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Probing Magnetospheric Infall onto CTTS with Time-resolved Veiling Measurements.

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Abstract.

We show that time-resolved veiling measurements over a large wavelength range can probe individual accretion events onto Classical T Tauri Stars (CTTS). We demonstrate two methods of measuring veiling. Using these measurements, we model CTTS spectra as a superposition of two components representing stellar and accretion emission. The simple but functional method allows us to estimate the temperature of the accretion shock and the relative surface area of the accretion regions on the star. We apply this method to a series of spectra of the CTTS RU Lupi and present our first results.

1. Introduction

The presence of a veiling pseudo-continuum in CTTS was discovered as early as CTTS themselves, first in the form of a process filling in photospheric absorption lines. This effect was later interpreted as a hot excess continuum on top of the stellar spectrum. This so-called veiling continuum originates just above the stellar surface, where accreted matter from the circumstellar enviroment shocks into the stellar photosphere.

Because the veiling continuum is closely related to the accretion process and particularly the instantaneous accretion rate, veiling is an important diagnostic of the accretion activity of CTTS. The relation between veiling and accretion in CTTS has been discussed in detail by Calvet & Gullbring (1998). We study the changes in the level of veiling in order to gain a better understanding of the evolution of the accretion rate. The changes in the level of veiling is also a diagnostic of the size of the accretion region, which in turn allows the nature of variability in the accretion flow to be constrained.

Up to now, the search for any spectral features in this pseudo-continuum has been unsuccessful; the existence of such features remains an open question.

2. Veiling Measurement

The veiling factor V, by which the pseudo-continuum from the hot accretion shock decreases the line depth of photospheric lines, is defined in the following way :

$$V = I_{\mathrm{pc}}/I_{\mathrm{sc}} \tag{1}$$

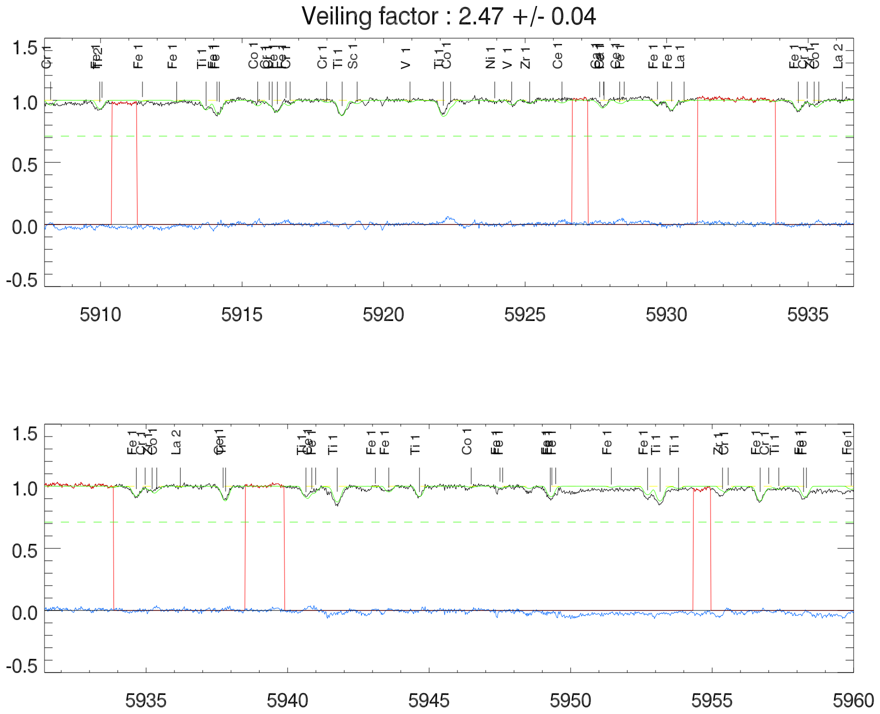

Figure 1. Illustrating fit (using the 'first method') of a veiled synthetic spectrum (green) to a region of our observations (black). The dashed green line represents the zero offset of the unveiled synthetic spectrum. The blue line marks the residual and the red regions were used for continuum determination.

Here $I_{\rm SC}$ is the stellar continuum intensity, and $I_{\rm pc}$ the intensity of the pseudo-continuum. Then the observed relative line depth d^* can be expressed in terms of the unveiled relative line depth d as :

$$d^* = \frac{d}{1+V} \;\rightarrow\; V = \frac{d - d^*}{d^*} \tag{2}$$

It is important to realize that in CTTS the veiling effect in essence is the result of the sum of two spectra, where the excess continuum can be described (at least as a first approximation) by a black body spectrum scaled with the surface filling factor. If the shape of the intrinsic stellar spectrum is known, the shape of the veiling continuum will be a measure of the temperature of the accretion shock. Such a model also provides a diagnostic of the surface filling factor of the hot accretion shock, because the veiling factor is proportional to the visible area of the shock emission. As the filling factor affects all the wavelengths in the same way, it can be determined simultaneously with the temperature of the shock.

In order to determine the veiling factor V for a certain wavelength, we developed two methods based on least-squares fitting. As the veiling is caused by a hot pseudo-continuum on top of a relatively cool stellar spectrum it is

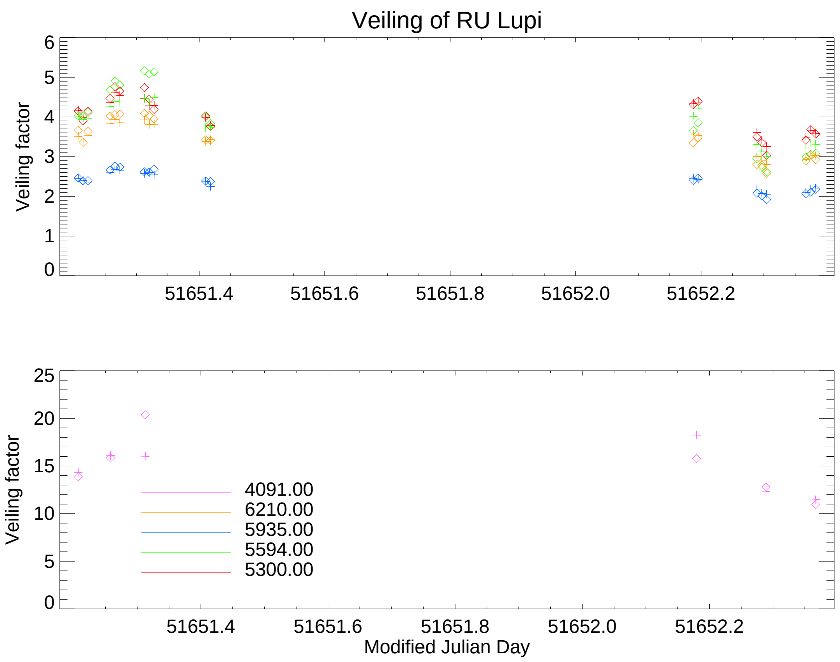

Figure 2. Evolution of the veiling factor at different wavelengths during the observations. Diamonds denote the first method of veiling determination, and crosses the second method. Results of the second method are only relative (see text), and therefore scaled to the mean of the first method.

reasonable to assume that the veiling factor does not change over a short spectral interval. Then the sum to be minimized is :

$$\chi^2 = \sum_{\lambda,(\phi)} \left\{ d^* - \frac{d}{1+V} \right\}^2 \tag{3}$$

2.1. First method

The first method assumes that the intrinsic line depth d is known, for example from a template star or a synthetic spectrum. Then, one can determine the most likely V for a region of the spectrum by minimizing Eq. 3 with respect to V. This is done for each individual observation ϕ.

2.2. Second method

A second method is based on the the assumption that the intrinsic unveiled spectrum does not change from observation to observation. Then it is possible to treat the unveiled line depth d as a free parameter instead of assuming an artificial or template spectrum. The introduction of another free parameter can be compensated for by summing over all observed observations ϕ, and minimizing Eq. 3 with respect to both V and d. The minimum is found by iteratively solving the system of equations for d_λ and V_ϕ arising from the usual condition

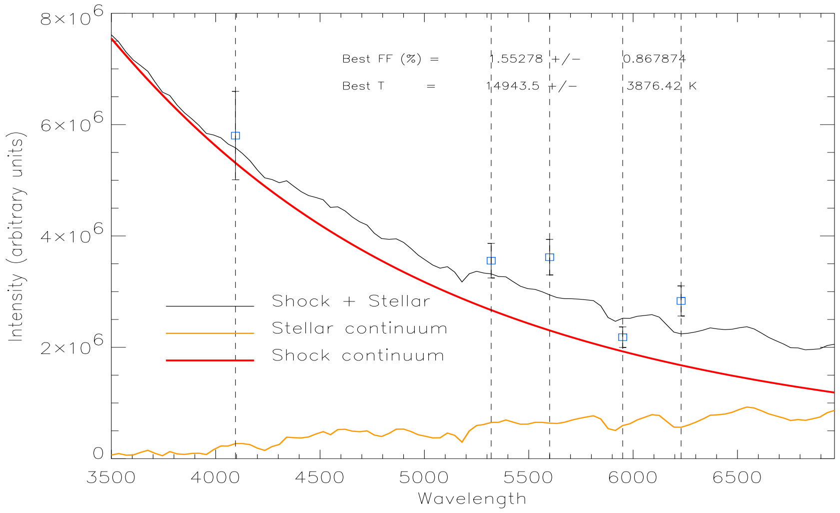

Figure 3. Example of a two-component fit to veiling measurements at different wavelengths. The quoted errors of the filling factor and temperature are for the case of independent variables (see text).

that the partial derivatives at the minimum be equal to zero. It is important to realize that for this method, because we did not make any assumption about the unveiled line depth d, there is a degeneracy between d and $1+V$. Any increase of d can be compensated by a corresponding increase of $1+V$. In other words, we cannot determine the zero point for the veiling.

Both methods have their advantages. The first method is capable of deriving the absolute value of the veiling, but requires knowledge of the intrinsic spectrum. Such a spectrum may not always be available. The second method can be applied without *a priori* knowledge of the spectral region, but offers only relative veiling measurements. The combination of the two methods provides us with the best veiling measurements and allows the shock temperature and the filling factors to be derived.

3. Probing Magnetospheric Infall

In April 2000, in the course of two nights, we acquired 19 high-quality spectra of the CTTS RU Lupi with the UVES spectrograph on the VLT ($R \approx 60000$, SNR $\geq$ 200 and $3700 < \lambda < 6700$ Å). This heavily accreting star ($\dot{M} \approx 3 \cdot 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$) shows accretion-related variability on timescales as short as 15 minutes. To this set of observations, we applied a detailed veiling analysis and here we present our first results (See Stempels & Piskunov 2002 for a more detailed description and analysis of the observations). We determined the veiling during these observations at four wavelengths with both methods. An example fit of the template spectrum to a section of observations using the first method is shown in Fig. 1. The results of both methods are summarized in Fig. 2.

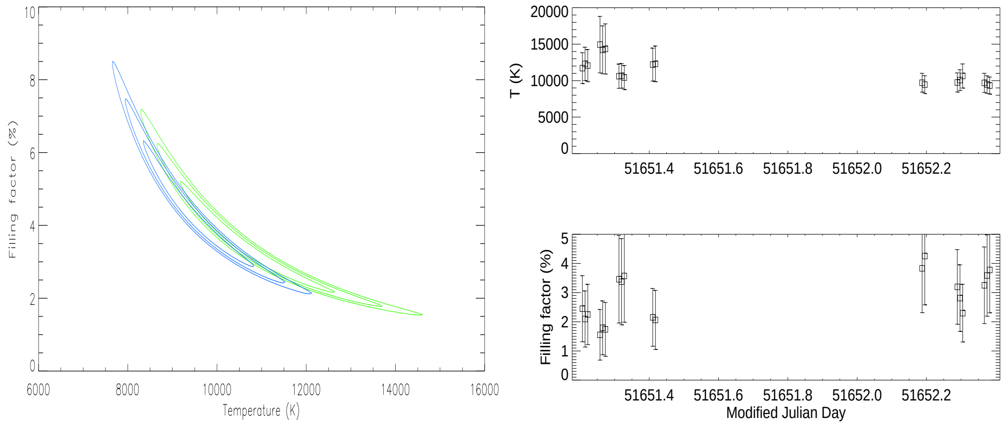

Figure 4. *Left frame :* Examples of confidence regions in parameter space of the temperature and filling factor for two observations of the second night. The contours denote the 1, 2 and 3 sigma confidence intervals. *Right frame :* Evolution of the temperature and filling factor during the observations. The error bars may be slightly misleading because they are for the case of independent parameters (see text for explanation). Comparison with the left panel clearly shows that changes are significant, though correlated.

3.1. Two-component model

As was mentioned in the previous section, the wavelength dependence of the veiling can provide estimates of the temperature and filling factor of the accretion regions. In order to determine these parameters, we developed a simple but functional two-component model. In this model, we approximated the veiling continuum contribution with a black-body function, and the stellar contribution with a template flux spectrum. This can be expressed as follows:

$$F = F_{\text{star}} + S_{\text{ff}} \cdot \pi B_{\lambda}(T_{\text{pc}}) \tag{4}$$

where F_{star} is the astrophysical flux of the stellar component, T_{pc} the temperature of the pseudo continuum, and S_{ff} the filling factor.

3.2. Nature of the accretion flow

With this model in mind, the evolution of the temperature and filling factor of the accretion regions was determined by a least-squares fit of the veiling measurements we obtained at four different wavelengths to a scaled black-body function superimposed on a stellar flux spectrum. An example of such a fit is shown in Fig. 3. However, the values of the parameters T_{pc} and S_{ff} are strongly correlated; an increase in the veiling temperature can be compensated by a decrease in the filling factor. Therefore we performed full error propagation to obtain confidence regions of the filling factor and temperature. We show two such confidence regions in the left panel of Fig. 4. Because the confidence regions of the individual observations do not overlap, it is clear that the changes in the evolution of the temperature and filling factor of the accretion region are significant.

In the right panel of Fig. 4 we show a time-series of the derived temperatures and filling factors during our observation run. The quoted errorbars may be slightly misleading, because they must be interpreted with the left panel of the same figure. Although the error bars show the 1σ confidence limit for each parameter, as if the parameters were independent, *detectable* variations, though correlated, occur on a much smaller scale. The evolution of the filling factor and temperature, as related to the evolution of the veiling factor in Fig. 2 indicates that there are detectable changes in the size of the accretion region after an accretion event. This suggests that the flow of material from the disk to the star is inhomogeneous. The nature of the mechanism which triggers this inhomogeneous flow is still unclear.

References

Calvet, N. & Gullbring, E., 1998, ApJ, 509, 802

Stempels, H.C. & Piskunov, N., 2002, in preparation