THE STRUCTURE AND EMISSION OF THE ACCRETION SHOCK IN T TAURI STARS.
II. THE ULTRAVIOLET-CONTINUUM EMISSION

ERIK GULLBRING,¹ NURIA CALVET,²,³ JAMES MUZEROLLE,²,⁴ AND LEE HARTMANN²

Received 2000 April 23; accepted 2000 July 3

ABSTRACT

We compare accretion-shock models with optical and ultraviolet spectra of pre-main-sequence stars to (1) make the first determinations of accretion rates in intermediate-mass T Tauri stars from continuum emission and (2) derive improved estimates of accretion rates and extinctions for continuum T Tauri stars. Our method extends the shock models developed by Calvet & Gullbring to enable comparisons with optical and archival International Ultraviolet Explorer ultraviolet spectra. We find good agreement between the observations and the model predictions, supporting the basic model of magnetospheric accretion shocks as well as previous determinations of accretion rates and interstellar reddening for the low-mass T Tauri stars. The accretion rates determined for the intermediate-mass T Tauri stars agree well with values obtained through the other methods of Muzerolle and coworkers that use near-infrared hydrogen line strengths.

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

1. INTRODUCTION

More than 25 years ago Lynden-Bell & Pringle (1974) pointed out the importance of an accretion disk as the source of excess emission of T Tauri stars—infrared emission from the outer disk and ultraviolet emission from the boundary layer where disk material in Keplerian rotation settles down on the slowly rotating stellar surface. When the existence of circumstellar disks around pre-main-sequence stars became observationally established, mainly from infrared observations by IRAS, attempts were made to model the excess emission that veils the absorption lines at optical and UV wavelengths by means of emission from boundary-layer regions (Bertout et al. 1988; Basri & Bertout 1989; Kenyon & Hartmann 1987).

In the last few years a different picture for loading the disk material onto the surface of the star has developed. In this scenario the accretion disk is disrupted at a few stellar radii by the stellar magnetic field, and the material falls along the field lines at nearly free-fall velocity. The evidence for magnetospheric accretion is based mainly on three observational properties: (1) the broad emission lines, often with redshifted absorption components, are consistent with emission from infalling gas channeled by the magnetosphere (Calvet & Hartmann 1992; Hartmann et al. 1994; Muzerolle et al. 1998; Gullbring et al. 1996); (2) the near-infrared colors and spectral energy distributions (SED) of classical T Tauri stars indicate emission from disks that is truncated at a few stellar radii (Kenyon et al. 1994; Meyer et al. 1997); and (3) the accretion-shock models are used to derive physical parameters from the optical spectra and the large ultraviolet-continuum fluxes in T Tauri stars. Ardila & Basri (2000) have used shock models to interpret the IUE data of T Tauri stars. Ardila & Basri also conclude that the overall features of the ultraviolet spectra, although more refinements are needed to understand the details of the variability.

The change of accretion rate with stellar age, as the pre-main-sequence stars evolve toward the main sequence, provides important information on the evolution and physical processes of circumstellar disks (Hartmann et al. 1998). Unfortunately, to date no direct way exists to measure the accretion luminosity for intermediate-mass stars. The reason is that at optical wavelengths the intrinsic stellar
luminosity for stars with spectral types earlier than K5 dominates over the accretion emission, making it difficult to measure the latter. However, at ultraviolet wavelengths the stellar contribution drops significantly, and intermediate-mass T Tauri stars do show excess emission there. The lack of reliable models for the UV emission of young stars has prevented any use of the UV excess to infer mass accretion rates. In this paper we model this excess emission and determine the accretion rates for a number of intermediate-mass T Tauri stars for the first time.

Similarly, there is no way to measure accurate accretion rates for T Tauri stars with very high amounts of excess radiation, which dominates completely over the emission from the stellar photosphere. Because the spectral type of the underlying star cannot be determined accurately, the intrinsic stellar spectrum is uncertain. Moreover, because the stellar photospheric lines can only be detected over a limited range of wavelengths, the observed colors of the stellar photosphere are also poorly known. This means that the reddening of the stellar photosphere cannot be determined accurately. However, extinction corrections are essential for an accurate measurement of the excess ultraviolet continuum. In Paper I we proposed a method to estimate the extinction and accretion rates toward the continuum stars by assuming that the SED is similar to that of the extracted accretion emission of less veiled T Tauri stars. Here we test the validity of this method with measurements extending to much shorter wavelengths.

In § 2 we review the shock model; § 3 outlines the analysis of archive IUE data; in § 4 we show the agreement of the predicted shock emission with IUE spectra for low-mass T Tauri stars and use the model to derive accretion rates of continuum stars and intermediate-mass T Tauri stars. Finally, in § 5 we discuss some important implications of our determinations.

2. SHOCK MODEL

Details concerning the shock-model calculations are presented in Paper I. In summary, the accreting gas impacts the stellar surface and shocks to a temperature of \( \approx 10^5 \) K, releasing the energy as soft X-ray radiation. This radiation is absorbed by the accretion stream above and the stellar photosphere below the shock and thermalizes, producing optical and UV emission. The spectral distribution of this excess emission can be understood as optically thick emission from the heated photosphere below the shock, appearing mostly in the Paschen and Brackett continua, and optically thin emission from the preshock and attenuated postshock regions, becoming important at wavelengths shorter than the Balmer threshold. In general, roughly three-quarters of the total column luminosity is emitted by the heated atmosphere and the rest by the postshock and preshock regions.

The accretion luminosity and rate depend on two parameters: the fractional surface coverage of the column, \( f \), and the energy flux of the accretion flow, \( \mathcal{F} = \frac{1}{2} \rho v_s^3 \), where \( \rho \) and \( v_s \) are the density and the inflow velocity of the accretion stream, respectively. Therefore, given the stellar parameters (mass, radius, and effective temperature) the accretion rate for a star is given by fitting \( f \) and \( \mathcal{F} \) to the excess emission spectrum.

In Paper I we compared the continuum emission predicted by the model with the optical excess emission of T Tauri stars, extracted from spectra collected in the wavelength region 3200–5400 Å (GHBC). In this wavelength region the shock emission is dominated by the diffuse emission from the preshock plus the emission from the heated atmosphere. However, a deveiling procedure is required to separate the excess emission from the photosphere, which introduces uncertainties due to the reddening correction, selection of template, etc. In the ultraviolet, on the other hand, shock emission dominates over the photosphere, allowing a more direct comparison between observations and shock-model predictions.

3. OBSERVATIONAL DATA

We have extracted ultraviolet fluxes for T Tauri stars from the IUE Archive for the LWP and LWR (LW) and the SWP (SW) modes of the spectrograph on board the IUE satellite. For the stars analyzed in this paper, we took all the spectra available in the archives.

To test the shock model we combine optical and UV data for the stars and determine if the model can explain both the UV emission and the properties of the excess emission in the optical, in particular, the observed veiling. However, the intrinsic variability of T Tauri stars makes it difficult to compare optical, LW, and SW spectra for a given star, all obtained at different times. Since more than one LW and SW spectra exist for many T Tauri stars, we decided to calculate a mean spectrum to compare with the optical data. When sufficient IUE observations exist, the spread of the individual spectra around the mean would give a good indication of the range of variability of the UV spectra for a given star. Also in this case, it would be reasonable to expect that the mean level of the optical data at 3200 Å should fall within the range of the mean levels of the LW fluxes at the same wavelength. Unfortunately, we do not have a similar constraint for the SW spectra, since the ranges in which the SW and the LW spectra have a better signal-to-noise ratio (S/N) do not overlap. We restricted our test to the demonstration that the model that fits both the optical and the LW data fell within the range of variability of the SW fluxes. A better test will be done when simultaneous UV coverage from short to long wavelengths is obtained; our forthcoming HST/STIS observations will provide such data.

To calculate the mean spectra for a set of LW (or SW) spectra of a given star, we carried out the following analysis. We fitted each spectrum, \( F_\lambda(\lambda) \), logarithmically as in log space:

\[
\log F_{\lambda,i}(\lambda) = A_i + B_i(\log \lambda - \log \lambda_0), \quad i = 1, \ldots, N, \tag{1}
\]

where \( N \) is the number of LW or SW spectra for the star. The fit was done to the wavelength range where the S/N per resolution element is highest, 2400–3100 Å for the LW spectra and 1700–2000 Å for the SW spectra, with \( \lambda_0 = 2700 \) and 1800 Å, respectively. From the dispersion of the data around the fitted line, \( \sigma_\lambda \), we can calculate the uncertainties in the absolute level \( A_i \) and in the slope \( B_i, \sigma_{A_i}, \) and \( \sigma_{B_i} \) (Bevington 1969) for each spectrum.

In many cases the noise in the continuum level of the T Tauri star spectra in the IUE Archive is very large because the exposure times were only long enough to obtain the fluxes of the emission lines. We expect that the uncertainty in the continuum level, \( \sigma_{A,i} \), gives a good estimation of this noise, so we define a mean spectrum as

\[
F(\lambda) = \frac{\sum w_i F_{\lambda,i}(\lambda)}{\sum w_i}, \tag{2}
\]

with \( w_i = 1/\sigma_{A,i}^2 \).
We can also calculate weighted means for the slope and the absolute flux

\[ \bar{A} = \frac{\sum w_i A_i}{\sum w_i}, \]

\[ \bar{B} = \frac{\sum w_i B_i}{\sum w_i}, \]

where \( w_i = 1/\sigma_{B_i}^2 \) and the dispersion of the slope and the flux level of all spectra around these weighted means is

\[ \sigma_A^2 = \frac{\sum_i (A_i - \bar{A})^2}{(N - 1)}, \]

\[ \sigma_B^2 = \frac{\sum_i (B_i - \bar{B})^2}{(N - 1)}. \]

These dispersions give a measure of the intrinsic variability of the UV spectra of each star. Although the above analysis is strictly valid only if the scatter in the flux level of the spectra is normally distributed, which is not formally satisfied for all spectra, it provides an acceptable method to measure the characteristics of the spectra and their variations.

4. RESULTS

4.1. Testing the Model with a Low-Mass T Tauri Star: BP Tau

In Paper I we showed how the accretion-shock model simultaneously explained the slope of the Paschen and the Balmer continua by the combined emission from optically thin and thick regions. The UV fluxes provide a longer “level arm” in wavelength to test the predictions far in the Balmer continuum, which was traced over only a few hundred angstroms in the optical. For a direct application of the shock model, we have compared theoretical spectra with the combined optical, LW, and SW data of the low-mass T Tauri star BP Tau, all dereddened according to the values for \( A_v \) from GHBC. Figure 1 shows this comparison. The optical fluxes are taken from GHBC. The UV spectra are weighted means, calculated as described in § 3, of 60 LW spectra and 16 SW spectra of varying S/N levels. The value of \( \bar{A} \) and error bars corresponding to 1 \( \sigma_A \) at \( \lambda = 2700 \) and 1800 Å are also shown. The LW data has been scaled by a factor of 0.9 to match the optical data, which is well within the 1 \( \sigma \) of the variability of the flux.

The total model emission is the sum of the stellar photosphere and the shock, which in turn is the sum of the emission of the heated photosphere and the preshock emission (Paper I). The parameters of the shock shown in Figure 1 are the same as those used in Paper I, while the stellar photosphere was taken from the Bruzual & Charlot (1993) spectral library. The model emission can explain the observed optical and UV fluxes very well, both in slope and in absolute level, within the range due to variability. In addition, the model yields a veiling at 4900 Å of 0.8, consistent with the measured value of 0.7 (GHBC). The very good agreement between theory and observations renders strong support for the physical parameters derived in Paper I and for the accretion-shock model in general. In addition, since the UV emission is easily extincted (with an \( A_{2400}/A_v = 2.5 \) for a normal interstellar extinction curve; Mathis 1990), the agreement makes firmer the extinction determination from the optical spectrum in GHBC.

4.2. The Continuum Stars

A number of T Tauri stars show a very high amount of excess radiation that completely dominates over the emission from the stellar photosphere. This makes it very difficult to estimate the spectral type and color of the underlying star and renders estimates of the amount of interstellar reddening very uncertain. In Paper I we proposed a method to estimate the extinction toward the continuum stars by assuming its SED to be similar to that of the extracted accretion emission of less veiled T Tauri stars, at least for \( \lambda < 5400 \) Å (the upper wavelength limit of our spectra). The strong extinction dependence of the UV spectra and the larger wavelength coverage of the combined optical and ultraviolet spectra offer an efficient way to test this method and refine our extinction determination.

In Figure 2 we show optical spectra from GHBC and weighted-mean SW and LW spectra for DG Tau and DR Tau, both highly veiled stars (Basri & Batalha 1990; Hartigan, Edwards, & Ghandour 1995; Hessman & Guenther 1997). The values of \( \bar{A} \) and \( \sigma_A \) are also shown. DR Tau has 31 spectra in the IUE Archive, 20 LW and 11 SW. However, we found that a significant number of them, nine LW and five SW, were obtained during the period 1989 January 20–25. We used these spectra in our analysis to mitigate the uncertainties introduced by variability.

We have adjusted the reddening to give a better fit to the optical and LW data, the latter scaled to the optical, subject to the condition that the model should be within the variability range of the SW spectra. The scalings of the LW fluxes...
to match the optical at 3200 Å were 0.9 for DR Tau and 1.3 for DG Tau, both within the range expected from variability in the LW spectra. The values of the reddening and of the shock-model parameters are given in Table 1; the new values are consistent with those obtained in Paper I.

We have also estimated the mass accretion rate using the expression (Paper I)

\[ M = \frac{8\pi R^2}{v_\theta^2} \mathcal{F} f, \]  

assuming \( M_\odot = 0.5 M_\odot \) and \( R_\odot = 2 R_\odot \). These values are also shown in Table 1. We stress again the point made in Paper I, namely, that the continuum stars have accretion columns with similar values of energy flux as the more typical T Tauri stars, but their accretion columns cover a larger fraction of the stellar surface, resulting in higher mass accretion rates. In support of our conclusion, Ardila & Basri (2000) find a correlation between the mass accretion rate and the accretion-shock surface filling factor in their study of the variability of the IUE spectra of less veiled T Tauri stars.

4.3. Intermediate-Mass T Tauri Stars

For intermediate-mass T Tauri stars with early spectral types (G to early K), the stellar emission dominates over the accretion emission in the optical. This makes it difficult to measure the amount of accretion luminosity, and therefore the accretion rate for these stars, by conventional methods such as veiling measurements. This problem is relaxed in the UV spectral region, where the stellar contribution is lower and therefore the relative contribution of the excess emission higher. Measurement of the excess energy above the photosphere yields the most direct and reliable determination of the accretion luminosity and thus of the mass accretion rate.

We have applied the shock model to explain the dereddened fluxes of a sample of intermediate-mass T Tauri stars: SU Aur, GW Ori, and T Tau N. These stars are generally brighter in the UV, and the S/N is somewhat higher than for the later-type T Tauri stars. Adopted stellar parameters, like spectral type, radius, and distance, were taken from Kenyon & Hartmann (1995) (T Tau, SU Aur) and Cohen & Kuhi (1979) (GW Ori) and are shown in Table 2. We calculated shock models for the range of masses and radii covered for these stars: 2.2 \( M_\odot \) and 3.2 \( R_\odot \) for T Tau and SU Aur and 3.5 \( M_\odot \) and 8 \( R_\odot \) for GW Ori.

An advantage of the earlier-type T Tauri stars, as compared to the typical T Tauri star, is that estimates of the interstellar extinction can be made with less ambiguity, since the observed optical color \((V-I)\) is expected to be less contaminated from shock emission. Nonetheless, since there is a range of extinctions available in the literature, we checked all the extinctions of the stars in the sample in a consistent way, adopting standard colors for the adopted spectral types from Kenyon & Hartmann (1995) and the reddening law from Mathis (1990). The adopted extinctions are shown in Table 2.

In Figure 3 we show the dereddened IUE and optical data for the stars. The IUE fluxes are weighted means obtained as described in § 3. Optical fluxes are from the blue narrowband photometry of Kuhi (1974). The stellar photosphere is taken from the Bruzual-Charlot (1993) library.

The models that provide the best fit to the combined optical and UV data are shown in Figure 3. In addition to fitting the SED, we have required that the model yield a veiling consistent with observations. The predicted veiling

---

**TABLE 1**

**SHOCK PARAMETERS FOR "CONTINUUM" T TAU RISE STARS**

| Object     | \( A_v \) | \( \log \mathcal{F} \) | \( f \) | \( M^* \)  |
|------------|----------|-----------------|-------|------|
| DR Tau     | 1.2      | 11.5            | 0.05  | 3    |
| DG Tau     | 1.6      | 11.5            | 0.05  | 5    |

\( M = 0.5 M_\odot \) and \( R = 2 R_\odot \) have been assumed.

**TABLE 2**

**PARAMETERS FOR INTERMEDIATE-MASS T TAU RISE STARS**

| Object        | Type | \( R^* \) (\( R_\odot \)) | \( A_v \) | Distance (pc) | \( \log \mathcal{F} \) | \( f \) | \( r_{6000} \) | \( M \) (10^-7 \( M_\odot \) yr^-1) | \( M_{\text{NIRH}} \) (10^-7 \( M_\odot \) yr^-1) |
|---------------|------|-----------------|-------|-------------|----------------|-------|------------|-------------------------------|-----------------|
| T Tau N ...... | K0   | 3.7             | 1.7   | 140         | 12              | 0.003 | 0          | 0.4                           | 0.9             |
| SU Aur ......  | G2   | 3.2             | 0.9   | 140         | 11              | 0.01  | 0          | 0.1                           | 0.1             |
| GW Ori ......  | G5   | 8.3             | 0.8   | 440         | 11              | 0.03  | 0.15       | 4                             | 3               |
at 6000 Å is shown in Table 2. The models for T Tau and SU Aur predict essentially no optical veiling, \( \lesssim 0.1 \), as observed (Basri & Batalha 1990). For GW Ori, the model predicts a veiling of 0.15, consistent with the veiling at H\(\alpha\) of 0.1–0.2 found by Basri & Batalha (1990).

By fitting the observed SED with the shock model plus stellar atmosphere we obtained values for both the filling factor and the energy flux. These values, together with the stellar parameters, enabled us to estimate the accretion rate for the stars from equation (7). The accretion-rate values are presented in Table 2. SU Aur and T Tau show values of \( \dot{M} \) that are only slightly higher than the mean of the K7–M3 T Tauri stars (GHBC). In contrast, we find a higher value for the mass accretion rate for GW Ori, comparable to those inferred for the low-mass continuum stars (Table 1). The star is not so highly veiled as the continuum stars because of its brighter photosphere, but otherwise it seems to be similar to their low-mass counterparts in that the accretion column carries similar energy flux, \( \log F \sim 11–12 \), but the surface coverage of the accretion columns is larger.

5. DISCUSSION

5.1. Calibration of IR Indicators of \( \dot{M} \)

The UV-derived measurements of the accretion luminosity in intermediate-mass T Tauri stars also serve as a test of other accretion indicators, namely, infrared emission lines. Such diagnostics are ultimately the most desirable for intermediate-mass stars since they can be observed in large samples of objects much more easily than UV-continuum fluxes. In order to apply the line indicators, however, the line-luminosity–accretion-luminosity relation must first be calibrated with blue/UV-continuum data.

Muzerolle et al. (1998b) observed the infrared emission lines Pa\(\beta\) and Br\(\gamma\) for the GHBC sample of low-mass T Tauri stars in Taurus in addition to a separate sample of intermediate-mass T Tauri stars in both Taurus and Orion. These observations were taken with the IR Cryogenic Spectrometer on the 2.1 m telescope at KPNO in 1998 January (see Muzerolle et al. 1998b for further details of the observations, data, and analysis of the low-mass star sample). A tight correlation between the accretion luminosity (as determined from the blue excess in GHBC) and the Pa\(\beta\) and Br\(\gamma\) line luminosities for the low-mass T Tauri stars was found. This correlation can be employed as a calibration for determining accretion luminosities from the line luminosities, important for higher mass and highly extincted young objects where the short wavelength continuum is difficult or impossible to observe.

We plot the Pa\(\beta\) line luminosities versus UV-derived accretion luminosities of the intermediate-mass stars considered in this paper in Figure 4, on top of the low-mass T Tauri star sample. The three stars follow the trend seen in the lower mass stars, which supports the extension of the emission-line calibration to higher mass stars, although a larger sample is needed to make a definitive test. Assuming this correlation holds regardless of stellar mass, we can derive independent estimates of the accretion luminosity in the three stars from the line emission. The resulting accretion rates are shown in Table 2 and are in excellent agreement with the values derived from the UV excess.

5.2. Accretion and the GW Orionis Disk “Gap”

We derive a high accretion rate for GW Ori, \( \sim 4 \times 10^{-7} \) \( \dot{M}_\odot \) yr\(^{-1} \), compared with typical lower mass T Tauri stars. Unless GW Ori is undergoing a current, rare epoch of rapid accretion, this requires a relatively large disk-mass reservoir. Consistent with this finding, the large submillimeter dust-continuum flux observed from GW Ori suggests a disk mass of \( \geq 0.3 \) \( \dot{M}_\odot \), within a radius of 500 AU.
We have extended the accretion-shock models of Calvet & Gullbring (1998) to shorter wavelengths for comparison with ultraviolet data of accreting T Tauri stars. The shock models agree well with the observed SED, helping to support our previous determinations of accretion rates and providing further evidence in favor of our methods of determining mass accretion rates and extinctions in continuum stars. We provide the first direct estimates of accretion rates for T Tauri stars of early spectral types (G2–K0). These estimates agree with accretion rates estimated from the near-infrared hydrogen line strengths (Muzerolle et al. 1998b). We confirm the result of Paper I that the continuum stars have similar energy fluxes as less veiled stars but larger surface coverage.

We thank C. Johns-Krull and J. Valenti for providing data for early versions of this paper. The ultraviolet data used in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG 5-7584 and by other grants and contracts. This work was supported in part by a grant from the Swedish Natural Research Council and by NASA grant NAG 5-4282 and NASA through grant GO-08317.01-97A from the Space Telescope Science Institute.

6. SUMMARY

References

Ardila, D., Basri, C. 2000, ApJ, 539, 834
Basri, G., & Batalha, C. 1990, ApJ, 363, 654
Basri, G., & Bertout, C. 1989, ApJ, 341, 340
Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350
Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
Calvet, N., & Gullbring, E. 1998, ApJ, 509, 802 (Paper I)
Calvet, N., & Hartmann, L. 1992, ApJ, 386, 239
Calvet, N., Hartmann, L., Kenyon, S. J., & Whitney, B. A. 1994, ApJ, 434, 330
Cohen, M., & Kuh, L. V. 1979, ApJS, 41, 743
Gullbring, E., Barwig, H., Chen, P. S., Gahm, G. F., & Bao, M. X. 1996, A&A, 307, 791
Gullbring, E., Hartmann, L., Briceño, C., & Calvet, N. 1998, ApJ, 492, 323
Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736
Hartmann, L., Calvet, N., Gullbring, E., D'Alessio, P. 1998, ApJ, 495, 385
Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669
Herbst, W., Herbst, D. K., & Grossman, E. J. 1994, AJ, 108, 1906
Hessman, F. V., & Guenther, E. W. 1997, A&A, 321, 497
Kenyon, S. J., & Hartmann, L. 1987, 323, 174
Kenyon, S. J., et al. 1994, AJ, 107, 2153
Kuhi, L. V. 1974, A&AS, 15, 47
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
Mathieu, R. D., Adams, F. C., Fuller, G. A., Jensen, E. L. N., Koerner, D. W., & Sargent, A. I. 1995, AJ, 109, 2655
Mathieu, R. D., Adams, F. C., & Latham, D. W. 1991, AJ, 101, 2184
Mathieu, R. D., Basri, G., Jensen, E. L. N., Johns-Krull, C. M., Valenti, J., & Hartmann, L. W. 1997, AJ, 113, 1841
Mathis, J. S. 1990, ARA&A, 28, 37
Meyer, M., Calvet, N., & Hillenbrand, L. A. 1997, AJ, 114, 288
Muzerolle, J., Calvet, N., & Hartmann, L. 1998, ApJ, 492, 743
Muzerolle, J., Hartmann, L., & Calvet, N. 1998a, AJ, 116, 455
———, 1998b, AJ, 116, 2965

(Mathieu et al. 1995). With such a large disk mass, the GW Ori accretion rate can be maintained in principle for \( \geq 7.5 \times 10^5 \) yr, approaching the estimated stellar age of \( \sim 10^6 \) yr (Mathieu, Adams, & Latham 1991). However, GW Ori is also a spectroscopic binary, with a period of 242 days (Mathieu et al. 1991); its bimodal SED has been interpreted as requiring a disk gap between \( \sim 0.17 \) and 3.3 AU, evacuated by the companion. Because the gap can be filled in with relatively small amounts of dusty material (compare to the case of DQ Tau; Mathieu et al. 1997), this interpretation of the SED makes it highly unlikely that material from the outer disk is accreting across the gap. Our accretion rate, coupled with a reasonable system lifetime, would then require an uncomfortably large disk mass within \( \sim 0.2 \) AU.

Alternatively, the long-wavelength IR excess could be dominated by a dusty envelope, not the disk. Calvet et al. (1994) showed that an infalling dusty envelope with an outflow cavity could produce a double-peaked SED qualitatively like GW Ori's if viewed roughly along the outflow axis. In this model the star and inner disk are essentially not extincted, accounting for the optical to near-IR emission, while the far-IR peak at \( \sim 30 \mu \)m is produced by the dusty envelope. The near-IR emission of the envelope is reduced or eliminated by the evacuation at small radii, both by the outflow and by rotation (the latter causes material to fall onto the disk rather than into the central star). Thus, in the envelope model the "gap" apparent in the SED is a hole in the infalling envelope, not in the disk. By eliminating the large disk gap, the envelope model makes it easier to suppose that disk material can accrete past the binary, as in DQ Tau, and maintain the accretion rate we determine for a reasonable lifetime.

A&A, 307, 791

A&A, 307, 791