THE ASTROPHYSICAL JOURNAL, 482:465–469, 1997 June 10

ACCRETION AND UV VARIABILITY IN BP TAURI[1]

ANA I. GÓMEZ DE CASTRO AND M. FRANQUEIRA
Departamento de Astronomía y Geodesia, Facultad de CC. Matemáticas, Universidad Complutense de Madrid, Madrid 28040, Spain
Received 1996 October 23; accepted 1997 January 13

ABSTRACT

BP Tau is one of the few classical T Tauri stars for which the presence of a hot spot in the surface has been reported without ambiguity. The most likely source of heating is gravitational energy released by the accreting material as it shocks with the stellar surface. This energy is expected to be radiated mainly at UV wavelengths. In this work we report the variations of the UV spectrum of BP Tau for 1992 January 5–19, when the star was monitored with *IUE* during two rotation periods. Our data indicate that lines that can be excited by recombination processes, such as those from O I and He II, have periodic-like light curves, whereas lines that are only collisionally excited do not follow a periodic-like trend. These results agree with the expectations of the magnetically channeled accretion models. The kinetic energy released in the accretion shocks is expected to heat the gas to temperatures of $\sim 10^6$ K, which henceforth produces ionizing radiation. The UV (Balmer) continuum and the O I and He II lines are direct outputs of the recombination process. However, the C IV, Si II, and Mg II lines are collisionally excited not only in the shock region but also in inhomogeneous accretion events and in the active (and flaring) magnetosphere, and therefore their light curves are expected to be blurred by these irregular processes.

We also report the detection of warm infalling gas from the presence of redshifted (81 km $\mathrm{s^{-1}}$) absorption components in some of the high-resolution Mg II profiles available in the *IUE* and *Hubble Space Telescope* archives.

Subject headings: accretion, accretion disks — shock waves — stars: individual (BP Tauri) — stars: magnetic fields — stars: pre–main-sequence

1. INTRODUCTION

Classical T Tauri stars show enhanced continuum and line emission in the UV with respect to main-sequence stars of similar spectral types (Imhoff & Appenzeller 1989; Gómez de Castro & Franqueira 1997). There is mounting evidence of this excess being produced by the release of gravitational energy from infalling material (Bertout, Basri, & Bouvier 1988; Simon, Vrba, & Herbst 1990, hereafter SVH; Gómez de Castro, Lamzin, & Shatskii 1994; Gómez de Castro & Fernández 1996). The detection of hot spots on the stellar surface of some classical T Tauri stars has increased the suspicion that the infall material could be channeled by strong dipolar fields on the stellar surface (SVH; Königl 1991; Lamzin et al. 1996). The presence of hot spots has been reported without ambiguity for 11 classical T Tauri stars: DN Tau, GI Tau and GK Tau (Vrba et al. 1986, hereafter VRCSZ), BP Tau (VRCSZ; SVH), DF Tau (Bouvier & Bertout 1989), DE Tau, DG Tau, IP Tau, GM Aur, and TAP 57NW (Bouvier et al. 1993), and DI Cep (Fernández & Eiroa 1995). Nine of these have been observed at least once with the *International Ultraviolet Explorer* (*IUE*), but only two have been properly monitored in the wavelength range between 1200 and 2000 Å: DI Cep (Gómez de Castro & Fernández 1996) and BP Tau. The UV monitoring of DI Cep allowed us to obtain the UV spectrum of the hot spot. The light curves are similar in all the lines (O I, C IV, Si IV, and Si II), suggesting that there is a broad range of temperatures in the hot spot (from 10^4 to 10^5 K) that is best explained by magnetically channeled accretion, although variations in the spot properties during several years lead to the conclusion that the material is channeled by a variable loop structure rather than by dealing with a strong dipolar field.

BP Tau is a classical T Tauri star of spectral type K7 V (Herbig & Bell 1988). The *UBVRI* photometric variations are well fitted by a model based on a hot spot with temperature 8211 K covering 0.36% of the visible hemisphere (VRCSZ). A first attempt to monitor BP Tau in the UV was carried out by SVH, who found that the UV continuum and the *UBVRI* photometric variability were correlated. Unfortunately, the phase coverage in the short wavelength range (1200–2000 Å) was very limited. This prevented the study of the variations of the main resonance lines (C IV, Si IV, He II, Si II, O I) and therefore the study the thermal structure of the spot. During the last few years we have carried out a detailed analysis of *all* the observations of T Tauri stars obtained with *IUE* (Gómez de Castro & Franqueira 1997). We have found that BP Tau was monitored during 14 days in 1992 January with a good phase coverage. In this work we present the light curves of the O I, Si II, and Mg II lines (tracing plasma at 10^4 K) and species such as C IV and He II that trace plasma at $T \sim 10^5$ K. We also present high-resolution profiles of the Mg II lines from the *IUE* and the *Hubble Space Telescope* (*HST*) archives showing the presence of redshifted absorption components in the profiles. The low-dispersion archive data and the light curves derived from them are presented in § 2. The high-resolution profiles are discussed in § 3. Finally, § 4 is devoted to an overall discussion and the conclusions.

---

[1] Based on observations made with the *International Ultraviolet Explorer* (*IUE*) and with the NASA/ESA *Hubble Space Telescope* (*HST*) obtained from the *HST* data archive at the Space Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

2. LOW-DISPERSION OBSERVATIONS

BP Tau was monitored with *IUE* from 1992 January 5 to 1992 January 19. A detailed description of the spacecraft configuration at the time when the observations were taken can be found in Gonzalez-Riestra et al. (1995). BP Tau was observed every other day in the low-dispersion mode with the short-wavelength prime (SWP) and the long-wavelength prime (LWP) cameras. Typically, it was observed twice with the LWP and once with the SWP per observing day. The date and time of observation, camera, image number, and exposure time of each spectrum are given in Table 1. Also, the visual magnitude of BP Tau at the beginning of each observation is indicated in the last column of Table 1. The fine error sensor (FES) gives estimates of the visual magnitude with rms errors of 0.08 mag, and rms errors associated with the reproducibility are even better: just ~0.04 mag (Holm & Rice 1981). Therefore, accurately measuring small variations such as those of BP Tau (typically 0.2 mag in V, see, e.g., VRCSZ) with the FES camera requires differential photometry (Guinan 1990), which was not carried out at the time when the observations were done. The magnitudes given in Table 1 have been obtained from the net FES counts using the algorithm by Perez (1991); they are corrected from color effects, the sensitivity degradation of the cameras (Fireman & Imhoff 1989), and the change of the FES reference point after 1990 January at Goddard Space Flight Center (GSFC). The spectra have been processed with the *IUE* Spectral Image Processing System (IUESIPS). No further reprocessing (see Gómez de Castro & Fernández 1996) was required since the signal-to-noise ratio (S/N) of the data was fairly good (≥ 10). Each image has been cleaned from bright spots and cosmic-ray hits after visual inspection of the line-by-line spectrum. No extinction correction has been applied.

The mean UV spectrum of BP Tau is displayed in Figure 1. The inset shows in more detail the spectrum between 1200 and 1950 Å. The main spectral features are those of O I (λ1303), Si IV ($\lambda\lambda$1393, 1402), C IV ($\lambda\lambda$1548, 1551), He II

TABLE 1

LOG OF *IUE* DATA

Date	Time (hr:minute)	Camera and Image Number	$T_{\rm exp}$ (minutes)	V(FES) (mag)
		Low Dispersion		
1992 Jan 5	16:52	LWP 22194	18	11.9
	17:21	SWP 43552	300	12.0
	22:30	LWP 22195	18	12.0
1992 Jan 7	16:18	LWP 22211	18	11.8
	16:46	SWP 43563	305	11.9
	17:46	LWP 22212	12	11.9
	22:35	LWP 22213	12	12.0
1992 Jan 9	16:08	LWP 22226	18	12.2
	16:36	SWP 43585	310	12.3
	19:16	LWP 22227	18	12.1
	22:33	LWP 22228	18	12.1
1992 Jan 11	15:49	LWP 22238	12	12.1
	16:13	SWP 43610	340	12.1
	18:47	LWP 22239	18	12.0
	22:25	LWP 22240	18	12.0
1992 Jan 13	16:07	LWP 22243	18	12.1
	16:32	SWP 43635	310	12.0
	19:12	LWP 22244	18	12.1
	22:26	LWP 22245	18	12.1
1992 Jan 15	15:59	LWP 22248	18	12.1
	16:28	SWP 43650	350	12.0
	22:28	LWP 22249	18	12.0
1992 Jan 17	16:22	LWP 22261	18	12.2
	16:50	SWP 43672	300	12.2
	19:28	LWP 22262	18	12.3
	22:32	LWP 22263	18	12.2
1992 Jan 19	15:55	LWP 22276	18	12.1
	16:27	SWP 43689	305	12.0
	19:11	LWP 22277	18	12.2
	22:30	LWP 22278	18	12.0
		High Dispersion		
1981 Jul 24	06:40	LWP 11130	210	...
1985 Oct 22......	02:00	LWP 06963	180	...
1986 Oct 10......	00:50	LWP 09282	270	...
1986 Oct 26......	23:19	LWP 09417	270	...

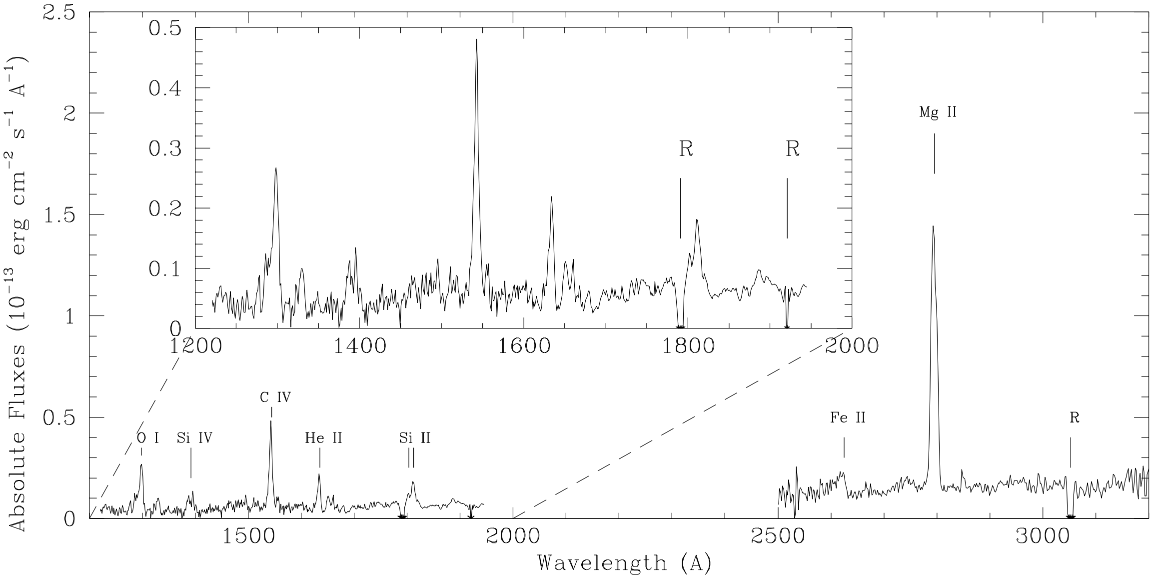

FIG. 1.—Mean UV spectrum of BP Tau during the *IUE* monitoring campaign. The position of the main emission lines is marked, as well as the location of the reseau marks (R) for the geometric calibration of the *IUE* images.

(λ1640), Si II ($\lambda\lambda$1808, 1817), Fe II (UV resonance multiplet 1), and Mg II ($\lambda\lambda$2795, 2802). Reseau marks used for the geometric calibration of the *IUE* images are also marked in Figure 1. The far UV (FUV) (1200–2000 Å) spectrum of DI Cep also shows a bump between 1400 and 1600 Å and a weak continuum from 1750 Å toward longer wavelengths.

2.1. *The Light Curves*

2.1.1. *The LWP Range*

The light curves corresponding to the UV continuum and the Mg II lines are displayed in Figure 2. The UV continuum variations have been measured in a window of 50 Å width centered at 2900 Å. The light curve is periodic-like: the maximum brightness is reached on January 7 and again on January 16. The first maximum is more symmetric than the second. The rotation period derived from optical photometry is between 6.1 and 8.3 days (VRCSZ; SVH; and Gullbring et al. 1996a, hereafter GBCGB). We have overplotted sine curves with periods of 8.3 and 12.2 (2 × 6.1) days, but none of them fit the data well. The period inferred from the UV continuum is slightly larger (~10 days). The flux varies by a factor of 2.5 (or 1 mag) during the monitoring. This amplitude is similar to the reported one for the *U* band during the rotational monitorings. We also observe some rapid fluctuations on timescales of a few hours.

The Mg II light curve is very different from the behavior of the UV continuum; it seems to be dominated by short timescale fluctuations. The maximum brightness on January 7 appears quite clearly; the maximum on January 16 is only barely detected. Moreover, we detect a strong and rapid rising of the Mg II flux on January 11. On that date GBCGB detected a large event that lasted for few hours on their *UBVRI* monitoring of BP Tau. The amplitude of the event was ~0.25 mag in the *U* band, similar to that observed in the UV (continuum and Mg II lines).

2.1.2. *The SWP Range*

The light curves corresponding to the strongest lines (O I, C IV, He II, and Si II) in the range covered by the SWP camera are shown in Figure 3. The UV continuum light curve has been binned to the same time resolution as the SWP spectra and plotted for reference. An overall trend can be observed: the light curves have two main brightness maxima on January 7 and 16 and then a weaker maximum on January 11 coinciding with the rapid event. The O I and UV continuum light curves are very similar. The C IV light curve is rather chaotic (as it is the Si IV one). The He II is the only species that does not show any sign of the rapid event and has the most regular light curve; the period seems to be slightly longer than 10 days.

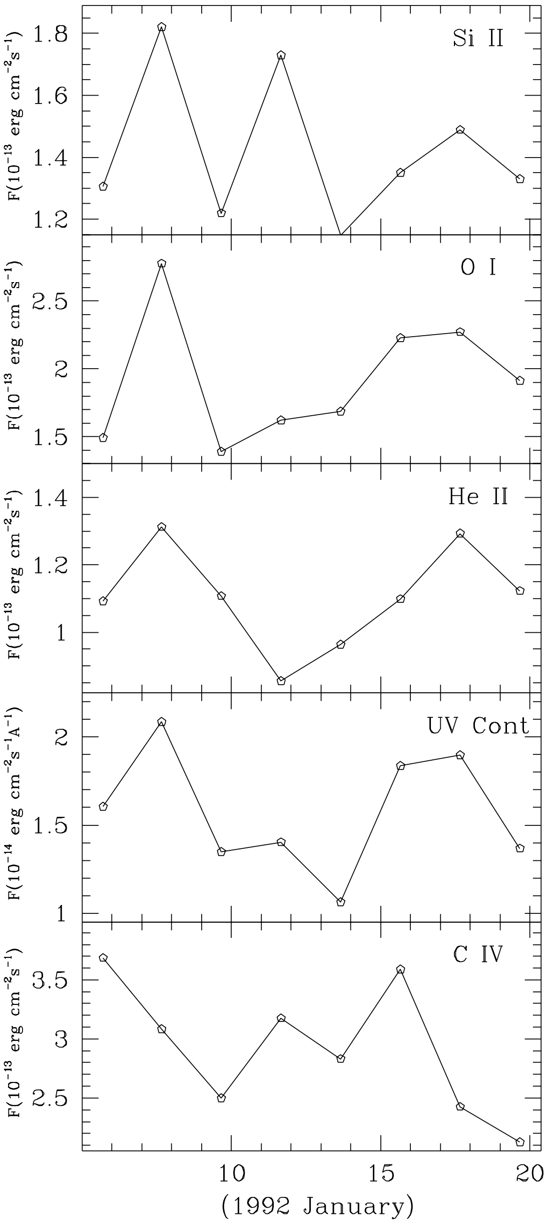

FIG. 3.—Light curves based on data obtained with the SWP camera. The light curve of the UV continuum has been binned to the same time resolution of the SWP spectra and is shown for comparison.

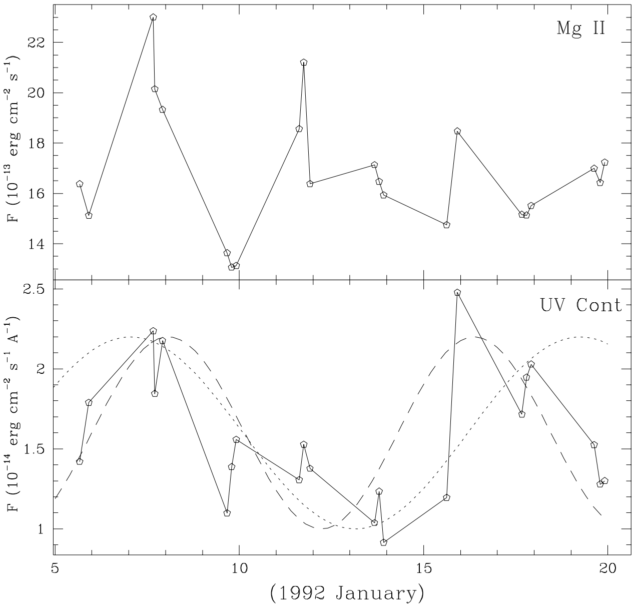

FIG. 2.—Light curves based on data obtained with the LWP camera. Both rapid and long-term variability data points are shown. Two sine curves have been plotted over the UV continuum light curve. They have periods of 8.3 (*dashed*) and 2 × 6.1 (*dotted*) days (see text).

The Si II and Mg II curves are fairly similar, as expected, since these lines are formed in similar physical conditions. They all have a maximum on January 7. Moreover the rapid event on January 11 is clearly detected in both of them; however, the January 16 maximum is very weak or absent.

There is always an underlying line emission level indicating either that the spot is continuously visible or that there are other emitting sources, such as an active atmosphere, involved. BP Tau does not deviate from active stars in the C IV–Si II flux-flux diagram.

3. THE Mg II LINES PROFILES

High-resolution profiles of the Mg II lines are available in the *IUE* and *HST* archives, although none of them were obtained during the monitoring. The *IUE* data are summarized in Table 1. The *HST* spectrum was obtained on 1993 July 30 with the Goddard High Resolution Spectrograph (GHRS) and the grating G270M. The accuracy of the *IUE* and *HST* wavelength calibrations is ∼20–30 km s^{-1}. The profiles can be generically described as broad emission lines (∼320 km s^{-1} full width at 10% intensity) with a major narrow absorption feature superposed to the emission (see Fig. 4). The absorption is redshifted by 20 km s^{-1} with respect to the laboratory wavelength. The radial velocity of BP Tau is 15.8 ± 1 km s^{-1} (Hartmann et al. 1986), and the average radial velocity of the molecular gas in L1495 is 6.9 km s^{-1} (Ungerechts & Thaddeus 1987). Therefore, the feature is most likely produced by warm circumstellar (CS) gas probably blended with the molecular cloud absorption. We will use it for reference to discuss the velocity field of the material detected through the Mg II line.

The Mg II profile is variable, as well as the optical depth of the lines' formation region; note that the ratio between the intensity of the two lines of the multiplet varies. There is also a noticeable sharp cut in the blue edge of the profiles at about −100 km s^{-1} with respect to the CS absorption that is lost in the 1993 *HST* profile, where a broad absorption component seems to be present. Also, the line centroid varies: it is redshifted by 70 km s^{-1} on 1993 July 30 and by only 35 km s^{-1} on 1985 October 22 (LWP 06963). A narrow absorption component redshifted by 81 km s^{-1} is clearly seen in the *HST* spectrum. The presence of redshifted absorbing gas is also detected in the LWP 06963 and LWP 09417 spectra, although the signal-to-noise ratio of the *IUE* data is much worse. Therefore, the Mg II profiles provide *direct evidence of the presence of warm material* ($T \sim 10^4$ K) falling onto BP Tau.

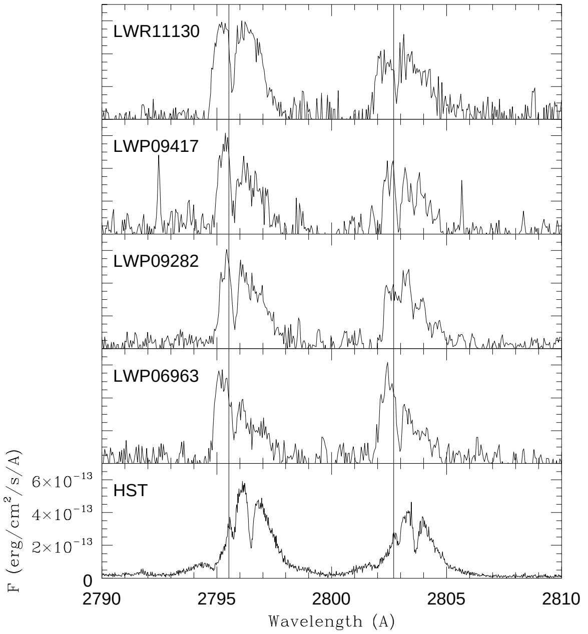

FIG. 4.—High-resolution Mg II profiles of BP Tau obtained with the *HST* + GHRS. The laboratory wavelengths of the Mg II lines are marked. Note that there is a circumstellar feature slightly redshifted with respect to the rest wavelength. In the *HST* spectrum the presence of an additional redshifted absorption component is clearly seen.

4. DISCUSSION AND CONCLUSIONS

The UV continuum and the *UBVRI* variations are correlated (SVH); therefore, they can be taken as bona fide tracers of the optical light curve. The light curve shows rapid variations (timescales of a few hours) superposed to a long-term variability pattern.

The short-term variations were particularly dramatic on January 11, when a fast brightness increase was detected in the Si II and Mg II light curves. The event was also observed in the C IV and UV continuum light curves; however, it was very weak or absent in the O I and He II light curves. It was associated with the rapid event detected by GBCGB, who showed that, indeed, rapid events with durations of 0.6 to a few hours were frequently observed in BP Tau. They found that most of the events were very different from those observed in flare stars; they were cool (T = 7000–8000 K) and had light curves with similar rise and fall times. Our data indicate that the events have an UV counterpart in continuum and line emission from 10^4 to 10^5 K plasma. UV-line flux variations have been reported as a result of the presence of flares in magnetically active stars (see, e.g., Linsky 1991 and references therein). During flares, the line fluxes increase dramatically in a few hours (for instance, in the 1981 October flare of V711 Tau, the C IV flux rose by a factor of 340 with respect to the preflare value; Rodonó et al. 1987). The variations in the UV line fluxes are not so dramatic in BP Tau however, confirming that, if they were related with flare activity, this would be very peculiar. In fact, Gullbring et al. (1996b) did not find any correlation between the short-term *UBVRI* and the X-ray (*ROSAT*) variability and suggested inhomogeneous accretion as the source of this short-term irregular variability.

The long-term variations are most likely related with the rotational modulation of the stellar flux due to the presence of spots on the surface. The period inferred from the UV continuum variations is slightly larger (1 day) than that derived from previous monitorings, but this could be partially due to the poor phase coverage of the *IUE* observations and also to the contribution of irregular "short-term" variations. Note however the two main maxima in the UV continuum are broad and prominent despite the good short-term coverage in the LWP monitoring; henceforth, we think that they are most likely tracing the rotation period. The similarity between the UV continuum and the O I light curves, as well as the very regular He II light curve, confirms our interpretation. Note also that variations in the rotation period of BP Tau have been previously reported (see, e.g., GBCGB and references therein). The comparison between the light curves of the different species and the light curve of the UV continuum suggests that the phenomenon is more complex than expected from simple theoretical models (e.g., Königl 1991). Our data indicate that lines that can be excited by recombination processes, such as those from O I and He II, have periodic-like light curves. However, lines that are only collisionally excited do not follow a periodic-like trend.

A hot boundary layer between the star and the accretion disk cannot account for the presence of regions at $T \sim 10^5$ K. Current accretion disk models cannot account for regions as hot as 10^5 K, since the hottest regions are the boundary layers with temperatures between 7000 and 11,000 K (Basri & Bertout 1993). Moreover, the typical timescales for the development of instabilities are ~ 12 hr, similar to the duration of the short-term variations, and much shorter than the 6.1–10 day variation timescale observed in BP Tau (see, e.g., GBCGB). The long-term variations can be naturally explained if the star has a strong enough magnetic field to channel the accreting gas into a hot spot or "ring" as has been proposed by Simon et al. (1990). Our UV light curves can also be interpreted in this context. The kinetic energy released in the accretion shocks is expected to heat the gas to temperatures of $\sim 10^6$ K (see, e.g., Königl 1991) that henceforth radiates in soft X-rays ($\lambda \sim 29$ Å). This radiation ionizes the gas in the postshock region, as well as the infalling gas column, producing a recombination spectrum as the spectral signature. The UV (Balmer) continuum and the O I and He II lines are direct outputs of the recombination process. H Lyβ can pump the O I line, and recombination from He III or collisional excitation plus photon trapping in the He II Lyβ line are competing processes for the He II line excitation (see Brown, Ferraz, & Jordan 1984). However, the C IV, Si II, and Mg II lines are collisionally excited not only in the shock region but also in the active (and flaring) magnetosphere and in the inhomogeneous accretion events suggested to occur by GBCGB. This is, in fact, shown by the relevance of the January 11 event in the light curves of the different spectral tracers (see Fig. 3). Therefore, the light curves of these species could be blurred by these irregular processes. Moreover, part of the Mg II (and Si II) line flux emitted by the spot could be absorbed by the warm infalling material in the accretion column, as the presence of redshifted absorption components in the Mg II line suggests.

The corotation radius between BP Tau and the surrounding accretion disk is at $r = 7.2R_*$, assuming that the rotation is Keplerian in the stressed inner disk. We have adopted a mass and a radius for BP Tau of $M = 0.8\ M_\odot$ and $R_* = 2.5\ R_\odot$, respectively (SVH). The inferred free-fall speed from the corotation radius is $V_{\rm ff} = 145$ km s^{-1}. This velocity is larger than the velocity of the redshifted components detected in the Mg II lines profiles, although this difference could be caused by projection effects . A high spectral resolution monitoring of BP Tau in the UV (at least in the Mg II, C IV, and He II lines) is necessary to make progress in the study of the accretion column geometry and excitation.

We thank Sergei Lamzin for very interesting conversations on the UV signatures of accretion shocks. We are indebted to Benjamin Montesinos for his careful reading of the manuscript and the thorough revision of the English. Mercedes Franqueira is supported by a Predoctoral Research Fellowship of the Ministerio de Educación y Ciencia (MEC) of Spain. Most of this work was carried out making use of the Computer Facilities at the ESA-*IUE* Observatory at VILSPA (Madrid, Spain). We want to thank the VILSPA staff for their support while carrying out this project. This research was supported by the MEC of Spain through the research grant PB 93-491.

REFERENCES

Basri, G., & Bertout, C. 1993, in Protostars and Planets III, ed. E. H. Levy & J. L. Lunine (Tucson: Univ. Arizona Press), 543

Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350

Bouvier, J., & Bertout, C. 1989, A&A, 211, 99

Bouvier, J., Cabrit, S., Fernández, M., Martín, E. L., & Matthews, J. M. 1993, A&A, 272, 176

Brown, A., Ferraz, M. C. de M., & Jordan, C. 1984, MNRAS, 207, 831

Fernández, M., & Eiroa, C. 1995, A&A, 310, 143

Fireman, G. F., & Imhoff, C. L. 1989, NASA *IUE* Newsletter, 40, 10

Gómez de Castro, A. I., & Fernández, M. 1996, MNRAS, 283, 55

Gómez de Castro, A. I., & Franqueira, M. 1997, ULDA Access Guide to T Tauri Stars Observed with *IUE* (ESA SP-1205; Noordwijk: ESA)

Gómez de Castro, A. I., Lamzin, S. A., & Shatskii, N. I. 1994, AZh,71, 60

Gonzalez-Riestra, R., de Martino, D., Hermoso, D., Barylak, M., Rodriguez, P., & Wamsteker, W. 1995, ESA *IUE* Newsletter, 45, 7

Guinan, E. 1990, in IUE Symp., Evolution in Astrophysics, ed. E. J. Rolfe (ESA SP-310; Noorwijk: ESA), 73

Gullbring, E., Barwig, H., Chen, P. S., Gahm, G. F., & Bao, M. X. 1996a, A&A, 307, 791

Gullbring, E., Petrov, P. P., Ilyin, I., Tuominen, I., & Lodén, K. 1996b, A&A, in press

Hartmann, L., Hewett, R., Stahler, S., & Mathieu, R. D. 1986, ApJ, 309, 275

Herbig, G. H., & Bell, K. R. 1988, Lick Observatory Bulletin, 1111, 1

Holm, A., & Rice, G. 1981, NASA *IUE* Newsletter, 15, 74

Imhoff C. L., & Appenzeller, I. 1989, in Exploring the Universe with the *IUE* Satellite, ed. Y. Kondo (Dordrecht: Reidel), 295

Königl, A. 1991, ApJ, 370, L39

Lamzin, S. A., Bisnovatyi-Kogan, G. S., Errico, L., Giovannelli, F., Katysheva, N. A., Rossi, C., & Vittone, A. A. 1996, A&A, 306, 877

Linsky, J. L. 1991, in Mechanisms of Chromospheric and Coronal Heating, ed. P. Ulmschneider, E. R. Priest, & R. Rosner (New York: Springer), 166

Pérez, M. R. 1991, ESA *IUE* Newsletter, 38, 27

Rodonó, M., et al. 1987, A&A, 176, 267

Simon, T., Vrba, F. J., & Herbst, W. 1990, AJ, 100, 1957

Ungerechts, H., & Thaddeus, P. 1987, ApJS, 63, 645

Vrba, F. J., Rydgren, A. E., Chugainov, P. F., Shakovskaya, N. I., & Zak, D. S. 1986, ApJ, 306, 199

Note added in proof.—An earlier discussion of the data presented here has been brought to the authors' attention (T. Simon, C. L. Imhoff, G. S. Basri, & T. R. Ayres, in ASP Conf. Proc. 64, Cool Stars, Stellar Systems, and the Sun: Eighth Cambridge Workshop, ed. J.-P. Caillault [San Francisco: ASP], 729 [1994]).