

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 ($R \approx 10\,000$) spectrum was obtained with the infrared spectrometer ISAAC mounted on *VLT – ANTU*. Modeling of the profile suggests that the hot ($T_{\text{gas}} = 2000\text{--}4000$ 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 ($T_{\text{gas}} = 500\text{--}900$ 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 extends 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 young low- and high-mass stars (e.g., Bik & Thi 2004; and Najita et al. 2000, for an overview). The inner disk is likely gas-rich but dust-free since dust grains evaporate at $T \approx 1500$ K.

51 Oph is a peculiar Be (B9.5IIIe) star located at 130 pc with an observed rotation velocity $v \sin i = 267 \pm 5$ km s⁻¹ (Dunkin et al. 1997); however, the exact spectral type is still disputed. The Spectral Energy Distribution (SED) shows a strong near- till mid- infrared excess but contrary to its lower-mass counterparts the Herbig Ae stars, the flux in the (sub)-millimeter domain is low, indicating a lack of small cold dust grains. 51 Oph is the only Be star in a sample of 101 whose infrared excess is dominated by warm dust and not by free-free emission (Waters et al. 1988). Both fits to the SED and direct imaging of the disk around 51 Oph agree on the

compactness of the disk (Jayawardhana et al. 2001; Leinert et al. 2004; Waters et al. 1988). The disk probably does not extend beyond 100 AU. Silicate emission features were first detected by Fajardo-Acosta et al. (1993) and further analyzed by Bouwman et al. (2001). The UV and optical part of the SED are well fitted by a Kurucz model and show no excess testifying that the accretion of matter onto the star is low (Waters et al. 1988; Malfait et al. 1998). However, infalling ionic and atomic gases were observed which prompted Grady et al. (1991) to claim that 51 Oph is in the same evolutionary state as β Pic (see also Roberge et al. 2002). Contrary to β Pic, large amount of molecular gas (CO, CO₂, H₂O and NO) has been seen around 51 Oph by the Short-Wavelength-Spectrometer on board the Infrared Space Observatory (ISO) (van den Ancker et al. 2001). A controversy remains about the quantity of CO. Absorption lines by CO in the Far-Ultraviolet were not detected by FUSE (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_{IR}/L_* of 51 Oph is 0.028, a value between the younger Herbig Ae stars (>0.1) and the Vega-like objects ($10^{-5}\text{--}10^{-3}$). 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 ($N(\text{CO}) = (0.1\text{--}10) \times 10^{21}$ 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).

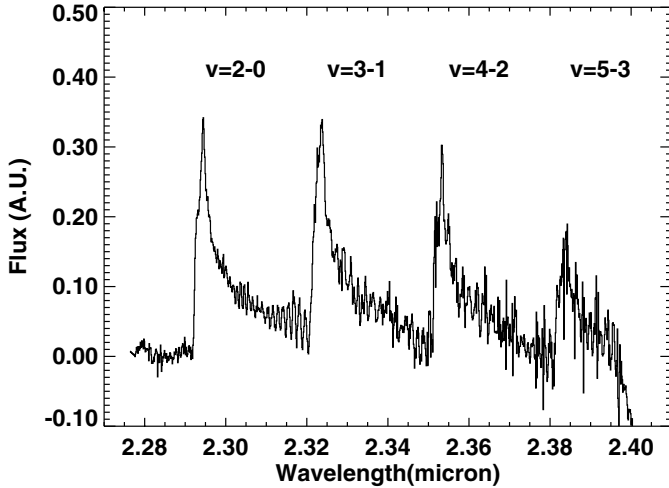


Fig. 1. Continuum subtracted CO bandheads toward 51 Oph in arbitrary units. Four bandheads are detected. The spectrum of the last two bandheads is heavily blended.

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 10 000 (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 similar airmass than 51 Oph were used to correct for telluric OH emission and absorption.

3. Results and modeling

The continuum subtracted and normalized spectrum is shown in Fig. 1. Four bandheads are detected with high signal-to-noise ratio ($S/N > 100$), namely $\Delta v = 2-0$ ($\lambda \approx 2.2935 \mu\text{m}$), $\Delta v = 3-1$ ($\lambda \approx 2.3227 \mu\text{m}$), $\Delta v = 4-2$ ($\lambda \approx 2.3535 \mu\text{m}$), $\Delta v = 5-3$ ($\lambda \approx 2.3829 \mu\text{m}$). The first bandhead shows a prominent blue wing. The higher bandheads are contaminated by emission from the *P*-branch from lower bandheads.

We decided to fit the first bandhead only since the emission from higher bandheads is blended and contributions from different bandheads are difficult to disentangle. A spherically symmetric and radially expanding wind results in flat-topped profiles for optically thin lines (Beals 1931). A flat-topped profile cannot reproduce the blue-wing seen in our spectrum; therefore our data definitely rule out hot gas in an expanding shell. The signature of CO bandhead emission from a narrow Keplerian rotating disk is commonly found around young stars over a large range of masses. Therefore, we constructed a simple model that is detailed below. The distribution of CO lines generated by a plane-parallel isothermal slab is convolved

with the double-peaked profile produced by a narrow ring extending from R_{\min} to R_{\max} . The ring rotates at Keplerian velocity $v_{\text{Kep}} = \sqrt{GM_*/r}$. The line frequencies and Einstein coefficients are provided by Chandra et al. (1996). The rotational levels within each vibrational level are assumed to be in local thermodynamic equilibrium because the critical density for thermalization of the rotational levels is relatively low ($n_{\text{rot,crit}} \approx 10^3 \text{ cm}^{-3}$). On the other hand, the vibrational levels are only thermalized at densities greater than 10^{10} cm^{-3} . Therefore, each vibrational level can be characterized by its own vibrational temperature T_{vib} . A large range of temperatures was explored ($T = 1000\text{--}4000 \text{ K}$) and the maximum temperature allowed for the dust is set at 1500 K. The gas temperature was allowed to vary with a power-law of index $-3/4$ ($T(r) = T_0(r/R_{\min})^{-3/4}$), typical for a flat accretion disk (Adams et al. 1988) and the gas surface density decreases with radius as r^{-1} ($N(r) = N_0(r/R_{\min})^{-1}$). The free parameters of the models are the inclination i , the inner and outer radius (R_{\min} and R_{\max}) of the hot CO emitting area, and the temperature and CO column density at the inner radius (T_0 and N_0). A grid of models was performed and the model with the lowest reduced chi-square is shown in the lower panel of Fig. 2. The gas is located in a Keplerian disk seen with inclination angle of $88_{-35}^{+2} \text{ }^\circ$ with respect to the rotational axis. The CO column density and temperature at 0.15 AU are $(0.17\text{--}2.5) \times 10^{20} \text{ cm}^{-2}$ and $2850 \pm 500 \text{ K}$ respectively. The amount of CO gas can be inferred from the modeling and is $M(\text{CO}) \approx (0.17\text{--}2.5) \times 10^{-10} M_\odot$. Our results show that the CO gas is located well within the inner first AU from the central star (Table 1). The maximum distance R_{\max} where the CO bandhead is emitted depends on the inclination, which is not a well constrained parameter, but is probably smaller than the dust sublimation radius r_d because the gas is at a much higher temperature than the dust sublimation temperature.

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_{-35}^{+2} 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 NI, SII and FeIII 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 ($10^{20}\text{--}10^{21} \text{ cm}^{-2}$) 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_{\min} and R_{\max} are the emission area inner and outer radius, $T_o(\text{CO})$ is the gas temperature at R_{\min} and $N_o(\text{CO})$ is the column density of CO at R_{\min} .

i ($^\circ$)	R_{\min} (AU)	R_{\max} (AU)	$T_o(\text{CO})$ (K)	$N_o(\text{CO})$ (cm^{-2})
88_{-35}^{+2}	0.15 ± 0.05	0.35 ± 0.05	2850 ± 500	$(0.17-2.5) \times 10^{20}$

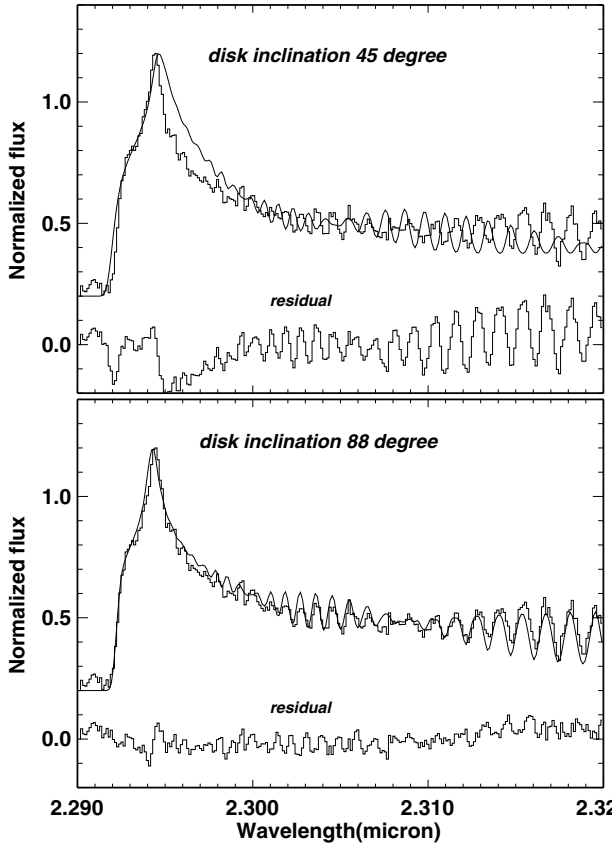


Fig. 2. Fits to the CO first bandhead ($v = 2-0$). In the upper panel the thin line corresponds to the normalized observed spectrum while the thick line is the best fit if the disk is viewed at an inclination of 45° . The lower plot is the residual of the fit. The lower panel shows the best fit obtained with a disk viewed at an inclination of 88° . The complete set of parameters is reported in Table 1.

The large abundances in H_2O , 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_{\min}) and outer (R_{\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 Ω_* (e.g., Shu et al. 1994). Assuming that $\Omega_* = v \sin i = 267 \text{ km s}^{-1}$ (i.e. $i = 90^\circ$), we obtain $r_{\text{rot}} \approx 0.05 \text{ AU}$ (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: $r_d = \sqrt{Q_R(L_* + L_{\text{acc}})/16\pi\sigma/T_{\text{sub}}^2}$ where $Q_R = Q_{\text{abs}}(a, T_*)/Q_{\text{abs}}(a, T_{\text{sub}})$ the ratio of the dust absorption efficiency at stellar temperature T_* to its emission efficiency at the dust sublimation temperature T_{sub} , a is the mean grain radius and σ is the Stefan constant. For large silicate grains ($a \geq 1 \mu\text{m}$), Q_R 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_R is significantly increased (Monnier & Millan-Gabet 2002). We found for 51 Oph that $r_d = 0.56 \text{ AU}$ (see Table 2) assuming $L_{\text{acc}} \ll L_* = 260 L_\odot$ and $Q_R \approx 1$ (large grains). If the grains were as small as $0.1 \mu\text{m}$ in radius, then $Q_R \approx 20$ and $r_d = 4.50 \text{ AU}$.

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_{rot} ($0.5-2.45 \text{ AU}$) 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 $\lambda \sim 4.67 \mu\text{m}$) are sensitive to gas at temperature $\sim 1500 \text{ K}$. Blake & Boogert (2004); Brittain et al. (2003) found CO gas at $T \approx 1000-1500 \text{ K}$ in the disk around HD 163296 and AB Aur. Likewise, CO gas at $\sim 1500 \text{ K}$ was detected by van den Ancker et al. (2001) toward 51 Oph.

The opacity of dust-poor gas at $T_{\text{gas}} = 2000-3000 \text{ K}$ is dominated by H_2O and H_2 , which may eventually deprive the inner dust rim of large amount of stellar UV photons below 1215 \AA . 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 band-head 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).

	51 Oph	HD 163296	AB Aur
SpT	B9.5IIIe	A3Ve	A0Ve+sh
M_* (M_\odot)	3.8	2.0 ± 0.2	2.4 ± 0.2
L_* (L_\odot)	260^{+60}_{-50}	26 ± 5	47 ± 12
L_{acc} (L_\odot)	...	23	28
$v \sin i$ km s ⁻¹	267 ± 5	133 ± 6	97 ± 20
r_{rot} (AU)	0.05	0.13	0.33
r_{d} (AU) ($a = 1.0 \mu\text{m}$)	0.56	0.18	0.24
r_{d} (AU) ($a = 0.1 \mu\text{m}$)	2.50	0.80	1.07
$r_{\text{d}} - r_{\text{rot}}$ (AU) ($a = 1.0 \mu\text{m}$)	0.51	0.05	-0.09
$r_{\text{d}} - r_{\text{rot}}$ (AU) ($a = 0.1 \mu\text{m}$)	2.45	0.38	0.74
CO bandhead emission	yes	no	no
CO fundamental emission	yes	yes	yes
Puffed-up inner rim	no	yes	yes

explain the general absence of inner puffed-up rim in most T Tauri disks (Muzerolle et al. 2003). We compare the thickness of the dust free region of 51 Oph with two classical Herbig Ae stars in Table 2 for grains with radius of $0.1 \mu\text{m}$ and $1 \mu\text{m}$. It is clear that 51 Oph constitutes a special case among the Herbig Ae stars since it combines a large rotation velocity and a large luminosity. Indeed CO bandhead emission has not been detected toward HD 163296 and AB Aur (R. Waters, private communication). The anti-correlation between CO bandhead emission and puffed-up rim should be tested in a larger sample of young stars surrounded by a disk.

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 ($r_{\text{rot}} \ll r_{\text{d}}$) 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 ($80\text{--}150 \text{ km s}^{-1}$).

- Another test for the existence of the dust-free gas would be the detection of strong H₂ fluorescence lines in the UV (e.g., Herczeg et al. 2004, who found H₂ UV lines in the inner disk around the T Tauri star TW Hya). The observation of near-infrared H₂ lines with the $v = 2\text{--}1$ S(1) intensity at $2.2477 \mu\text{m}$ higher than the $v = 1\text{--}0$ S(1) at $2.1218 \mu\text{m}$ would also provide another diagnostic of dust-free gas.

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