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LETTER

Letter to the Editor

Veiling derivation from high to low resolution spectra of T Tauri stars

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Abstract. We propose a simple and efficient approach to extract the veiling from low resolution spectra (few hundreds) of T Tauri stars. The method is based on a point to point energy balance, over large scale and deep spectral structures, between the T Tauri spectrum and a template spectrum. We validate the new algorithm, with derivations of the veiling in quasi-simultaneous high resolution (≈10000) and low resolution spectra (≈300) of the Classical T Tauri star BP Tau. For this half veiled object the results coincides within 10%. The low resolution approach is a powerful tool which makes it possible to study variability problems in T Tauri stars, related to e.g. flare or accretion activity, in timescales as short as minutes.

Key words: methods: data analysis – techniques: spectroscopic – stars: pre-main sequence – accretion, accretion disks

1. Introduction

At the end of the eighties, it has been noted that the photospheric absorption lines of Classical T Tauri Stars (CTTS) were not as deep as the corresponding lines of "normal" stars with the same spectral type. The veiling, a quantitative measure of this effect, was rapidly interpreted as due to the line filling by a smooth blue continuum presumably related to the accretion process. This continuum excess has apparently several spectral components which may indicate that there are actually several sources of veiling (Costa et al. 1999). It is assumed to be additive, however simultaneous photometric and spectroscopic data is required to definitively show it (Chelli et al. 1999).

Hartigan et al. (1989, HHKHS hereinafter) were the first to propose a simple algorithm to extract the veiling from high to very high resolution spectra of T Tauri stars. Recently, Chelli (1999, CH99 hereinafter) investigated further the method proposed by HHKHS, making a detailed balance of its astronomical performances and a rigorous analysis of the sources of bias. An important theoretical conclusion of this study stated that, in principle, it is possible to extract the veiling from the large scale structures of low resolution spectra of CTTS. The present work aims to demonstrate the validity of this statement reporting a practical application to quasi-simultaneous high (≈10000) and low (≈300) resolution spectra of the CTTS BP Tau.

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2. Veiling derivation: the state of the art

The veiling of a T Tauri star has been defined as the ratio of its excess flux to either the local photospheric continuum of the comparison template, named r, or to the mean flux of the template spectrum within the working band, named R (HHKHS). In the veiling derivation process, the template spectrum is assumed to represent the object underlying unveiled spectrum.

Two main classes of algorithms have been proposed to extract the veiling from CTTS spectra. The first class was introduced by HHKHS and is based on a point to point comparison between the photospheric absorption *lines* of the object and those of the template star through an appropriate χ^2 minimization. The second class is based on a comparison between the *lines* energy content of the object and that of the template star. The comparison is made either through the concept of equivalent width or through the concept of cross and auto correlation (Basri & Bertout 1989, Basri & Bathala 1990, Guenther & Hessman 1993). In principle, these two algorithmic classes are equivalent from the point of view of the signal to noise ratio. Although the lines energy content method is much easier to use than the point to point method, we hardly see how this global approach can give an insight to the problems of bias inherent to any veiling derivation (see CH99 and below). For this reason, although the question deserves a more detailed study, we think that the point to point approach of HHKHS should, whenever possible, be preferred.

HHKHS proposed to extract the veiling r from a point to point comparison between photospheric absorption lines of the object spectrum $O(\lambda)$ and those of an appropriate template spectrum $T(\lambda)$, each normalized to their local continua. In practice, the comparison is made over a spectral interval small enough (a few tens of Angstroms), where r can be assumed wavelength independent. For constant noise on both the object and the template spectra, the problem of veiling derivation consists in minimizing, as a function of the two unknowns p and r, the quantity:

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

where the index k stands for the sampled wavelength domain, w_k is a window function, p is a scaling factor, σ_o is the inferred object spectrum noise and $\xi = \sigma_t/\sigma_o$ is the inferred noise ratio between the template and the object spectra.

Let us summarize the conclusions of CH99 with respect to the bias in veiling calculations from Eq. (1). There are two classes of bias coming from: 1) bad noise ratio estimates ξ and, 2) spectral mismatches of any kind, real or due to systematic errors, between the object and the comparison template. Recently, Guenther et al. (1999) have shown that the presence of strong magnetic fields in T Tauri stars may lead to wrongly determined spectral types and may induce veiling overestimates. Let r_c be the calculated veiling and $\delta r = r - r_c$ be the difference between the true and the calculated veiling. Let us assume for the moment that there is no spectral mismatches. The veiling bias $\delta r = r - r_c$ is obviously equal to zero if the input noise ratio ξ in Eq. (1) represents the real noise ratio. On the other hand, the relative veiling bias is bounded by a positive upper limit and a negative lower limit:

$$\frac{\delta r}{1+r} = +\frac{1}{q_t^2} \qquad \text{for} \qquad \xi = 0, \tag{2}$$

and

$$\frac{\delta r}{1+r} = -\frac{1}{1+q_o^2} \qquad \text{for} \qquad \xi = \infty, \tag{3}$$

where $\xi = \infty$ means $\sigma_o^2(1+p^2\xi^2) = p^2\sigma_t^2$ in Eq. (1) and q_t^2 (resp. q_o^2) is the variance with wavelength – square of the spectral constrast – in noise units of the template (resp. object) spectrum in the selected spectral bandpass, i.e.:

$$q_t^2 = \frac{1}{\sigma_t^2}\left[\frac{\sum_{k=1}^m T_k^2}{m} - \left(\frac{\sum_{k=1}^m T_k}{m}\right)^2\right]. \tag{4}$$

The q^2's are the parameters scaling the bias. Eqs. (2) and (3) clearly show that when the object and the template noises tend to zero, the upper and the lower limits of the veiling bias also tend to zero and the solution of Eq. (1) becomes more and more independent of any input parameter ξ. This simple result allows us to consider the problem of spectral mismatches.

Let us now assume relatively not noisy spectra (q_t and $q_o \gg 1$). Any variation of the calculated veiling as a function of the ξ input value in Eq. (1) must be attributed to spectral mismatches between the object and the template spectra. In this case, as we do not know the true object underlying photospheric spectrum, it is no longer possible to strictly bound the object veiling with minimum and maximum values. But, it is still possible to compute the "extreme" veiling values $r_{\xi=0}$ and $r_{\xi=\infty}$. CH99 has shown that if the difference $r_{\xi=0} - r_{\xi=\infty}$ is equal to zero, then Eq. (1) is exact and the bias is dominated by the apparent veiling of the template, if any [see Eq. (12) of CH99]. Otherwise, the difference $r_{\xi=0} - r_{\xi=\infty}$ can be interpreted as the goodness of the fit to the veiling equation. In practice, there is *a priori* and to the knowledge of the author, no objective reasons to choose one solution rather than the other one ($\xi = 0$ or $\xi = \infty$) or any intermediate solution. However, we can always define an upper limit, necessarily somewhat arbitrary, to the relative difference between the extreme veiling values, $(r_{\xi=0} - r_{\xi=\infty})/(1+r)$, for example 10 to 20%, below which we consider that the template spectrum is a "good" representation of the object underlying photospheric spectrum and hence the solution is acceptable. Under these conditions, we propose to adopt the mean value between $r_{\xi=0}$ and $r_{\xi=\infty}$ as representative of the true veiling and their half difference as its associated error.

3. Veiling derivation from high resolution spectra

In this and the next section, we study from an experimental point of view the veiling derivation from the HHKHS approach in the light of the analysis of CH99. Here we examine the high spectral resolution case. For this purpose, we use a high resolution spectrum ($\approx$ 40000) of the K7 CTTS BP Tau obtained with one hour integration time on November 28, 1995 (JD=2450050.32), at the 1.93m telescope of the Observatoire de Haute Provence (France) with the instrument ELODIE (Baranne et al. 1995). The selected template is the bright K7V star HD 201092 observed with the same instrument. The spectra are composed of 67 orders covering roughly the wavelength domain [4000 Å, 6800 Å]. Although HD 201092 is perhaps not the best template to be used for veiling derivation in BP Tau through the whole spectral range, this is not important here because we are just interested in probing the algorithm. We restrict the analysis to 8 spectral orders, each of a few tens of Angstroms width, corresponding to a deep spectral depression between 4950 and 5280 Å, seen at low resolution. The orders are first regularly resampled and oversampled with a 0.03 Å wavelength step. They are then smoothed by gaussian filtering to a spectral resolution of about 10000, leading to q values larger than 6 and 25 for BP Tau and the template, respectively. From Eqs. (2) and (3), we conclude that the relative veiling bias will be dominated by spectral mismatches, but not by bad noise estimates whose maximum effect is of a few % only.

Figs. 1a and 1b show a selected spectrum of BP Tau and the relevant template, each one normalized to its mean flux. We can check by eye that the system of absorption lines of BP Tau is roughly the same than that of the template and that it is about half less deep, which would correspond to a veiling around 1. To asses quantitatively this point, we apply the HHKHS algorithm, adopting the R definition for the veiling, in which the excess is referred to the mean flux of the template (see Sect. 2). The veiling is still assumed constant through the working band, but to take into account a possible slope difference between the object and the template spectra, we do not longer assume a constant scaling factor p. Instead, we approximate its variations within the band by a linear function. The quantity Q given by Eq. (1) then becomes a function of three unknowns (the veiling R plus two for the function p). Its minimum is automatically found, to a precision of one fourth of point in wavelength, by recentering one of the spectra via Fourier transform.

Fig. 1c and 1d show the best fits of BP Tau selected spectrum (solide line) by the veiled template (dotted line), $p[T(\lambda)+R]$,

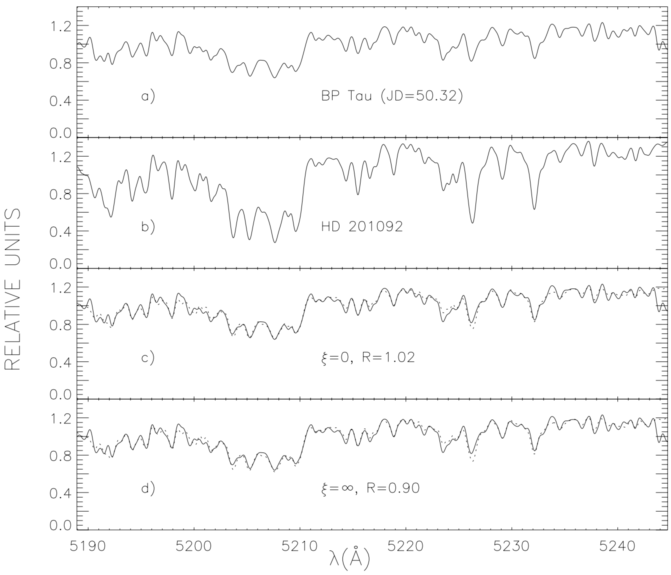

Fig. 1. a High resolution (≈10000) BP Tau selected spectral order, **b** Template spectrum, **c** and **d** Fits of BP Tau spectrum with the veiled template (dotted lines), for $\xi = 0$ and $\xi = \infty$.

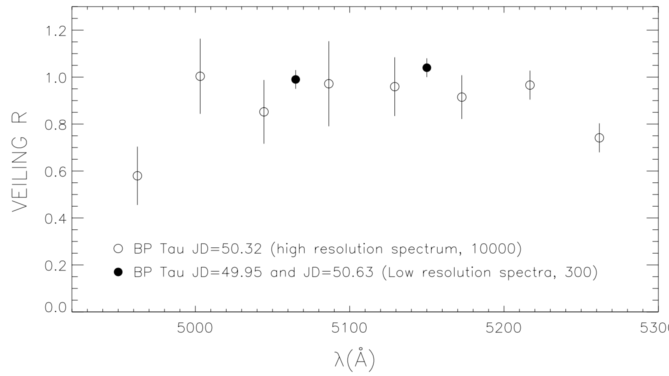

Fig. 2. White points: veiling of BP Tau as a function of the wavelength, calculated from the eight high spectral resolution (≈10000) orders obtained at JD=2450050.32. Black points: veiling of BP Tau calculated from low resolution spectra (≈300) at JD=2450049.95 and JD=2450050.63, using the structure between 4950 and 5280 Å. The two black points have been separated along the x-axis for clarity.

for $\xi = 0$ and $\xi = \infty$. The results of the fits are $R_{\xi=0}$=1.02 and $R_{\xi=\infty}$=0.90, corresponding to a relative difference $(R_{\xi=0} - R_{\xi=\infty})/(1 + R)$ of about 6% and essentially attributable to spectral mismatches between the object and the template spectra. A careful examination of the fits over the eight spectral orders shows that the template deepest absorption lines are not as well adjusted for $\xi = \infty$ as for $\xi = 0$. For $\xi = \infty$, i.e. $\sigma_o^2(1 + p^2\xi^2) = p^2\sigma_t^2$, the algorithm will in someway tend to interpret part of the high frequency information of the template spectrum, mostly contained in the deepest lines, as if it was spurious noise and will not try to closely adjust it (CH99). Although the solution for $\xi = 0$ seems to be in general apparently better than the solution for $\xi = \infty$, it cannot be considered as such. The reason just lies in spectral mismatches, which make that the object cannot be exactly represented by the veiled template. Fig 2 presents the veiling with its error bar (mean and half difference between $R_{\xi=0}$ and $R_{\xi=\infty}$) as a function of wavelength (white points). Clearly, from 4950 to 5280 Å, the veiling is fairly constant with a mean through the band of $\bar{R}$=0.89 and a standard deviation of $\sigma_{\bar{R}}$=0.11 (excluding the two end points $\bar{R} = 0.94 \pm 0.05$).

4. Veiling derivation from low resolution spectra

The need of high to very high spectral resolution for veiling derivations, claimed by various authors, comes naturally within the framework of the use of individual absorption *lines*. Based on this standard approach, Gullbring et al. (1998) have calculated veilings in the visible domain from the lowest spectral resolution used so far, of about 2000. The problem we would like to study here is: can we derive veilings of CTTS from much lower spectral resolution, of a few hundreds only? The answer is clear: we cannot within the current framework for the following reasons. At very low spectral resolution, it is no longer possible: i) to properly isolate individual absorption lines and, ii) to use bandpasses of a few tens of Angstroms only, because spectral mismatches together with the small number of independent spectral points, small spectral contrasts $\sigma_t q_t$ and $\sigma_o q_o$ [see Eq. (4)] and small q's, will lead to unsuperable biases.

To overcome these difficulties, we must change the framework. A very simple approach consists to work on large scale *structures* of high contrast, extending over spectral widths of a few hundreds Angstroms, and to make a point to point energy balance between the CTTS and the template. The prominent and deep structure seen from 4950 to 5280 Å in K and M spectral types is ideal for this purpose, although it is not the only one which can be used. In this context, we propose to approximate the p function by a second degree polynom and to solve Eq. (1) for a single veiling value R which, given that the veiling is slowly varying with wavelength, would represent its mean value within the band.

In order to test experimentally these ideas, we used two low resolution spectra (≈400) of BP Tau observed with the Faint Object Spectroscopic Camera (Zickgraf et al. 1997) at the 2.1m telescope of the Guillermo Haro Observatory at Cananea (Sonora, México). They were obtained during the night of November, 1995, with 5 minutes integration each, one spectrum 9 hours before (JD=2450049.95) and the other spectrum 7.5 hours after (JD=2450050.63) the BP Tau high resolution spectrum presented in the previous section. Unfortunately, HD 201092 has not been observed at Cananea, hence we used the ELODIE high resolution spectrum of this star properly reconstructed from the spectral orders. The BP Tau spectra from Cananea (with hydrogen emission lines removed) and the HD 201092 spectrum from ELODIE, both smoothed by gaussian filtering to the same spectral resolution of approximatively 300, are shown in Fig. 3. The structure selected for veiling derivation between 4950 and 5280 Å is indicated by the two vertical dotted lines and corresponds to q values of about 7 and larger than 100 for BP Tau and the template (spectral

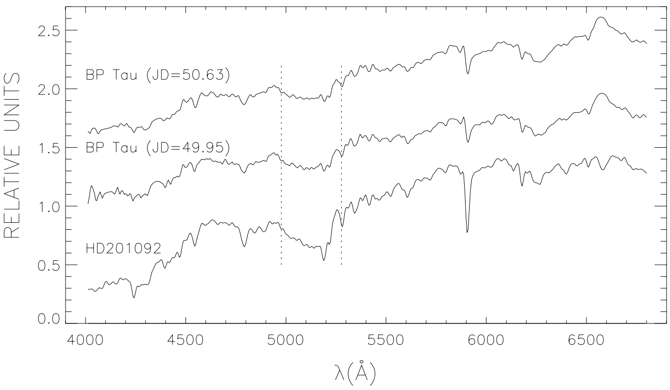

Fig. 3. Low resolution (≈300) spectra of BP Tau (with hydrogen emission lines removed) and HD 201092. The structure selected for veiling derivation between 4950 and 5280 Å is indicated by the two vertical dotted lines. The vertical scale is given by the spectrum of HD 201092, those of BP Tau have been shifted by 0.6 and 1.2.

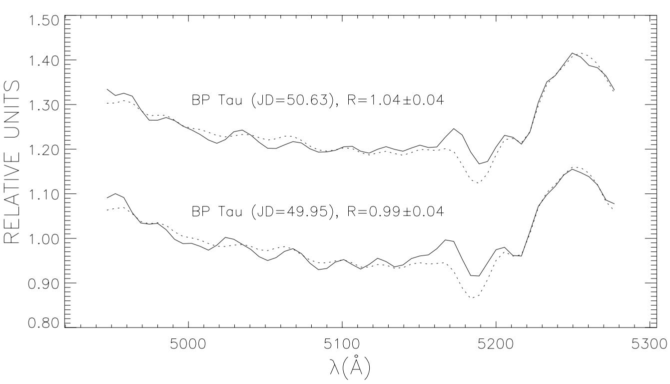

Fig. 4. Low resolution (≈300) spectra of BP Tau (solid line) in the range [4950 Å, 5280 Å], together with the best fit by the veiled template (dotted line) for the case $\xi = 0$. The vertical scale is given by the bottom spectrum, the upper spectrum has just been shifted by 0.25.

contrasts of 7% and 15%), respectively. The region between 5160 and 5200 Å, which is highly contaminated by emission or partially filled lines, has been excluded from the fit. More generally, strong emission lines must be excluded. Weak emission lines have no appreciable effect on the derived veiling value because their energy content is small. They will be interpreted by the algorithm as slight spectral mismatches, often comparable to systematic errors, and will only produce slightly larger veiling errors.

The results of the fits are shown in Fig. 4 and the calculated veilings, $R = 0.99 \pm 0.04$ for JD=49.95 and $R = 1.04 \pm 0.04$ for JD=50.63, are reported in Fig. 2 (black points) and separated along the x-axis for better clarity. The agreement between the veiling derivations from the quasi-simultaneous (within a few hours) high (10000) and low (300) resolution spectra of BP Tau is excellent. These results validate the proposed algorithm and demonstrate that the veiling can be extracted from low resolution spectra of CTTS by making a point to point energy balance between the object and the template over large scale and deep spectral structures.

5. Conclusions

We have shown that in BP Tau the veiling extracted from low resolution spectra coincides with that derived from high resolution spectra. The calculated veiling of 1 is moderate, but the proposed approach can be applied to higher veiled spectra. Chelli et al. (1999) succeeded to measure veilings as high as 4 from low resolution spectra (≈300) of the CTTS DF Tau. This is because the method is based on the energy contained in deep and large scale structures of a few hundreds Angstroms width. A big advantage is that the differences between the object and the template spectra seen at high resolution are minimized or even completely cancelled. Yet, spectra which are highly contaminated with emission lines may be a problem. However, this problem is, to our opinion, as difficult to solve at high spectral resolution, because large spectral mismatches between the object and the template may be present in this case.

The low resolution approach is not meant to replace the high resolution approach and *vice versa*: we simply do not get the same kind of information. For example, it will probably be difficult to study the spectral variations of the veiling at resolutions as low as a few hundreds only. But on the other hand, the low resolution approach can be a powerful tool, in particular via differential methods, to study variability problems in T Tauri stars, related to e.g. flare or accretion activity (see Chelli et al. 1999), in timescales as short as minutes.

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