ$</td>
<td>0.15 ± 0.05</td>
<td>0.35 ± 0.05</td>
<td>2850 ± 500</td>
<td>(0.17−2.5) $\times$ 10$^{20}$</td>
</tr>
</tbody>
</table>

The large abundances in H$_2$O, CO$_2$ and CO testify of a hot and dense chemistry (van den Ancker et al. 2001). It is interesting to compare the inner ($R_{\text{min}}$) and outer ($R_{\text{max}}$) CO emitting radius to other relevant radii in the disk. The co-rotation radius $r_{\text{rot}} = GM_*/\Omega^2$ is defined as the distance from the central star where the star and the Keplerian disk rotate at the same speed $\Omega$ (e.g., Shu et al. 1994). Assuming that $\Omega = v \sin i = 267$ km s$^{-1}$ (i.e. $i = 90^\circ$), we obtain $r_{\text{rot}} = 0.05$ AU (Table 2). Disk material falls on to the star surface only when the disk truncation, whose value is close to the magnetospheric radius $r_m$, is smaller than the co-rotation radius for an accretion disk. The magnetospheric radius depends on the stellar magnetic field and the disk accretion rate, which are unknown for 51 Oph. We therefore assume that $r_m \approx r_{\text{rot}}$. Dust grains do not exist above their sublimation temperature, which is around 1500 K. The dust sublimation radius is the distance from the star beyond which dust can condense: $r_d = \sqrt{Q_{\text{eff}}(L + L_{\text{acc}})/16 \pi \sigma / T_{\text{sub}}}$ where $Q_{\text{eff}} = Q_{\text{abs}}(a, T_*/T_{\text{sub}})$ the ratio of the dust absorption efficiency at stellar temperature $T_*$ to its emission efficiency at the dust sublimation temperature $T_{\text{sub}}$. $a$ is the mean grain radius and $\sigma$ is the Stefan constant. For large silicate grains ($a \geq 1 \mu m$), $Q_{\text{eff}}$ is relatively insensitive to the stellar effective temperature and close to unity because most stellar radiation lies at wavelengths shorter than the grain radius. For smaller grains, the value of $Q_{\text{eff}}$ is significantly increased (Monnier & Millan-Gabet 2002). We found for 51 Oph that $r_d = 0.56$ AU (see Table 2) assuming $L_{\text{acc}} \ll L_* = 260 L_\odot$ and $Q_{\text{eff}} = 1$ (large grains). If the grains were as small as 0.1 $\mu m$ in radius, then $Q_{\text{eff}} \approx 20$ and $r_d = 4.50$ AU.

The disk around 51 Oph is not strongly accreting as testified by the absence of UV excess. The disk is passively heated with the gas in the upper layer being warmer than the mid-plane. It should be noticed that the dust sublimation radius is a lower limit where dust grains can exist. Radiative pressure, which is particularly effective for a B9.5V star, will push the grains much further out than $r_d$. At radii greater than the dust sublimation radius, the dust and gas are probably thermally coupled and emission in the near-infrared will be dominated by the dust, reducing drastically the gas emission lines over continuum contrast. The large difference between $r_d$ and $r_{\text{rot}}$ (0.5−2.45 AU) implies the presence of a gas-rich dust-poor inner disk extending from the truncation radius, which is close to the magnetospheric radius, till the dust sublimation radius. It should be noticed that beyond 1 AU the gas will become too cold to excite the high vibrational levels ($v > 2$). On the other hand high-J CO fundamental lines ($v = 1$−0 centered at $\lambda \sim 4.67$ mm) are sensitive to gas at temperature $\sim 1500$ K. Blake & Boogert (2004); Brittain et al. (2003) found CO gas at $T = 1000$−1500 K in the disk around HD 163296 and AB Aur. Likewise, CO gas at $\sim 1500$ K was detected by van den Ancker et al. (2001) toward 51 Oph.

The opacity of dust-poor gas at $T_{\text{gas}} = 2000$−3000 K is dominated by H$_2$O and H$_2$, which may eventually deprive the inner dust rim of large amount of stellar UV photons below 1215 Å. Indeed, the SED of 51 Oph is well fitted by the emission from an optically thick geometrically flat disk and does not show significant near-infrared bump, consistent with the absence of a puffed-up rim (Dullemond et al. 2001; Meeus et al. 2001).

In summary, the presence of hot CO, traced by the bandhead emission, and at the same time the absence of an inner puffed-up rim are probably linked, requiring that $r_{\text{rot}} \ll r_d$. This criterion implies simultaneously a high total luminosity $L = L_* + L_{\text{acc}}$ (Natta et al. 2001) and a relatively fast rotating star. Interestingly, this criterion has also been advocated to...
Table 2. Comparison of the co-rotation and dust sublimation radius between 51 Oph and two well studied Herbig Ae stars. The spectral type and rotation velocity for HD 163296 and AB Aur are taken from Mora et al. (2001). The other stellar characteristics are provided by van den Ancker et al. (1998, 2001). The accretion luminosities were measured by Hillenbrand et al. (1992). The fits to the Spectral Energy Distribution of HD 163296 and AB Aur are discussed in Dominik et al. (2003).

<table>
<thead>
<tr>
<th>SpT</th>
<th>51 Oph</th>
<th>HD 163296</th>
<th>AB Aur</th>
</tr>
</thead>
<tbody>
<tr>
<td>M$<em>*$ (M$</em>\odot$)</td>
<td>B9.5IIIe</td>
<td>A3Ve</td>
<td>AOVe+sh</td>
</tr>
<tr>
<td>L$<em>*$ (L$</em>\odot$)</td>
<td>3.8 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>L$<em>{acc}$ (L$</em>\odot$)</td>
<td>260$^{+40}_{-50}$ ± 5</td>
<td>26 ± 5</td>
<td>47±12</td>
</tr>
<tr>
<td>$v$ sin $i$ km s$^{-1}$</td>
<td>...</td>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>$r$$_{rot}$ (AU)</td>
<td>267 ± 5</td>
<td>133 ± 6</td>
<td>97 ± 20</td>
</tr>
<tr>
<td>$r_a$ (AU) (a = 1.0 µm)</td>
<td>0.05</td>
<td>0.13</td>
<td>0.33</td>
</tr>
<tr>
<td>$r_a$ (AU) (a = 0.1 µm)</td>
<td>0.56</td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>$r_a$ - $r$$_{rot}$ (AU) (a = 1.0 µm)</td>
<td>0.51</td>
<td>0.05</td>
<td>-0.09</td>
</tr>
<tr>
<td>$r_a$ - $r$$_{rot}$ (AU) (a = 0.1 µm)</td>
<td>2.45</td>
<td>0.38</td>
<td>0.74</td>
</tr>
<tr>
<td>CO bandhead emission</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>CO fundamental emission</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Puffed-up inner rim</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

- Another test for the existence of the dust-free gas would be the detection of strong H$_2$ fluorescence lines in the UV (e.g., Herczeg et al. 2004, who found H$_2$ UV lines in the inner disk around the T Tauri star TW Hya). The observation of near-infrared H$_2$ lines with the $v = 2$–$1$ S(1) intensity at 2.2477 µm higher than the $v = 1$–$0$ S(1) at 2.1218 µm would also provide another diagnostic of dust-free gas.

**5. Conclusions**

The principle results are summarized here:

- A high column density of hot molecular (CO) gas is present in the inner Astronomical Unit of 51 Oph. The gas rotates around the star in a Keplerian orbit.
- The apparent discrepancy on the amount of CO gas around 51 Oph between the ISO-SWS and FUSE data can be resolved if the disk is geometrically flat and is seen with a large angle but not entirely edge-on.
- The CO bandhead emission is located inside the dust sublimation radius. We propose that only star-disk systems where the co-rotation radius is much smaller than the dust sublimation radius ($r_{rot} \ll r_a$) will show high line over continuum contrast CO bandhead emission. This later prediction can be tested with future high resolving power near-infrared interferometric instruments like Amber at the VLT. 51 Oph is a special case since its rotation speed of 267 km s$^{-1}$ is much higher than the average value for Herbig Ae stars (80–150 km s$^{-1}$).

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**References**