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LETTER

Letter to the Editor

Periodic changes of veiling and circumstellar grey extinction in DF Tauri

I. Dust clouds spiraling into a T Tauri star?

A. Chelli[1], L. Carrasco[2], R. Mújica[2], E. Recillas[2], and J. Bouvier[1]

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble, B.P. 53X, F-38041 Grenoble Cedex, France
[2] Instituto Nacional de Astrofisica, Optica y Electronica, Ap. 51 y 216 Z.P., 72000 Puebla, México

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Abstract. We present 110 simultaneous BVI photometric measurements and low resolution (≈ 400) spectra obtained during 17 consecutive days on the Classical T Tauri star DF Tau. Applying a new method for veiling extraction from low resolution spectra, we derive veiling curves in the B and V photometric bands which closely resemble their corresponding light curves. Analysis of the combined light and veiling curves allows to disentangle the stellar and excess fluxes. The BV stellar fluxes derivation is validated by the I photometric curve which is only slightly contaminated by the excess. The stellar flux exhibits grey variations, up to a factor 2, between the B and I bands. In the first 12 days, these variations are periodic with two minima separated by about 6 days. Yet from day 13th, both the stellar flux *and* the veiling steadily increase. The overall picture emerging from these results is that of an optically thick accreting cloud, which partially occults the star. As this cloud, located initially within the corotation volume, spirals into the star, the accretion rate increases and its opacity decreases. We also discuss the stellar rotation period and the detection of flare events of few hours duration.

Key words: stars: pre-main sequence – stars: variables: general – stars: starspots – stars: individual: DF Tau – accretion, accretion disks

1. Introduction

The inference of physical processes that contribute to the light and spectral variations of Classical T Tauri stars (CTTs) has been a challenging problem. In order to gain insight into this aspects and to understand the various causes of variations in timescales of hours to days, we have selected for our study the intensively observed CTTs DF Tau. This star is known to present rotational photometric modulations associated with a bright hot spot.

We have obtained simultaneous $BVRI$ ($\approx$30 days) plus $H\alpha$ photometry, low resolution visible spectroscopy ($\approx$17 days) and near IR photometry and spectroscopy ($\approx$9 days). In the present work, we analyse the first results of the simultaneous visible photometry and spectroscopy. We apply a new method for veiling derivation from low resolution spectra. These veiling estimates, jointly with simultaneous BVI photometry, allow us for the first time to detect periodic variable grey circumstellar extinction in DF Tau.

2. Observations and data processing

We have carried out an extensive observing program of DF Tau with the 2.1m telescope of the Guillermo Haro Observatory (INAOE) at Cananea (Sonora, México), equipped with the LFOSC (Zickgraf et al. 1997), during the nights of Nov 15th through Dec 1st, 1995. This instrument allows us to obtain both CCD direct $BVRI$ and $H\alpha$ images covering a field of 6 by 10 arcmin, as well as, spectra with a wavelength coverage from 4000 Å to 7000 Å and a resolution of about 400. During those 17 nights, atmospheric conditions were suitable for photometric and spectroscopic studies. We got in total 110 spectra followed by 110 $BVRI$ and $H\alpha$ CCD images. Each spectrum is the result of the sum of two or three consecutive individual spectra, each of 150 seconds of integration on the source. The aim was to obtain spectral information with a mean signal to noise (S/N) ratio of at least 100. The integration times for the CCD direct images were such that a minimum S/N ratio of 300 was generally achieved. In particular, this database provides us with 110 simultaneous (96 within 10 minutes) BVI images and spectra. On the average, our coverage of DF Tau represents 7 to 8 individual photometric and spectroscopic points per night separated by about 1 hour. We also observed various Weak T Tauri stars (WTTs) and cool dwarfs, to be used as comparison templates for veiling derivation. The M1.5–2 WTTs San1 (Gahm et al. 1995) was found to be the best match to the photospheric spectrum of DF Tau.

Differential BVI photometry in the 6 by 10 arcmin field was extracted from properly bias removed and flat fielded frames,

Send offprint requests to: A. Chelli

yielding photometric data with 0.03 mag error. Spectral data were reduced with the standard IRAF reduction package procedure, adopting an average atmospheric extinction law for the site and the spectrophotometric standard Hiltner 600. Next, the spectra were recentered, median normalized and gaussian filtered, degrading the spectral resolution to about 300, to obtain a mean S/N ratio larger than 100 for each spectrum.

3. Veiling derivation from low resolution spectra

In a Classical T Tauri star, the veiling has been defined as the ratio r of the continuum radiation excess flux $E(\lambda)$ (which is presumably due to the accretion process) to the local continuum of the underlying photospheric spectrum $S(\lambda)$; or alternatively, the quantity R is defined as the ratio of $E(\lambda)$ to the mean value of $S(\lambda)$ in the working band (Hartigan et al. 1989). In the past, the veiling r has been extracted from high resolution spectra of the object and a comparison template $T^n(\lambda)$, which is assumed to properly describe the unmeasurable $S^n(\lambda)$ spectrum, the upper index n standing for continuum normalized. This approach has been successfully applied in intervals of a few tens of Å for which both the veiling and the extinction can be considered as wavelength independent. For constant noise in the spectral data, according to Hartigan et al. (1989), the problem of veiling estimate is reduced to minimize, as a function of the two unknowns p and r, the quantity:

$$Q = \sum_{k=1}^{m} \frac{|O_k^n - p(T_k^n + r)|^2 w_k}{\sigma_o^2(1 + p^2\xi^2)}, \quad (1)$$

where the index k refers to the sampled wavelength domain, p is a scaling factor, σ_o is the estimated noise on the object spectrum, ξ is the estimated noise ratio between the template and the object spectra, and $w(\lambda)$ is an appropriate window function. The sensitivity to biasses of this technique has been investigated by Chelli (1999). This author concludes that there are two main classes of bias to be considered: an incorrect estimate of real noise ratio ξ_0, and spectral mismatches between the object and the comparison template. It has been demonstrated i) that the amount of bias is inversely proportional to the square of the spectral contrast, ie. the variance with wavelength of the chosen spectral bandpass normalized to its mean flux, ii) that in the absence of noise, when the extreme values $r_{\xi=0}$ and $r_{\xi=\infty}$ are equal, then the solution of the veiling equation is unbiassed. This in turn, implies that $T^n(\lambda)$ is an exact representation of $S^n(\lambda)$, under the asumption that $T^n(\lambda)$ is not veiled. Otherwise, the difference between $r_{\xi=0}$ and $r_{\xi=\infty}$ represents the goodness of fit to the veiling equation.

In the light of the above arguments, Chelli (in preparation) has developed and validated a robust methodology to derive the veiling from low resolution spectra. In this approach we choose to use the veiling definition R because at low resolution the concept of local continuum for a late type spectrum has little sense. From the template star San1, we select bandpasses, where the spectral features are more prominent, from which the veiling can be estimated with minimum systematic errors. With our resolution, we cannot adopt narrow bandpasses of a few tens of Å, since the associated contrast in those would be of a few percent only, which would result in unacceptable large veiling biasses. Hence, we chose bandpasses of about 400 Å in which the contrast is at least about 10% and then, much larger than any local systematic error in our spectra (1 to 2%). However, for these large bandpasses, we cannot longer assume that p in Eq. (1) is constant. Instead, we approximate its variation within the band by a linear function and we solve Eq. (1) for a single veiling value r in the band. As the veiling is slowly varying with wavelength, the derived veiling r is a good estimate of its mean value within the band.

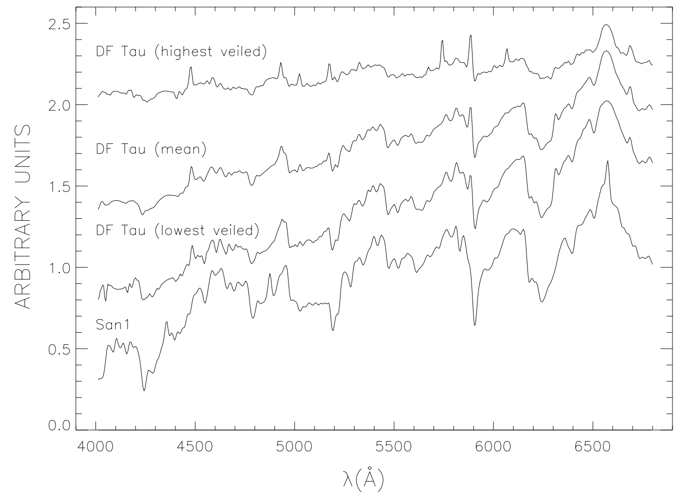

Fig. 1. Low resolution spectrum (≈300) of the M1.5–2 WTTs San1, together with the mean spectrum, the lowest and highest veiled spectra of DF Tau with hydrogen emission lines cancelled. The vertical scale is given by the spectrum of San1, those of DF Tau have been shifted by constant values of 0.4, 0.8 and 1.2.

We have applied this methodology to San1 itself, comparing it with M2V template stars and finding that its apparent veiling is close to zero. From minimally veiled spectra of DF Tau and assuming that San1 (see Fig. 1) is a good representation of the underlying photospheric spectrum of the former, we calculate the associated values R_{min}, in the following bandpasses: [4120 Å, 4560 Å], [4560 Å, 4945 Å] and [5330 Å, 5715 Å]. For each bandpass, we estimate the veiling for the extreme cases of $\xi = 0$ and $\xi = \infty$, finding that those values always differ by less than 0.1 to 0.2. The corresponding bias is at most of the order of the systematic error inherent to any veiling determination, regardless of the spectral resolution used. We adopt the mean value of $R_{\xi=0}$ and $R_{\xi=\infty}$ as representative of the true veiling and their half difference as its associated error. This procedure provides us at the same time with zero veiling points and a minimally veiled spectrum of DF Tau itself. This spectrum is now adopted as a new template, to derive a differential veiling for the rest of the spectra in our sample. This approach minimizes the biasses arising from potentially real spectral mismatches. Finally we linearly interpolate the derived values for veiling in the first two bands to obtain a mean value centered at λ=4530 Å, which roughly corresponds to the photometric B band effec-

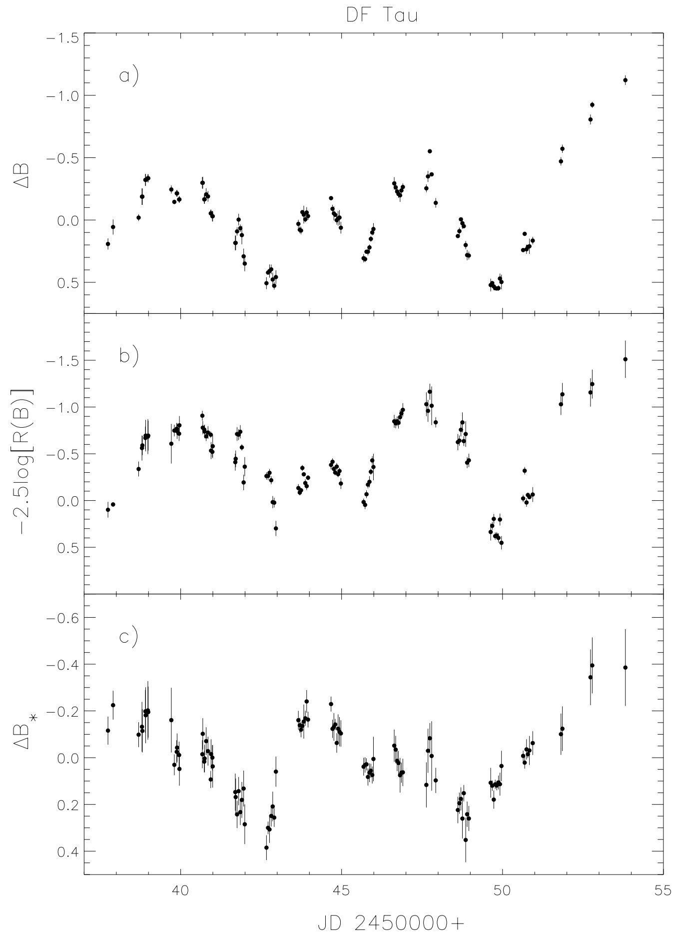

Fig. 2. a Magnitude variations of DF Tau in the photometric B band; **b** Veiling $R(B)$ in magnitude units, calculated in a 825 Å bandpass, centered at λ=4530 Å; **c** Stellar magnitude variations ΔB_* in the B band (see text).

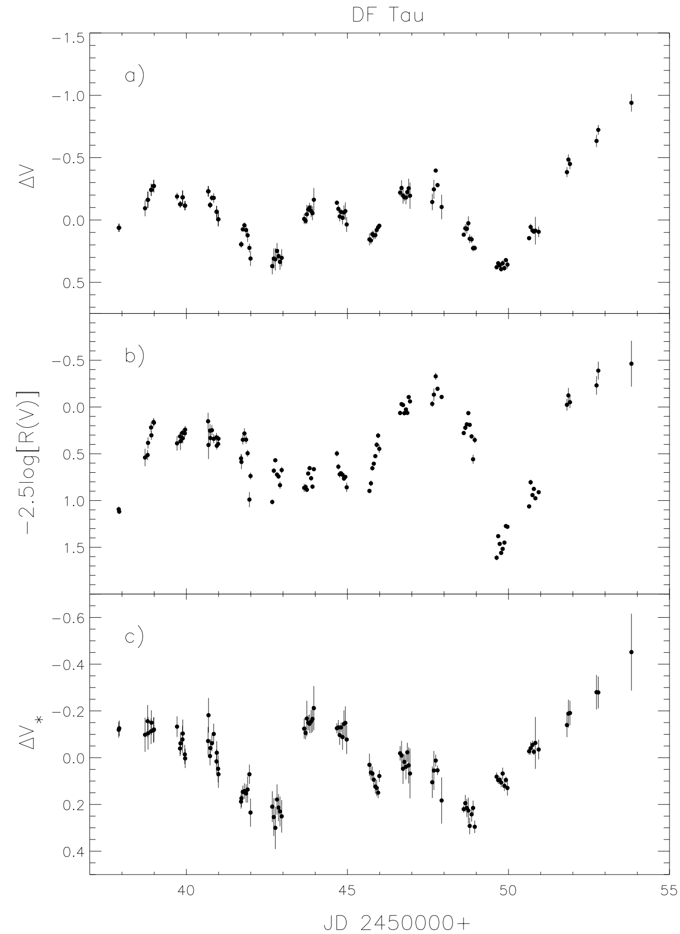

Fig. 3. a Magnitude variations of DF Tau in the photometric V band; **b** Veiling $R(V)$ in magnitude units, calculated in a 385 Å bandpass, centered at λ=5520 Å; **c** Stellar magnitude variations ΔV_* in the V band (see text).

tive wavelength. The central wavelength of the third bandpass is λ=5520 Å which corresponds to that of the photometric V band. We tried various DF Tau spectra as templates, even the mean spectrum, finding that the derived veilings differed by less than 10 to 20%.

4. Results and discussion

Although DF Tau is a binary system (Chen et al. 1990), the measured photometric variations represent largely changes in the primary (Ghez et al. 1997). In Fig. 1, we present the mean spectrum, the lowest and highest veiled spectra of DF Tau with the hydrogen emission lines cancelled. For comparison, we also plot the spectrum of San1 which is undoubtfully a good representation of the underlying photospheric spectrum of the binary system. Hence, for veiling derivation it is fair to treat the system as a single source. In the extreme spectra of Fig. 1, we can also see that our resolution is highly sensitive to contrast changes associated with the veiling process.

In Figs. 2ab and 3ab, we present the light and the veiling curves derived for the B and V bands in DF Tau for the time-base of our observations. Worth noticing is the remarkable resemblance of the photometric and veiling curves in every band which closely follow one another, even for data points contained in a single night. This result illustrates the quality of our data and validates the robustness of our veiling extraction algorithm from low resolution spectroscopy, since those curves are derived from totally independent techniques, ie. photometry and spectroscopy. There, we can clearly notice the maxima of light at about JD≈40 and ≈47.5, associated with the hot spot previously seen by other authors (Bouvier & Bertout 1989). From the appearance and disappearance of this hot spot present in the light and veiling curves, we can easily deduce a rotational period of 7.2 ± 0.3 days. Johns & Basri (1995) have determined a rotational period of 7.3 ± 0.4 days from $H\alpha$ spectroscopy, and Johns-Krull & Basri (1997) found a period of 7.0 ± 0.2 days from HeI 5875 Å emission line, both consistent with the value reported here.

We also detect the presence of flare events (rapidly varying flux) of duration of a few hours, clearly at JD≈42, ≈48 and ≈49 (see also Guenther & Hessman, 1993). The recurrence of flares in our data is telling us that this kind of event is rather common

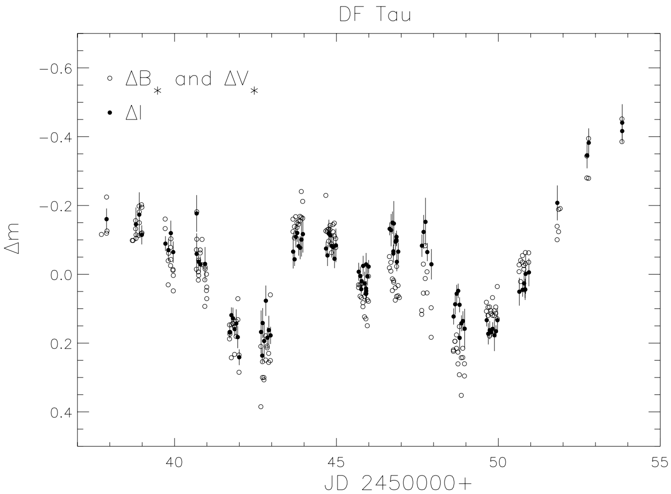

Fig. 4. Stellar magnitude variations ΔB_* and ΔV_* (white points) together with magnitude variations in the I band (black points), as a function of time. Note the excellent agreement between the derived ΔB_* and ΔV_* curves and the I curve which validates our stellar flux derivations (see text).

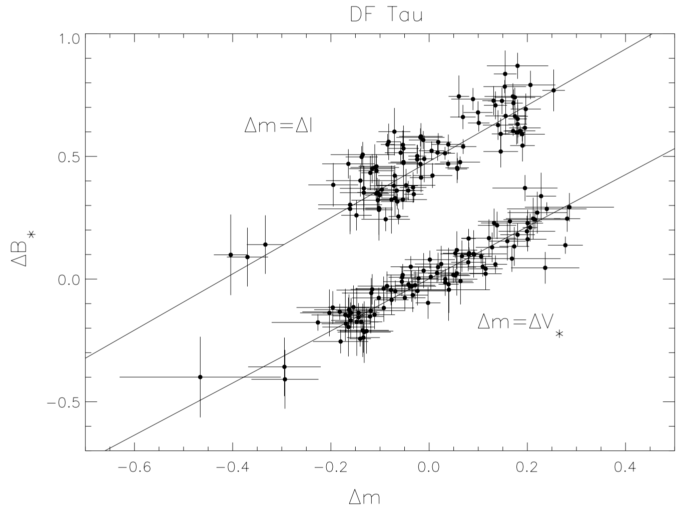

Fig. 5. Stellar magnitude variations ΔB_* as a function of ΔV_* and ΔI, the (ΔI, ΔB_*) curve has been shifted vertically by 0.5. The straight lines represent the best linear fits and are given by $\Delta B_* = (1.06 \pm 0.05)\Delta V_*$ and $\Delta B_* = (1.15 \pm 0.06)\Delta I$, which corresponds to basically grey variations.

in DF Tau. The luminosity source of the flaring process could be related to the presumed accretion phenomenon via magnetic tubes of disk material into the photosphere. If so, the accretion rates must be highly variable even in very short timescales. Alternatively, the presence of relatively strong magnetic structures could have associated chromospheric activity similar to that seen in the Sun, but with much larger energetics. From the light and veiling curves, we also detect a luminosity increase associated with an increase in the amount of veiling starting at JD≈50, and suggestive of a steady increase of the accretion rate from this date. During our observing period, the veiling in the B band was in the range [0.7, 4.0], with a mean value of 1.6; and that in the V band was in the range [0.2, 1.5], with a mean value of 0.7. Those values are comparable with previous veiling determinations in DF Tau from high to extremely high resolution studies (Hartigan et al. 1995, Johns-Krull & Basri 1997, Gullbring et al. 1998).

Combining simultaneous light and veiling curves allows to separate the stellar and excess fluxes. Here, we focus on the stellar flux only, the excess flux as well as the hydrogen emission lines and the whole set of visible data will be discussed in a forthcoming paper (Chelli et al., in preparation). To a first approximation, the observed total photometric flux F_t of DF Tau can be written as: $F_t \propto 10^{-0.4A_*} F_*^0 + 10^{-0.4A_e} F_e^0$, where F_*^0 and A_* are the intrinsic photospheric flux and its associated extinction, and F_e^0 and A_e are the corresponding quantities for the excess flux. Then, introducing the veiling $R = 10^{-0.4A_e} F_e^0 / 10^{-0.4A_*} F_*^0$, it holds:

$$\frac{F_t}{(1+R)} \propto 10^{-0.4A_*} F_*^0. \quad (2)$$

The associated stellar magnitude variations $\Delta m_*(\lambda)$, with respect to the mean stellar magnitude during the observing timebase, are shown for the B and V bands, in Figs. 2c and 3c, respectively. During the first 12 days, the stellar flux exhibits periodic behavior, with two minima separated by about 6 days, followed from the 13th day by a steady increase. We cross-checked these results with the observed magnitude variations in the I band. As the veiling is generally small in this band for CTTs, the associated flux curve must closely follow the derived BV stellar flux curves. In Fig. 4, we plot ΔI, ΔB_* and ΔV_* as a function of time. With the exception of JD≈47, ≈48 and ≈49, where the I flux is probably affected by a small excess, the agreement between the 3 curves is excellent, which confirms the robustness of our stellar flux derivation. Fig. 5 shows ΔB_* as a function of ΔV_* and ΔI, respectively. The straight lines represent the best linear fits and yields, $\Delta B_* = (1.06 \pm 0.05)\Delta V_*$ and $\Delta B_* = (1.15 \pm 0.06)\Delta I$, which correspond to a basically grey stellar variation between the B and I bands. The higher dispersion of the I points compared to the V points must be attributed to a small excess in the I band, which corresponds most of the time to a veiling smaller than 10%.

From Eq. (2), the stellar magnitude variations can be written as: $\Delta m_* = \Delta A_* + \Delta m_*^0$. In practice, Δm_* can be due to either a change in the circumstellar extinction ΔA_* or in the intrinsic stellar magnitude Δm_*^0, associated to cold spots, or both. It is very to difficult disentangle these two contributions as in both cases we can always find a set of parameters which fits the observed stellar slopes between the B and I bands. In our specific case, the stellar flux changes are consistent, for example, with the presence of a cold spot if the star temperature is 3800 K and the spot temperature is 2600 K. But to reproduce the overall dynamics of about 0.75 mag derived from ΔB_* and ΔV_* (see Figs. 2c and 3c), and that of 0.65 mag observed in the I band (see Fig. 4), this hypothetical spot must cover at least 50% of the stellar surface. It would be the largest cold spot ever detected in a T Tauri star. Furthermore, this spot must be variable to explain the broken periodicity from JD≈49. Although we cannot dismiss definitively the presence of cold spots, we find more reasonable variable circumstellar extinction by an optically thick cloud which covers at least 50% of the stellar surface at maximum occultation. The similarity between the stellar rotational period and the 6 days time difference between minima in Figs. 2c and 3c, and the quasi simultaneous steady increase of the stellar flux and the veiling (i.e. the accretion rate) after JD≈50, can naturally be explained by the occultation effects of a cloud being accreted, located initially within the corotating volume. As this cloud spirals into the star, two things occur: 1) the accretion rate increases, and 2) the cloud opacity decreases, as parts of it fall into the star.

To conclude, we would like to emphase that the method presented in this work can in principle be applied to any pre-main sequence (PMS) star which is not permanently highly veiled. In the case of low veiled PMS stars like WTTs, we have no reliable veiling value. However, from a differential veiling approach, it would be possible to follow the veiling variations, which could help to estimate the magnitude of the veiling. More generally, simultaneous photometry and low resolution spectroscopy with veiling extraction allow to disentangle the stellar and excess fluxes. It can be an important tool to understand the true nature of the excess and the causes of stellar photometric variations.

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