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Panic, O.

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CHAPTER 4

An arc of gas and dust around the young star DoAr 21

M. R. Hogerheijde, O. Panić, H. Schouten and B. Merín

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THE dissipation of protoplanetary disks is currently thought to occur inside-out, either through photoevaporation or gap formation following giant-planet formation. So-called ‘transitional’ disks, with cleared-out inner regions, are characterized by nearly photospheric near-infrared fluxes and strong mid-infrared excess. We investigate the spatial distribution of circumstellar material around the ~ 0.3 – 1.0 Myr old, weak-line T Tauri star DoAr 21, which has a ‘transitional’ SED. We resolve the emission of the H_2 1–0 S(1) line at a resolution of ~ 250 mas using adaptive-optics assisted Integral Field Unit spectroscopic measurements from VLT/SINFONI. We also detect the H_2 1–0 S(0) line, but at insufficient signal-to-noise to spatially resolve the emission; and we obtain upper limits to several other H_2 lines. Diffraction limited VLT/VISIR imaging at $\lambda = 18.72 \mu\text{m}$ shows the emission from warm dust at a resolution of $0''.48$. The H_2 line emission and the $18.72 \mu\text{m}$ dust continuum reveal a 230° arc of emission located on the northwest side of the star at 73–219 AU distances. The mass of the circumstellar material is estimated at $\gtrsim 1 \times 10^{-4} M_\odot$ of gas and dust. The temperature of the dust traced at $18.72 \mu\text{m}$ is estimated at ~ 50 – 100 K, while the H_2 lines appear to be thermally excited in gas heated to 1000–2000 K, likely by stellar X-rays. We conclude that this arc may be caused by an unseen companion of no more than a few Jupiter masses interacting with disk material; perturbation of the disk by a stellar fly-by is considered unlikely. Alternatively, it may be the result of unrelated cloud material illuminated by the star. Our results illustrate that the presence of a cleared-out disk cannot be inferred from spatially unresolved observations alone. At the same time, they suggest that detectable ro-vibrational H_2 lines arise when X-rays are not confined to the immediate surroundings of the star.

4.1 INTRODUCTION

The disks that surround many newly formed stars have typical lifetimes of 2–3 Myr, although some disks disappear much earlier and others retain significant amounts of mass up to 10 Myr (e.g., Hillenbrand 2008; Meyer 2009). The presence of circumstellar disks is usually inferred from infrared and (sub) millimeter excess emission apparent in the object’s Spectral Energy Distribution (SED), while their mass is obtained from continuum and/or molecular-line measurements at (sub) millimeter wavelengths (see, e.g., Isella et al. 2009, for a recent example). Recently, much attention has been given to so-called ‘transitional’ or ‘cold’ disks (e.g., Forrest et al. 2004; D’Alessio et al. 2005; D’Alessio 2009; Piétu et al. 2007; Hughes et al. 2007, 2009; Brown et al. 2007, 2008), which lack excess at near-infrared wavelengths but have mid-infrared fluxes comparable to those of ‘classical’ disks. The favored explanation is that the inner regions of these disks (one to tens of AU) are devoid of (small) dust, but that the outer regions ($\gtrsim$ tens of AU) still contain enough material to form a planetary system ($\gtrsim 10^{-4} M_{\odot}$). Mechanisms responsible for the clearing of the inner disk can be photoevaporation of the gas and dust by the stellar radiation (Shu et al. 1993; Clarke et al. 2001; Matsuyama et al. 2003; Alexander et al. 2006) or dynamic interaction with a giant planet (Lin & Papaloizou 1993). The presence of (previously unknown) (sub)stellar companions may also explain a number of disks with cleared-out inner regions (e.g., Ireland & Kraus 2008). In some cases, residual amounts of gas remain in the inner disks that are otherwise free of dust (e.g., Goto et al. 2006; Pontoppidan et al. 2008; Salyk et al. 2009), hinting at the complex dynamics of the gas and dust in accretion disks.

In this Chapter we present spatially resolved observations of molecular gas and warm dust of DoAr 21, a young star with a ‘transitional’ SED, and show that such measurements are essential to interpret the spatial distribution of the circumstellar material. Sub-arcsecond resolution is required to spatially resolve the emission at the typical distances of young stars (50–200 pc). Common tracers that allow such resolution include (sub) millimeter continuum and molecular-line emission as studied in Chapters 2 and 3 of this thesis (e.g., Guilloteau & Dutrey 1998; Simon et al. 2000; Andrews & Williams 2005, 2007a,b; Piétu et al. 2007; Qi et al. 2004, 2006, 2008; Hughes et al. 2008; Isella et al. 2009), near-infrared scattered light imaging (e.g., Grady et al. 2000; Schneider et al. 2003; Roberge et al. 2005; Pinte et al. 2008), and mid-infrared imaging with 8-m class telescopes (e.g., Geers et al. 2007). In this Chapter we use this latter approach, presenting diffraction limited ($0''.48$) imaging at $18.72 \mu\text{m}$ with VISIR on the Very Large Telescope (VLT), and we explore a novel technique using Adaptive-Optics (AO) assisted spectroscopic imaging of ro-vibrational H_2 lines in the near-infrared K-band with the Integral Field Unit (IFU) SINFONI on VLT.

Ro-vibrational and pure-rotational emission of H_2 has been detected around numerous young stars (e.g., van Langevelde et al. 1994; Richter et al. 2002; Lahuis et al. 2007; Martin-Zaïdi et al. 2007, 2008, 2009; Beck et al. 2008). The pure-rotational lines are thermally excited in warm (~ 100 K) gas, but can generally only be observed with some difficulty at their mid-infrared wavelengths. Ro-vibrational lines at near-infrared wavelengths are much more easily accessible through, for example, long-slit spectroscopy, but require higher temperatures (> 1000 K) or non-thermal mechanisms

to be excited.

Around a dozen young stars spatially unresolved, narrow emission of H_2 1–0 S(1) at $2.1218 \mu\text{m}$ has been detected (including LkH α 264, GG Tau A, V773 Tau, DM Tau, LkCa 15, GM Aur, CS Cha, DoAr 21, and TW Hya; Weintraub et al. 2000; Bary et al. 2002, 2003, 2008; Itoh et al. 2003; Ramsay Howat & Greaves 2007; Carmona et al. 2007). Because these lines are narrow and centered on the stellar velocity, these authors conclude that the emission originates in quiescent gas, presumably in their circumstellar disks, and not from gas that is heated by shocks (cf. Beck et al. 2008). Interestingly, about one-third (6/18) of the objects with detected quiescent ro-vibrational H_2 emission have ‘transitional’ SEDs suggesting cleared-out inner disk regions (Bary et al. 2008).

A viable mechanism to heat disk material to $> 1000 \text{ K}$ temperatures required to excite ro-vibrational H_2 lines, is offered by the secondary electrons produced by X-ray photoionization (e.g., Gredel & Dalgarno 1995; Maloney et al. 1996; Tiné et al. 1997; Glassgold et al. 1997; Igea & Glassgold 1999; Glassgold et al. 2004; Nomura et al. 2007; Gorti & Hollenbach 2008). Alternatively, a *non*-thermal process is offered by excitation of electronic states of H_2 by ultraviolet radiation, followed by a radiative cascade and fluorescent emission in the 1–0 S(1) and other ro-vibrational lines (Black & van Dishoeck 1987; Sternberg & Dalgarno 1989; Draine & Bertoldi 1996). Using intensity ratios of several ro-vibrational H_2 transitions, thermal processes can be distinguished from non-thermal fluorescence (e.g., Mouri 1994). In this way, Carmona et al. (2007) conclude that the ro-vibrational H_2 emission from LkH α 264 originates from $\sim 1000 \text{ K}$ gas heated by the stellar X-rays; a similar mechanism has been suggested for the other stars with detected H_2 1–0 S(1), based on their strong X-rays (e.g., DoAr 21; Bary et al. 2002).

The young star DoAr 21 (also known, among other names, as V2246 Oph, ROXR1 13, and ROX 8), $\alpha_{2000} = 16^{\text{h}}26^{\text{m}}03^{\text{s}}.031$, $\delta_{2000} = -24^{\circ}23'36''.43$, (Dolidze & Arakelyan 1959) is a $2.2 M_{\odot}$ K1 star (Luhman & Rieke 1999) located at $121.9^{+5.8}_{-5.3} \text{ pc}$ (Loinard et al. 2008) in the Lynds 1688 star-forming cloud in Ophiuchus; it is located just outside the Oph A millimeter condensation (Loren & Wootten 1986; Motte et al. 1998), $6'$ (0.2 pc) west of the core’s center. From the star’s luminosity ($15\text{--}30 L_{\odot}$; Bouvier & Appenzeller 1992; Luhman & Rieke 1999; Bontemps et al. 2001) and effective temperature (5080 K), Luhman & Rieke (1999) estimate an age of $\sim 0.3 \text{ Myr}$ using evolutionary tracks of D’Antona & Mazzitelli (1996). Its $\text{H}\alpha$ equivalent width of $-0.6 \text{ \AA}$ (Bouvier & Appenzeller 1992) classifies it as a weak-line T Tauri star. In a recent paper, Jensen et al. (2009) obtain a similar age and mass for the star when assumed single, and slightly lower masses and higher age of 1.0 Myr when assumed to be an equal-mass binary. They also show that the $\text{H}\alpha$ emission is variable and has a complex line profile.

Mid-infrared observations of DoAr 21 by Barsony et al. (2005) and, more recently using measurements from the Spitzer Space Telescope, Jensen et al. (2005) and Cieza et al. (2007) reveal significant amounts of warm dust. DoAr 21 is not detected at 1.3 mm by André & Montmerle (1994) to an upper limit of 5 mJy ; however, significant extended cloud emission is visible in archival JCMT/SCUBA data (Di Francesco et al. 2008) making it difficult to discern any possible continuum emission directly related to the star.

Similar extended emission is visible in Spitzer IRAC and MIPS images (Padgett et al. 2008). The object emits copious (L_X of a few times 10^{31} erg s $^{-1}$, or $L_X/L_{\text{bol}} \sim 10^{-4}$) and hard (3–4 keV) X-rays (Koyama et al. 1994; Casanova et al. 1995; Grosso et al. 2000; Gagné et al. 2004; Imanishi et al. 2002), and appears to be in a continuously flared state. DoAr 21 has also long been known to be variable at radio wavelengths (Feigelson & Montmerle 1985; Stine et al. 1988). Recent VLBI measurements resolve the object into a 15 mas binary, supporting the hypothesis that DoAr 21 is directly comparable to the object V773 Tau (Feigelson & Montmerle 1985; Loinard et al. 2008). In V773 Tau (Massi et al. 2006, 2008), and in the similar system DQ Tau (Salter et al. 2008), the periodic overlap of the magnetospheres of the two stars on an eccentric binary orbit generate periodic radio flares, and a similar mechanism may operate for DoAr 21.

Quiescent H $_2$ emission from DoAr 21 was reported by Bary et al. (2002), who estimate 4.4×10^{-10} M $_{\odot}$ of emitting gas and extrapolate this to a total disk mass of 10^{-3} – 1.0 M $_{\odot}$. From the (marginally) resolved line width, they infer that the emission originates between 5 and 30 AU from the star. Bitner et al. (2008) detect pure-rotational emission from DoAr 21 at 12.28 μm , finding a ~ 5 times larger mass of warm (~ 100 K) gas, and conclude that the material is located outside 30 AU. Our spatially resolved observations directly address the question of the spatial distribution of the circumstellar material traced through the SED and the H $_2$ line emission.

Section 4.2 of this Chapter describes our observations¹ and Section 4.3 list the results. Instead of an axisymmetric circumstellar disk, we find that the emission originates from an arc of material circling the star at radii between 70 and 220 AU, and in Section 4.4 we explore various explanations for the observed characteristics. Section 4.5 summarizes our findings and addresses their relevance for the class of objects with ‘transitional’ SEDs and for the class of objects with quiescent H $_2$ emission.

When this thesis was completed, a manuscript by Jensen et al. (2009) appeared, presenting mid-infrared imaging, and optical and X-ray spectroscopy of DoAr 21. The results of their imaging are consistent with our 18.72 μm data, and they reach similar conclusions regarding the spatial extent of the circumstellar material. Their spectroscopy confirms the assumptions made by us about the energy input by the stellar radiation field. Our work presented in this Chapter strongly complements the work of Jensen et al. by presenting spatially resolved data of the H $_2$ line emission – directly confirming their suggestion that the warm dust and H $_2$ 2.12 μm line emission are co-spatial –, and by placing observational limits on the excitation mechanism of the H $_2$ lines. Our observations show that the H $_2$ lines arise in gas heated to 1000–2000 K by X-rays and that FUV fluorescence is likely collisionally quenched (Sect. 4.4).

¹Collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile, under proposal numbers 075.C-0378 and 081.C-0742.

4.2 OBSERVATIONS

4.2.1 SINFONI observations

Using the Spectrograph for Integral-Field Observations in the Near Infrared (SINFONI) on the European Southern Observatory's Very Large Telescope UT4 (Yepun), we observed the star DoAr 21 on 2005 July 1. The observing conditions were good with light cirrus and a visual seeing of $0''.35$ – $0''.6$. The K-band grating was selected with a spectral resolving power of $R = 4000$. With its K-band magnitude of 6.16 (Barsony et al. 1997) and V-band magnitude of 13.9 (Bouvier & Appenzeller 1992), DoAr 21 was sufficiently bright to serve as a reference for the Adaptive Optics system. Strehl ratios of 0.43–0.48 were reached, and the full width at half maximum (FWHM) of the Point Spread Function (PSF) FWHM was 63 mas, consistent with diffraction-limited observations at K band. Using a plate scale of $250 \text{ mas pixel}^{-1}$, we obtained eight 1-second integrations. At this plate scale, the PSF is undersampled by the pixels, and only very short integrations were possible to avoid saturating the detector array. Using a plate scale of $25 \text{ mas pixel}^{-1}$, we obtained twenty 15-second integrations for a total of 300 second integration time. This plate scale resolves the PSF well.

In addition to DoAr 21, observations of DoAr 20 and DoAr 34 were also obtained to serve as PSF standards (six integrations of 20 seconds at a plate scale of $25 \text{ mas pixel}^{-1}$). Standard calibration observations were performed including darks and flats, using the stars HIP 93393 (HD 176871, $m_K = 5.8$) and HIP 64075 (HD 113949, $m_K = 8.7$) as standard stars. All observations were obtained while chopping with a $30''$ offset to subtract the sky background, and a jitter of 4 pixels, using the standard observing mode `SINFONI_ifs_obs_AutoJitterOffset`.

The data reduction and calibration was carried out using the standard recipes provided by the ESOREX and GASGANO packages. Integrated light images were constructed summing over a $0.245 \mu\text{m}$ bin centered on $2.20 \mu\text{m}$. A continuum-subtracted H_2 1–0 S(1) line emission image was obtained on a pixel-by-pixel basis by summing six channels with detected emission, and subtracting the contribution from the stellar continuum obtained from 16 channels on either side, selected to be free of spectral features (either stellar, atmospheric, or due to imperfect standard-star subtraction). This procedure resulted in a very accurate subtraction of the stellar continuum, with a dynamic range of ~ 100 at the core of the PSF increasing to 500–1000 outside the central $\sim 0''.2$. For DoAr 20 and DoAr 34 (which do not show H_2 line emission), residual emission (both positive and negative) remains present within $0''.1$ of the stellar images, due to imperfections of the continuum subtraction. For DoAr 21, negative emission fills the 25 mas plate-scale image, as well as the inner $0''.7$ around the star in the 250 mas plate-scale image. If this were due to line-of-sight absorption by H_2 , the required optical of $\tau \sim 0.01$ corresponds to unrealistically high values for the hydrogen column density of $\sim 6 \times 10^{23} \text{ cm}^{-2}$ and the optical extinction A_V of 500. We therefore conclude that the negative residual is due to imperfect subtraction of the stellar radiation. However, this does not affect our results.

4.2.2 VISIR observations

Using the VLT spectrometer and imager for the mid-infrared (VISIR) on VLT UT3 (Melipal), we observed the star DoAr 21 on 2008 April 10. The Q2-filter was selected with a central wavelength of $18.72 \mu\text{m}$ and a width of $0.88 \mu\text{m}$. At this wavelength the VLT is diffraction limited, and a FWHM of the PSF of $0''.48$ was measured. The plate scale of the detector is $75 \text{ mas pixel}^{-1}$ resolving the PSF well. A total integration time of 1 s was reached in 38 observations of 25 ms each. The observations were obtained with a chop throw of $4''.8$ (half-array size) and the telescope was offset by one-quarter of the field-of-view in RA and Dec, so that both positive and negative images were recorded. Observations of the star HD 145897 (χ Sco, $m_V = 6.7$) were obtained for flux calibration; from its effective temperature of 5000 K (Bouvier & Appenzeller 1992; Luhman & Rieke 1999) we estimated a Q2-band flux of 2.02 Jy. Subsequent reduction and calibration was carried out with the standard pipeline recipes provided by the ESOREX package.

At these mid-infrared wavelengths the sky generates a highly variable background, and no flatfielding is usually performed. However, in our observations of the relatively weak and extended emission (see §4.3), a variable background is clearly discernible. A background of similar shape is seen in the observations of the standard star, and we have used these to ‘flatfield’ the exposures of the science target. We first subtracted a PSF-fit from the standard star image consisting of a diffraction-limited Airy pattern followed by a Gaussian convolution with a FWHM of $0''.217$. We then smoothed the residual to a resolution of $0''.75$ and normalized the image. And finally we subtracted the resulting flatfield from the science image. This generates better images with a flatter background; it does not affect our conclusions on emission extended over $\lesssim \frac{1}{4}$ of the field, but the flatfielding procedure (and the presence of the varying background) limits our possibility to detect emission extended over larger scales.

4.3 RESULTS

Figure 4.1² shows the images of DoAr 21: the integrated-light images in K-band from SINFONI showing the stellar continuum (both plate scales); the continuum-subtracted H_2 -line images (both plate scales); and the $18.72 \mu\text{m}$ VISIR image.

The stellar photosphere is clearly detected at 2.20 and $18.72 \mu\text{m}$; it completely dominates the emission at the shorter wavelength. At both wavelengths the stellar image is (nearly) diffraction limited with respective PSF cores of FWHM $73 \times 69 \text{ mas}$ (at $2.20 \mu\text{m}$) and $0''.48$ (at $18.72 \mu\text{m}$); at the $250 \text{ mas pixel}^{-1}$ plate scale at $2.20 \mu\text{m}$ (Fig. 4.1b) the PSF is under-resolved and diffraction spikes are clearly visible. At $18.72 \mu\text{m}$ extended emission $\sim 1''$ NW of the star is also clearly detected, roughly forming an arc of 90° with a radius of $1''.2$ (146 AU) and a width of $0''.5$ (61 AU), i.e., close to the diffraction limit in the radial direction. The $18.72 \mu\text{m}$ image is very similar to the $18.3 \mu\text{m}$ results presented by Jensen et al. (2009).

²Panels (c) and (e) of this figure can be seen in colour on page 8 of this thesis, Fig. 1.2.

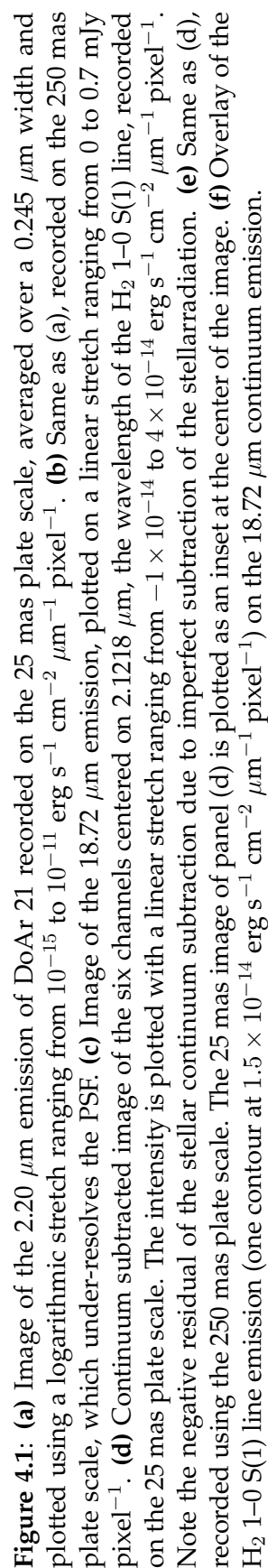


Table 4.1: Measured continuum and line fluxes of DoAr 21

Measurement	Value
DoAr 21: F_λ ($\lambda = 2.20 \mu\text{m}$)	$2.3 \pm 0.02 \text{ Jy}$
DoAr 21: F_λ ($\lambda = 18.72 \mu\text{m}$)	$84 \pm 2 \text{ mJy}$
Arc: F_λ ($\lambda = 18.72 \mu\text{m}$)	$\sim 159 \text{ mJy}$
Total: F_λ ($\lambda = 18.72 \mu\text{m}$)	$\sim 700 \text{ mJy}$
H ₂ 1–0 S(1), 2.1218 μm : $\int F_\lambda d\lambda$	$8.0 \pm 0.5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$
H ₂ 1–0 S(0), 2.2235 μm : $\int F_\lambda d\lambda$	$2.2 \pm 0.3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$

No H₂ line emission is detected in the 25 mas plate-scale image, down to a noise level of $5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \mu\text{m}^{-1} \text{ pixel}^{-1}$. In the 250 mas plate-scale image, an arc of emission in the H₂ 1–0 S(1) line is detected extending from the north to the southwest of the star, where the emission is lost in the noise. This arc starts at a position angle of -40° (as measured from north to west), where the H₂ emission ranges from $0''.6$ (73 AU) to $1''.0$ (122 AU) from the star, over 230° to a position angle of $+170^\circ$, where the H₂ emission stretches from $1''.1$ (134 AU) to $1''.8$ (219 AU) from the star. Panel (f) of Fig. 4.1 shows an overlay of the 18.72 μm continuum and H₂ line emission, indicating that both trace the same region (with the H₂ emission apparently outlining the inner side from the 18.72 μm emission as seen from the star). The location of the H₂ emission is consistent with the conclusion of Bitner et al. (2008) that it originates outside 30 AU from the star.

Figure 4.2 shows the H₂ 1–0 S(1) line spectrum integrated over the region where the emission was detected above the noise in the 250 mas plate-scale image, roughly corresponding to the contour in Fig. 4.1f. In addition to the H₂ 1–0 S(1) line at 2.1218 μm , at least a dozen other H₂ ro-vibrational lines have wavelengths within the SINFONI spectrum; of these, only H₂ 1–0 S(1) is detected at sufficient signal-to-noise for imaging. The H₂ 1–0 S(0) line at 2.2235 μm is detected when integrating over the same area where the 1–0 S(1) was found to emit. No other lines H₂ were detected. For example, an upper limit of $\sim 1.5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ is found for the H₂ 2–1 S(1) line at 2.2477 μm . Figure 4.2 also shows the detected 1–0 S(0) line and the location of the (undetected) 3–2 S(4) line. Other features in the spectra are residual lines resulting from the standard star subtraction, as verified by inspection of the similarly processed spectra of DoAr 20 and DoAr 34 that show the same artifacts but no H₂ lines.

Line strengths and continuum fluxes are listed in Table 4.1. The integrated line strength of the 1–0 S(1) line of $8.0 \pm 0.5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ agrees within the noise with the value reported by Bary et al. (2002) of $15 \pm 9 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Bary et al. 2002). This indicates that we have recovered essentially all H₂ 1–0 S(1) line emission by summing over the observed arc. Likewise, the 18.72 μm flux of the star of $84 \pm 2 \text{ mJy}$ agrees well with the expected photospheric value of $\sim 59 \text{ mJy}$ given that the flatfielding procedure described in Sect. 4.2.2 complicates the extraction of accurate fluxes. This uncertainty strongly affects estimates of the extended fluxes: we estimate that the flux of the arc amounts to 160 mJy and that the entire field contains $\sim 700 \text{ mJy}$, but note that the latter values are uncertain by a factor of 2. However, the value of 700 mJy is

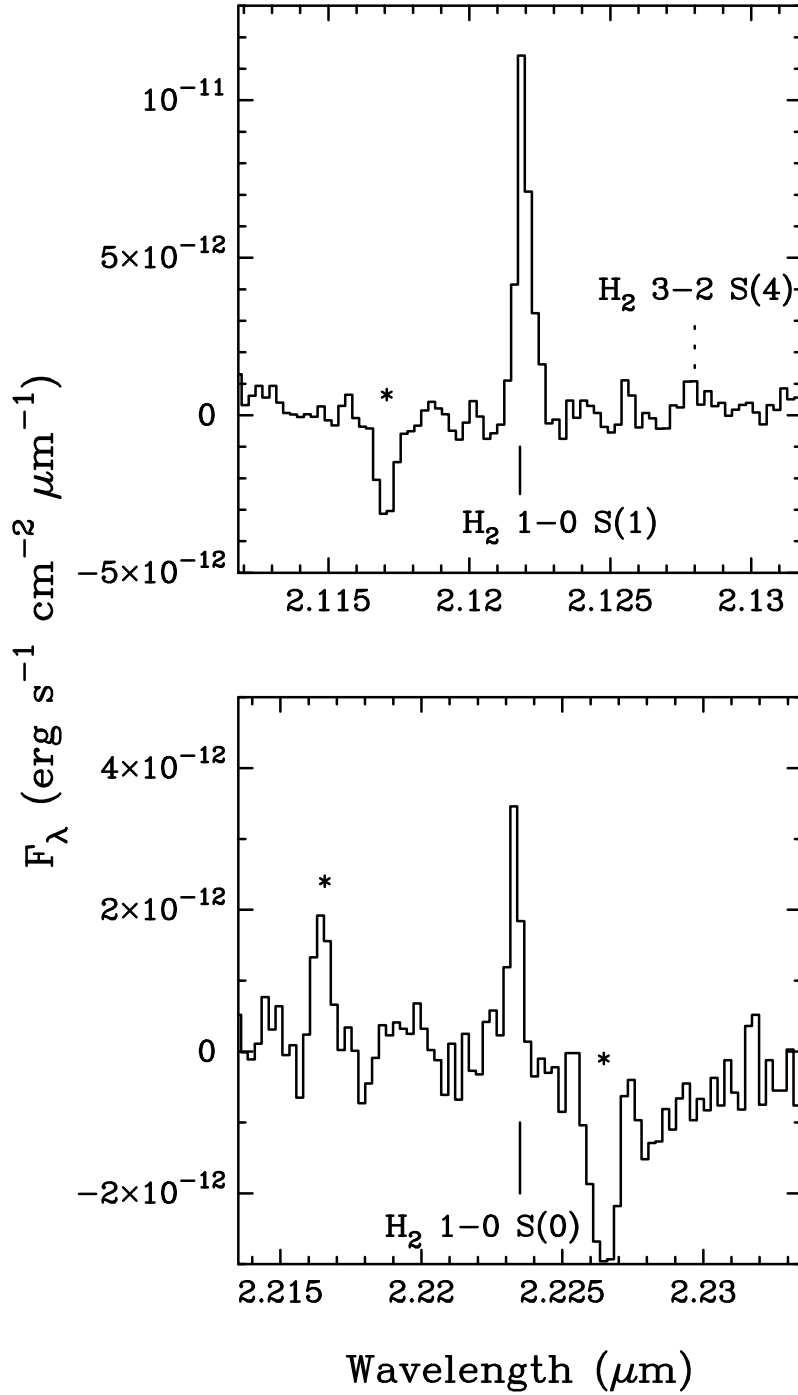


Figure 4.2: Spectrum of the H_2 1-0 S(1) (top) and H_2 1-0 S(0) (bottom) line emission, integrated over those areas of the 250 mas plate-scale image with 1-0 S(1) emission detected at $> 2\sigma$. Also indicated is the position of the 3-2 S(4) line, which is not detected. Other spectral features, marked with *, are residuals from the standard spectrum subtraction.

consistent with the mid-infrared SED as we will see in Sect. 4.4.1 (see also Fig. 4.3).

4.4 DISCUSSION

4.4.1 Location and mass of the emitting material

The previous Section and Fig. 4.1 convincingly show that the H_2 emission does not originate from radii of 5–30 AU in a circumstellar disk, as suggested before by the spatially unresolved observations of Bary et al. (2002), but instead from an arc on the northwest of DoAr 21 at distances of 73–219 AU. At least one-quarter of the excess emission at $18.72\ \mu\text{m}$ emission originates from this same arc, comparing the measured flux of 160 mJy to the total flux of 700 mJy.

The SED of Fig. 4.3 clearly shows the presence of excess emission at mid- and far-infrared wavelengths. PAH bands contribute to the 7–12 μm flux (Hanner et al. 1995). We take two approaches to determine the amount of circumstellar material and its typical temperatures. In the first approach, we add a small number of components at different temperature to match the SED. Using emissivities from Ossenkopf & Henning (1994) for dust particles without ice mantles and a gas-to-dust mass ratio of 100, we find a reasonable match for a mass of $5 \times 10^{-3}\ M_\odot$, with the bulk of the material at 30 K, and 2% at 60 K, 0.02% at 90 K, and 1 part in 5×10^5 at 200 K.

In the second approach we use the grid of SED models and the fitting routines of Robitaille et al. (2006, 2007) to find a best fit. The best match is found for a stellar age of 5×10^5 yr, a rather low effective temperature of 3872 K (compared to the 5080 K of DoAr 21), and disk mass of $6.7 \times 10^{-5}\ M_\odot$ and disk radius of 163 AU, and a surrounding envelope of $3.7 \times 10^{-2}\ M_\odot$ and 5000 AU radius (model # 3015448). Although this model fits very well, with a χ^2 value of 3.6, we caution that other models with very different parameters give fits that appear to the eye as nearly as good.

Both models described in the previous two paragraphs fit the SED equally well (Fig. 4.3). Clearly, without going into the full details of modeling the spatial extent of the emission, the SED alone does not provide sufficient constraints to provide a unique fit. A further complication may arise from the fact that the points in the SED are not contemporaneous. It appears that the flux around, e.g., 10 μm can vary by a factor of ~ 2 . These variations may be caused by the different heating input from the stellar X-rays that are known to flare.

From our simple four-component model, we find that the $18.72\ \mu\text{m}$ flux of the arc corresponds to $\sim 1 \times 10^{-4}\ M_\odot$ at 60 K. We take this value as a conservative estimate of the total mass traced by the $18.72\ \mu\text{m}$ emission. The amount of gas traced by the H_2 1–0 S(1) line was estimated by Bary et al. (2002). Scaling their value to our slightly lower intensity, we obtain a gas mass of $2.3 \pm 0.1 \times 10^{-10}\ M_\odot$ emitting in the H_2 1–0 S(1) line. This is $\lesssim 10^{-6}$ times the mass inferred from the $18.72\ \mu\text{m}$ dust emission of $\gtrsim 10^{-4}\ M_\odot$, a similar small fraction as found toward other systems (Bary et al. 2003) and consistent with the notion that the ro-vibrational H_2 emission arises in a thin, hot surface layer heated by X-rays (e.g., Nomura et al. 2007) – but not necessarily that of a disk. The spatial correlation of the H_2 emission and $18.72\ \mu\text{m}$ continuum emission (Fig.

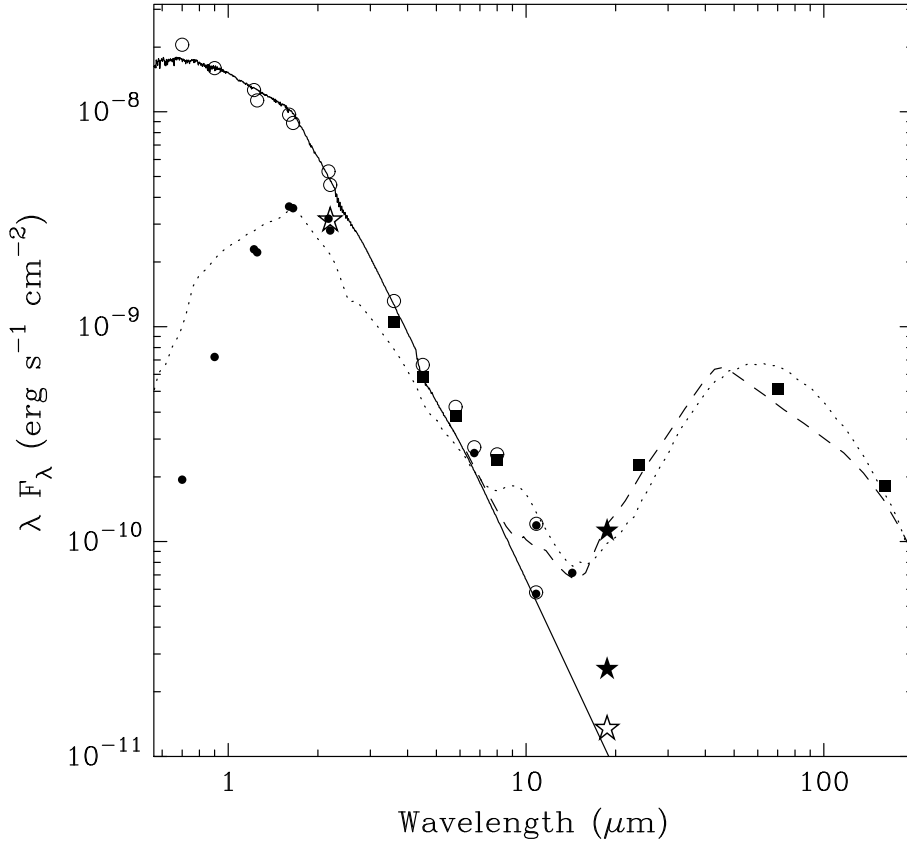


Figure 4.3: Spectral energy distribution of the star DoAr 21. Literature values are shown by filled circles. Open circles show dereddened values, assuming $A_V = 4.5$ mag. Filled squares are Spitzer measurements in apertures of $8''.4$ for the four IRAC bands, $17''.2$ for MIPS1, and $28''$ for MIPS2. The open stars are our measurements of the $2.20 \mu\text{m}$ and $18.72 \mu\text{m}$ of the stellar photosphere. The filled stars are our estimates of the flux at $18.72 \mu\text{m}$ from the star and the arc together (lower point) and the entire VISIR FOV (upper point). The solid line shows a Kurucz model for an effective temperature of 5000 K. The dashed line shows our four-component fit to the circumstellar material, and the dotted line the disk+envelope model (# 3015448) from the grid of calculations presented by Robitaille et al. (2006, 2007). Data points are taken from Lada & Wilking (1984); Bouvier & Appenzeller (1992); Barsony et al. (1997); Bontemps et al. (2001); Barsony et al. (2005) and the catalog of the ‘Cores to Disks’ Spitzer Legacy Survey (Evans et al. 2009).

4.1f) supports this model. A more accurate determination of the amounts of gas and dust traced by our observations would require a detailed modeling of the geometry, irradiation, and heating and cooling balance; this is beyond the scope of our analysis. Interferometric measurements at (sub) millimeter wavelengths are also essential for a proper assessment of the total amount of dust.

For a mass of $\sim 10^{-4} M_\odot$ distributed over the area traced by the arc at $18.72 \mu\text{m}$ ($\sim 1.35 \times 10^4 \text{ AU}^2$), the dust is optically thin at $18.72 \mu\text{m}$ ($\tau \approx 1$) and moderately optically thick at $2.20 \mu\text{m}$ ($\tau \approx 2\text{--}3$). We can, therefore, be sure that we did not miss significant amounts of material due to opacity, and conclude that the circumstellar ma-

terial consists of at least $1 \times 10^{-4} M_{\odot}$ located in a 230° arc at 73–219 AU from DoAr 21, but may be as large as $3.7 \times 10^{-2} M_{\odot}$ with most mass at low temperatures ($\lesssim 30$ K) and undetected by our observations.

The temperature of the H_2 line emitting gas, and the excitation mechanism, can be constrained from the ratios of the detected lines, 1–0 S(1) and 1–0 S(0), and from the upper limit on the 2–1 S(1) line. We find 1–0 S(0) / 1–0 S(1) = 0.28 ± 0.06 and 2–1 S(1) / 1–0 S(1) $\lesssim 0.2$. The various model results presented by Mouri (1994, their Fig. 3) indicate that these ratios are consistent with thermal excitation at a temperature of 1000–2000 K and strongly rule out ultraviolet fluorescence, for which a 2–1 S(1) / 1–0 S(1) ratio of ~ 0.55 is expected. This supports the assumptions made above and by Bary et al. (2002). Carmona et al. (2007) find similar conditions for the emission from LkH α 264, which favor a slightly lower temperature of ~ 1000 K.

Jensen et al. (2009) estimate that the FUV field of DoAr 21 is likely easily strong enough to excite the H_2 line through fluorescence. Our limit on the 2–1 S(1) line indicates that densities above $\sim 10^5 \text{ cm}^{-3}$ are present in the emitting gas that collisionally quench the fluorescently excited levels, leaving only the thermal emission from the 1–0 S(1) and 1–0 S(0) (cf. Sternberg & Dalgarno 1989). Such densities are expected for the estimated mass and size of the emitting volume: a mass of $\gtrsim 10^{-4} M_{\odot}$ and a volume of $(100 \text{ AU})^3$ results in a density of $\gtrsim 10^7 \text{ cm}^{-3}$.

4.4.2 Possible explanations for the observed arc of emission

This Section explores several scenarios for the observed asymmetric distribution of emission around DoAr 21. We start by stating that because the $18.72 \mu\text{m}$ emission is optically thin, we can rule out that the arc is a result from partial obscuration in a tilted ring, or even a PSF subtraction error. We therefore need to explain why the emitting material itself is distributed asymmetrically around the star, a distribution that is dynamically unstable. Our source is unique in the degree of asymmetry observed in the circumstellar material, with a contrast of a factor of > 6 between the region of maximum emission and the regions without detected emission. However, other sources with cleared-out inner disks (for example, HR4796A: Jayawardhana et al. 1998; Kerner et al. 1998; Telesco et al. 2000; AB Aur: Pantin et al. 2005; and LkH α 330: Brown et al. 2008) also show non-axisymmetric structure ('blobs').

Interaction of a disk with a passing star

A close encounter with a passing star can disrupt a circumstellar disk. Because the observed arc is dynamically unstable, if orbiting DoAr 21, its lifetime is of the order of several orbital time scales, or roughly 10^4 yr. Again assuming a typical dispersion of stellar velocities of a few km s^{-1} we estimate that any such passing star must still lie within $\sim 1'$ from DoAr 21. Inspection of the Spitzer/IRAC images reveal a handful of point sources within this distance, but all are likely background sources. The closest young stellar object is located $1'.8$ south of DoAr 21, identified by the 'Cores to Disks' Spitzer Legacy survey with a typical sensitivity of $0.2 M_{\odot}$ (cf. Merín et al. 2008). We

cannot exclude the passage of a substellar object, possibly as small as a few Jupiter masses; in the latter case, the distance of closest approach to the disk must have been very small, and we conclude that this scenario is unlikely.

Interaction with a substellar or planetary companion orbiting DoAr 21

Planets or substellar companions can excite resonances in disk material (although these are usually symmetric, and not asymmetric as is the case here; Roques et al. 1994; Ozernoy et al. 2000; Kuchner & Holman 2003, e.g.), or the migration of a planet or companion to the 73–219 AU region could disrupt a previously stable outer disk. With the detection of giant planets at $\gtrsim 100$ AU distance from their star, such migration mechanisms are relevant (Kalas et al. 2008; Marois et al. 2008). No companion is visible in our data, to a limit of $m_K=15$ mag and 13 mag in the 250 and 25 mas fields, respectively, obtained after subtracting an azimuthally averaged image of the star from the images, leaving only non-axisymmetric residuals. Similarly, no object can be firmly detected in the $18.72\ \mu\text{m}$ image, down to a flux limit of a few mJy. There is a tentative detection $\sim 1''.5$ south of the star, with a flux of 5.6 ± 0.8 mJy, but we estimate that this is too faint to constitute a firm detection³. Assuming an age of ~ 0.3 Myr for the system, we can limit the mass of any unseen companion to less than $\sim 5\ M_{\text{Jupiter}}$, using the tracks of Baraffe et al. (2003). However, an unseen body of a few M_{Jupiter} could still explain the observations.

Illumination of unrelated cloud material

In this scenario, the emitting material belongs to the surrounding Ophiuchus cloud and is unrelated to the star. As mentioned before, JCMT/SCUBA and Spitzer/IRAC and MIPS images reveal extended emission within a few arcmin from DoAr 21. Clearly, significant cloud material is located (in projection) near DoAr 21. For a typical velocity dispersion of young stars in star-forming regions of a few km s^{-1} (Herbig 1977; Jones & Herbig 1979; Hartmann et al. 1986; Dubath et al. 1996), DoAr 21⁴ traverses large distances (~ 1 pc) over its age of ~ 0.3 Myr. If it is currently moving through a denser region of the Ophiuchus cloud, its stellar radiation will heat up the dust and the star's X-rays will heat a gas layer at the surface to > 1000 K and excite the observed H_2 ro-vibrational emission. The arc-like appearances of the $18.72\ \mu\text{m}$ and H_2 line emission are explained in this scenario by the combined results of the fact that only within ~ 100 AU from the star can dust and gas be sufficiently heated, and the shape of any material swept up by the stellar motion. Density variations in the surrounding material can explain the somewhat irregular shape of the arc. This scenario is somewhat similar to that proposed by Gáspár et al. (2008) for the infrared excess of the star δ Velorum.

³The $18\ \mu\text{m}$ imaging by Jensen et al. (2009) does not show this source, and it is likely spurious.

⁴Jensen et al. (2009) quote a relative motion of DoAr 21 with respect to the surrounding gas of $9.5 \pm 1.3\ \text{km s}^{-1}$ to the west.

Capture of a cloud condensation and a brown-dwarf disk

In a variation on the previous scenario, a sufficiently close passage of DoAr 21 to a small cloud condensation or a brown dwarf with a surrounding disk, may result in gravitational capture by the star (i.e., a passage at a velocity smaller than the escape velocity at the impact parameter, e.g., $\sim 3 \text{ km s}^{-1}$ at 100 AU). At the smallest and largest radius of the arc, 73 and 219 AU, the orbital time scales around a $2.2 M_{\odot}$ star are 400 and 2300 yr, respectively. A spherical distribution of gas with a diameter of 146 AU ($=219-73$ AU) in an orbit around DoAr 21 would shear to an arc of 230° in approximately 330 yr. The likelihood of the close, low-velocity encounter between DoAr 21 and this putative cloud condensation is difficult to estimate.

Other explanations

Finally we note that the distribution of the material may be caused by a collision between a Jupiter-mass (proto)planet and an other planetary object such as a 10 km sized asteroid as described by Grigorieva et al. (2007), resulting in a spray of material slowly spreading over several orbits. The distribution may also be the result of a global gravitational instability of a disk which has undergone progressive stages of disk clearing, dust coagulation, and gas loss (e.g., Klahr & Lin 2001, 2005). However, we regard both scenarios as speculative at this stage.

Future observations

To decide which of these scenarios is correct follow-up observations of DoAr 21 are required in the H_2 line, at $18.72 \mu\text{m}$, and/or at millimeter wavelengths. Our SED modeling suggests a flux of $\lesssim 1 \text{ mJy}$ at 1 mm, sufficient for high signal-to-noise imaging with ALMA at $< 1''$ resolution. If the material orbits around DoAr 21, in 10 years the arc is expected to rotate by 8° (80 mas) at its smallest radius of 73 AU and 1.6° (50 mas) at its largest radius of 219 AU. If DoAr 21 is travelling through the cloud, a proper motion of DoAr 21 of a few km s^{-1} corresponds to a positional shift of 10 AU or 100 mas in 10 years. Either motion can be detected. In this context we recall that the mid-infrared flux of DoAr 21 appears to vary (Sect. 4.4.1; Barsony et al. 2005), which suggests that the position of DoAr 21 with respect to the emitting material may have changed or that the spatial distribution of the material has changed. We estimate that the reported flux variations could reflect a relative motion of DoAr 21 with respect to the illuminated material by ~ 5 AU; accurately calibrated follow-up observations are required to confirm this. However, as noted in Sect. 4.4.1, stellar flares as traced through the X-rays may also explain this mid-infrared variation.

4.5 CONCLUSIONS

We present spatially resolved observations of the 0.3–1.0 Myr old weak-line T Tauri star DoAr 21 at $2.20 \mu\text{m}$ and at $18.72 \mu\text{m}$. The $2.20 \mu\text{m}$ AO-assisted IFU observations allow accurate continuum subtraction and subsequent imaging of the H_2 1–0 S(1) line, while

the 18.72 μm diffraction limited imaging reveals the location of warm (50–100 K) dust. We detect the stellar photosphere at both wavelengths, and find an arc of emission in the H_2 line and in 18.72 μm emission located between 73 and 219 AU from the star and stretching over 230° along the northwest side of the star. We calculate that the circumstellar material contains $\gtrsim 1 \times 10^{-4} M_\odot$. We conclude that the distribution of the extended emission reflects the true distribution of the emitting material and is not due to a radiative transfer / geometric effect. Since an asymmetric distribution of material at these radii cannot persist for more than a few orbital times scales ($\sim 10^4$ yr; in the absence of resonant motion with an unseen companion which we rule out to a mass limit of $5 M_{\text{Jupiter}}$), we conclude that the observed distribution is the result of a recent event. We discuss the possibility of a recent stellar fly-by (unlikely because of the absence of a likely candidate) or internal instability which disrupted a (cleared-out) disk around DoAr 21. Other ‘transitional’ disks also show non-axisymmetric, ‘blobby’ structures, albeit at much lower contrast than seen toward DoAr 21 (Brown et al. 2008). An alternative explanation for the observed structure around DoAr 21 is, that the star is illuminating, and partially sweeping up unrelated material from the Ophiuchus cloud. Future epoch observations are required to rule out any of these scenarios.

Our observations show that not all young stars with ‘transitional’ SEDs are surrounded by disks with cleared-out inner regions. Spatially resolved observations are essential to firmly determine the nature of the circumstellar material. Deep mid-infrared imaging and aperture synthesis observations at (sub)millimeter wavelengths with, e.g., ALMA provide good tools to locate the warm and cold dust, respectively.

Conversely, our observations may provide a clue as to why objects with ‘transitional’ SEDs are overrepresented in the list of stars with detected quiescent ro-vibrational H_2 emission (Bary et al. 2008). First, excitation of these lines requires the presence of hot gas (> 1000 K), likely heated by stellar X-rays. These same X-rays may cause the inner disk regions to photoevaporate on a short timescale (e.g., Gorti & Hollenbach 2009). Second, and perhaps most important, once the region immediately around the star has been cleared of gas, the surface illuminated by the X-rays increases (provided there is dense material at these larger radii). As long as the X-ray luminosity is sufficiently high to heat this larger surface to > 1000 K, a larger H_2 line emitting area results, and therefore a higher line flux. At the same time, the dust in these regions will also be heated by the stellar radiation, generating the mid-infrared excess. In contrast, objects with a strong near-infrared excess have large amounts of gas and dust near the star, sufficient to block X-rays from penetrating to larger distances. In this picture, detectable quiescent ro-vibrational H_2 emission will arise when the distribution of circumstellar material allows the stellar X-rays to illuminate a sufficiently large area on the sky. In these cases, AO-assisted IFU observations of the H_2 in the K-band uniquely offer the possibility for high spatial-resolution imaging of the (illuminated) molecular gas.

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