THE EVOLUTION OF ACCRETION IN YOUNG STELLAR OBJECTS: STRONG ACCRETORS AT 3–10 Myr*

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ABSTRACT

While the rate of accretion onto T Tauri stars is predicted to decline with age, objects with strong accretion have been detected at ages of up to 10 Myr. We analyze a sample of these old accretors, identified by having a significant U band excess and infrared emission from a circumstellar disk. Objects were selected from the ~3 Myr σ Ori, 4–6 Myr Orion OB1b, and 7–10 Myr Orion OB1a star forming associations. We use high-resolution spectra from the Magellan Inamori Kyocera Echelle to estimate the veiling of absorption lines and calculate extinction for our T Tauri sample. We also use observations obtained with the Magellan Echellette and, in a few cases, the SWIFT Ultraviolet and Optical Telescope to estimate the excess produced in the accretion shock, which is then fit with accretion shock models to estimate the accretion rate. We find that even objects as old as 10 Myr may have high accretion rates, up to \(10^{-8} M_\odot\) yr\(^{-1}\). These objects cannot be explained by viscous evolution models, which would deplete the disk in shorter timescales unless the initial disk mass is very high, a situation that is unstable. We show that the infrared spectral energy distribution of one object, CVSO 206, does not reveal evidence of significant dust evolution, which would be expected during the 10 Myr lifetime. We compare this object to predictions from photoevaporation and planet formation models and suggest that neither of these processes have had a strong impact on the disk of CVSO 206.

Key words: accretion, accretion disks – circumstellar matter – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

The timescales relevant for circumstellar disk evolution are key to consider for planetary formation scenarios. For example, the surface density of gas in the disk determines the migratory path of young planets and establishes traps where planet migration may be halted (Kretke & Lin 2012), so the gas dispersal time impacts the ability for a planet to survive. Inner disk gas is difficult to observe directly because many lines are emitted in the far-ultraviolet (FUV) spectra (France et al. 2012; Schindhelm et al. 2012). Alternatively, the accretion of material from the disk onto the star provides a tracer of the amount of inner disk gas through the mass accretion rate, or \(M_{\text{acc}}\). In the current paradigm for mass accretion, the stellar magnetic field truncates the disk at a few stellar radii, where material falls onto the star along the magnetic field lines forming a shock at the stellar surface (Uchida & Shibata 1984; Hartmann et al. 1994). Calvet & Gullbring (1998) showed that the shock emits high energy photons that are re-processed in the accretion streams, producing an accretion spectrum peaked in the ultraviolet (UV). T Tauri stars are identified as classical T Tauri stars (CTTSs) or weak T Tauri stars (WTTSs), accreting and non-accreting, respectively, by observing Hα, thought to be formed in the accretion flows (Edwards et al. 1994; Muzerolle et al. 1998, 2001). Originally, CTTSs and WTTSs were distinguished by measuring the Hα equivalent width (Herbig & Bell 1988); however, the definition has evolved with the availability of high-resolution spectra. The equivalent width cutoff between CTTS and WTTS was shown to depend on the spectral type of the star (White & Basri 2003; Barrado y Navascués & Martín 2003). Additionally, sources with wide wings or asymmetric line profiles were identified as accretors, whereas narrow (<200 km s\(^{-1}\)) symmetric lines are produced by chromospheric activity in non-accretors (White & Ghez 2001; Natta et al. 2004). The distinction between CTTS and WTTS typically distinguishes between Class II and Class III objects as well. Class II and Class III refer to an infrared (IR) tracer of the properties of dust in the circumstellar disk, where Class II objects have full disks and Class III objects have little to no dust in the inner disk. So far, only one known star, MN Lup, has no indication of a disk in Spitzer 3.6–70 µm data but is accreting at a very low rate. A soft X-ray excess and wide Hα wings were detected as evidence for accretion. This object is expected to be going through a very short-lived phase in which the disk is optically thin and the last of the gas is accreting (Guenther et al. 2013).

Observations of young stars have revealed that accretion rates start high, up to \(10^{-4} M_\odot\) yr\(^{-1}\) during the early FU Ori outburst phase (Hartmann & Kenyon 1985; Vorobyov & Basu 2006), fall to approximately \(10^{-8} M_\odot\) yr\(^{-1}\) after the outbursts end (Calvet et al. 2005), and drop to very low levels (\(10^{-10}–10^{-11} M_\odot\) yr\(^{-1}\)) or stop completely by 10 Myr (Muzerolle et al. 2000; Espaillat et al. 2008; Ingleby et al. 2011). Indeed, the fraction of accreting objects in a given star-forming region decreases with the age of the region (Fedele et al. 2010). There are a number of ways in which magnetospheric accretion may be halted. If the disk is truncated outside of the co-rotation radius, all the gas will disperse in a slow wind away from the star instead of accreting onto the star (Bouvier et al. 2007). Alternatively, the disk material may be depleted in both the inner and outer disk (Ingleby et al. 2012), stopping the inward flow of
material through the disk. Processes for depleting the full disk include viscous evolution combined with photoevaporation by the central star (Clarke et al. 2001; Font et al. 2004; Alexander et al. 2006; Gorti et al. 2009; Owen et al. 2010, 2012) or nearby hot stars (Adams et al. 2004; Anderson et al. 2013) and clearing of disk regions by planet formation (Lubow & D'Angelo 2006; Zhu et al. 2011). One or more of these processes may be ongoing in a circumstellar disk and each deplete the disk on different timescales (Rosotti et al. 2013).

Clearly, the disk and accretion properties are related and both are expected to evolve with age; the disk mass decreases (as well as the fraction of sources with disks) while the accretion rate drops (Hernández et al. 2007b; Fedele et al. 2010). Typically, older CTTS have low mass accretion rates; however, very few CTTS remain at 10 Myr, so they have not been well studied. In this paper, we calculate accretion rates for eight CTTS in the 3–10 Myr age range to illustrate that objects may continue accreting strongly out to 10 Myr, possibly posing an issue for disk evolution theory. This span of ages covers the time when only half of the stars in a cluster retain disks (~3 Myr) to ages greater than the expected time for all sources to lose their disks, around 6 Myr (Hernández et al. 2008). These objects have $U$-band excesses over the expected $U$-band emission from a WTTS of the same spectral type, indicating ongoing accretion. The $U$-band excess is a common way to measure $\dot{M}_{\text{acc}}$, using calibrations between $L_U$ and the accretion luminosity $\dot{L}_{\text{acc}}$ (Gullbring et al. 1998); however, it does not provide information on the shape of the excess in the ultraviolet (UV) or optical spectra, which is important for accurate accretion rate estimates. Obtaining a UV spectrum is time consuming and difficult to do for weak or distant objects, so here we use optical spectra containing the Balmer jump combined with accretion shock models to determine the shape of the accretion excess. The Balmer jump provides crucial information about the slope of the excess extending into the UV spectra. In fact, the ratio of the continuum on each side of the Balmer jump has been shown to depend on the accretion rate (Herczeg & Hillenbrand 2008).

In Section 2, we discuss our targets and the observations used in our analysis, including optical spectra from the Magellan Observatory, optical photometry from the Michigan–Dartmouth–MIT (MDM) Observatory, and UV photometry from SWIFT when available. Section 3 outlines the steps involved in calculating accretion rates and Section 4 presents the results from our analysis. Finally, in Section 5, we compare our results to theories of pre-main-sequence evolution and highlight one of the oldest objects in our sample as a source with unexpected disk and accretion emission at an advanced age.

### 2. SAMPLE AND OBSERVATIONS

#### 2.1. The Targets

The widespread star-forming complex in Orion offers an ideal opportunity to study evolving stars in diverse environments. Outside of the Orion A and B clouds, which contain the youngest stars such as the dense Orion Nebular Cluster, lie older, less extincted young stellar associations. Here, we focus on a few sources in the ~3 Myr $\sigma$ Ori, 4–6 Myr Orion OB1b and 7–10 Myr Orion OB1a regions (Table 1). These associations are interesting because they are older than the well-studied 1 Myr Taurus and 2 Myr Chamaeleon I star-forming regions, but still contain CTTS. Sources in $\sigma$ Ori (SO 540 and SO 1036) were selected from Class II sources in Hernández et al. (2007b) and were expected to be accreting. Objects in OB1a (CVSO 206 and OB1a 1630) and OB1b (CVSO 58, CVSO 90, CVSO 107, and CVSO 109) were identified as accreting in Briceño et al. (2005). Orion OB1b and OB1a targets were also classified as

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### Table 1

Log of Observations

| Object | R.A. (J2000) | Decl. (J2000) | Telescope/Instrument | Date of Obs | UT (h/m/min) |
|--------|-------------|--------------|----------------------|-------------|--------------|
| SO 540 | 05 38 29.14 | −02 16 15.7 | Magellan/MIKE        | 2009 Nov 21 | 07:07        |
|        |             |              | Magellan/MagE        | 2009 Nov 21 | 06:09        |
|        |             |              | MDM/4k               | 2009 Nov 22 | 08:20        |
|        |             |              | SWIFT/UVOT          | 2011 Mar 11 | 07:28        |
| SO 1036| 05 39 25.23 | −02 38 22.0 | Magellan/MIKE        | 2009 Nov 21 | 07:28        |
|        |             |              | Magellan/MagE        | 2009 Nov 21 | 06:25        |
|        |             |              | MDM/4k               | 2009 Nov 22 | 08:26        |
| CVSO 58| 05 29 23.26 | −01 25 15.5 | Magellan/MIKE        | 2009 Nov 22 | 03:07        |
|        |             |              | Magellan/MagE        | 2009 Nov 22 | 05:31        |
|        |             |              | MDM/4k               | 2009 Nov 23 | 05:44        |
| CVSO 90| 05 31 20.63 | −00 49 19.8 | Magellan/MIKE        | 2009 Nov 22 | 06:47        |
|        |             |              | Magellan/MagE        | 2009 Nov 22 | 06:34        |
|        |             |              | MDM/4k               | 2009 Nov 22 | 12:19        |
| CVSO 107| 05 32 25.79| −00 36 53.4 | Magellan/MIKE        | 2009 Nov 22 | 07:11        |
|        |             |              | Magellan/MagE        | 2009 Nov 22 | 06:08        |
|        |             |              | MDM/4k               | 2009 Nov 23 | 05:50        |
| CVSO 109| 05 32 32.65| −01 13 46.1 | Magellan/MIKE        | 2009 Nov 20 | 05:56        |
|        |             |              | Magellan/MagE        | 2009 Nov 20 | 03:27        |
|        |             |              | MDM/4k               | 2009 Nov 21 | 08:47        |
| CVSO 206| 05 24 41.03 | 01 54 38.6  | Magellan/MIKE        | 2009 Nov 22 | 04:01        |
|        |             |              | Magellan/MagE        | 2009 Nov 22 | 05:46        |
|        |             |              | MDM/4k               | 2009 Nov 23 | 05:38        |
| OB1a 1630| 05 26 55.37| 01 40 22.4  | Magellan/MIKE        | 2009 Nov 22 | 07:34        |
|        |             |              | Magellan/MagE        | 2009 Nov 22 | 06:18        |
|        |             |              | MDM/4k               | 2009 Nov 23 | 05:44        |
|        |             |              | SWIFT/UVOT          | 2010 Apr 9  |              |
Figure 1. Youths indicators in the CTTS sample. A portion of the MagE spectrum is shown for each source in the sample, revealing the presence of the H\(\alpha\) and the 6707.8 Å Li\(\text{I}\) absorption line. The Li\(\text{I}\) line in CVSO 90 is weak due to veiling (see Section 3.2). He\(\text{I}\) emission at 6678 Å is an indicator of accretion detected in the MagE spectra.

Class II objects in Hernández et al. (2007a). Our OB1a objects reside in a distinct group within OB1a, 25 Ori (Briceño et al. 2007).

The membership of the CIDA Variability Survey of Orion (CVSO) objects to the subassociations Orion OB1a or 1b was determined in Briceño et al. (2005) and Briceño et al. (2007). They were initially selected as variable objects that fell above the zero age main sequence in a \(V\) versus \(V-I\_C\) diagram and were confirmed as members based on the depth of the Li\(\text{I}\)\(\lambda 6707\) line and/or other indicators of youth. In Figure 1, we show a portion of the MagE spectra of these stars, including the Li\(\text{I}\) and H\(\alpha\) lines, in agreement with those results. Membership was further confirmed using radial velocities in Briceño et al. (2007). Object OB1a 1630 was selected as a member of 25 Ori from its location in the region of Class II sources in the Spitzer Infrared Array Camera (IRAC) [4.5]–[5.8] versus [5.8]–[8.0] and [3.6]–[5.8] versus [4.5]–[8.0] diagrams (Hernández et al. 2007a). Here, we confirm its membership from the presence and depth of Li\(\lambda 6707\) (Figure 1). Membership of SO 540 and SO 1036 to σ Ori was established by Caballero (2008) and Sacco et al. (2008), based again on the strength of the Li\(\text{I}\) line, which we confirm with our spectra in Figure 1. In addition, their colors in the [4.5]–[5.8] versus [5.8]–[8.0] and [3.6]–[5.8] versus [4.5]–[8.0] diagrams showed them to be Class II objects (Hernández et al. 2007b).

In this paper, we consider that the age of the object is the same as the mean age of the population to which it belongs. The σ Ori cluster has been well studied in the literature and the range of ages estimated is 2–4 Myr (Zapatero Osorio et al. 2002; Oliveira et al. 2002; Sherry et al. 2004). Briceño et al. (2005) estimated the ages of the subassociations OB1b and OB1a, taking into account uncertainties in the distance and depth of each association and in the isochrones used, resulting in a range from 7.4–10 Myr for 25 Ori and 5.5–6 Myr for Orion OB1b.

The sample also includes five WTTS of varying spectral types used for comparison to the CTTS spectra, listed in Table 2. WTTS were selected from σ Ori, Orion OB1b, and Orion OB1a when available and were confirmed to be WTTS based on
high-resolution Hα spectra discussed in the next section. CHXR 48 is a WTTS in the Chamaeleon I star-forming region and was included due to the lack of a suitable late-type WTTS in the regions of interest in this analysis.

### 2.2. Spectral Observations with MagE

We observed eight CTTS and five WTTS with the Magellan Echellette (MagE) and the Magellan Inamori Kyocera Echelle (MIKE) on the Magellan Clay telescope at Las Campanas Observatory during 2009 November. The combination of instruments provided long wavelength coverage, with medium-resolution spectra \( R \sim 4100 \) extending down to 3300 A with MagE and high resolution of fainter red absorption lines with MIKE \( R \sim 35,000 \). We focus on data from the red arm of MIKE, which cover 4900–9500 A and do not include the blue (3350–5000 A) because MIKE does not have the needed sensitivity in the blue. MagE and MIKE data were reduced using the Image Reduction and Analysis Facility (IRAF) tasks CCDPROC, APFLATTEN, and DOECSLIT (Tody 1993). Due to the variable nature of T Tauri stars, we observed each source with MIKE and MagE as near to each other as possible. Ideally, observations were separated by 15 minutes to 3 hr. On some occasions, sources were observed with MIKE and MagE on subsequent nights due to unforeseen weather complications.

### 2.3. Photometry with MDM

In order to flux calibrate the MagE spectra, we coordinated the Magellan observing run with observations at the MDM observatory near Tucson, Arizona. Given variable weather conditions at the two sites, we were able to get photometric observations within one night of our spectral observations. We obtained optical photometry with the Ohio State University Blue 4K CCD (hereafter the 4K imager) on the MDM 1.3 m McGraw-Hill telescope. The 4K imager has a 21.3” square field of view. We used 2 × 2 binning, which gives a plate scale of 0.63. The 4k imager has a known issue of crosstalk between the four CCD segments. When a CCD pixel is saturated, it creates spurious point sources in corresponding pixels on the other three segments. The exposure sequence consisted of one set of short exposures (30, 20, 20, and 15 s) and one set of long exposures (300, 240, 180, and 180) in the \( U, V, R, \) and \( I \) photometric bands. Landolt standard fields were obtained each night for photometric calibration in the Johnson photometric system. Since the readout of the 4K imager uses four amplifiers, we have four overscan regions in each CCD frame. First, we applied an overscan correction using the IDL program proc4k written by Jason Eastman. We then performed the basic reduction following the standard procedure using IRAF. We obtained aperture photometry with the IRAFphot package, using an aperture of 8”, or \( \sim3.4 \) times the FWHM. The rms departures of the standard stars from the calibration equations are \( \sim0.03 \) mag for \( V, R, \) and \( I \) bands, and \( \sim0.08 \) for \( U − V \) color. Observed magnitudes are provided in Table 3. CTTS are known to vary on timescales from hours to years. While high cadence light curves are not available for the objects in this sample, Briceño et al. (2007) found that typically CTTS vary in \( V \) by \( \sim0.6 \) mag. Due to time differences in our Magellan and MDM observations, this introduces an uncertainty in the flux of \( \sim50\% \).

### 2.4. Producing the MagE Spectrum

MagE is an echellette and therefore the orders must be pieced together in order to produce a continuous spectrum over all wavelengths. To correct for the sensitivity function across each order, we also observed flux standards during our observing program. Ideally, the flux standards were observed at the same airmass and near the same time as the targets. These flux standards are part of the European Southern Observatory’s Optical and UV Spectrophotometric Standard Stars sample, which provides flux calibrated spectra over the wavelength range we are interested in. We compared each order of the observed flux standard to the spectrum in the catalog and calculated the correction between the observation and catalog spectrum. This same correction was then applied to our T Tauri stars. This step does not flux calibrate the T Tauri star spectra but does remove the sensitivity function of each order. In order to flux calibrate our source spectra, we scaled the MagE spectrum to photometry obtained at MDM as close to our MagE observations as possible.

### 2.5. SWIFT/UVOT Photometry

Accretion emission is best observed in the UV, where the shock excess peaks and the stellar photosphere is dim. We obtained UV observations of a few of the CTTS in this sample

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**Table 2**

| Object  | SpT | \( A_v \) | Region  |
|---------|-----|---------|---------|
| 2MASS J05264681+0226039 | M1 | 0.2 | Orion OB1a |
| CHXR 48 | M1.5 | 1.1 | Chamaeleon I |
| CVSO 127 | M0.5 | 0.4 | Orion OB1b |
| CVSO 173 | K7 | 0 | Orion OB1b |
| SO 774 | K7.5 | 1.6 | σ Ori |

**Note.** a Error on spectral type is ±1 subclass.

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**Table 3**

| Object | \( U^a \) | \( V^a \) | \( R^a \) | \( I^a \) | \( U/VW^b \) | \( U/VM^b \) | \( U/VW^b \) | \( U/VW^b \) | \( R^b \) | \( V^b \) |
|--------|--------|--------|--------|--------|------------|------------|------------|------------|--------|--------|
| SO 540 | 16.03  | 14.50  | 13.64  | 12.87  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| SO 1056| 15.58  | 14.72  | 13.74  | 12.77  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| CVSO 58| 15.55  | 14.92  | 14.16  | 13.28  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| CVSO 90| 15.16  | 15.71  | 14.85  | 13.87  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| CVSO 107| 16.04 | 14.88  | 13.98  | 12.98  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| CVSO 190| 15.67 | 14.33  | 13.46  | 12.45  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| CVSO 206| 15.17 | 14.39  | 13.58  | 12.76  | 17.58      | 17.52      | 16.57      | 15.72      | 15.66  | 14.63  |
| OB1a 1630| 16.26 | 15.60  | 14.84  | 13.94  | 17.07      | 16.56      | 16.04      | 15.91      | 16.64  | 16.03  |

**Notes.**

- a Photometry from MDM.
- b Photometry from SWIFT.
with the Ultraviolet and Optical Telescope (UVOT) on the SWIFT Gamma-Ray Burst Explorer in SWIFT GI program No. 6090725 (PI: N. Calvet). We chose fields of view with SWIFT that covered as many young stars as possible while avoiding bright stars that were not safe for the UVOT detector. The UVOT camera is ideal for accretion rate analysis because it has three filters in the near-UV (NUV; UVW1, UVW2, and UVW2) as well as U, B, and V filters and observations in all six filters could be obtained in approximately 1 hr. The bandpass of each UV filter is 2200–4000 Å for UVW1, 2000–2800 Å for UVM2, and 1800–2600 Å in UVW2. Unfortunately, the UVW1 and UVW2 filters have a red leak, where the tail of the transmission curves extends well into optical wavelengths. As late-type stars, our objects are very red, especially for those with low $M_{\text{acc}}$, and therefore a significant fraction of the UVW1 and UVW2 fluxes comes from the star instead of the NUV excess produced by the shock. Alternatively, the $UVM2$ filter at 2221 Å does not have a red leak and therefore the observed flux in that band is expected to be accurately probing the NUV excess. Our SWIFT observations were not simultaneous with the optical data; however, with $U, B, V$ observations from SWIFT and contemporaneous $U$ and $V$ photometry from MDM, we may determine whether there was significant variability between the optical and NUV sets of observations.

The SWIFT UVOT observations were analyzed using UVOTBADPIX, UVOTEXPMAP, and UVOTDETECT. UVOTBADPIX finds bad pixels in the sky images and creates a bad pixel map. UVOTEXPMAP takes the bad pixel map and creates an exposure map in sky coordinates, which gives areas in the image flagged as bad an exposure time of 0. Finally, UVOTDETECT uses the exposure map made in the previous step to identify sources detected with a signal-to-noise ratio of 3. UVOTDETECT also extracts the count rate for each detection from a region defined by an ellipse. We compared the list of $V$ band detections to lists of known T Tauri stars (Briceno et al. 2005; Hernandez et al. 2007a). Two sources, one in Orion OB1a and one in $\sigma$ Ori, were observed with all instruments in this analysis, including MIKE, MagE, the MDM 4k imager, and SWIFT. The remaining sources were not in the SWIFT fields of view due to their proximity to bright stars. A log of all observations may be found in Table 1, while UVOT magnitudes are in Table 3.

### 3. ANALYSIS OF OBSERVATIONS

#### 3.1. Spectral Types

Although spectral types were previously determined for our sample (Briceno et al. 2005, 2007; Hernandez et al. 2007b), here we re-determine them based on the MagE spectra. We use the code SPTCLASS (SPectral CLASSificator code), which classifies late K and M stars based primarily on TiO molecular bands, with an uncertainty of $\pm$1 subclass (Hernandez et al. 2004). The spectral types derived here (listed in Table 4) agree with those from the literature, within the errors. Similarly, we use SPTCLASS to confirm the spectral types of the WTTS used as templates in our analysis (see Table 2). CTTS with large continuum excesses produced in the shock may be incorrectly classified. The addition of the excess emission to the stellar photospheric spectrum produces shallower photospheric absorption lines (Hartigan et al. 1989), complicating spectral typing. SPTCLASS may assign an earlier spectral type to heavily veiled objects, in particular CVSO 90, so the given spectral type may be considered an early-spectral type limit (Hsu et al. 2012). Manara et al. (2013) showed that by not accounting for strong veiling, objects may be misclassified as much as one spectral class.

#### 3.2. Calculating Veiling in MIKE Spectra

It is important to determine the extent to which the absorption lines are veiled because it provides information of the relative contributions to the spectra from the emission of the accreting material and the underlying stellar photosphere. Figure 2 shows examples of veiled absorption lines for the sources in our sample. We measure veiling as the ratio of the continuum to the emission of the accreting material and the underlying stellar photosphere. Figure 2 shows examples of veiled absorption lines for the sources in our sample. We measure veiling as the ratio of the continuum to the emission of the accreting material and the underlying stellar photosphere. Differential veiling over a short wavelength range and the possibility of emission cores produced on photospheric absorption lines contribute to errors in our veiling estimates (Gahm et al. 2008; Dodin & Lamzin 2012). Therefore, we measure veiling across the entire available MIKE spectrum, following the methods of Gullbring et al. (1998), by splitting the MIKE spectra into pieces of $\sim$15 Å, avoiding any known emission lines produced by shock emission. We use a WTTS of the same spectral type as a template with the continua of both the WTTS and CTTS normalized to unity. Continuum emission is added to the spectrum of the WTTS in each 15 Å interval in small increments between some minimum and maximum amount of veiling determined by eye and then renormalized by dividing by $1 + r_\lambda$, where $r_\lambda$ is the veiling per wavelength. A reduced $\chi^2$ test, $\chi^2_{\text{red}}$, is calculated for each spectrum of the WTTS plus the continuum compared to the CTTS and the fit with the lowest $\chi^2_{\text{red}}$ is assumed for that interval.
Figure 2. Observed veiling in MIKE spectra between 6100 and 6130 Å. The black solid line in each panel is the CTTS and the red dashed line is a WTTS template of the same spectral type. We list the measured veiling in this region at the bottom. Strong Ca\textsc{i} absorption lines are observed at 6102.7 and 6122.2 Å (Merle et al. 2011). Li\textsc{i} absorption is also detected against the Ca\textsc{i} line at 6103.5 Å in most sources. (A color version of this figure is available in the online journal.)

This process is completed for each interval and the best fit is examined by eye and either accepted or rejected. We are using real data as templates rather than models, so there are unforeseeable imperfections in the templates. For most sources, we used two different WTTS with spectral types equal to or within ±0.5 subclasses to confirm that veilings were not dependent on the WTTS template chosen. Finally a veiling “spectrum” was made and a third-order polynomial was fit to determine the function of veiling versus wavelength (Figure 3).

The line was first fit to all the data and then the standard deviation from that line was determined. A new line was fit to the data within one standard deviation of the first fit in order to omit any spurious veiling measurements. In most cases, veiling decreases as wavelength increases due to the shock emission peak in the UV. From this fit, we determined the veiling ($r_{V}$) at $V$ and $I$ and extend the function to estimate veiling at $J$. Once the veiling is known, we have an estimate of the excess emission through $r_{\lambda}$, where $e$ = excess is the shock excess producing the veiling and $p$ = photosphere is the flux of the underlying star. We use veiling at $V$ and $I$ to estimate extinction and veiling at $J$ to determine the stellar luminosity in the next section. Errors on $r_{V}$ and $r_{I}$ are listed in Table 4.

3.3. Extinction and Stellar Parameters

While these objects reside in regions with low extinction, $A_{V}$ values calculated from optical colors are >0. A significant problem with determining $A_{V}$ from optical colors is that the emission produced in the shock alters optical colors from the underlying photospheric colors. Therefore, the commonly used method of comparing $V - I$ of the CTTS to $V - I$ for a standard star of the same spectral type has error for the CTTS. We did use $V - I$ for the WTTS as there is no accretion excess to contaminate optical bands. For CVSO 127 and SO 774, we obtained $V$ and $I$ photometry with MDM. Photometry for 2MASS J05264681+0226039 and CVSO 173 came from the CIDA variability survey. The $A_{V}$ for CHXR 48 is from Luhman (2004).

For the CTTS, we used $V - I$ after correcting for the amount of veiling measured in the MIKE spectra and $F_{\lambda,\text{star}} = F_{\lambda,\text{obs}}/(1 + r_{\lambda})$, where $F_{\lambda,\text{obs}}$ is the observed flux. By correcting $V$ and $I$ by the estimated veiling at each wavelength (listed in Table 4), we have information regarding the photospheric emission below the shock excess and are able to discern how reddened the photospheric fluxes are. Using corrected $V$ and $I$ and comparing to the standard colors from Kenyon & Hartmann (1995), we estimate the extinction for our sample of T Tauri stars. Errors in $A_{V}$ are dominated by spectral type uncertainty. Recently, Pecaut & Mamajek (2013) re-evaluated the colors of dwarf stars and they differ from the Kenyon & Hartmann (1995) colors particularly for mid K to early M spectral types. The new colors would decrease our estimated $A_{V}$’s by 0.2–0.4 mag. When calculating the accretion rates in Section 4.2, the lower values of $A_{V}$ would decrease $\dot{M}_{\text{acc}}$ by a factor of 1.8–2.4. Here, we use the Kenyon & Hartmann (1995) colors to calculate $A_{V}$ for better comparison of our accretion rates to values calculated previously but note the error introduced by $A_{V}$ estimates.

To calculate stellar parameters, we used the calibration between spectral type and effective temperature in Kenyon & Hartmann (1995). We used the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) de reddened $J$ magnitudes,
Figure 3. Veiling vs. wavelength measured in MIKE spectra. For all stars except CVSO 109 and OB1a 1630, we calculated veiling using two different WTTS as templates. We found poor fits with a second WTTS template for CVSO 109 and OB1a 1630 and therefore included only one template in the analysis of these objects. The red line is a fit to the points, which we use to determine veiling at a given wavelength.

(A color version of this figure is available in the online journal.)

de-veiled using our estimated veiling from the MIKE data, and the bolometric correction per spectral type from Kenyon & Hartmann (1995) to estimate bolometric luminosities. The masses of the stars were estimated using the evolutionary tracks of Siess et al. (2000) and the stellar radii were calculated assuming distances of 440, 400, and 330 pc for σ Ori, OB1b, and OB1a, respectively. All stellar parameters may be found in Table 4. The MagE spectra and MDM photometry were de-reddened using the calculated AV and the reddening law toward HD 29647 discussed in Whittet et al. (2004).

3.4. Determining the Excess using the Veiling

To calculate the excess (or veiling) spectrum produced in the accretion shock, we scaled a WTTS of the same spectral type to the CTTS based on the veiling at V, calculated from the MIKE spectra. Figure 4 shows the MagE spectra of the CTTS sample and scaled WTTS templates. We then subtracted the WTTS from the CTTS and located continuum regions in the spectrum of the shock excess. We include the excess short of 3600 Å, and between 3800 and 8000 Å omitting wavelengths with Balmer emission lines, Ca ii h and k lines, and Na D lines. The fits are weighted toward the blue end of the spectrum, where the shock excess is stronger. These regions were used to fit the shock models to the excess spectrum (described below).

4. CALCULATING ACCRETION RATES

4.1. Description of Shock Model

The disks of CTTS are inwardly truncated at the radius where the magnetosphere intercepts the disk. Here, the strong magnetic field lines channel disk material onto the surface of the star. The material reaches the star traveling at approximately free fall velocities, forming a shock that irradiates both the star below (post-shock and heated photosphere) and the material falling along the accretion column (pre-shock) with soft X-rays. These regions reprocess the X-ray emission and the re-emitted emission peaks at UV or blue optical wavelengths (Calvet & Gullbring 1998).

An in-depth description of the accretion shock model may be found in Calvet & Gullbring (1998), where these models were first introduced. Calvet & Gullbring (1998) assumed that the shock emission was formed in a single column of accreting material, perpendicular to the stellar surface, characterized by a single energy flux (F) and filling factor (f) on the stellar
Motivated by models of the magnetosphere geometry (Donati et al. 2008; Gregory & Donati 2011; Gregory et al. 2012), Ingleby et al. (2013) showed that including multiple accretion columns, characterized by a range in energy flux and filling factor, were capable of fitting the blue as well as the red excesses observed in CTTS (Edwards et al. 2006; Fischer et al. 2011). To do so, high $F$, low $f$ columns were assumed to co-exist with low $F$, high $f$ columns. We again use the assumption that there are accretion columns with a range in properties when we fit accretion shock models to the current optical sample.

### 4.2. Results

We fit the excess spectrum of each object using accretion shock models with $\log F = 10, 10.5, 11, 11.5, \text{ and } 12 \text{ erg s}^{-1} \text{ cm}^{-2}$. For each $F$ model, we varied the filling factor and added the contribution from each column. We calculated the $\chi^2_{\text{red}}$ of each model fit to the CTTS excess spectrum to determine which combination of accretion columns gave the best fit to the MagE excess spectrum. We found that the standard accretion columns could not accurately fit most spectra in the region of the Balmer jump, around 3600 Å, with not enough excess produced at the bluest wavelengths. Objects with larger Balmer jumps can be explained by assuming lower electron densities in single temperature slab models or a larger emitting area for the low density preshock emission in the accretion shock models (Herczeg & Hillenbrand 2008). We found that in all objects except OB1a 1630, larger preshocks were needed with up to five times more preshock emission necessary. While it has not been shown where the additional low optical depth material giving rise to this excess emission resides, it is likely that the preshock emission is underestimated here due to the assumed simple geometry of the accretion columns. From models fitting Zeeman splitting observations, it is known that the magnetosphere is

![Figure 4. MagE observations of CTTS sample. The de-reddened CTTS spectra (black) are plotted along with WTTS templates (red). MagE spectra of CTTS were scaled to the contemporaneous MDM photometry (blue asterisks) for flux calibration. When available, we include SWIFT $U, V, B$ photometry (magenta squares). Errors in the photometry are smaller than their symbol sizes.](image-url)
complex, including higher-order magnetic fields (Donati et al. 2008; Gregory & Donati 2011). Therefore, the footprints of these fields on the stellar surface are likely complex and variable as well (Long et al. 2011).

The total accretion rate for each object is the sum of the accretion rates for each individual column,

$$M_{\text{acc}} = \frac{8\pi R_\star^2 v_s^2}{v_s^2} F_f,$$

where $v_s$ is the velocity of the infalling material and $R_\star$ is the radius of the star. Our best fits to the shock excess are shown in Figure 5, with a close view of the Balmer jump region shown in Figure 6. When available, we also plot the SWIFT W2, M2, and W1 photometry, keeping in mind that the red leak in the W1 and W2 filters causes the flux to be overestimated and that the M2 filter is the most reliable for this reason. While we did not explicitly fit the SWIFT photometry, it agrees well with the fit to the optical spectra even though they are not simultaneous.

The red leak is not apparent in the higher accretor OB1a 1630; however, the contamination in the short and long wavelength filters is observed in SO 540, where the accretion luminosity is low. Properties of the accretion shock model for each source are provided in Table 5. Including errors in mass, radius, and $A_V$, uncertainties in $M_{\text{acc}}$ are approximately a factor of two. Here we are not attempting to fit the emission lines produced by accretion, only the excess continuum. We note that several of the CTTS have a remaining red excess, CVSO 90, OB1a 1630, and SO 1036, in particular. These excess peaks are due to imperfect matches between the CTTS and WTTS, a result...
of slight differences in effective temperature or surface gravity. Mismatches between the CTTS and WTTS are more easily observable at red wavelengths, where the shock contribution is low. Another possibility is that the excess emission from dust in the disk is contributing a red excess; however, in most cases the flux from the disk is significantly lower than the stellar flux near 8000 Å (McClure et al. 2013a).

5. DISCUSSION

5.1. Evolution of the Accretion Rate

The objects presented in this paper are interesting because at their age, they would be expected to be weakly accreting; however, they have accretion rates similar to objects in the 1–2 Myr

![Figure 6](image-url). Accretion shock fits to Balmer jump. Spectra and lines are as defined in Figure 6 but the Balmer jump is zoomed in to show the fits of the models in this region. All sources except OB1a 1630 have larger Balmer jumps than predicted by the standard model and additional optically thin pre-shock material is needed to reproduce the observations.

(A color version of this figure is available in the online journal.)

| Object       | $f(10^{10})$ | $f(3 \times 10^{10})$ | $f(10^{11})$ | $f(3 \times 10^{11})$ | $f(10^{12})$ | $f_{\text{tot}}$ | $M_{\text{acc}}$ ($M_\odot$ yr$^{-1}$) | $L_{\text{acc}}$ ($L_\odot$) |
|--------------|--------------|------------------------|--------------|------------------------|--------------|-----------|---------------------------------|-------------------|
| SO 540       | 0            | 0.04                   | 0            | 0.0005                 | 0            | 0.0405    | $8.5 \times 10^{-9}$            | 0.1               |
| SO 1036      | 0.05         | 0                      | 0            | 0                      | 0.0002       | 0.0502    | $2.0 \times 10^{-8}$            | 0.1               |
| CVS0 58      | 0            | 0.03                   | 0            | 0                      | 0.0005       | 0.035     | $1.6 \times 10^{-8}$            | 0.3               |
| CVS0 90      | 0.002        | 0                      | 0            | 0.003                  | 0.001        | 0.006     | $1.0 \times 10^{-8}$            | 0.08              |
| CVS0 107     | 0            | 0                      | 0            | 0.0004                 | 0.0004       | 0.0004    | $2.5 \times 10^{-9}$            | 0.03              |
| CVS0 109     | 0.1          | 0                      | 0            | 0                      | 0.0003       | 0.0003    | $4.0 \times 10^{-8}$            | 0.2               |
| CVS0 206     | 0            | 0                      | 0.03         | 0                      | 0.004        | 0.034     | $4.7 \times 10^{-9}$            | 0.2               |
| OB1a 1630    | 0.005        | 0                      | 0            | 0.0002                 | 0.0003       | 0.0073    | $7.7 \times 10^{-10}$           | 0.01              |
AV has the highest average against detecting the lowest accretors in Orion OB1b because it saturation in the were not included in the sample of Rigliaco et al. (2011) due to from the star to the total flux. The highest accretors in $\sigma$ Ori (Rigliaco et al. 2011, R11), Orion OB1b, and Orion OB1a (Calvet et al. 2005, C05). One Orion OB1a transitional disk plotted, CVSO 224, has a low accretion luminosity of 0.0007 $L_\odot$ (Espaillat et al. 2008).

(A color version of this figure is available in the online journal.)

Figure 7. Accretion luminosity vs. age. Red diamonds are accretion luminosities calculated in this paper. Blue squares show accretion luminosities calculated for $\sigma$ Ori (Rigliaco et al. 2011, R11), Orion OB1b, and Orion OB1a (Calvet et al. 2005, C05). One Orion OB1a transitional disk plotted, CVSO 224, has a low accretion luminosity of 0.0007 $L_\odot$ (Espaillat et al. 2008).

Orion, Orion OB1b, and Orion OB1a (Calvet et al. 2005). One Orion OB1a transitional disk plotted, CVSO 224, has a low accretion luminosity of 0.0007 $L_\odot$ (Espaillat et al. 2008).

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(A color version of this figure is available in the online journal.)

Taurus and Chamaeleon I star-forming regions. Figure 7 compares the accretion luminosities, $L_{\text{acc}}$, found in this analysis to previously estimated $L_{\text{acc}}$ values for $\sigma$ Ori (Rigliaco et al. 2011), Orion OB1b, and Orion OB1a (Calvet et al. 2005; Espaillat et al. 2008) for objects with spectral types between K6 and M3. We select a small mass range for comparison due to the dependence of $M_{\text{acc}}$ on stellar mass (Muzerolle et al. 2005). The literature values were obtained using the $U$-band excess, which while not as accurate as multi-wavelength observations, provides an estimate of the total excess. The $L_{\text{acc}}$ for Orion OB1b objects differ from the values calculated by Calvet et al. (2005), primarily for CVSO 90 and CVSO 58. This is due to the inclusion of veiling in our estimates for $A_V$ and when determining the contribution from the star to the total flux. The highest accretors in $\sigma$ Ori were not included in the sample of Rigliaco et al. (2011) due to saturation in the $U$-band photometry. There may also be a bias against detecting the lowest accretors in Orion OB1b because it has the highest average $A_V$ of the three regions. Clearly there is a large spread in accretion properties for sources of a given age, with a range of two to three orders of magnitude in $L_{\text{acc}}$.

To investigate the range of star and disk properties responsible for creating the large distribution in $L_{\text{acc}}$ and to eliminate differences introduced by the method of obtaining the accretion properties, we compare values of $M_{\text{acc}}$ for the older objects presented here to those calculated for other star-forming regions using the same methods employed in this paper (Ingleby et al. 2013), again using objects with similar masses to the Orion samples. In particular, Ingleby et al. (2013) used the same accretion shock model to determine accretion rates for a significant sample of objects in the 1 Myr Taurus region, as well as one object in the Chamaeleon I star-forming region (at ~2 Myr) and a few older objects in the 8 Myr $\eta$ Cha and 10 Myr TW Hydra Association (TWA). The samples of accretors in $\eta$ Cha and TWA are almost complete as these are small associations with only a few known CTTS and no strong accretors. Figure 8 shows $M_{\text{acc}}$ from this work and Ingleby et al. (2013) versus the age of the association or group.

Figure 8 also shows the predicted change of $M_{\text{acc}}$ onto the star due to viscous evolution of the circumstellar disk (calculated at the disk truncation radius, R = 5 $R_\odot$), following Hartmann (2009) and Hartmann et al. (1998);

$$M_{\text{acc}} = 6 \times 10^{-7} \frac{e^{-R/R_{\text{tr}}}}{t_{\text{d}}^{1/2}} \left(1 - \frac{2R}{R_{\text{tr}}t_{\text{d}}}ight) \left(\frac{M_\odot}{0.1 M_\odot}\right) \times \left(\frac{R_1}{10 \text{ AU}}\right)^{-1} \left(\frac{\alpha}{10^{-2}}\right) \times \left(\frac{M_\odot}{0.5 M_\odot}\right)^{-1/2} \times \left(\frac{T_{100}}{10 \text{ K}}\right) M_\odot \text{ yr}^{-1},$$

where $M_{\text{acc}}$ is the accretion rate, $R_{\text{tr}}$ is the disk truncation radius, $R_1$ is the distance from the star to the disk, $\alpha$ is the viscosity parameter, $M_\odot$ is the solar mass, $T_{100}$ is the temperature of the disk, and $t_{\text{d}}$ is the disk lifetime.
where \( M_d(0) \) is the initial mass of the disk, \( \alpha \) is the dimensionless viscosity parameter, and \( T_{100} \) is the disk temperature at 100 AU. The parameter \( t_d \) is related to the age of the disk through

\[
t_d = 1 + \frac{t}{t_s},
\]

where the viscous time, \( t_s \), is given by

\[
t_s \approx 8 \times 10^3 \left( \frac{R_1}{10 \text{ AU}} \right) \left( \frac{\alpha}{10^{-2}} \right)^{-1} \times \left( \frac{M_*}{0.5 M_\odot} \right)^{1/2} \left( \frac{T_{100}}{10 \text{ K}} \right)^{-1} \text{ yr.}
\]

The quantity \( R_1 \) is the radius at which 60% of the mass resides initially. The fiducial viscous evolution model of Hartmann et al. (1998) is shown in Figure 8 as the thick dashed blue line, with parameters \( M_d(0) = 0.1 M_\odot, \alpha = 10^{-2}, M_* = 0.5 M_\odot, R_* = 2 R_\odot, R_1 = 10 \text{ AU}, \text{ and } T_{100} = 10 \text{ K}. \) This model assumes a similarity solution for disk evolution where the viscosity varies with radius in the disk but is constant in time. Angular momentum is transported by viscous stresses and the disk expands to conserve angular momentum. For a detailed description of the model, see Hartmann et al. (1998).

Given the variables in Equation (2), there are several disk or stellar properties that may extend the accretion lifetime. Increasing the initial disk mass achieves the desired effect as \( M_{\text{acc}} \propto M_d(0) \); however, at \( M_d(0) = 0.1 M_\odot \), the disk mass is nearing a critical point where it is too large relative to the mass of the star (in the range of 0.4 and 0.8 \( M_\odot \) for the Orion sample), causing the disk to be gravitationally unstable (Pringle 1981; Larson 1984; Gammie 2001). However, detailed analysis of the spectral energy distribution (SED) of young disks indicates that in some cases \( \alpha \) can be lower than in the fiducial model. McClure et al. (2013b) modeled the IR spectra of four CTTS in Taurus using the D'Alessio et al. (2006) disk models and found values of \( \alpha \) between \( 8 \times 10^{-4} \) and 0.05, therefore low \( \alpha \) values may contribute to the long disk lifetime.

In addition, circumstellar disk properties depend on the initial conditions of the cloud core that collapses to form the star and disk. Bae et al. (2013) reproduced observed disk frequencies for a given age by assuming objects form from clouds with a distribution of angular momenta. The angular velocity of the cloud core (\( \Omega \)) determines where the mass is deposited in the disk, so it is related to \( R_1 \). We assume \( R_1 \) may be approximated by the centrifugal radius (\( R_c \)), \( R_1 \approx R_c \propto \sqrt{\Omega} \) (Cassen & Moosman 1981). This means that we expect to find a distribution of \( R_1 \) consistent with the distribution of cloud angular momenta. Angular velocities derived from the velocity gradients observed in NH\(_3\) cores range between \( 5 \times 10^{-15} \) and \( 5 \times 10^{-13} \) rad s\(^{-1}\) (Goodman et al. 1993). A wider distribution was predicted by Dib et al. (2010), who used simulations of magnetized, self-gravitating molecular clouds. They found that the distribution of specific angular momentum (core angular momentum \( J \) divided by core mass \( M \)) peaks near log\((J/M) = 20 \text{ cm}^2 \text{s}^{-1}\), corresponding to \( \Omega = 1 \times 10^{-15} \) rad s\(^{-1}\), assuming uniform rotation at 0.1 pc, but can extend down to \( 10^{-16} \) rad s\(^{-1}\).

Figure 8 explores viscous evolution of \( M_{\text{acc}} \) over the parameter space in \( \alpha \) and \( \Omega \), for \( \alpha = 10^{-3} \) and \( \Omega = 10^{-6} - 10^{-14} \) rad s\(^{-1}\). Each type of line (solid, dashed, or dotted) shows constant \( \Omega \), while the color and line weight (thin black or thick blue) represents constant \( \alpha \). The behavior of \( M_{\text{acc}} \) with age may be understood by considering two cases: (1) when the viscous timescale is short compared to the age of the disk and (2) when it is the same or greater than the disk age. In the first case, \( t_s \) goes to \( t/t_s \) and \( M_{\text{acc}} \propto (R_1/\alpha)^{1/2} \propto \Omega/\alpha^{1/2} \). This condition is applicable to viscous evolution with low \( \Omega \), shown by the solid and dashed lines in Figure 8. In the second case, for long viscous timescales, \( M_{\text{acc}} \propto R_1^{-1} \alpha \) or \( M_{\text{acc}} \propto \Omega^{-2} \alpha \). At early times in Figure 8, where \( t_s > t \) (dotted lines, where \( \Omega \) is large), the evolution of \( M_{\text{acc}} \) follows this relation. Eventually, \( t \) increases until the age of the disk is larger than even long viscous timescales and the relation for \( t < t_s \) takes over and describes the remaining evolution.

Compared to measured accretion rates, we find that the models still cannot explain high \( M_{\text{acc}} \) objects in the Orion regions. In fact, the simple models cannot explain even the highest accretors, at 1 Myr, in Taurus either. In order to fit the measured accretion rates, it is necessary to increase \( M_d(0) \) to 0.5 \( M_\odot \), 5x higher than the fiducial model. It is likely that these high disk masses are gravitationally unstable. Up to the epoch of observation, most objects have accreted \(<0.1 M_\odot \), which is estimated by assuming each object has been accreting at the measured rate from \( t = 0 \) to its present age. The orange dash-dotted line in Figure 8 shows the upper limit on \( M_{\text{acc}} \), where \( \leq 0.1 M_\odot \) has been accreted over the source lifetime.

A few explanations of the discrepancy between the measured and predicted \( M_{\text{acc}} \) include time variability of accretion and the inapplicability of the similarity solution at large \( t_s \). T Tauri stars are known to be variable and significant changes in brightness, up to 3 mag, have been observed on timescales of hours to weeks, with the shortest brightening events attributed to accretion (Herbst et al. 1994). Therefore, high states of accretion may be responsible for some of the objects that cannot be described by viscous evolution, though it is unlikely that more than half the objects in this analysis were observed during these short bursts of accretion. Additionally, Equations (2)–(4) assume that \( t_s \) is short enough that any initial conditions in the disk are quickly erased and further evolution may be described by the similarity solution. However, if the viscous timescale is long, initial conditions are important and the above equations are not valid. Long viscous timescales may be necessary to explain the remaining high \( M_{\text{acc}} \) objects at 10 Myr and therefore we cannot assume the similarity solution. Initial conditions like dead zones, which are not accounted for in the analysis so far, may provide an additional reservoir of material available in the disk.

Dead zones are regions in the disk mid-plane that are not accreting (Gammie 1996). Dead zones have low (or 0) values of \( \alpha \) and therefore have long viscous timescales. For \( \alpha = 10^{-5} \), \( t_s > 10 \) Myr, allowing the dead zone to retain its mass. The maximum mass of the dead zone that may be stable against gravitational collapse is found by assuming the Toomre stability criterion is met,

\[
Q = \frac{c_s \Omega}{\pi G \Sigma} < 1.4,
\]

where \( c_s \) is the sound speed, \( \Omega_k \) is the orbital frequency, and \( \Sigma \) is the surface density in the disk. The mass inside a dead zone extending to 10 AU is

\[
M_d = \int_0^{10 \text{ AU}} \Sigma 2\pi R dR.
\]

Using the minimum \( \Sigma \) for the dead zone to be stable (Equation (5)) and assuming that the temperature scales as \( T(R) = 300 \) K (1 AU/R\(^{1/2}\)) from irradiated disk models at radii \( \gg \) than the stellar radius (D’Alessio et al. 1998, 1999, 2001).
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Figure 9. SED of CVSO 206. The range of MDM U, V, R, I photometry (black bars), taken over a four-night span is plotted along with 2MASS JHK, IRAC, and MIPS photometry from Hernández et al. (2007a), shown as black asterisks. A K7 photosphere is shown (red dashed) and the median SED of Taurus is plotted as well (D'Alessio et al. 1999, blue dotted), both normalized at J. Magenta points represent non-simultaneous optical data from Briceño et al. (2005) as well as Z, Y, J, H, K data from Visible and Infrared Survey Telescope for Astronomy (VISTA) and IR photometry from Wide-field Infrared Survey Explorer (WISE). The IR emission from CVSO 206 is in clear excess over the median of Taurus, indicating that it retains a full disk.

(A color version of this figure is available in the online journal.)

2001), the maximum mass available in the dead zone is 0.2 \( M_\odot \). This provides a significant amount of material available for accretion at later stages.

In addition to viscous evolution, there are other processes that may deplete the disk and shorten the accretion lifetime, particularly photoevaporation and planet formation, which we address in the next section.

5.2. Photoevaporation and Planet Formation in the Case of CVSO 206

Significant evolution of the circumstellar disk is likely to happen in the first 10 Myr, so objects in Orion OB1a are expected to show evidence of this evolution. We consider a member of this subassociation, CVSO 206, as an example of a 7–10 Myr object with significant ongoing accretion. Figure 9 shows the SED of CVSO 206. Compared to the median SED of all objects with disks in the Taurus star-forming region, CVSO 206 has a significant excess, showing that it retains a full dust disk. Gas is not probed by the IR excess; however, given the accretion rate, it is likely that the CVSO 206 has a full gas disk as well. With an accretion rate of \( 1 \times 10^{-8} M_\odot \) yr\(^{-1} \), the star would have accreted a minimum of 0.06–0.09 \( M_\odot \) between 1 Myr and its current age. Therefore, the minimum mass of the disk around CVSO 206 when it was 1 Myr was greater, \( M_d(1 \text{ Myr}) > 0.06–0.09 M_\odot \).

With \( M_\alpha = 0.8 M_\odot \), the disk-to-star mass ratio of this object at 1 Myr would have been \( M_d(1 \text{ Myr})/M_\star > 0.0875–0.125 \), or \( \sim 10\% \). Typical disk masses in Taurus are in the range of 0.2%–0.6% of the stellar mass (Andrews et al. 2013), indicating that CVSO 206 had an atypically massive disk at 1 Myr.

Many processes attempt to deplete the disk, including photoevaporation by high energy radiation from the central star or nearby hot stars and planet formation. Photoevaporation by the central star does not become a factor until the mass accretion rate onto the star drops below the mass loss rate. According to photoevaporation models, once the mass accretion and mass loss rates are comparable, a gap will open in the circumstellar disk, after which the inner disk accretes quickly onto the central star. After the inner disk is gone, the outer disk is directly exposed to radiation from the star and is itself depleted quickly, all in \( \sim 10^5 \) yr. For some models, this event may occur earlier than others; for instance, X-ray and FUV photoevaporation models predict mass loss rates of \( 10^{-8} M_\odot \) yr\(^{-1} \) (Owen et al. 2010; Gorti et al. 2009) while in extreme ultraviolet (EUV) photoevaporation models, the mass loss occurs at lower rates of \( 10^{-10} M_\odot \) yr\(^{-1} \) (Clarke et al. 2001; Alexander et al. 2006). The fact that there are a number of sources with accretion rates \( <10^{-8} M_\odot \) yr\(^{-1} \) in the 5 and 10 Myr Orion OB1b and OB1a regions lends more support to the low mass loss rates.

External photoevaporation by FUV radiation from nearby OB stars is another disk dispersal mechanism. Massive stars drive mass loss from the outer radii of nearby circumstellar disks, dispersing the disk mass in short timescales for the closest disks. Anderson et al. (2013) showed that even if external FUV radiation is low, the disk is quickly truncated to 100 AU or smaller. However, combining low values of \( G_0 \) (the ratio of UV radiation in a cluster to the typical value of the interstellar medium) with low \( \alpha \) results in a circumstellar disk that may be sustained against external photoevaporation. The group 25 Ori, where CVSO 206 is located, has a population of \( N \approx 500 \) stars, assuming a standard initial mass function (IMF) covering 7 pc (Briceño et al. 2005). According to results of Fataazzu & Adams (2008), the mean FUV luminosity of a cluster with 500 stars is \( \sim 5 \times 10^{37} \) erg s\(^{-1} \). Assuming the Be star 25 Orionis is at the center of the cluster, the projected distance of CVSO 206 from the center is 0.4 pc. The external FUV flux at this distance, compared to the typical interstellar value of \( 1.6 \times 10^{-17} \) erg s\(^{-1} \) cm\(^{-2} \), gives \( G_0 = 1630 \). For the disk to have survived this level of external radiation, it must have a very low \( \alpha \) value.

Dust grain coagulation, while not depleting the disk, decreases the number of small grains responsible for producing the IR excess (Dullemond & Dominik 2005). The growth of grains to planetary sizes is expected to occur between 1 and 10 Myr (Pollack et al. 1996) and planets appear to form frequently, with more than 1000 planetary candidates identified in a recent Kepler release (Batalha et al. 2013). Massive planets may form gaps or holes in the dust distribution by sweeping up material as they orbit (Lin & Papaloizou 1986; Bryden et al. 1999; Calvet et al. 2002; Espaillat et al. 2010). Zhu et al. (2011) showed that it may require multiple planets to open a gap large enough to be identified in infrared spectra. CVSO 206 shows no evidence for a gap or hole in the disk and must have remaining small grains to produce the observed IR excess. Still, it may contain planets that are not massive enough to open a detectable gap.

In summary, to explain the remaining full disk around CVSO 206, the disk may have low viscosity, slowing the spread to large radii and diminishing the effect of external radiation driving mass loss from the disk. Given that lower \( \alpha \) values increase the accretion lifetime and therefore may be characteristic of this disk, it is feasible that the disk of CVSO 206 could survive against external photoevaporation as long as 10 Myr (Anderson et al. 2013). With \( M_{\text{acc}} = 1 \times 10^{-8} M_\odot \) yr\(^{-1} \), photoevaporation by the central object may be dominated by any of the X-ray, FUV, or EUV fields as the accretion rate still exceeds the mass loss rates predicted by all models. As a result, we would not expect internal photoevaporation to have significantly altered the disk. Finally, the IR SED shows that planets the size or quantity capable of opening a large gap in the disk must not be present, though small planets in the disk cannot be ruled out. Birnstiel
et al. (2009) showed that collisions causing fragmentation of large grains in the disk are capable of replenishing the supply of small grains that are the main opacity source at near-IR wavelengths. This may be an indication that the collisions that have contributed to the remainder of small dust grains have halted efficient planet formation.

6. SUMMARY

We used optical spectra along with optical and ultraviolet photometry to estimate mass accretion rates for objects in the distributed star forming region around Orion, including the σ Ori cluster, Orion OB1b, and the 25 Ori group within Orion OB1a. The following conclusions were drawn from our analysis.

1. Previous observations of older CTTS, in the 5–10 Myr range, indicate that accretion slows with the age of the object; however, samples of evolved CTTS are small. Here, we showed several examples of objects as old as 10 Myr with ongoing significant accretion rates. These objects have values of $M_{\text{acc}}$ similar to objects in the Taurus star-forming region.

2. We compared the accretion rates of our objects to the predicted decline in $M_{\text{acc}}$ due to viscous evolution. We found that simple viscous evolution models, which take into account a range of viscosities and disk outer radii, cannot explain high accretors at either 1 Myr or 10 Myr unless the initial disk mass is very high. The disk masses needed would cause the disk to be gravitationally unstable. Time variability or accretion high states may explain some of the discrepancy. Additionally, the similarity solutions we assume to describe the viscous evolution are not applicable when the viscous timescale is comparable to or longer than the age of the system, a condition that is likely needed for prolonged accretion.

3. CVSO 206 is a 7–10 Myr strong accretor, with $M_{\text{acc}} = 7 \times 10^{-9} M_\odot \, \text{yr}^{-1}$, indicating that it had a disk mass at 1 Myr $> 0.06 M_\odot$, or $M_\text{d}(1 \text{ Myr})/M_\star \sim 0.1$, significantly higher than the typical disk mass in Taurus. In addition, CVSO 206 has IR fluxes similar to the median of Taurus and therefore significant grain growth and massive or multiple planet formation has not occurred. Photoevaporation by either the central star or external stars has not played a key role in the disk evolution, likely because the high mass accretion rate is capable of replenishing the inner disk material dispersed by radiation from the star.

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