Interpretation of the Veiling of the Photospheric Spectrum for T Tauri Stars in Terms of an Accretion Model

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Received May 12, 2012

Abstract—The problem on heating the atmospheres of T Tauri stars by radiation from an accretion shock has been solved. The structure and radiation spectrum of the emerging so-called hot spot have been calculated in the LTE approximation. The emission not only in continuum but also in lines has been taken into account for the first time when calculating the spot spectrum. Comparison with observations has shown that the strongest of these lines manifest themselves as narrow components of helium and metal emission lines, while the weaker ones decrease significantly the depth of photospheric absorption lines, although until now, this effect has been thought to be due to the emission continuum alone. The veiling by lines changes the depth of different photospheric lines to a very different degree even within a narrow spectral range. Therefore, the nonmonotonic wavelength dependence of the degree of veiling found for some CTTS does not suggest a nontrivial spectral energy distribution of the veiling continuum. In general, it makes sense to specify the degree of veiling $r$ only by providing the set of photospheric lines from which this quantity was determined. We show that taking into account the contribution of lines to the veiling of the photospheric spectrum can cause the existing estimates of the accretion rate onto T Tauri stars to decrease by several times, with this being also true for stars with a comparatively weakly veiled spectrum. Neglecting the contribution of lines to the veiling can also lead to appreciable errors in determining the effective temperature, interstellar extinction, radial velocity, and $v\sin i$.

DOi: 10.1134/S1063773712100027

Keywords: stars—individual: RU Lup, S CrA NW, S CrA SE, DR Tau, RW Aur—T Tauri stars—stellar atmospheres—radiative transfer—spectra.

INTRODUCTION

Long ago Joy (1949) noticed that the depths and equivalent widths of photospheric lines in the spectra of T Tauri stars were smaller than those for main-sequence stars of the same spectral types, especially at short wavelengths. This effect is commonly explained by the fact that the absorption lines of the stellar photosphere are “veiled” by the emission continuum, the understanding about the nature of which changed as the views of the cause of activity in T Tauri stars changed.

The emission in optical lines and continuum as well as the very intense ultraviolet (UV) and X-ray emissions had long been thought to be due to the existence of thick chromospheres and coronas around young ($t < 10^7$ yr) low-mass ($M < 2M_\odot$) stars that to some extent are analogous to the solar ones (see the reviews by Bertout (1989) and references therein). However, it had become clear by the early 1990s that this explanation is appropriate only for moderately active young stars in the spectra of which the equivalent width ($EW$) of the H\textalpha emission line does not exceed 5–10 Å and there is virtually no veiling. Below, we will not talk about these objects called weak-lined T Tauri stars.

Here, we will deal with the so-called classical T Tauri stars ($EW_{\text{H}\alpha} > 10$ Å). Their observed manifestations can be explained in terms of the model of mass accretion from a protoplanetary disk onto a young star that has a global magnetic field with a strength $\sim 1–3$ kG. The model suggests that the matter from the inner disk is frozen in the magnetic field lines and slides down toward the star along them, being accelerated by gravity to a velocity $V_0 \sim 300$ km s$^{-1}$. A shock wave at the front of which the gas velocity decreases approximately by a factor of 4 and the gas is abruptly heated to a temperature of $\sim 10^6$ K emerges near the stellar surface. The post-shock matter cools down while gradually radiating its thermal energy in the UV and X-ray ranges and settles to the stellar surface while reducing its velocity.

One half of the short-wavelength radiation flux of the shock from the cooling zone escapes upward,
heating and ionizing the pre-shock gas, and the second half irradiates the star, producing the so-called hot spot on its surface. Estimations (Königl 1991; Lamzin 1995) and numerical calculations (Calvet and Gullbring 1998) show that for classical T Tauri stars (CTTS) at a particle number density in the gas on-flowing onto the front $N_0$ above $\sim 10^{13}$ cm$^{-3}$, the pre-shock region becomes opaque in optical continuum. This means that the shock photosphere must be located upstream of its front at $\log N_0 > 13$ and downstream of its front at lower $N_0$.

Now, there is no doubt that the so-called narrow components of emission lines in the spectra of CTTS are formed inside the hot spot (see Dodin et al. (2012) and references therein). The observability of these components implies that the shock photosphere is in even deeper layers, i.e., in the hot spot and not upstream of the front. Since half of the kinetic energy of the accreting material is radiated in the spot, it is natural to assume that precisely the hot-spot photosphere is the source of the veiling continuum.

If all the short-wavelength radiation of the shock incident on the stellar atmosphere is assumed to be reemitted outward in the form of an emission continuum, then the mass accretion rate onto the star $\dot{M}$ can be found from the relation $L_c = 0.5 \dot{M} V_0^2 / 2$, where $L_c$ is the bolometric luminosity of the veiling continuum, which, just as the pre-shock gas velocity, can be determined by analyzing the spectrum. Basically, the $\dot{M}$ estimates for most CTTS were obtained precisely in this way (see, e.g., Valenti et al. 1993; Hartigan et al. 1995; Gullbring et al. 1998, 2000).

The only (at present) calculation of the vertical hot-spot structure and the veiling continuum spectrum was performed by Calvet and Gullbring (1998) without any allowance for the emission in lines. Comparison of the calculated and observed spectra allowed one not only to determine the accretion rate and the hot-spot sizes but also to self-consistently find the star’s spectral type and the interstellar reddening, which are used to determine the emission continuum spectrum from observations. Moreover, as yet there is no other way to reliably determine the spectral type and the degree of interstellar reddening precisely for heavily veiled CTTS.

A method for separating the veiling continuum by comparing the equivalent widths of photospheric lines in the spectra of CTTS and a comparison star was proposed by Hartigan et al. (1989) and has been used with slight modifications up until now. Having analyzed the spectrum of the star BP Tau, Hartigan et al. (1989) concluded that the veiling was attributable precisely to the emission continuum rather than stemmed from the fact that weak emission lines were superimposed on photospheric lines, thereby reducing their depth.

However, Petrov et al. (2001) found that the presence of emission lines inside photospheric ones in the spectrum of RW Aur led to noticeable observed effects, while Gahm et al. (2008) and Petrov et al. (2011) showed that for several heavily veiled CTTS, the emission in lines contributed significantly to the decrease in the depth of photospheric lines. Theoretically, the presence of emission lines in the hot-spot radiation spectrum seems quite natural, because the temperature above the spot photosphere increases outward. It is reasonable to assume that the strongest of these lines manifest themselves in the spectra of CTTS as narrow emission components, while the weaker ones to a certain extent blend the photospheric lines.

Since the contribution of lines to the veiling has been disregarded so far, it can be concluded that the intensity of the emission continuum in the spectra of CTTS has been systematically overestimated and, hence, all of the available calculated accretion rates have also been overestimated. The goal of this paper is to calculate the radiation spectrum of the hot spot not only in continuum but also in lines and to apply the results obtained to ascertain the extent to which allowance for the emission in lines can change the available estimates of the accretion rate and effective temperature of CTTS and the interstellar extinction.

**FORMULATION OF THE PROBLEM AND INPUT PARAMETERS**

To calculate the hot-spot radiation spectrum, the problem on heating the atmosphere of a young star by radiation from an accretion shock should be solved. The heating of a stellar atmosphere by external radiation has been studied in many papers devoted to the reflection effect in binary systems (see the monograph by Sakhibullin (1997) and references therein). However, these calculations cannot be directly used to determine the radiation spectrum of the hot spots on CTTS for the following reasons. First, the radiations from the hot companions of stars and the accretion shock are different in spectral composition. Second, in our case, the atmosphere being heated is immediately adjacent to the region that serves as an irradiation source. Consequently, the radiation from all sides will be incident on each point of the hot spot, while the radiation from the hot companion arrives at each point of the atmosphere of the neighboring star in the form of an almost parallel flux. For the same reason, in our case, the pressure at the outer boundary of the atmosphere being heated should be equal not to zero but to the pressure that is established far downstream of the shock front (Zel’dovich and Raizer 1966):

$$P_0 = \rho_0 V_0^2,$$

(1)