A SLOWLY ACCRETING ~10 Myr–OLD TRANSITIONAL DISK IN ORION OB1a

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Abstract

Here we present the Spitzer IRS spectrum of CVSO 224, the sole transitional disk located within the ~10 Myr old 25 Orionis group in Orion OB1a. A model fit to the spectral energy distribution of this object indicates a ~7 AU inner disk hole that contains a small amount of optically thick dust. In previous studies, CVSO 224 had been classified as a weak-line T Tauri star based on its Hα equivalent width, but here we find an accretion rate of $7 \times 10^{-11} M_\odot yr^{-1}$ based on high-resolution Hectochelle data. CVSO 224’s low $M$ is in line with photoevaporative clearing theories. However, the Spitzer IRS spectrum of CVSO 224 has a substantial mid-infrared excess beyond 20 μm which indicates that it is surrounded by a massive outer disk. Millimeter measurements are necessary to constrain the mass of the outer disk around CVSO 224 in order to confirm that photoevaporation is not the mechanism behind creating its inner disk hole.

Subject headings: accretion, accretion disks — circumstellar matter — stars: formation — stars: pre–main-sequence

Online material: color figures

1. INTRODUCTION

Stars surrounded by transitional disks have characteristics that fall between objects that have clear evidence for disks and stars with no disk material. They have deficits of infrared flux at $\lambda < 8 \mu m$ but show strong excesses at longer wavelengths, indicating that the innermost regions have undergone significant clearing of small dust grains (Strom et al. 1989; Skrutskie et al. 1990).

The Spitzer Space Telescope has greatly improved our resolution in the infrared and has recently provoked extensive modeling studies of several transitional disks around T Tauri stars, e.g., TW Hya (Uchida et al. 2004), GM Aur, DM Tau (Calvet et al. 2005a), CS Cha (Espaillat et al. 2007a), HD 98800B (Furlan et al. 2007), and Hen 3-600 (Uchida et al. 2004). These objects have been explained as inwardly truncated disks which are optically thick to the stellar radiation, with most of the mid-infrared emission originating in the inner edge or “wall” of the outer disk. Spectral energy distributions (SEDs) point to holes in these disks of less than ~40 AU. The inner holes of the transitional disks around DM Tau and CoKu Tau/4 are cleared of small dust grains (D’Alessio et al. 2005; Calvet et al. 2005a) while the transitional disks GM Aur, TW Hya, CS Cha, HD 98800B, and Hen 3-600 have a small yet detectable near-infrared excess produced by some submicron- and micron-sized optically thin dust remaining in the inner disk hole (Calvet et al. 2002, 2005a; Espaillat et al. 2007a; Furlan et al. 2007; Uchida et al. 2004). In addition to these disks with holes (i.e., large reductions of small dust grains from the star out to an outer optically thick wall), the “pretransitional disk” class has recently been identified (Espaillat et al. 2007b). These objects, exemplified by UX Tau A and LkCa 15, have an inner optically thick disk separated from an outer optically thick disk by an optically thin gap (Espaillat et al. 2007b, 2008).

One possible cause for these dust clearings in transitional and pretransitional disks is planet formation. Hydrodynamical simulations have shown that a newly formed planet could accrete and sweep out the material around it through tidal disturbances (Quillen et al. 2004; Rice et al. 2003; Paardekooper & Mellema 2004; Varnière et al. 2006). Stellar companions could also dynamically clear the inner disk (Artymowicz & Lubow 1994). Additional dust clearing theories include inside-out evacuation induced by the magnetorotational instability (MRI; Chiang & Murray-Clay 2007) and photoevaporation (Clarke et al. 2001).

The holes of GM Aur, TW Hya, and DM Tau can potentially be explained by the MRI. It has been proposed that the MRI can operate on the ionized inner wall of the disk which leads material to accrete from the wall onto the star, creating a hole in the disk that grows from the inside-out (Chiang & Murray-Clay 2007). In order for photoevaporation to be effective, the disk mass must be below ~0.005 $M_\odot$ and the disk accretion rate must fall below the wind rate (~$10^{-10} M_\odot yr^{-1}$; Alexander & Armitage 2007, hereafter AA07). Photoevaporation cannot explain the holes of these three objects since their outer disks are massive ($M_{\text{disk}} > 0.05 M_\odot$; Calvet et al. 2002, 2005a) and their accretion rates are higher than the photoevaporative wind rate. Neither the MRI nor photoevaporation can explain the gaps seen in UX Tau A and LkCa 15 given that these inside-out clearing mechanisms cannot account for a remnant optically thick inner disk. Photoevaporation could in principle explain CoKu Tau/4’s hole since this object has a weak outer disk ($M_{\text{disk}} \sim 0.0005 M_\odot$; Andrews & Williams 2005) and a non-detectable accretion rate; however, its disk clearing is most likely caused by its recently discovered stellar companion (Ireland & Kraus 2008). HD 98800B and Hen 3-600 are additional examples of a transitional disk where a stellar companion is apparently responsible for the disk’s hole (Furlan et al. 2007;
Uchida et al. (2004). Guenther et al. (2007) also found a companion in the inner hole of CS Cha although the separation of the stellar pair is less than 5 AU (E. Guenther 2007, private communication), which is too small to explain the truncation of the outer disk at ~43 AU (Espaillat et al. 2007a) with existing models (Artymowicz & Lubow 1994). To date, a radial velocity detection of a planetary companion in a transitional disk has only been claimed in TW Hydra by Guenther et al. (2007) also found a companion in the inner hole of CS Cha although the separation of the stellar pair is less than 5 AU (E. Guenther 2007, private communication), which is too small to explain the truncation of the outer disk at ~43 AU (Espaillat et al. 2007a) with existing models (Artymowicz & Lubow 1994). To date, a radial velocity detection of a planetary companion in a transitional disk has only been claimed in TW Hydra by Guenther et al. (2007) as well as J, H, and K-band (2MASS) are shown. IRAC and MIPS data were taken from Hernández et al. (2007). An $A_V$ of 0.21 for CVSO 224 is derived from fitting an M3 photosphere (Kenyon & Hartmann 1995) to the observations, and the data are dereddened with the Mathis (1990) reddening law. The derived $A_V$ is consistent with a mean extinction of 0.5 mag found toward Orion OB1a by Calvet et al. (2005b). Stellar parameters ($M_*, R_*$; Table 1) are derived from the H-R diagram and the Baraffe evolutionary tracks (Baraffe et al. 2002) using a $T_e$ of 3470 K (Kenyon & Hartmann 1995) for an M3 star (Briceño et al. 2007). The distance to 25 Orionis is 330 pc (Espaillat et al. 2007).}

**2. OBSERVATIONS AND DATA REDUCTION**

We present the SED of CVSO 224, which is also known as 1a_1200 (Hernández et al. 2007) and 05254675+0143303 (2MASS), in Figure 1. B- and R-band photometry were taken from the USNO database, V- and I-band photometry (Briceño et al. 2007) as well as J-, H-, and K-band (2MASS) are shown. IRAC and MIPS data were taken from Hernández et al. (2007). An $A_V$ of 0.21 for CVSO 224 is derived from fitting an M3 photosphere (Kenyon & Hartmann 1995) to the observations, and the data are dereddened with the Mathis (1990) reddening law. The derived $A_V$ is consistent with a mean extinction of 0.5 mag found toward Orion OB1a by Calvet et al. (2005b). Stellar parameters ($M_*, R_*$; Table 1) are derived from the H-R diagram and the Baraffe evolutionary tracks (Baraffe et al. 2002) using a $T_e$ of 3470 K (Kenyon & Hartmann 1995) for an M3 star (Briceño et al. 2007). The distance to 25 Orionis is 330 pc (Espaillat et al. 2007). CVSO 224 was observed by the Spitzer IRS instrument on 2006 March 8 (AOR ID: 16264960) with the short-wavelength, low-resolution (SL) module of IRS and the long-wavelength, low-resolution (LL) module, covering ~5 to 40 μm, at a resolving power of $\lambda/\delta\lambda = 60–100$. The observation was carried out in IRS Staring Mode. We used the Spectral Modeling, Analysis, and Reduction Tool (SMART) software package developed by the IRS instrument team (Higdon et al. 2004) to extract and calibrate the spectrum. Furlan et al. (2006) can be consulted for further data-reduction details.

In Figure 2 we show the high-resolution ($R \sim 34,000$) spectrum of CVSO 224 centered on the Hα 6563 Å line. It was obtained with the Hectochelle multifiber instrument (Szentgyorgyi et al. 1998) mounted on the 6.5 m MMT at Mount Hopkins, Arizona for the data set presented in Briceño et al. (2007). We refer the reader to that article for details on the observations and data reduction.
3. ANALYSIS

3.1. Accretion Properties

According to theories of magnetospheric accretion, the inner disk is truncated by the stellar magnetic field and material is channeled onto the star via accretion columns. This leads to strong, broad Hα emission profiles due to the high temperatures and velocities of the accreting material (Muzerolle et al. 2001). White & Basri (2003) showed that a star is accreting if $\text{EW}(\text{H} \alpha) \geq 20 \, \AA$ for M3 stars. According to this criteria, CVSO 224, a M3 star (Briceno et al. 2007) with $\text{EW}(\text{H} \alpha)$ of $\leq 20 \, \AA$, can be classified as a weakly accreting T Tauri star (WTTS) (Briceno et al. 2007). However, some stars which lie just below this $\text{EW}(\text{H} \alpha)$ limit could be slow accretors (Barrado y Navascues & Martin 2003). When analyzing the high-resolution spectrum of CVSO 224 taken with Hectochelle (Fig. 2) we find that the width of the Hα profile at 10% is larger than 200 km s$^{-1}$ indicating that this star is accreting (White & Basri 2003).

We estimated the accretion rate using the magnetospheric accretion models of Muzerolle et al. (2001). See that paper for the details of the fitting procedure. In short, we calculated models using the mass, radius, and effective temperature of the star as fixed inputs. The gas temperature, density (calculated from $M$), and inclination were then varied to find the best fit to the observed line profile. The profile of CVSO 224 has a central self-reversal as seen in WTTS (e.g., Fig. 1 of Muzerolle et al. 2000), but also has broad wings and redshifted absorption. This suggests that we are seeing signatures of both the stellar chromosphere and the accreting material traveling in the magnetospheric field lines. Since the line core is dominated by chromospheric emission, which is not included in the models, only the line wings were considered in the fit.

The resulting best-fit model parameters are $i = 30^\circ$, $T_{\text{max}} = 12,900$ K, $M = 7 \times 10^{-11} M_\odot$ yr$^{-1}$. The inclination angle derived here is constrained to about 50% of the nominal value of 30$^\circ$ since the actual geometry is likely much more complicated (Muzerolle et al. 2001). We adopt this value for CVSO 224 since there is no other estimate for the inclination angle.

3.2. Disk Properties

When we compare CVSO 224 to the median SED of Taurus (Fig. 1; D’Alessio et al. 1999, Furlan et al. 2006), which has been shown to be representative of a full disk (D’Alessio et al. 1999, 2006), it is apparent that there is a strong infrared deficit, indicating that CVSO 224 is surrounded by a transitional disk. We follow D’Alessio et al. (2005) to calculate the structure and emission of the optically thick disk’s inner edge or “wall,” assumed to be vertical and axisymmetric. The radiative transfer in the wall atmosphere is calculated with $M_r, R_s, T_s, \text{distance}, \text{inclination, and M as well as minimum and maximum grain sizes (Table 1).}$ We use a grain-size distribution that follows a power law of $a^{-3.5}$, where $a$ is the grain radius. We assume ISM-sized grains and adopt $a_{\text{min}} = 0.005 \, \mu m$ and $a_{\text{max}} = 0.25 \, \mu m$ (Draine & Lee 1984). The wall has a radial gradient of temperature and we use its outermost temperature, $T_{\text{wall}}$, as a free parameter in fitting the SED. This temperature, combined with the dust composition, determines the wall radius (D’Alessio et al. 2005). The best fit to the SED is shown in Figure 3 and corresponds to $T_{\text{wall}} = 120$ K and $R_{\text{wall}} = 7$ AU. The wall height, $z_{\text{wall}}$ (1 AU), is also a free parameter which is dependent on the best-fit to the SED. Varying the inclination angle within 50% of 30$^\circ$ does not change the size of the inner hole.

CVSO 224 has a near-infrared excess; the ratio of its observed to photospheric emission at 5.8 $\mu m$ is 1.6. The low value of $T_{\text{wall}}$ implies that the wall can account for neither the 10 $\mu m$ silicate-feature emission nor the small near-IR excess. While a wall with a higher $T_{\text{wall}}$ produces more 10 $\mu m$ emission, it cannot account for the excess beyond 20 $\mu m$. As is seen in previous studies (Calvet et al. 2005a; Espaillat et al. 2007a), a small amount of optically thin dust can account for the 10 $\mu m$ emission and the near-IR excess. Following Calvet et al. (2002) the spectrum for the optically thin region is calculated as the sum of the emergent flux from optically thin annuli where the dust in each annulus is heated by stellar radiation. We hold the inner radius fixed at the dust destruction radius (0.04 AU) and the outer radius is determined by the best fit (1 AU). The silicate feature is well fit with $a_{\text{max}} = 4 \, \mu m$ and probes temperatures of $\sim 190-1110$ K. About $4 \times 10^{-12} M_\odot$ of dust exists in the optically thin region which can be composed of $\sim 80\%$ amorphous silicates, $\sim 14\%$ organics, $\sim 3\%$ amorphous carbon, $\sim 2.6\%$ troilite, and less than 1% enstatite and forsterite. The total emission of this optically thin region is scaled to the vertical optical depth at 10 $\mu m$, $\tau_0 \sim 0.025$.

Since there are no far-infrared or millimeter measurements for CVSO 224, we cannot constrain the contribution to the SED from the outer disk. However, previous papers have shown that the wall and optically thin dust region dominate the mid-infrared flux (Calvet et al. 2005a; Espaillat et al. 2007a, 2007b) and so in this first approximation we neglect the outer disk.

4. DISCUSSION AND CONCLUSIONS

CVSO 224 is $\sim 10$ Myr old, making it one of the oldest transitional disks around a classical T Tauri star. TW Hya is another $\sim 10$ Myr old transitional disk that has been studied in
in transitional disks. Photoevaporation will create an
degrees of dust processing (Watson et al. 2008).
result in crystalline silicates. This lack of cystallization is in
plain given that one would expect 10 Myr of processing to
signs of crystalline silicates in their disks. This is hard to ex-
Aur and LkCa 15, CVSO 224 and TW Hya have no obvious
the optically thin dust and dust evolution over time. Like GM
are possibly the result of the inward drift of small dust grains
from the outer disk (Rice et al. 2006). Larger dust grains in
optically thin regions of older transitional disks may imply
that there is some correlation between the process that creates
the optically thin dust and dust evolution over time. Like GM
Espaillat et al. 2007b; Calvet et al. 2005a). These optically thin disks
photoevaporated, one can speculate that the of the outer
disk hole we observe in CVSO 224. In addition, AA07 show that
mass accretion rate past a planet and into the inner disk is
10%–25% of the mass accretion rate outside the planet’s orbit.
Alternatively, the low mass accretion rate of CVSO 224 could also be due to a stellar companion. Hen 3-600 is another weakly
accreting ∼10 Myr old transitional disk (5 × 10^{-11} M_☉ yr^{-1}
Muzerolle et al. 2000) whose hole is most likely due to dy-
namical clearing by its companion (Uchida et al. 2004). Its low
M also indicates that photoevaporation should be clearing this
disk; however, Hen 3-600 has a small hole (∼1 AU; Uchida et al. 2004) and its infrared excess (Low et al. 2005) indicates a substantial outer disk. Hen 3-600’s M_{disk} could be limited by binary tidal forces (Artymowicz & Lubow 1996) and not be reflective of M_{disk}.

CVSO 224 presents an opportune test of photoevaporation and planet formation in older disks and further observations of this object will help clarify the role of photoevaporation in disk clearing. Millimeter studies of CVSO 224 are necessary to derive the mass of its outer disk. If a massive disk is present, its low M could be due to a planetary or stellar companion and more study will be needed to distinguish between these two scenarios.

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