

# On formation of H- $\alpha$ from classical T Tauri stars: the disc, wind, and magnetospheric-accretion hybrid model

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## ABSTRACT

We present disc–wind–magnetosphere hybrid radiative transfer models for classical T Tauri stars, and investigate the formation of H $\alpha$  to understand their complex circumstellar environment, and to understand the wide variety of emission line profiles seen in observations. To overcome the limited applicability of the radiative transfer models with only magnetospheric accretion to fitting observed H $\alpha$  profiles, and to any other lines affected by the stellar wind) presented, two types of kinematic wind models are introduced: (1) the bipolar wind model in which the wind is originated from the star itself, and (2) the disc-wind model in which the wind originates from the inner part of the accretion disc. We perform systematic investigations of the model parameters for the wind and the magnetosphere to search for possible geometrical and physical conditions which lead to the types of the profiles seen in observations. We find both wind models can reproduce the wide range profile types seen in observations. We also find the inclination dependency of the line equivalent width predicted by the bipolar wind model agree with trends seen in the observation, but the disc-wind model does not. Using the model results, we examine the H $\alpha$  spectroscopic classification used by Reipurth et al., and discuss the basic physical conditions required to reproduce the profiles in each classified type. Using the hybrid model, we fit the observed H $\alpha$  from the optical component of T Tau triple system (T Tau N), and find its ratio of the mass-loss to mass-accretion rate to be  $\sim 0.18$  with the cold ( $T_{\text{wind}} \approx 8000$  K) bipolar wind model.

**Key words:** stars: formation – circumstellar matter – radiative transfer – stars: pre-main-sequence

## 1 INTRODUCTION

T Tauri stars (TTS) are young ( $< \sim 3 \times 10^6$  yrs, Appenzeller & Mundt 1989) low-mass stars, and known as progenitors of solar-type stars. Classical T Tauri stars (CTTS) exhibit strong H $\alpha$  emission, and typically have spectral types of F–K. Some of the most active CTTS show emission in higher Balmer lines and metal lines (e.g., Ca II H and K). They also exhibit an excess amount of continuum flux in the ultraviolet (UV) and infrared (IR). Their spectral energy distribution and polarisation data suggest the presence of a circumstellar disc, and it plays an important role in regulating dynamics of gas flows around CTTS.

Many observational studies (e.g., Herbig 1962; Edwards et al. 1994; Kenyon et al. 1994; Reipurth et al. 1996; Alencar & Basri 2000) of CTTS line profiles show evidences for both outward wind flows and inward accretion flows, as seen in the blue-shifted absorption features in H $\alpha$  profiles and the redshifted inverse P Cygni (IPC) profiles respectively. Typical mass-loss rates of CTTS are about  $10^{-9} M_{\odot} \text{ yr}^{-1}$  to  $10^{-7} M_{\odot} \text{ yr}^{-1}$  (e.g., Kuhl

1964; Edwards et al. 1987; Hartigan et al. 1995), and the mass-accretion rates are also about  $10^{-9} M_{\odot} \text{ yr}^{-1}$  to  $10^{-7} M_{\odot} \text{ yr}^{-1}$  (e.g., Kenyon & Hartmann 1987; Bertout, Basri, & Bouvier 1988; Gullbring et al. 1998). Recent H $\alpha$  spectro-astrometric observations by Takami et al. (2003) show the direct evidence for the presence of bipolar and monopolar outflows down to  $\sim 1$  AU scale (e.g. CS Cha and RU Lup). Similarly, ESO VLT observation of high-resolution ( $R = 50\,000$ ) two-dimensional spectral of edge-on CTTS (HH30<sup>\*</sup>, HK Tau B, and HV Tau C) by Appenzeller et al. (2005) show the extended H $\alpha$  emission in the direction perpendicular to the obscuring circumstellar disc, and in both above and below the disc — suggesting the presence of the bipolar outflows. In slightly larger scale, *HST* observation of HH30 Burrows et al. (1996) shows the jet traced to within  $\lesssim 30$  AU from the star. The jet has a cone shape with an opening angle of  $3^\circ$  between 70 and 700 AU (Königl & Pudritz 2000). Alencar & Basri (2000) found about 80 per cent of their samples (30 CTTS) show blue-shifted absorption components in at least one of Balmer lines and Ca K (most commonly in H $\alpha$ ).

In a currently favoured model of accretion flows around CTTS, the accretion discs are disrupted by the magnetosphere of

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stars which channels the gas from the disc onto the surface of the stars (e.g., Uchida & Shibata 1985; Königl 1991; Collier Cameron & Campbell 1993; Shu et al. 1994). This picture of the accretion flows is supported by the evidences that CTTS have relatively strong ( $\sim 10^3$  G) magnetic field (e.g., Johns-Krull, Valenti, Hatzes, & Kanaan 1999; Guenther & Emerson 1996) and by the radiative transfer models which reproduce the observed profiles for some TTS (Muzerolle et al. 2001). The magnetospheric accretion model naturally explains the blue-ward asymmetric emission lines (seen in some of CTTS) caused by the partial occultation of the flow by the disc, and the redshifted absorption component at the typical free-fall velocities (a few hundred  $\text{km s}^{-1}$ ) seen in some of CTTS. Despite the success of the magnetospheric accretion model in explaining the line profiles in some CTTS, the overwhelming observational evidences for the outflow (mentioned above) in the CTTS profiles suggests that this model is only a part of a whole picture. Clearly, the modification to include the out-flowing wind/jet flow is necessary if one requires to predict the mass-accretion rate and the mass-loss rate of CTTS by modelling their emission profiles (e.g.  $\text{H}\alpha$ ).

Prior to the magnetospheric models, many alternative models had been considered to explain the observed spectroscopic features mentioned earlier. For example, (1) the Alfvén wave-driven wind model (e.g. Decampli 1981; Hartmann et al. 1982), (2) turbulent boundary layer (between the accretion disc and stellar surface) model (e.g. Bertout et al. 1988; Basri & Bertout 1989), (3) chromospheric model (e.g. Calvet et al. 1984), and (4) disc wind model (e.g. Calvet et al. 1992; Kwan & Tademaru 1995). Considering the success of the magnetospheric accretion flow model in some cases and the observational evidences for the outflows, it is likely that an improved spectroscopic model requires both inflow and outflow components. The combination of the magnetospheric accretion flow model with model 1 or 4 would be a reasonable starting point. Although time consuming to explore a larger parameter space, more realistic density, velocity and temperature structure from magnetohydrodynamic wind+accretion models should be considered as inputs for an radiative transfer model in the future. Recent work by Alencar et al. (2005) showed the observed  $\text{H}\alpha$ ,  $\text{H}\beta$  and Na D lines of RW Aur are better produced by the radiative transfer model which include the collimated disc-wind arising from near the inner edge of the accretion disc. Malbet et al. (2005) considered the combination of a spherical wind and the accretion disc in their radiative transfer model to reproduce Br $\gamma$  from the early-type Herbig Be star MWC 297.

The magneto-centrifugal wind model, first proposed by Blandford & Payne (1982), has been often used to reproduce the large-scale wind structure of T Tauri stars, or to model observed optical jets (e.g. HH 30 jet by Burrows et al. 1996; Ray et al. 1996). The launching of the wind from a Keplerian disc is typically done by treating the equatorial plane of the disc as a mass-injecting boundary condition (e.g., Shu et al. 1994; Ustyugova et al. 1995; Ouyed & Pudritz 1997; Krasnopolsky et al. 2003). Depending on the location of the open magnetic fields anchored to the disc, two different types of winds are produced. If the field is constrained to be near the co-rotation radius of stellar magnetosphere, an “X-wind” (Shu et al. 1994) is produced. If the open field lines are located in a wider area of the disc, a “disc-wind” similar to Königl & Pudritz (2000) is produced Krasnopolsky et al. (2003). Recent reviews on the jet/wind-disc connection can be found in Königl & Pudritz (2000) and Pudritz & Banerjee (2005). Interestingly, Matt & Pudritz (2005) showed the possibility that the stellar wind along the open magnetic field originating from the star can cause signif-

icant spin-down torque on the star, provided that mass-loss rate is high enough.

The main aim of this paper is to find a simple kinematic model which can reproduce the wide variety of the observed profiles, and to perform the empirical studies of the line formation. More specifically, we present disc-wind-magnetosphere hybrid models for CTTS, and perform parametric studies of the  $\text{H}\alpha$  formation. This study should provide preliminary physical conditions which lead to the wide variety of emission line profiles seen in the observation, and would help to construct more comprehensive circumstellar models (e.g. via MHD simulations) of T Tauri stars. Using the model results, we examine the  $\text{H}\alpha$  spectroscopic classification used by Reipurth et al. (1996), and compare models with observations. We will also discuss whether our model is consistent with some predictions made by the recent MHD studies i.e.  $\mu = \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}} \approx 0.1$  (e.g. Königl & Pudritz 2000).

In section 2, the model assumptions, and the basic model configurations are presented. We discuss the radiative transfer model used to compute the profiles in section 3, and the results of model calculations are given in section 4. The closer examination and discussion of the results are presented in section 5. Finally, the summary of this work and the conclusion are in section 6.

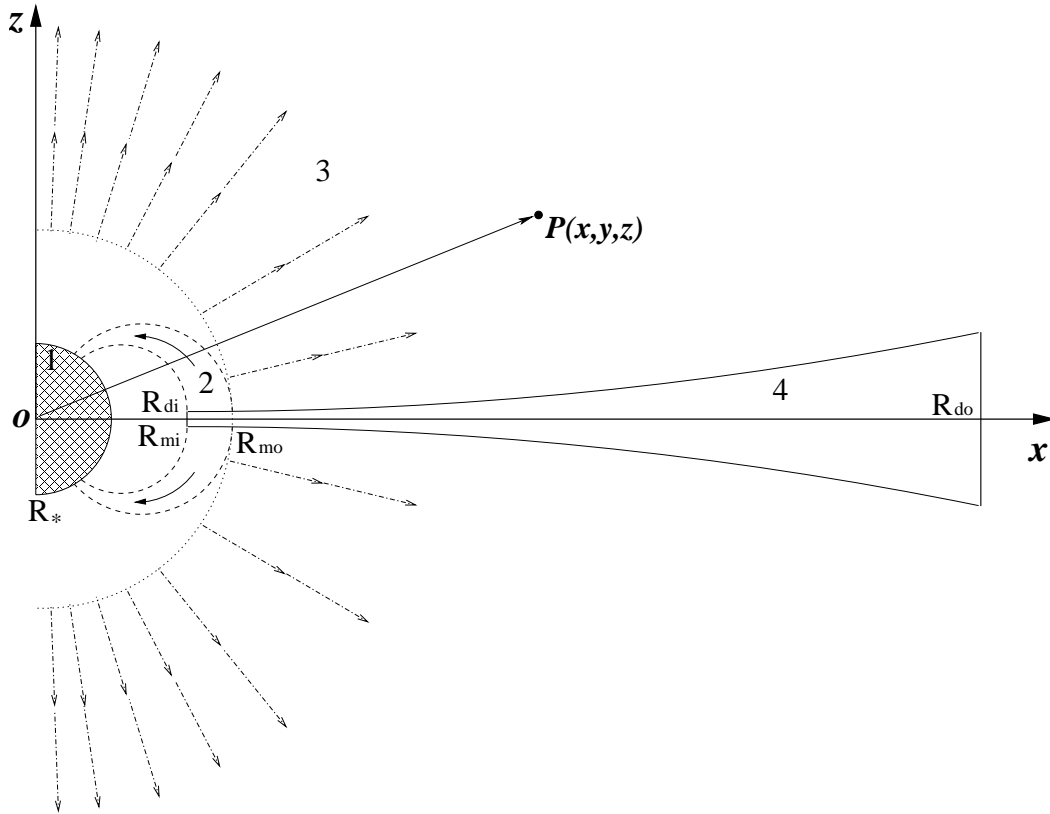
## 2 MODEL CONFIGURATION

To understand how the different part of the CTTS circumstellar environment contributes to the formation of  $\text{H}\alpha$ , the model space is divided into four different regions: 1. Central continuum source, 2. magnetosphere accretion flow, 3. wind outflow, and 4. accretion disc. Fig. 1 depicts the relative location in the model space. In all regions, the density is symmetric around the z-axis. The innermost radius of the magnetosphere at the equatorial plane coincides with the inner radius of the accretion disc. From the inner most part of the accretion disc, the gas freely fall, moving along the magnetic field onto the surface of the star. For the purpose of computational simplicity, the collimated bipolar wind are defined only in the outside of the largest radius of the magnetosphere (to avoid overlapping of the wind with the magnetosphere). In the following subsections, the details of model components will be described. In our models, two different types of the wind configurations are considered: (1) the bipolar wind resembling the density structure of the MHD simulation by Krasnopolsky et al. 2003 in large scale ( $\sim 100$  AU) in section 2.3, and (2) that in small scale ( $\sim 10$  AU) in section 2.5.

### 2.1 Continuum Source

Unless specified otherwise, we adopt stellar parameters of a typical classical T Tauri star for the central continuum source, i.e. radius ( $R_*$ ), mass ( $M_*$ ), and effective temperature the photosphere ( $T_{\text{ph}}$ ) are  $2 R_{\odot}$ ,  $0.5 M_{\odot}$ , and 4000 K respectively. The model atmosphere of Kurucz (1979) equivalently Kurucz (1993) with  $T_{\text{ph}} = 4000$  K and  $\log g_* = 3.5$  (cgs) is used to find the photospheric continuum at  $\text{H}\alpha$  wavelength. The parameters are summarised in Table 1.

For a model which includes magnetospheric accretion, an additional source of the continuum source is considered. As the infalling gas becomes closer to the stellar surface, it is decelerates in a strong shock, and heated to  $\sim 10^6$  K (with typical parameters). The X-ray radiation produced in the shock will be absorbed



**Figure 1.** Basic Model Configuration. The system consist of four components: (1) the continuum source located at the origin ( $o$ ) of the cartesian coordinates ( $x, y, z$ ) – the  $y$ -axis are into the paper, (2) magnetospherical accretion flow, (3) bipolar wind outflow, and (4) accretion disc. The density distribution is symmetric around the  $z$ -axis. The innermost radius of the magnetosphere (at the equatorial plane) coincides with the inner radius of the accretion disc. From the inner most part of the accretion disc, the gas freely fall, moving along the magnetic field onto the surface of the star. For a computational simplicity, the bipolar wind starts from just outside of the largest radius ( $R_{mo}$ ) of the magnetosphere (dotted line).

by the gas located near, and re-emitted in optical and UV radiation (Königl 1991; Hartmann et al. 1994). This will create hot rings near the stellar surface where the magnetic field intersects with the surface. For simplicity, the free-falling kinetic energy is assumed to be thermalized in the radiating layer, and re-emits as blackbody radiation (with a single temperature). With the parameters of the magnetosphere and the star given above (Table 1), about 8 per cent of the surface is covered by the hot rings, and its temperature is about 6400 K. If the mass-accretion rate is  $10^{-7} M_{\odot} \text{ yr}^{-1}$ , the ratio of this accretion luminosity to the photospheric luminosity is about 0.5. The continuum emission from the hot rings is taken into account when computing the line profiles.

## 2.2 Magnetosphere

We adopt the magnetospherical accretion flow model of Hartmann et al. (1994), as done so by Muzerolle et al. (2001) and by Symington et al. (2005), in which the gas accretion on to the stellar surface from the innermost part of the accretion disc occurs through a dipolar stellar magnetic field. The magnetic field is assumed to be so strong that the gas flow does not affect the underlying magnetic field itself. As shown in Fig. 1, the innermost radius ( $R_{mi}$ ) of the magnetosphere at the equatorial plane ( $z = 0$ ) is assigned to be same as the inner radius ( $R_{di}$ ) of the accretion disc where the flow is truncated. In our models,  $R_{mi}$  and the outer radius ( $R_{mo}$ ) of the magnetosphere (at the equatorial plane) are set to be

$2.2 R_{\odot}$  and  $3.0 R_{\odot}$  respectively. The former value corresponds to the co-rotation radius of the accretion disc, and the geometry of the magnetic field/stream lines is kept constant throughout this paper. The geometry of the magnetosphere is identical to the “small/wide” model of Muzerolle et al. (2001).

The magnetic field and the gas stream lines are assumed to have the following simple form:

$$r = R_m \sin^2 \theta \quad (1)$$

(see Ghosh et al. 1977) where  $r$ , and  $\theta$  are coordinates of the field point ( $p$ ) in Fig. 1 in spherical coordinates, and  $R_m$  is the radial distance to the field line at the equatorial plane ( $\theta = \pi/2$ ). The range of  $R_m$  is restricted between  $R_{mi}$  and  $R_{mo}$ . Using the field geometry above and the conservation of energy, the velocity and the density of the accreting gas along the stream line are found as in Hartmann et al. (1994).

The temperature structure of the magnetospheric used by Hartmann et al. (1994) is simply adopted here. They computed the temperature assuming a volumetric heating rate which is proportional to  $r^{-3}$ , and using the energy balance of the radiative cooling rate of Hartmann et al. (1982) and the heating rate (Hartmann et al. 1994). Although the temperature structure of the accretion stream could significantly affect the line source function, for the purpose of the exploring the general characteristics of the H $\alpha$  formation, this simple form is a reasonable assumption. Martin (1996) presented the self-consistent determination of the thermal structure of the in-

Parameters	$R_*$ [ $R_\odot$ ]	$M_*$ [ $M_\odot$ ]	$T_{\text{ph}}$ [K]	$R_{\text{mi}}$ [ $R_*$ ]	$R_{\text{mo}}$ [ $R_*$ ]	$\dot{M}_{\text{acc}}$ [ $M_\odot \text{ yr}^{-1}$ ]	$\dot{M}_{\text{wind}}$ [ $M_\odot \text{ yr}^{-1}$ ]	$v_\infty$ [ $\text{km s}^{-1}$ ]	$b$ [–]	$R_{\text{di}}$ [ $R_*$ ]	$R_{\text{do}}$ [AU]
Standard	2.0	0.5	4000	2.2	3.0	$10^{-7}$	$10^{-8}$	210	4.0	2.2	100

**Table 1.** The summary of the standard classical T Tauri star model parameters.

flowing gas along the dipole magnetic field (equation 1) by solving the heat equation couple to rate equations for hydrogen. He found that main heat source is adiabatic compression due to the converging nature of the flow, and the major contributors of the cooling process are bremsstrahlung radiation and line emission from Ca II and Mg II ions. The results of Martin (1996) qualitatively agrees with that of Hartmann et al. (1994).

### 2.3 Bipolar Wind

As mentioned earlier, the wind model presented here is to simulate the collimated MHD disc-wind model of Krasnopolsky et al. (2003) in large scale ( $\sim 100$  AU), and the alternative wind model which resembles the model of Krasnopolsky et al. (2003) in small scale ( $\sim 10$  AU) will be presented later (section 2.5).

Similar to the simple wind model of Appenzeller et al. (2005), the following parametrisation of collimated bipolar wind (region 3 in Fig. 1) is adopted. The wind velocity field,  $\mathbf{v}_{\text{wind}}(r, \theta)$ , is consist of radial and azimuthal components which depend on the spherical coordinates  $r$  and  $\theta$ . The radial component  $v_r(r)$  is assumed to be in the classical beta-velocity law (c.f. Castor & Lamers 1979), and the azimuthal component  $v_\phi$  is assumed to be a constant fraction ( $\gamma$ ) of the Keplerian velocity for a given distance ( $w = \sqrt{x^2 + y^2}$ ) from the symmetry axis ( $z$ -axis), i.e.:

$$\mathbf{v}_{\text{wind}} = v_r \hat{\mathbf{r}} + v_\phi \hat{\boldsymbol{\phi}} \quad (2)$$

where

$$v_r(r) = v_{r0} + (v_\infty - v_{r0}) \left(1 - \frac{R_{\text{mo}}}{r}\right)^\beta, \quad (3)$$

$$v_\phi(w) = \gamma \left(\frac{GM_*}{w}\right)^{1/2}, \quad (4)$$

Note that the base of the wind starts at  $r = R_{\text{mo}}$ . This is chosen so mainly for computational simplicity i.e. to avoid the overlap between the wind and the magnetosphere; however, see Matt & Pudritz (2005) for the possibility that wind originates from the stellar surface (restricted near the polar caps). The range of the polar angle for the wind is restricted to  $\theta > |\theta_{\text{disc}}|$  where  $\theta_{\text{disc}}$  is the opening angle of the accretion disc, to avoid the overlap.  $v_{r0}$  is the small radial velocity at the base of the wind ( $r = R_{\text{mo}}$ ). Normally,  $v_{r0} = 10 \text{ km s}^{-1}$  which is approximately equal to the thermal velocity of hydrogen with  $T = 7500$  K. Following Appenzeller et al. (2005),  $\gamma = 0.05$  is adopted. The dependency of  $v_r$  in polar direction ( $\theta = 0$ ) on the values of wind acceleration parameter  $\beta$  is shown in Figure 2. All other parameters describing the wind are fixed as the standard values given in Table 1.

Further, the density of the wind is assumed to be axisymmetric and separable in  $r$  and  $\theta$  for computational simplicity, i.e.,

$$\rho(r, \theta) = P(r) F(\theta) \quad (5)$$

with

$$F(\theta) = n \cos^b \theta \quad (6)$$

where  $b$  is normally positive even number (for the density symmetric about the equatorial plane), and  $n$  is the angular normalisation constant. For  $b = 0$ , the wind is spherically symmetric except for the parts disrupted by the accretion disc. The larger the value of  $b$ , the higher the degree of the collimation. By integrating equation 6 over angles and normalising the integral to  $4\pi$ , one finds

$$n = \frac{1 + b}{1 - \cos^{1+b} \theta_{\text{wind}}}. \quad (7)$$

Assuming the total mass-loss rate by the wind/jet is  $\dot{M}_{\text{wind}}$  and the mass-flux conserves in time, the radial part of the density function is reduced to  $P(r) = \dot{M}_{\text{wind}} [4\pi r^2 v_r(r)]^{-1}$ ; hence, Equation 5 becomes

$$\rho(r, \theta) = \frac{n \dot{M}_{\text{wind}} \cos^b \theta}{4\pi r^2 v_r(r)}. \quad (8)$$

For a given mass-accretion rate, the wind mass-loss rate in our typical model is assigned from the ratio of mass-loss to mass-accretion rate ( $\dot{M}_{\text{wind}}/\dot{M}_{\text{acc}} \approx 0.1$ ), indicated by both observations and MHD calculations (e.g. Königl & Pudritz 2000). Figure 2 shows the density along a streamline in the polar direction ( $\theta = 0$ ), for different values of  $\beta$  with all other parameters fixed as the standard values (Table 1). The density is relatively sensitive to the value of  $\beta$  for  $r < 10 R_{\text{mo}}$ , but a little difference is seen beyond  $r < 100 R_{\text{mo}}$ .

### 2.4 Accretion disc

Although it is possible, in our model, to compute the dust-sublimation radius and the vertical hydrostatic structure of the accretion disc self-consistently (assuming the radial dependency of the mid-plane density) by using the iterative Monte Carlo radiative transfer technique (c.f. Walker et al. (2004)), we find it to be too time consuming for the purpose of this paper – understanding the general characteristic of H $\alpha$  profile shapes hence exploring a large parameter space. For this reason, we adopt a simple analytical disc model, the steady  $\alpha$ -disc ‘standard model’ (Shakura & Sunyaev 1973; Frank, King, & Raine 2002) with the inner radius fixed at the inner radius of the magnetosphere at equatorial plane. This corresponds to Region 4 in Fig. 1.

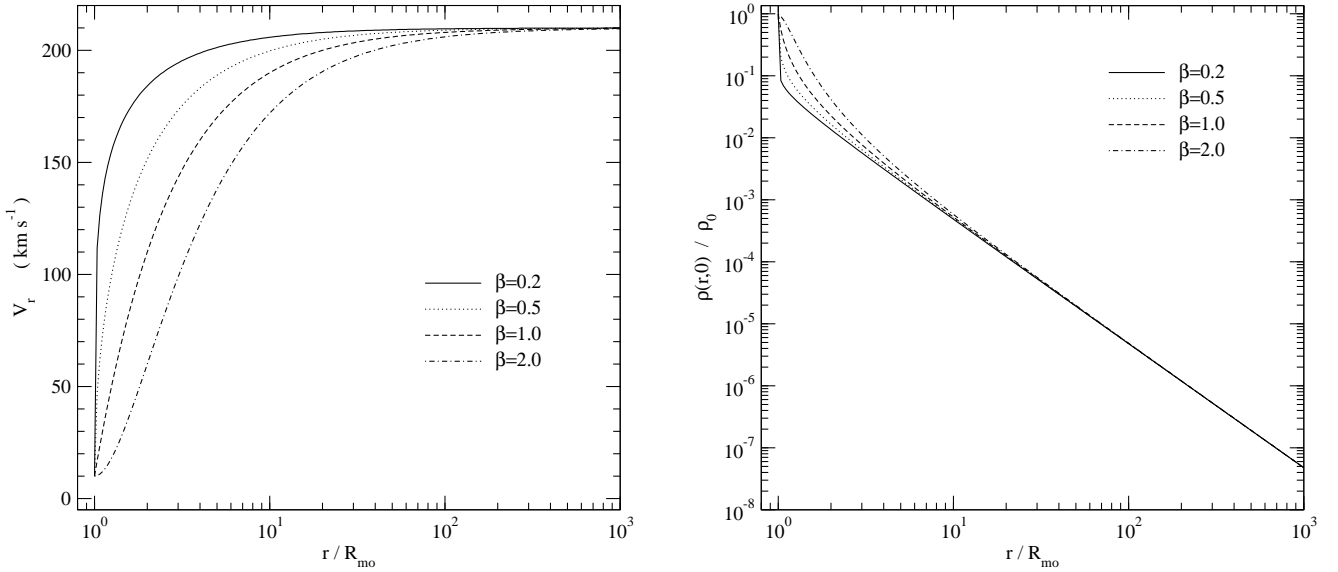
#### 2.4.1 Density and velocity

The disc density distribution is given by

$$\rho_d(w, z) = \Sigma(w) \frac{1}{\sqrt{2\pi} h(w)} e^{-\left(\frac{z}{h(w)}\right)^2} \quad (9)$$

where  $w$ ,  $h$ ,  $z$  and  $\Sigma$  are the distance from the symmetry axis, the scale height, the distance from the disc plane, and the surface density at the mid-plane, respectively. The mid-plane surface density and the scale height are given as:

$$\Sigma(w) = \frac{5M_d}{8\pi R_{\text{do}}^2} w^{-3/4} \quad (10)$$



**Figure 2.** The dependency of the bipolar wind velocity and density structures on the wind acceleration parameter  $\beta$ . The radial component of the wind velocity (equation 3) in polar direction,  $\theta = 0$  as a function of radius is shown on left. The wind density (equation 8 along polar direction as a function of radius is shown on right. For all  $\beta$  values, the density is normalized to the density at the base of the wind in polar direction, i.e.  $\rho_0 = \rho(R_{\text{mo}}, 0)$ . The smaller the value of  $\beta$ , the faster the acceleration of the wind. For the radius ( $r/R_{\text{mo}} < 10$ ), both velocity and density are sensitive to the value of  $\beta$ . For all  $\beta$  values, the radial velocity of the wind reaches the terminal velocity ( $\sim 210 \text{ km s}^{-1}$  by  $r/R_{\text{mo}} \sim 1000$ ). The initial velocity  $V_0 = 10 \text{ km s}^{-1}$ , which approximately corresponds to the thermal velocity of a hydrogen atom at 7500 K, is used for all  $v_r$  plots. Beyond  $r/R_{\text{mo}} = 100$ , little difference is seen in the polar density with different  $\beta$  values.

where  $R_{\text{do}}$  and  $M_{\text{d}}$  are the disc radius and the disc mass respectively.

$$h(w) = 0.05 R_{\text{do}} w^{9/8}. \quad (11)$$

With these parameters, the disc is slightly flared. The inner radius of the disc is set to  $R_{\text{di}} = R_{\text{mi}}$  (the inner radius of the magnetosphere at the equatorial plane), which is approximately same as the co-rotating radius of the system with the parameters in Table 1. The disc mass,  $M_{\text{d}}$ , of an object is assumed to be 1/100 of the central mass ( $M_*$ ), and the disc radius ( $R_{\text{di}}$ ) to be 100 au. The velocity of the gas/dust in the disc is assumed to be Keplerian.

#### 2.4.2 Dust model

To calculate the dust scattering and absorption cross section as a function of wavelength, the optical constants of Draine & Lee (1984) for amorphous carbon grains and Hanner (1988) for silicate grains are used. The model uses the “large grain” dust model of Wood et al. (2002) in which the dust grain size distribution is described by the following function:

$$n(a) da = (C_C + C_{\text{Si}}) a^{-p} \exp \left[ - \left( \frac{a}{a_c} \right)^q \right] da \quad (12)$$

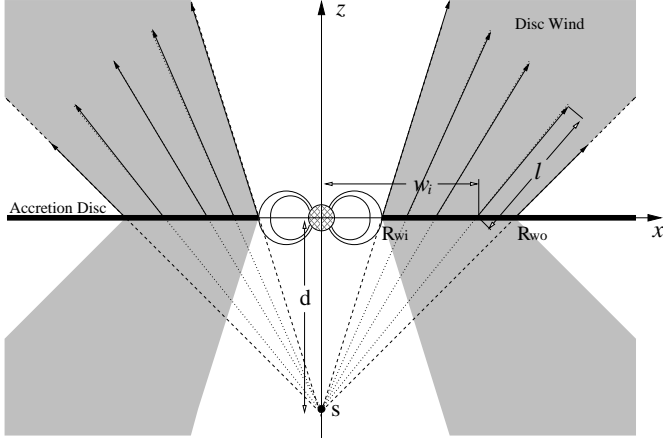
where  $a$  is the grain size restricted between  $a_{\text{min}}$  and  $a_{\text{max}}$ , and  $C_C$  and  $C_{\text{Si}}$  are the terms set by requiring the grains to completely deplete a solar abundance carbon and silicon. The parameters adopted in our model are:  $C_C = 1.32 \times 10^{-17}$ ,  $C_{\text{Si}} = 1.05 \times 10^{-17}$ ,  $p = 3.0$ ,  $q = 0.6$ ,  $a_{\text{min}} = 0.1 \mu\text{m}$ ,  $a_{\text{max}} = 1000 \mu\text{m}$ , and  $a_c = 50 \mu\text{m}$ . This corresponds to Model 1 of the dust model used by Wood et al. (2002). See also their Fig. 3 The relative number of each grain is assumed to be that of solar abundance,  $\text{C/H} \sim 3.5 \times 10^{-4}$  (Anders & Grevesse 1989) and  $\text{Si/H} \sim 3.6 \times 10^{-5}$  (Grevesse & Noels 1993) which are similar to values found in the ISM model of Mathis

et al. (1977) and Kim, Martin, & Hendry (1994). Similar abundances were used in the circumstellar disc models of Cotera et al. (2001).

#### 2.5 Alternative model: disc-wind model of Knigge et al. (1995)

The wind model presented here is to simulate the collimated MHD disc-wind calculations of Krasnopolsky et al. 2003 in small scale ( $\sim 10 \text{ AU}$ ). Knigge et al. (1995) introduced the “split-monopole” kinematic disc-wind model in their studies of the UV resonance lines formed in the winds of cataclysmic variable stars. In this model, the outflow arises from the surface of the rotating accretion disc, and has a biconical geometry. The specific angular momentum is assumed to be conserved along a stream line, and the poloidal velocity component is assumed to be simply a radial from vertically displaced “sources” from the central star. We adopt their disc-wind model here, and consider the combined effect of the disc-wind and the magnetospheric accretion flow model described earlier. In the following, we briefly described their disc-wind model. For details of the models, readers are referred to Knigge et al. (1995) and Long & Knigge (2002).

Four basic parameters for the models are: 1. mass-loss rate, 2. the degree of the wind collimation, 3. velocity gradients, and 4. the wind temperature. The basic configuration of the disc-wind model is shown in Figure 3. The disc wind originates from the disc surface, but the “source” point ( $S$ ), from which the stream lines diverges, are placed at distance  $d$  above and below the centre of the star. By changing the value of  $d$ , the degree of the wind collimation is controlled. The larger the value of  $d$ , the wind becomes more parallel to the rotation axis, i.e. the wind becomes more collimated. The mass-loss launching is restricted between  $R_{\text{wi}}$  and  $R_{\text{wo}}$  where the former is set to be equal to the outer radius of the mag-



**Figure 3.** Basic Model Configuration of the disc-wind, magnetosphere hybrid model. The system consist of four components: (1) the continuum source located at the origin ( $o$ ) of the cartesian coordinates ( $x, y, z$ ) – the  $y$ -axis are into the paper, (2) magnetospheric accretion flow, (3) collimated wind/jet outflow, and (4) geometrically thin (but opaque) accretion disc. The disc wind originates from the disc surface between  $w_i = R_{wi}$  and  $w_o = R_{wo}$ . The wind source points ( $S$ ), from which the stream lines diverges, are placed at distance  $d$  above and below the star. By changing the value of  $d$ , the degree of the wind collimation is controlled. The density distribution is symmetric around the  $z$ -axis.

netosphere ( $R_{mo}$ ) for simplicity and the latter is set to 1 AU as in Krasnopolsky et al. 2003.

The local mass-loss rate per unit area ( $\dot{m}$ ) is assumed to be proportional to the mid-plane temperature of the disc, and is a function of the cylindrical radius  $w = (x^2 + y^2)^{1/2}$ , i.e.

$$\dot{m}(w) \propto T(w)^\alpha. \quad (13)$$

Further, the mid-plane temperature of the disc is assumed to be expressed as a power-law in  $w$ ; thus,  $T \propto w^q$ . Using this in the relation above, one finds

$$\dot{m}(w) \propto w^p \quad (14)$$

where  $p = \alpha \times q$ . The index of the mid-plane temperature power law is adopted from the dust radiative transfer model of Whitney et al. (2003) who found the inner most part of the accretion disc has  $q = -1.15$ . To be consistent with the collimated disc-wind model of Krasnopolsky et al. (2003) who used  $p = -3/2$ , the value of  $\alpha$  is set to 1.3. The constant of proportionality in equation 14 is found by integrating  $\dot{m}$  from  $R_{wi}$  to  $R_{wo}$ , and the normalising the total mass-loss rate to  $\dot{M}_{dw}$ .

The azimuthal/rotational component of the wind velocity  $v_\phi(w, z)$  is computed from the Keplerian rotational velocity at the emerging point of the stream line i.e.  $v_\phi(w_i, 0) = (GM_*/w_i)^{1/2}$  where  $w_i$  is the distance from the rotational axis ( $z$ ) to the emerging point on the disc, and by assuming the conservation of the specific angular momentum along a stream line:

$$v_\phi(w, z) = v_\phi(w_i, 0) \left( \frac{w_i}{w} \right). \quad (15)$$

Based on the classic  $\beta$  velocity law of hot stellar winds (c.f. Castor et al. 1975), the poloidal component of the wind velocity ( $v_p$ ) parameterised as:

$$v_p(w_i, l) = c_s(w_i) + [f v_{esc} - c_s(w_i)] \left( 1 - \frac{R_s}{l + R_s} \right)^\beta \quad (16)$$

where  $c_s$ ,  $f$ , and  $l$  are the sound speed at the wind launching point on the disc, the constant scale factor of the asymptotic terminal velocity to the local escape velocity (from the wind emerging point on the disc), and the distance from the disc surface along stream lines respectively.  $R_s$  is the wind scale length, and  $R_s = 10 R_{mi}$  is adopted as similarly done by Long & Knigge (2002).

Assuming the mass-flux conservation and using the velocity field defined above, the disc wind density as a function of  $w$  and  $l$  can be written as

$$\rho(w_i, l) = \frac{\dot{m}(w_i)}{v_p(w_i, l) |\cos \delta|} \left\{ \frac{d}{Q(w_i, l) \cos \delta} \right\}^2 \quad (17)$$

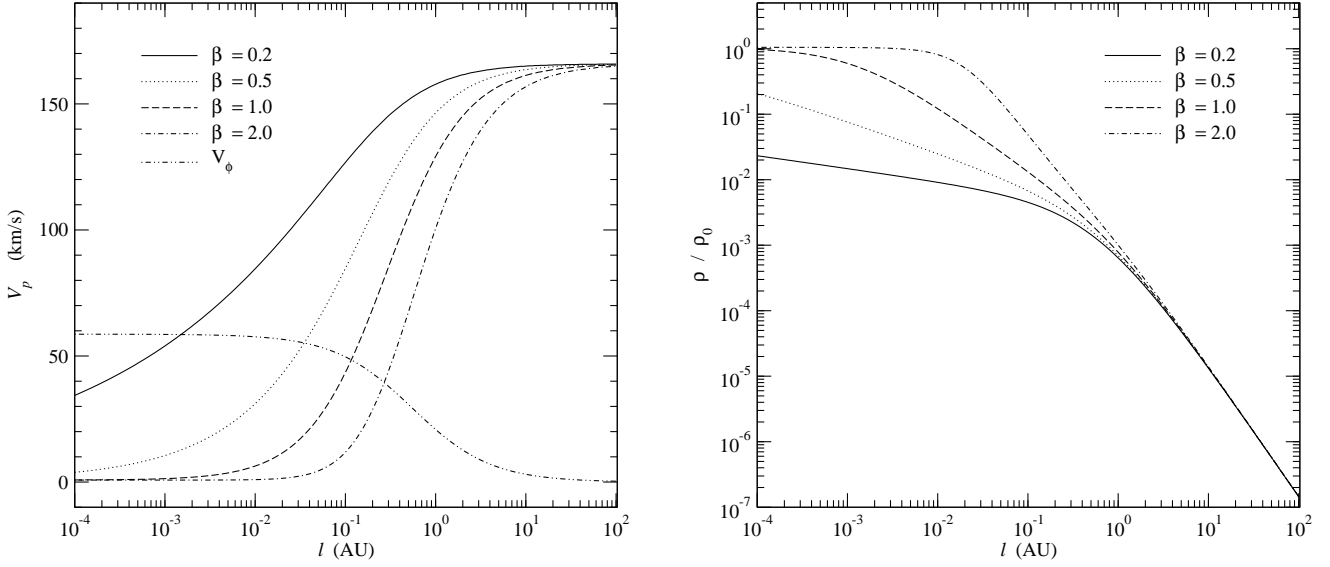
where  $Q$  and  $\delta$  are the distance from the source point ( $S$ ) to a point along the stream line and the angle between the stream line and the disc normal respectively. Figure 4 shows the density and the velocity components along the mid stream line (passing through  $w_i = (R_{wi} + R_{wo})/2$  on the disc plane ( $z = 0$ ) for different values of the wind acceleration parameter  $\beta$ .

### 3 RADIATIVE TRANSFER MODEL

We have extended the TORUS radiative transfer code (Harries 2000; Kurosawa et al. 2004; Symington et al. 2005) to compute the  $H\alpha$  profiles from pre-main-sequence stars which are surrounded by one or more of the followings: the magnetospheric accretion flow, the out-flowing collimated wind, and the accretion disc. Previously in Symington et al. (2005), the model used in the three-dimensional (3-D) adaptive mesh refinement (AMR) to investigate the line variability mainly associated with rotational motion of complex geometrical configurations of magnetospheric flow (see also Kurosawa, Harries, & Symington 2005). We modified the code to handle the two-dimensional (2-D) density distribution, and restricted our models to be axi-symmetric. It was done so in order to enable us to explore rather large number of parameter spaces (c.f. section 2). Note that the velocity field is still in 3-D – the third component can be calculated by using the symmetry for a given value of azimuthal angle. The examples of how the AMR grid for the purpose of the radiative transfer is constructed are presented in e.g. Wolf et al. (1999), Kurosawa & Hillier (2001) and Steinacker et al. (2003).

The computation of the  $H\alpha$  is divided in two parts: (1) the source function calculation ( $S_\nu$ ) and (2) the observed flux/profile calculation. In the first process, we have utilised the method by Klein & Castor (1978) (see also Rybicki & Hummer 1978; Hartmann et al. (1994)) in which the Sobolev approximation method is applied. The population of the bound states of hydrogen are assumed to be in statistical equilibrium, and the gas to be in radiative equilibrium. Our hydrogen atom model consist of 14 bound state and continuum. Readers are refer to Klein & Castor (1978) for details.

To compute the observed line profile, the Monte Carlo radiative transfer method (e.g. Hillier 1991) using the Sobolev escape-probability can be used when (1) a large velocity gradient is present in the gas flow, and (2) the intrinsic line width is negligible compared to the Doppler broadening of the line. In our earlier models (Harries 2000; Symington et al. 2005), this method was used to compute the line profiles since the condition (1) and (2) are reasonably satisfied. However, as noted and demonstrated by Muzerolle et al. (2001), even with a moderate amount of mass-accretion rate ( $10^{-7} M_\odot \text{ yr}^{-1}$ ), Stark broadening becomes important in the optically thick  $H\alpha$  line. Muzerolle et al. (2001) also pointed out that



**Figure 4.** Dependency of the disc wind density and the velocity on the wind acceleration parameter  $\beta$ . The wind density  $\rho$  (left panel) and the poloidal velocity component  $V_p$  (right panel) along the stream line starting from the mid point of the wind launching zone, i.e.  $(w, z) = (w_{\text{mid}}, 0)$  where  $w_{\text{mid}} = (R_{\text{wi}} + R_{\text{wo}}) / 2$ , are shown as a function of the distance ( $l$ ) from the wind launching point (c.f. equations 16 and 17). The azimuthal velocity component ( $V_\theta$ ), which is independent of  $\beta$  (c.f. equation 15), is also shown in the right panel for a comparison. The density is normalized to the density  $\rho_0$  at the wind launching point for  $\beta = 1.0$  case. The  $v_p$  reaches the terminal velocity by 100 AU for all  $\beta$ . In the far field ( $l > 10$  AU), the density is approximately proportional to  $\sim l^2$ . Up to  $l \sim 10$  AU, the density is smaller and the poloidal speed is larger for the wind with a larger  $\beta$  value.

the observed H $\alpha$  profiles from CTTS typically have the wings extending to  $500 \text{ km s}^{-1}$  (e.g. Edwards et al. (1994); Reipurth et al. (1996)) which cannot be explained by the infall velocity of the gas along the magnetosphere alone.

To implement the broadening mechanism, two modifications to our previous model (Symington et al. 2005) are necessary as similarly done by Muzerolle et al. (2001). First, the emission and absorption profiles must be replaced by a Voigt profile which is defined as:

$$H(a, y) \equiv \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y'^2}}{(y - y')^2 + a^2} dy' \quad (18)$$

where  $a = \Gamma / 4\pi\Delta\nu_D$ ,  $y = (\nu - \nu_0) / \Delta\nu_D$ , and  $y' = (\nu' - \nu_0) / \Delta\nu_D$  (c.f. Mihalas 1978).  $\nu_0$  is the line centre frequency, and  $\Delta\nu_D$  is the Doppler line width of hydrogen atom (due to its thermal motion) which is given by  $\Delta\nu_D = (2kT/m_H)^{1/2} \times (\nu_0/c)$  where  $m_H$  is the mass of a hydrogen atom. The damping constant  $\Gamma$ , which depends on the physical condition of the gas, is parameterised by Vernazza, Avrett, & Loeser (1973) as follows:

$$\Gamma = C_{\text{rad}} + C_{\text{vdW}} \left( \frac{n_{\text{HI}}}{10^{16} \text{ cm}^{-3}} \right) \left( \frac{T}{5000 \text{ K}} \right)^{0.3} + C_{\text{Stark}} \left( \frac{n_e}{10^{12} \text{ cm}^{-3}} \right)^{2/3} \quad (19)$$

where  $n_{\text{HI}}$  and  $n_e$  are the number density of neutral hydrogens and that of free electrons. Also,  $C_{\text{rad}}$ ,  $C_{\text{vdW}}$  and  $C_{\text{Stark}}$  are natural broadening, van der Waals broadening, and linear Stark broadening constants respectively. We simply adopt this parameterisation along with the values of broadening constants for H $\alpha$  from Luttermoser & Johnson (1992), i.e.  $C_{\text{rad}} = 6.5 \times 10^{-4} \text{ \AA}$ ,  $C_{\text{vdW}} = 4.4 \times 10^{-4} \text{ \AA}$  and  $C_{\text{Stark}} = 1.17 \times 10^{-3} \text{ \AA}$ . In terms of level populations and the Voigt profile, the line opacity for the transition  $i \rightarrow j$  can be written as:

$$\chi_l = \frac{\pi^{1/2} e^2}{m_e c} f_{ij} n_j \left( 1 - \frac{g_j n_i}{g_i n_j} \right) H(a, y) \quad (20)$$

where  $f_{ij}$ ,  $n_i$ ,  $n_j$ ,  $g_i$  and  $g_j$  are the oscillator strength, the population of  $i$ -th level, the population of  $j$ -th level, the degeneracy of the  $i$ -th level, and the degeneracy of the  $j$ -th level respectively.  $m_e$  and  $e$  are the electron mass and charge (c.f. Mihalas 1978).

The second modification in our model is the replacement of the method of solving the formal solution from the Monte Carlo radiative transfer method with Sobolev approximation to the direct integration method (c.f. Muzerolle et al. 2001). We specify the cylindrical coordinates  $(p, q, t)$  which is the original stellar coordinate system  $(\rho, \phi, z)$  rotated (around  $y$  axis) by the inclination of the line of sight, i.e. the  $t$ -axis coincides with the line of sight. The observed flux ( $F_\nu$ ) is given by:

$$F_\nu = \frac{1}{4\pi d^2} \int_0^{p_{\text{max}}} \int_0^{2\pi} p \sin q I_\nu dq dp \quad (21)$$

where  $d$ ,  $p_{\text{max}}$ , and  $I_\nu$  are the distance to an observer, the maximum extent to the model space in the projected (rotated) plane, and the specific intensity ( $I_\nu$ ) in the direction on observer at the outer boundary. For a given ray along  $t$ , the specific intensity is given by:

$$I_\nu = I_0 e^{-\tau_\infty} + \int_{t_0}^{t_\infty} S_\nu(t) e^{-\tau} d\tau \quad (22)$$

where  $I_0$  and  $S_\nu$  are the intensity at the boundary on the opposite to the observer and the source function ( $\eta_\nu / \chi_\nu$ ) of the stellar atmosphere/wind at a frequency  $\nu$ . For a ray which intersects with the stellar core,  $I_0$  is computed from the stellar atmosphere mode of Kurucz (1979) as described in section 2.1, and  $I_0 = 0$  otherwise. The initial position of each ray is assigned to be at the centre of the surface element ( $dA = p \sin q dq dp$ ). The code execution time is proportional to  $n_p n_q n_\nu$  where  $n_p$  and  $n_q$  are the number of cylindrical radial and angular points for the flux integration, and  $n_\nu$  is the number of frequency points. In the models presented in

the next (section 4),  $n_p = 180$ ,  $n_q = 100$ , and  $n_\nu = 101$  are used unless specified otherwise. The linearly spaced radial grid is used for the area where the ray intersects with magnetosphere, and the logarithmically spaced grid is used for the wind and the accretion disc regions.

The optical depth  $\tau$  is equation 22 is defined as:

$$\tau(t) \equiv \int_t^\infty \chi_\nu(t') dt'$$

where  $\chi_\nu$  is the opacity of media the ray passes through.  $\tau_\infty$  is the total optical depth measured from the initial ray point to the observer (or to the outer boundary closer to the observer). Initially, the optical depth segments  $d\tau$  are computed at the intersections of a ray with the original AMR grid in which the opacity and emissivity information are stored. For high optical depth models, additional points are inserted between the original points along the ray, and  $\eta_\nu$  are  $\chi_\nu$  values are interpolated to those points to ensure  $d\tau < 0.05$  for the all ray segments.

For a point in the magnetosphere and the wind flows, the emissivity and the opacity of the media are given as:

$$\begin{cases} \eta_\nu &= \eta_c^H + \eta_l^H \\ \chi_\nu &= \chi_c^H + \chi_l^H + \sigma_{es} \end{cases} \quad (23)$$

where  $\eta_c^H$  and  $\eta_l^H$  are the continuum and line emissivity of hydrogen.  $\chi_c^H$ ,  $\chi_l^H$ , and  $\sigma_{es}$  are the continuum, line opacity (equation 20) of hydrogen, and the electron scattering opacity. Similarly, for a point in the accretion disc,

$$\begin{cases} \eta_\nu &= 0 \\ \chi_\nu &= \kappa_{abs}^{dust} + \kappa_{sca}^{dust} \end{cases} \quad (24)$$

where  $\kappa_{abs}^{dust}$  and  $\kappa_{sca}^{dust}$  are the dust absorption, and scattering opacity which are calculated using the dust property described in section 12. For computational simplicity, we assumed that the dust emissivity is zero. Since the disc mass of CTTS are rather small ( $\sim 0.1 M_\odot$ ) and low temperature ( $< \sim 1600$  K), the continuum flux contribution at H $\alpha$  wavelength is expected to be negligible (e.g. Chiang & Goldreich 1997).

## 4 RESULTS

### 4.1 Magnetosphere

Using the standard parameters (Table 1) for the central star and the magnetosphere, we examine the dependency of H $\alpha$  on the temperature ( $T_{max}$ ) of accretion flow and the mass accretion rate ( $\dot{M}_{acc}$ ), as similarly done by Muzerolle et al. (2001) for H $\beta$ . The hot ring temperature is computed from the available kinetic energy of the free-falling gas as describe by Hartmann et al. (1994) while Muzerolle et al. (2001) used the constant hot ring temperature (8000 K) for most of their models. The accretion luminosity ( $L_{acc}$ ) of models with  $\dot{M}_{acc} = 10^{-7} M_\odot \text{ yr}^{-1}$  is about a half of the total luminosity (without the hot ring) of the star, and  $L_{acc}$  is proportional to  $\dot{M}_{acc}$ . The results are placed in Figure 5. Overall dependency on  $T_{max}$  and  $\dot{M}_{acc}$  are similar to that of Muzerolle et al. (2001). In general, the line strength becomes weaker as the accretion rate and the temperature become smaller. The red-shifted absorption becomes less visible for higher accretion rate and temperature models in which the flux in the damping wings become important. Figure 6 shows an example of the effect of the broadening of H alpha (with  $T_{max} = 7500$  K and  $\dot{M}_{acc} = 10^{-7} M_\odot \text{ yr}^{-1}$ ) due to the damping constants as described in section 3. Although the maximum flux

$T_{max}$ (K)	$10^{-7}$	$\dot{M}_{acc}$ ( $M_\odot \text{ yr}^{-1}$ )	$10^{-8}$	$10^{-9}$
6500	17.9	0.1	0.0	
7500	25.2	-0.9	-0.5	
8500	68.3	6.5	-0.7	
9500	98.6	52.4	1.3	

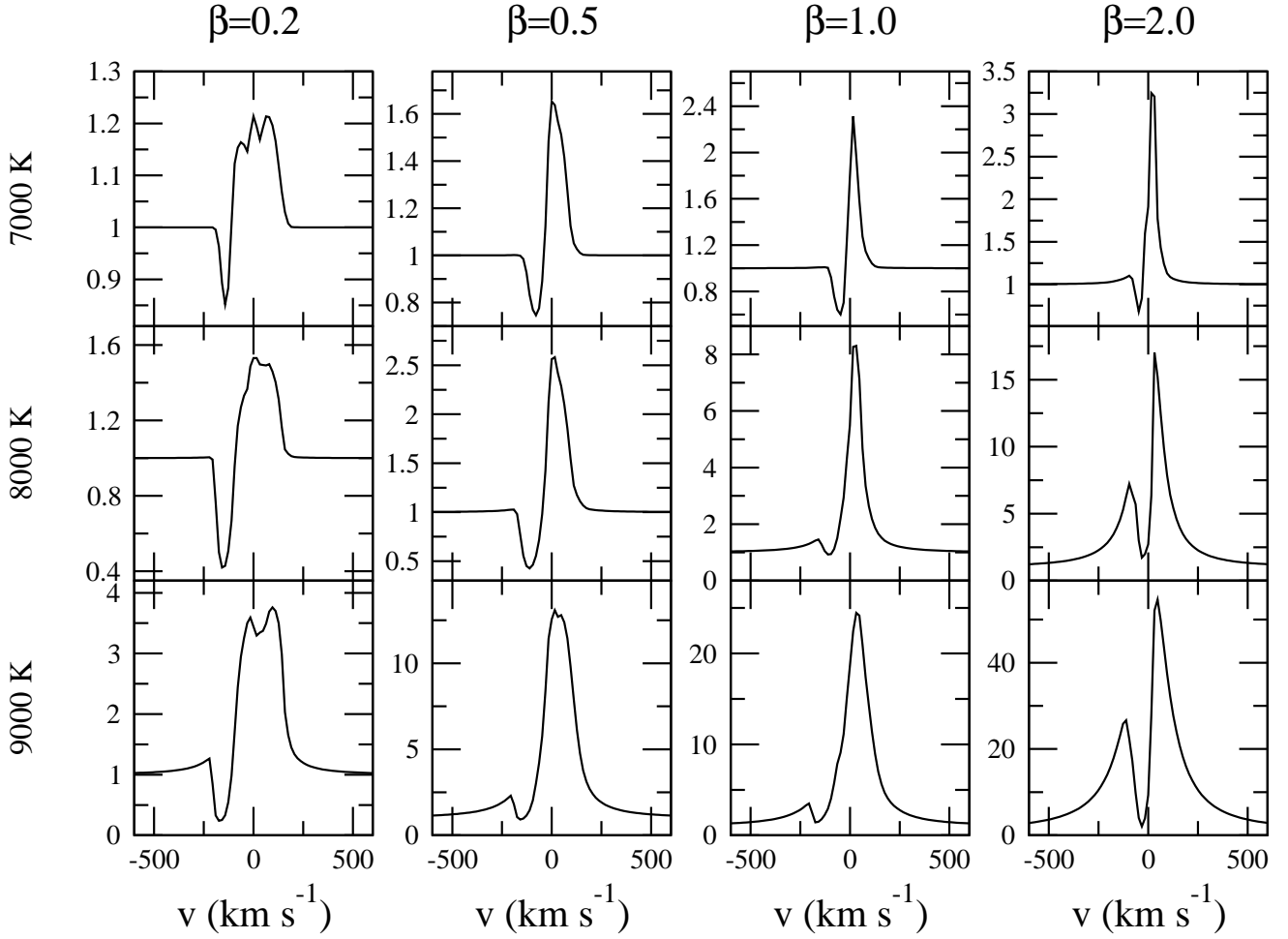
**Table 2.** The summary of H $\alpha$  equivalent widths from the magnetospherical accretion flow models show in Figure 5.

of the model with the broadening is almost identical to that of the model with no damping constant ( $\Gamma = 0$ ), a significant increase of the line flux in both red and blue wings of seen in the model with broadening. A weak red-shifted absorption component (which is a signature of the magnetospherical accretion) is weakened or eliminated by the flux in broadened wing.

Table 2 shows the EW for the models shown in Figure 5. About a half of the models shown the figure agree with the observed EW values of H $\alpha$  from 30 TTS presented by Alencar & Basri (2000) who found the EW of H $\alpha$  ranges from  $\sim 3 \text{ \AA}$  to  $\sim 160 \text{ \AA}$ , and the mean to be  $\sim 55 \text{ \AA}$ . For the lowest  $\dot{M}_{acc}$  models, the EW values are smaller than the minimum EW observed by Alencar & Basri (2000), and for some models the EWs are negative. Since the target selection criteria of Alencar & Basri (2000) is not stated in their paper, we can not conclude that these low  $\dot{M}_{acc}$  models disagree with the observation. Reipurth et al. (1996), who measured the EW of 43 TTS and found similar distribution of EW values, mentioned that their EW measurements are under-representing real samples since the selection of the targets are based on the strong H $\alpha$  emission in H $\alpha$  surveys.

The dependency of the profile on the inclination angle ( $i$ ) is demonstrated in Figure 7. The model uses the same parameters as in Figure 6 (with broadening,  $T_{max} = 7500$  K and  $\dot{M}_{acc} = 10^{-7} M_\odot \text{ yr}^{-1}$ ). The figure show that the peak (normalised) flux decrease as the inclination angle increases. Similarly, the equivalent width also decreases as the inclination increases. Because of the geometry of the magnetospherical accretion (c.f. Figure 1) and of the presence of the gas with the highest velocity close to the stellar surface, the highest red-shifted line-of-sight velocity is visible only at the high inclination angles. This explains the wider appearance of the profile with  $i = 80^\circ$  compared to the relatively narrow line appearance of the profile with  $i = 10^\circ$ . Although not show here, a similar dependency on the inclination angle is found for the models with different temperatures ( $T_{max} = 6500, 8500, 9500$  K).

As seen in the models of Hartmann et al. (1994) and Muzerolle et al. (2001), our models also show the blue-shifted peak and the blue-ward asymmetry caused by the occultation of the accretion flow by the equatorial disc and the stellar disc. On the hand, Alencar & Basri 2000 (see their Fig. 9) found a substantial fraction of the observed H $\alpha$  profiles also shows the “red-shifted” peak, and the P Cygni profiles which can not be explained by the magnetospherical accretion model alone. In addition, a recent study by Appenzeller et al. (2005) showed that the equivalent width of H $\alpha$  from CTTS increases as the inclination angle increases. Our model with the magnetospherical accretion flow clearly disagrees with their finding.



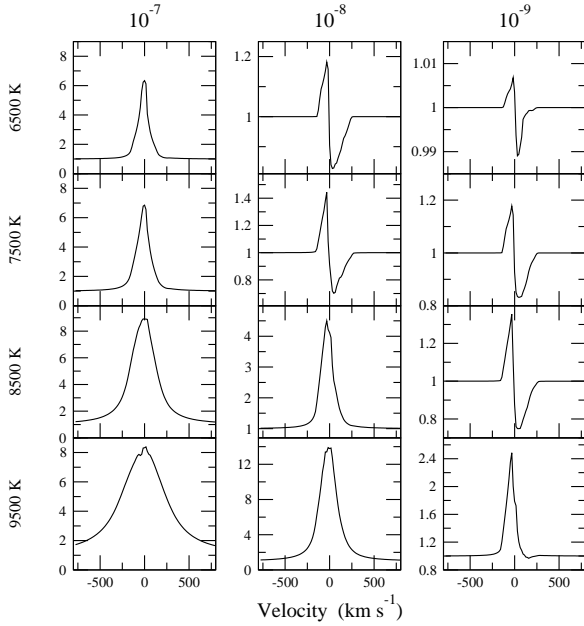
**Figure 8.** H $\alpha$  model profiles computed with wide ranges of the isothermal wind temperature ( $T_{\text{wind}}$ ) and the wind acceleration rate ( $\beta$ ). The profiles are computed with only wind (no magnetospheric accretion flow or accretion disc). The 'standard' model (Table 1) are applied here. The wind mass-loss rate ( $\dot{M}_{\text{wind}}$ ), the inclination ( $i$ ) and the degree of collimation ( $b$ ) are fixed at  $10^{-8} M_{\odot} \text{ yr}^{-1}$ ,  $55^{\circ}$  and 4.0 respectively. The temperature (indicated along the vertical axis) of the model increase from top to bottom, and the wind acceleration rate increases from left to right. The P Cygni profile are seen for lower  $T_{\text{wind}}$  and lower  $\beta$  (slow acceleration) models. The position of the absorption component moves toward the line centre as  $\beta$  increases. The effect of line broadening becomes more prominent for higher  $T_{\text{wind}}$  and higher  $\beta$  models.

## 4.2 Bipolar Wind

As mentioned in earlier, the magnetospheric accretion flow model alone cannot explain some of the features seen in observations. As an alternative model, we now examine formation of H $\alpha$  in a simple bipolar wind as described in section 2.3. The basic wind model parameters introduced earlier are  $\gamma$ ,  $\beta$ ,  $v_{\infty}$ ,  $b$ ,  $\theta_{\text{wind}}$ ,  $T_{\text{wind}}$  and  $\dot{M}_{\text{wind}}$ . To minimise the number of parameters to be explored, we initially adopt  $\gamma = 0.05$ ,  $v_{\infty} = 200 \text{ km s}^{-1}$  (Appenzeller et al. 2005) and  $\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ . Further, the angular extent of the wind (the opening angle of the wind) is assumed to be  $\theta_{\text{wind}} = 80^{\circ}$ . The degree of collimation is initially chosen to be  $b = 4$ , i.e. the ratio of the density in polar direction to the density at the edge of the wind closest to the accretion disc is about  $(\cos 0^{\circ} / \cos 80^{\circ})^4 \approx 10^3$ , for given radii. For simplicity, the wind temperature  $T_{\text{wind}}$  is assumed to be isothermal. Although the line is potentially sensitive to the temperature structure of the wind, determination of a self-consistent wind temperature is beyond the scope of this paper. Readers are referred to Hartmann et al. (1982) in which the wind temperature structure is determined by balancing

the radiative cooling rate (assuming optically thin) with the MHD wave heating rate. With these parameters kept constant, we examine the characteristics of H $\alpha$  profiles, as a function of the wind acceleration parameter  $\beta$  and the isothermal wind temperature  $T_{\text{wind}}$ . Dependency on the other parameters will be discussed later in this section.

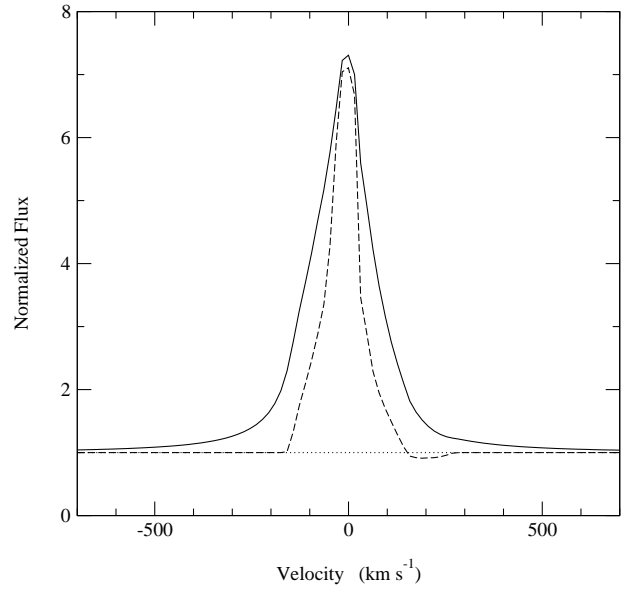
Figure 8 shows the profile computed at a mid inclination angle  $i = 55^{\circ}$  for the range of the wind temperature between 7000 K and 9000 K, and for the range of  $\beta$  between 0.2 and 2.0. The P Cygni profile are prominent in the models with lower values of  $T_{\text{wind}}$  and  $\beta$  (colder and faster acceleration wind). As the value of  $\beta$  increases, the position of the blue-shifted absorption component moves toward the line centre, which can be seen clearly in the  $T_{\text{wind}} = 7000 \text{ K}$  models. While the velocity position of absorption component for the fastest acceleration ( $\beta = 0.2$ ) is almost at the terminal velocity ( $v_{\infty} \sim 200 \text{ km s}^{-1}$ ), that for the slowest wind acceleration model ( $\beta = 4.0$ ) is located close the line centre ( $\sim 50 \text{ km s}^{-1}$ ). As one can see in Figure 2, the column density of the gas moving at  $v_{\infty}$  increases as the wind acceleration becomes larger since the gas moving at  $v_{\infty}$  becomes closer to the



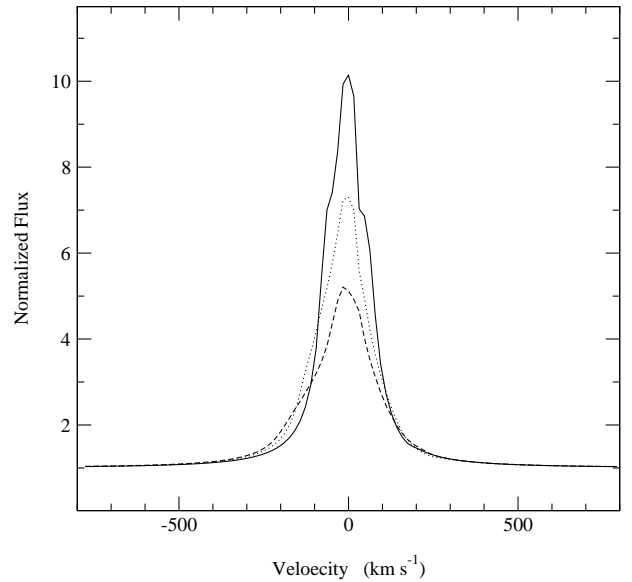
**Figure 5.**  $H\alpha$  model profiles for wide ranges of mass accretion rate ( $\dot{M}_{acc}$ ) and temperature ( $T_{max}$ ). The profiles are computed using only magnetospheric accretion flow (i.e. no wind/jet). All the profiles are computed using the parameters of the ‘standard’ model (Table 1) and inclination  $i = 55^\circ$ . The temperature (indicated along the vertical axis) of the model increase from top to bottom, and the mass accretion rate (indicated by the values in  $M_\odot \text{ yr}^{-1}$  at the top) increases from left to right. The profiles are similar to those of Muzerolle et al. (2001), available on-line ([http://cfa-www.harvard.edu/cfa/youngstars/models/magnetospheric\\_models.html](http://cfa-www.harvard.edu/cfa/youngstars/models/magnetospheric_models.html)).

photosphere. At the location where the absorption occurs, the gas is moving faster for the models with the faster wind acceleration models; hence, the location of the absorption component is bluer as  $\beta$  becomes smaller (as the wind acceleration faster). The figure also shows that the intensity of the emission component increases as  $\beta$  increases for a given  $T_{wind}$ . This is mainly because the density near the photosphere increases (more material near the photosphere) as the value of  $\beta$  increases (Figure 2); hence, the emissivity of increases. Unlike the magnetospheric accretion only models (Figure 5), the inverse P Cygni profiles are not seen here, nor the blue-ward asymmetry. Because of the absorption component in P Cygni profile, most of the profiles show red-ward asymmetry except for the low temperature wind models with high inclinations (not shown here).

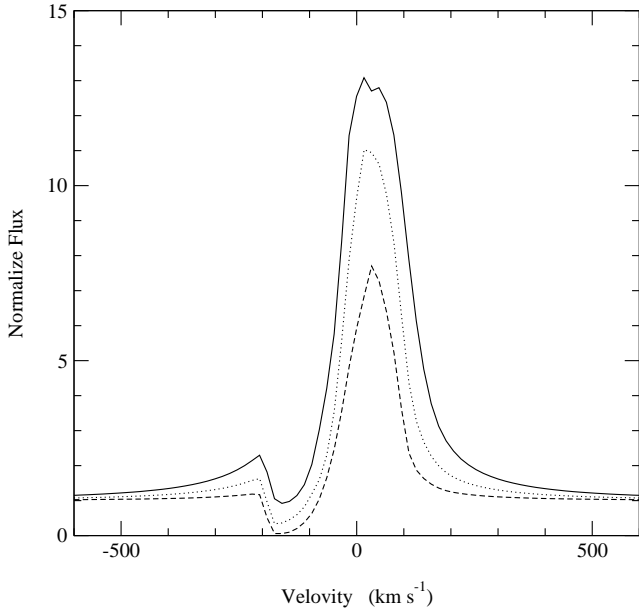
The dependency of the profile on the wind anisotropy parameter  $b$  is demonstrated in Figure 9. Three models presented in the figure have the same mass-loss ( $10^{-8} M_\odot \text{ yr}^{-1}$ ), and are computed at inclination angle  $i = 55^\circ$ . The P Cygni profile feature becomes more prominent, and the line flux becomes smaller as the wind becomes more isotropic (smaller  $b$  value). For a fixed mass-loss rate, the column density of along the line of a sight to the observer at a medium inclination angle (e.g.  $i = 55^\circ$ ) increases as  $b$  decreases (c.f. equation 8); hence, causing more absorption. Further more, the value of the highest density in the wind becomes smaller for a smaller  $b$  model. As the wind becomes more isotropic, the high gas concentrated more in the polar direction has to be spread in the wider angular angles. This results in a smaller highest density region in the wind; hence the smaller line emissivity. For the same reason, the emission in the wings is weaker for the model smaller



**Figure 6.** Effect of the line broadening for  $H\alpha$ . The model computed with the damping constant ( $\Gamma$ ), described in section 3 (solid), is compared with the model with no damping,  $\Gamma = 0$  (dashed). Both models are computed with  $T_{max} = 7500 \text{ K}$ ,  $i = 55^\circ$ , and the standard parameters given in Table 1. The two models have similar peak flux levels (around  $V \sim 0 \text{ km s}^{-1}$ ), but the total flux and the EW of the line increased drastically for the model with the damping constant. The broadened wings extend to  $\sim \pm 800 \text{ km s}^{-1}$ . The redshifted absorption feature (very weakly) seen in the  $\Gamma = 0$  model are not seen in the model with the broadening.



**Figure 7.** Dependency of  $H\alpha$  profiles on inclination ( $i$ ). The profiles are computed with the magnetospheric accretion flow using the standard parameters given in Table 1 and  $T_{max} = 7500 \text{ K}$ . The solid, dotted, and dashed lines are for  $i = 10^\circ$ ,  $55^\circ$ , and  $80^\circ$  respectively. As the inclination becomes larger, the peak flux and the equivalent width of the line becomes smaller. Similar dependency is seen in the models with the wide ranges of  $T_{max}$  and  $\beta$  (not shown here).



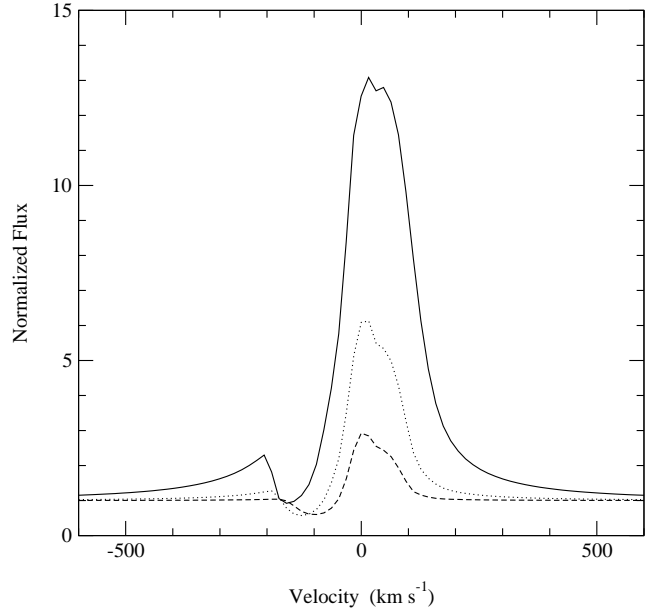
**Figure 9.** The effect of wind collimation. The line profiles computed with  $(T_{\text{wind}}, \beta) = (9000\text{K}, 0.5)$  for the wind anisotropy parameter  $b = 0, 2, 4$  are shown in dashed, dotted, and solid respectively. All the other parameters are same as in Figure 8. The P Cygni profile feature become prominent for the spherical wind models (especially in  $\beta = 0.5$  model) since the column density of along the line of a sight of the observer at a medium inclination angle ( $i = 55^\circ$ ) increases for lower  $b$  values for a fixed mass-loss rate of the wind. The blue-ward asymmetry is still present even in the isotropic wind case ( $b = 0$ ).

$b$  value. We also note that the asymmetry around the line centre decreases as the wind becomes more isotropic.

The effect of varying the wind mass-loss rate is shown in Figure 10. The line is very sensitive to the mass-loss rate. With all other parameters fixed constant,  $\dot{M}_{\text{wind}}$  acts as an scaling factor of the wind density (equation 8). For the formation of H $\alpha$ , the recombination process and the subsequent downward transition to  $n = 3$  level. Assuming the ionisation fraction remains constant, the recombination rate is proportional to the square of wind density. We have found the line flux of the models in the figure is approximately proportional to the square of the mass-loss rate. This very sensitive nature of H $\alpha$  would make the line a good candidate for a mass-loss rate indicator; however, without solving the ambiguity of the emission component from the magnetospherical accretion flow and the wind, and without knowing the detailed temperature structure of the wind, it could provide us a misleading a mass-loss rate estimate of a T Tauri star.

### 4.3 Disc + bipolar wind

Next, we examine the effect of the size of the inner radius of the disc and the distribution of the H $\alpha$  emission region. Figure 11 shows the wind emission profiles computed with and without the accretion disc at  $i = 55^\circ$ . The H $\alpha$  images (projected on to the plane perpendicular to the observer at the location of the star) are also shown in the same figure. Both models use the same parameters as in Figure 8, but with  $\beta = 0.5$  and  $T_{\text{wind}} = 9000\text{K}$ . The model without the disc can be also considered as a model with a large inner radius of the accretion disc, in which none of the wind



**Figure 10.** The effect of the wind mass-loss rate. The profiles computed with  $(T_{\text{wind}}, \beta) = (9000\text{K}, 0.5)$ , and  $\dot{M}_{\text{wind}} = 1.0 \times 10^{-8} M_{\odot} \text{yr}^{-1}$  (solid),  $0.5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$  (dotted), and  $0.25 \times 10^{-8} M_{\odot} \text{yr}^{-1}$  (dashed) are shown above. The models are computed with only the wind component (no magnetospherical accretion flow or accretion disc). With all other parameter fixed constant, the mass-loss rate behaves as a scaling factor for the wind density (equation 8.)

emission region is blocked by the disc — provided the inclination angle is not so high and the disc is not or slightly flared.

The bipolar nature of the wind is clearly seen in the images. In this example, the most of the wind emission occurs within a few to a several (depending mainly on the value of  $\beta$ ) stellar radii from the star. The figure also shows that the accretion disc blocking the wind emission from the bottom half of the wind which is moving away from the observer. This results in the reduction of the wind emission in the red wing. The image (mid panel) also shows that the accretion disc is not occulting the stellar disc at this inclination; therefore, the ratio of the wind emission flux to the photospherical continuum flux becomes slightly smaller for the model with the disc. This results in the reduction in the peak flux and the flux in the wings in the normalised profile shape. If the disc becomes more flared (if the opening angle exceeds  $45^\circ$  at the outer edge of the accretion disc), the occultation of the stellar disc by the accretion could be seen at this inclination angle. Although it is not shown here, the continuum level of the two models are identical. For the models with  $i < 30^\circ$ , the presence of the disc has little/no effect on the profile shapes. In the figures, the extent of the H $\alpha$  emission is smaller ( $\sim 0.2\text{ AU}$  or  $\sim 20 R_*$ ) compared to the spectroastrometric observations of Takami et al. (2003) for RU Lup and CS Cha which show 1–5 AU scale outflows<sup>1</sup>; however, if a slower wind acceleration rate ( $\beta = 4$ ) is the emission region become slightly larger ( $\sim 0.4\text{ AU}$ ).

Although not shown here, we have computed the H $\alpha$  profiles

<sup>1</sup> Takami et al. (2003) their observation also show that some objects (e.g Z CMa and AS 353A) displaying the outflows of larger scale ( $> 50\text{ AU}$ ); however, this could be formed by shocks rather than MHD-wave heating (e.g. Hartmann et al. 1982) or X-ray heating (e.g. Shang et al. 2002).

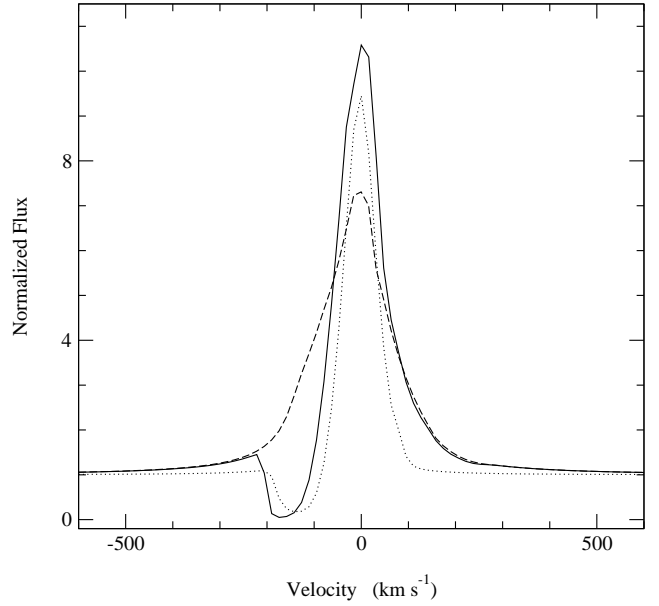
with the collimated wind and the accretion disc for the same range of  $\beta$  and  $T_{\max}$  values as in Figure 8. The inner and the outer radii of the accretion disc are  $R_{\text{di}} = R_{\text{mi}} = 2.2R_*$  and 100 AU respectively, and the disc is slightly flared (see section 2.4). Similar to the case in Figure 11, the line flux of the models with accretion disc decreases to less than the half of that without the accretion disc similar to the models shown in Figure 11. The overall behaviour of the line profile shapes as functions of  $\beta$  and  $T_{\text{wind}}$  are very similar to that for the models without the accretion disc. A significant reduction of the flux in the red wing is seen in the wind model with the accretion disc when compared with the wind only model. The wings appear to be weaker in these models compared to the wind only models because of the lower wind emission flux to the continuum flux as briefly mentioned earlier.

#### 4.4 Magnetosphere + disc + bipolar wind

We examine the characteristics of the line profiles arising from the combination of the magnetospheric accretion flow, the wind, and the accretion disc. For simplicity, the parameters for the magnetosphere ( $T_{\max} = 7500$  K and  $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$  are fixed as in Figure 5), and the wind mass-loss rate, the isothermal wind temperature and the wind anisotropy parameter to  $\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$  (i.e.  $\dot{M}_{\text{wind}} = 0.1 \dot{M}_{\text{acc}}$ ),  $T_{\text{wind}}$  and  $b = 4$  respectively. The profile computed for  $i = 55^\circ$  is given in Figure 12, along with the profile computed with the magnetosphere only and that with the wind plus accretion disc configurations for a comparison. As one can see from the figure, the profile computed for the disc–wind–magnetosphere hybrid model can be understood as a simple flux sum of the magnetospheric component and the wind component. In this example, the wind causes the absorption of the blue side of the profile, and it adds extra flux around the line centre. As seen before, the presence of the disc causes the reduction in the red side of the profile since the emission from the receding gas is block by the disc. The resulting profile appears to be narrower than that of the magnetosphere model.

The effect of changing the ratio of the wind mass-loss rate to mass-accretion rate ( $\mu = \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$ ) is demonstrated in Figure 13. With the fixed value of mass-accretion rate ( $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$ ), the mass-loss rate by the wind is varied. The figure shows that as  $\mu$  increases the P-Cygni absorption deepens, and the position of minimum flux in the absorption trough appears to move blue-ward. On the other hand, the emission component becomes stronger as  $\mu$  increases. With this combination of the parameters for the magnetosphere and the wind, the absorption component tends to be too strong for the models  $\mu > 0.025$  (with this model configuration), at all inclinations (not shown here), compared with the observed H $\alpha$  profiles (e.g. Reipurth et al. 1996; Alencar & Basri (2000)). As we will see later (section 18),  $\mu$  can be as large as  $\sim 0.3$  with different parameters of the magnetosphere; hence, this condition  $\mu > 0.025$  is always valid.

Again, the H $\alpha$  profiles with the same ranges of the wind temperature ( $T_{\text{wind}}$ ) and the wind acceleration parameter ( $\beta$ ) used in Figure 15 are computed with  $\mu = 0.01$ . The parameters of the magnetosphere fixed as in Figure 7, are shown in Figure 14 along with the model with only the magnetosphere, for a comparison. A relatively small value of  $\mu$  is chosen to avoid absorption component of the P-Cyg profile becoming too strong, as seen in Figure 13. In general, even with small values of the anisotropy parameter ( $b = 0$  and 2), the absorption component is found to be too strong when  $\mu = 0.1$  is used with this combination of the magnetosphere and the wind. The figure shows that the position of the wind absorp-



**Figure 12.** Comparison of the profiles computed with the magnetosphere, the wind, the disc, and their combinations. The model configurations used above are: (1) magnetosphere only (dashed), (2) wind and disc (dash), and (3) disc, wind and magnetosphere (solid). The parameters used here are  $T_{\max} = 7500$  K,  $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$ ,  $\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ ,  $T_{\text{wind}} = 8000$  K, and  $\beta = 0.5$ . The profile for the case 3 is can be understood as a simple flux sum of the profiles from case 1 and 2.

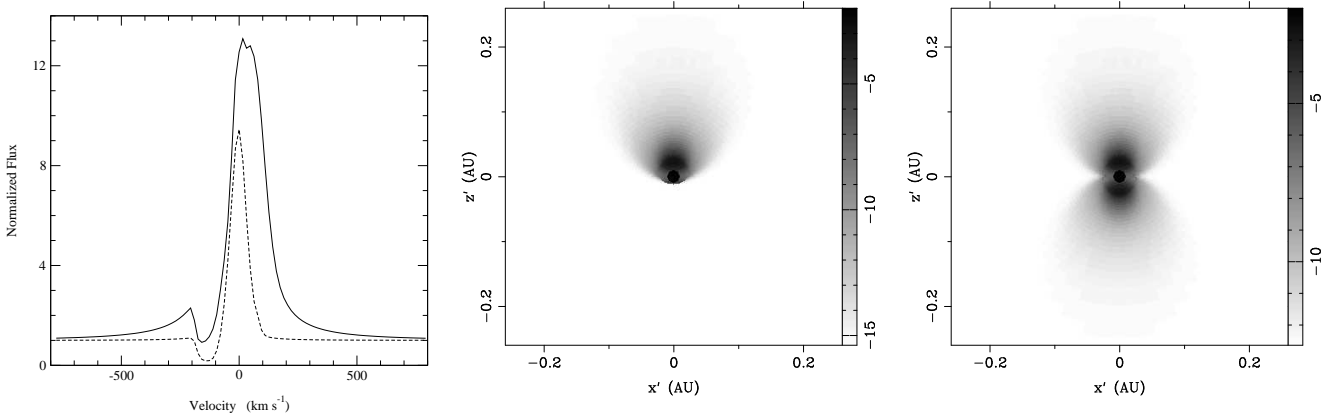
tion component moves toward the line centre as  $\beta$  becomes larger. Although little wind emission is seen in this temperature range, it becomes more important in a model with a higher temperature and a wind mass-loss rate. In fact, the model with  $\beta = 2.0$  and  $T_{\text{dw}} = 9000$  K displays a small amount of the wind emission at  $V \sim 50 \text{ km s}^{-1}$ .

As seen in Figure 12, the profiles shown here can be understood as the combination of the emission from the magnetosphere and the absorption of the flux by the wind component. In general, the emission from the accretion disc is negligible at H $\alpha$  wavelength, but the absorption of the continuum flux from the photosphere by the disc is important for predicting correct line strengths.

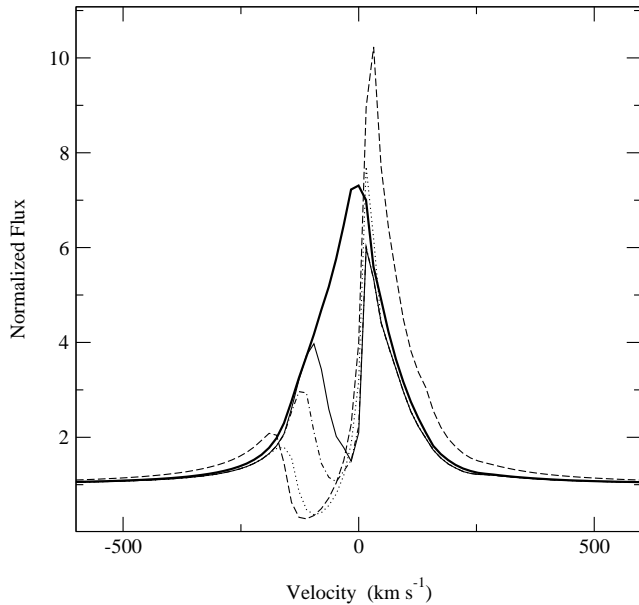
Although the profiles shown in Figure 14 are those at a single inclination angle ( $i = 55^\circ$ ), they are very similar to the Type II-B and III-B of the observed CTTS H $\alpha$  profiles (Reipurth et al. 1996), which are impossible to be explained by the magnetospheric accretion flow models (e.g. Muzerolle et al. 2001). Comparison of the model profiles with different types of the observed H $\alpha$  profiles will be given in section 5.1.

#### 4.5 Disc-wind model of Knigge et al. (1995)

As an alternative model for the bipolar wind models (with the combination of the magnetosphere and the accretion disc) shown in Figures 8 and 14, we have also considered the disc-wind model Knigge et al. (1995) as briefly described in section 4.3. The former resembles the density structure of Krasnopolsky et al. 2003 in large scale ( $\sim 100$  AU) which described in section 2.3, and the latter in small scale ( $\sim 10$  AU) of the same model. The main difference between the two models are in their density structure. For a given radius, the density increases toward the polar direction in the former model,



**Figure 11.** Comparison of the wind model with and without the optically-thick and geometrically-thin disc. The latter can be also equivalent to a model with a large inner radius of the accretion disc in which none of the wind emission region is not blocked provided the inclination is moderate. The left panel shows the profile computed with  $i = 55^\circ$ ,  $\beta = 0.5$  and  $T_{\text{wind}} = 9000$  K (see text for other parameters used). The flux in the red wing of the line profile from the model with the disc (solid) is greatly reduced by the presence of the accretion disc compared to that from the model without the disc (dashed). The peak flux and the flux in the wings are also reduced in the model with the disc because the disc does block the wind emission region, but none of the stellar disc, i.e. the continuum flux level is unchanged. The H $\alpha$  image (project in the plane of the observer) for the model with the disc (middle panel) and that for the model without (right plane) are also shown. The image flux is computed by integrating the specific flux over the wavelength range  $(-800 \text{ km s}^{-1} < v < 800 \text{ km s}^{-1})$ . The flux is in an arbitrary units and in logarithmic (base 10) scale.



**Figure 13.** Effect of the mass-loss rate to mass-accretion rate ratio ( $\mu = \dot{M}_w / \dot{M}_{\text{acc}}$ ). The H $\alpha$  profile computed with only the magnetospheric accretion (thick solid) –  $T_{\text{max}} = 7500$  K,  $\dot{M}_{\text{acc}} = 10^{-7} M_\odot \text{ yr}^{-1}$  – is compared with the magnetosphere, wind, and disc hybrid models for  $\mu = 0.01$  (solid),  $0.025$  (dash-dot),  $0.1$  (dot) and  $0.2$  (dashed). All the models are computed with the inclination angle  $i = 55^\circ$ . As  $\mu$  increases the P-Cygni absorption deepens and the emission component becomes stronger. In general, the absorption is too strong for the models  $\mu > 0.025$  compared with the observations (e.g., Reipurth et al. 1996).

but the density increases toward the equatorial plane for the models presented here.

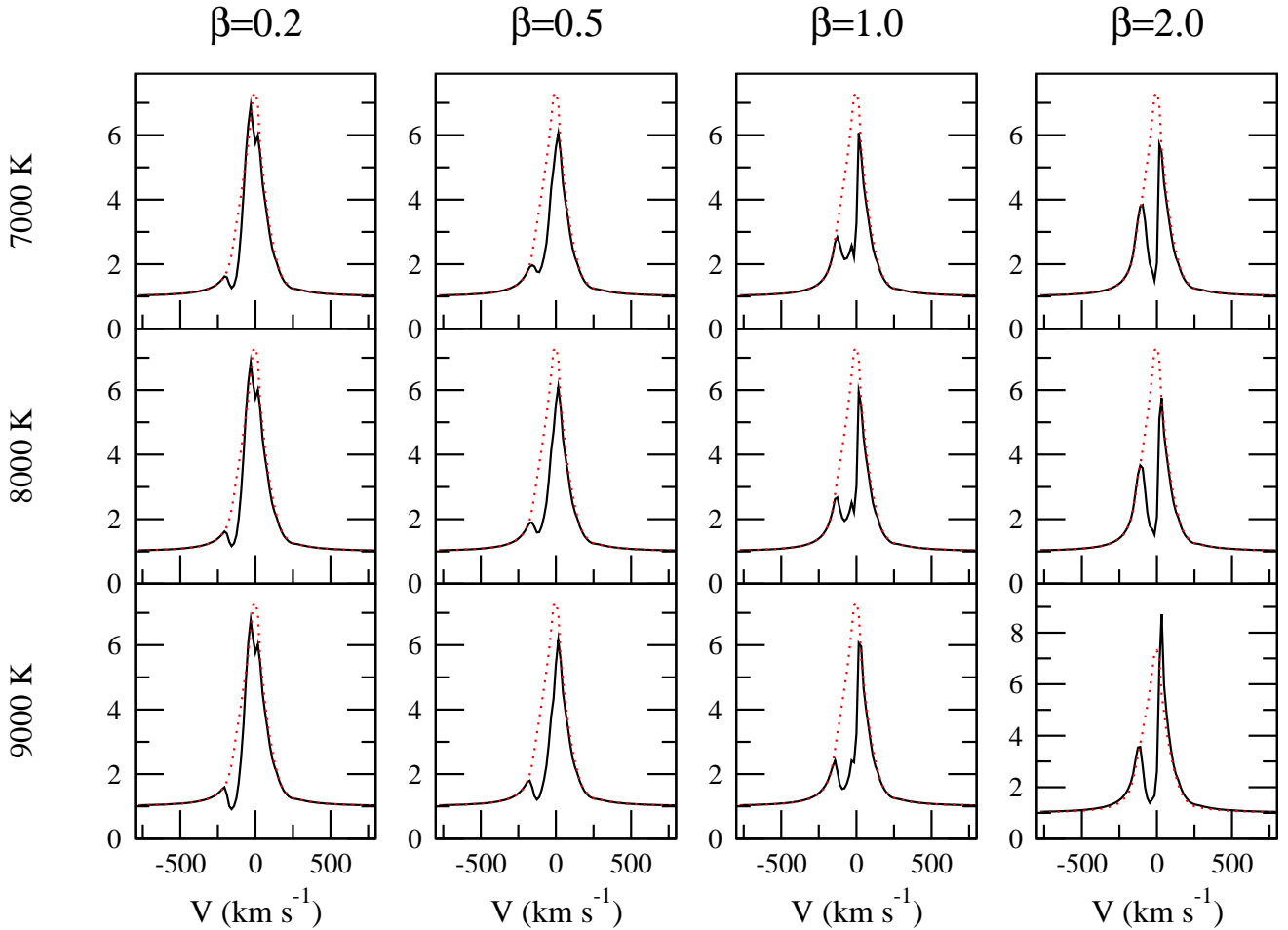
First, the disc wind models without the magnetosphere are considered. Figure 15 shows the H $\alpha$  profiles computed using only the disc-wind component (c.f. Figure 3) for the same isothermal

disc-wind temperature ( $T_{\text{dw}}$ ) and the wind acceleration parameter ( $\beta$ ) ranges used for the bipolar wind models. The parameters used for the central star are as in section 2.1, and the other disc-wind parameters are summarised in Table 3. The figure shows that the wind emission increases  $\beta$  and  $T_{\text{dw}}$  increase. Similar to the bipolar wind models, the location of the P-Cygni absorption component moves toward the line centre as  $\beta$  increases. The morphology of the profile exhibited by the model changes from FU-Ori type (IV-B) for the models with small  $\beta$  to III-B and II-B types (Reipurth et al. 1996) as the value of  $\beta$  increases. Although not shown here, we find that the profile shapes are relatively insensitive to the value of the wind collimation parameter  $d$ . The dependency on the disc wind mass-loss rate of the profile shape is similar to that of the collimated wind models (Figure 13).

We now consider the models computed with the combination of the disc-wind and the magnetospheric accretion components. The parameters used for the magnetosphere are set to be same as in the case for Figure 7, and are kept constant for simplicity. The mass-loss rate of the disc wind is set to  $\dot{M}_{\text{dw}} = 10^{-8} M_\odot \text{ yr}^{-1}$  (i.e.  $\mu = \dot{M}_{\text{dw}} / \dot{M}_{\text{acc}} = 0.1$ ) Figure 16 shows the models profiles computed using the same ranges of the disc-wind temperature and the wind acceleration parameter as in the previous cases.

As in the disc wind only models (Figure 15), the location of the absorption component moves toward the line centre as the value of  $\beta$  increases (as the wind acceleration slower). The figure shows that in the models with smaller  $\beta$  and  $T_{\text{dw}}$ , the line emission from the magnetosphere dominates. On the other hand, in the models with larger  $\beta$  and  $T_{\text{dw}}$ , the emission from the disc wind dominates. Compared to the observation of Reipurth et al. (1996) and Alencar & Basri (2000), the lines are too strong for  $(T_{\text{dw}}, \beta) = (9000 \text{ K}, 2.0)$  and  $(9000 \text{ K}, 1.0)$  models. The wide varieties of profile shapes are seen in this set of models which resembles II-B, III-B, IV-B, II-R and III-R<sup>2</sup> types of the observed

<sup>2</sup> Not shown here, but seen in the models with different combinations of  $i$ ,  $T_{\text{max}}$  and  $\dot{M}_{\text{acc}}$ .



**Figure 14.** Same as Figure 8, but the models include the magnetospheric accretion flow (with  $T_{\text{max}} = 7500$  K and  $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$ ), the accretion disc. The mass-loss rate of the wind used here is  $\dot{M}_{\text{wind}} = 10^{-9} M_{\odot} \text{ yr}^{-1}$ . A relatively small mass-loss rate is chosen to avoid unrealistically strong P-cyg absorption component (see text in section 4.4 and Figure 13). For a comparison, the profile computed with only the magnetospheric accretion flow (dotted) is overlaid. All the profiles are computed at the inclination angle  $i = 55^{\circ}$ . As  $\beta$  becomes larger, the position of the wind absorption component moves toward the line centre. Although little wind emission is seen in this temperature range, it becomes more important in a model with a higher temperature and a wind mass-loss rate. The profiles resemble the observed H $\alpha$  emission profiles affected by the wind.

H $\alpha$  profiles (Reipurth et al. 1996). The shape of the primary and secondary peaks in the profiles are slightly “rounder” compared to those of the accretion, collimated wind, disc hybrid model shown in Figure 14. The rounder peaks are caused by the rotation of the wind. The profiles from the disc wind models are affected more by the rotational motion of the wind since the gas is more concentrated toward the equator, but in the models with the collimated wind the gas is concentrated more in the polar directions.

We note the ambiguity seen between some of the disc-wind only models and the disc-wind, magnetosphere hybrid models. For example, the disc-wind only model with  $(T_{\text{wind}}, \beta) = (8000 \text{ K}, 1.0)$  in Figure 15 and the disc-wind model with  $(T_{\text{wind}}, \beta) = (9000 \text{ K}, 0.5)$  in Figure 16 give very similar profiles. Given such an observed profile, it is difficult to distinguish if the emission is dominated by the accretion or the wind unless some other lines, not affected associated with wind or magnetosphere, are used simultaneously.

General characteristics of the profiles from the disc-wind, magnetosphere hybrid model (Figure 16) are very similar to those of the disc, collimated wind, magnetosphere hybrid model (Fig-

$d$ [ $R_*$ ]	$R_{\text{wi}}$ [ $R_*$ ]	$R_{\text{wo}}$ [AU]	$\dot{M}_{\text{dw}}$ [ $M_{\odot} \text{ yr}^{-1}$ ]	$p$ [—]	$f$ [—]	$R_s$ [ $R_*$ ]
21.4	3.0	1.0	$10^{-8}$	$-3/2$	2.0	30

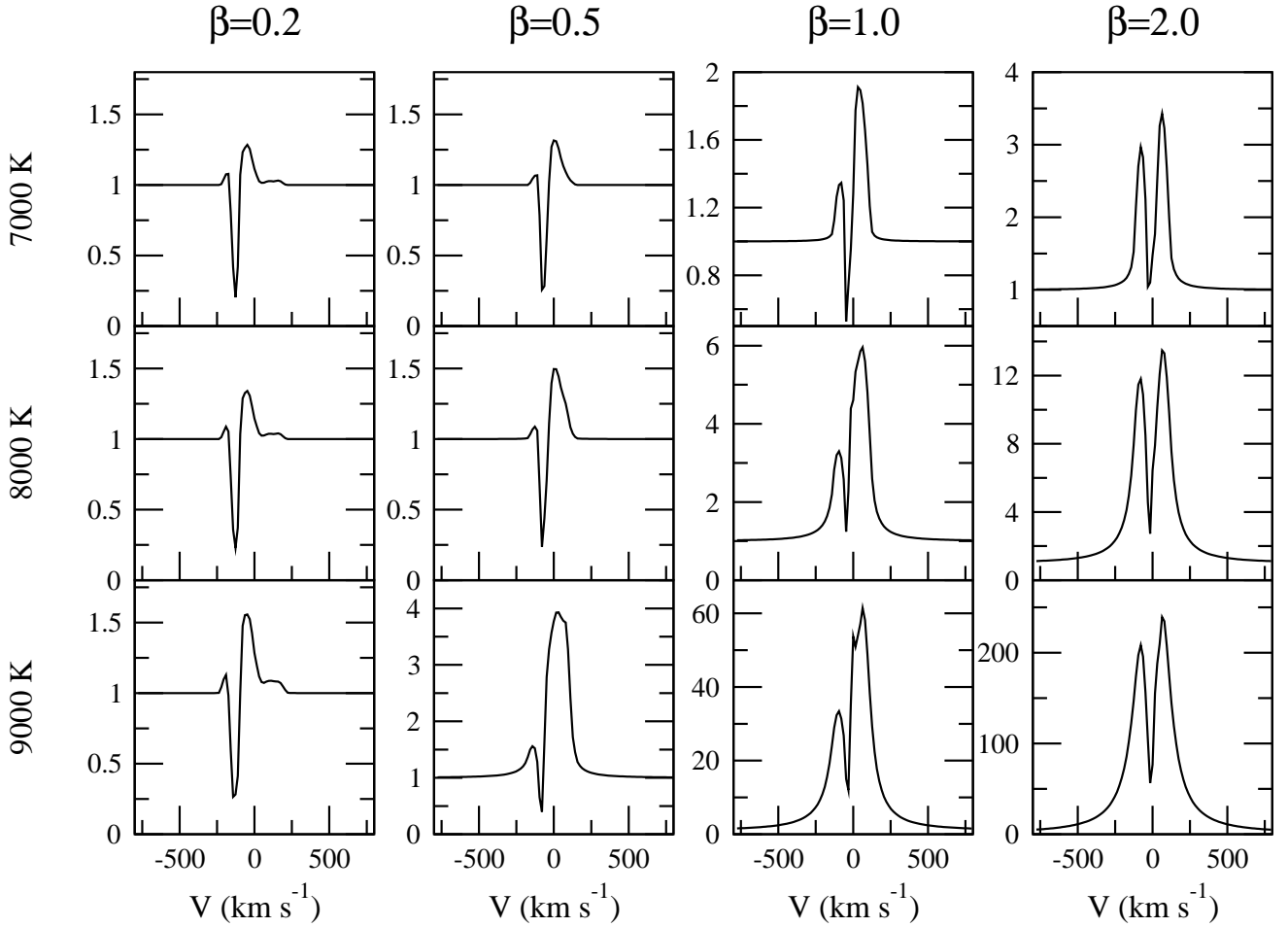
**Table 3.** The summary of the standard disc-wind model parameters used in section 4.5. See also section 2.5.

ure 14). The main difference between these two sets of models is the mass-loss rate to the mass accretion rate  $\mu$ . While the models presented in this section use  $\mu = 0.1$  which is consistent with the MHD jet models (e.g. Königl & Pudritz 2000), the models in Figure 14 use much smaller value ( $\mu = 0.01$ ).

## 5 DISCUSSION

### 5.1 Classification scheme proposed by Reipurth et. al (1996)

Reipurth et al. (1996) proposed the two-dimensional classification



**Figure 15.** The H $\alpha$  profiles computed with the disc-wind only models. For the wind mass-loss rate fixed at  $\dot{M}_{\text{dw}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ , the line profiles are computed with different combinations of the wind acceleration rate ( $\beta$ ) and the isothermal disc wind temperature ( $T_{\text{dw}}$ ). The wind emission increases as the values of  $\beta$  and  $T_{\text{wind}}$  increase (as the wind becomes accelerates slower and as the wind comes warmer. Similar to the bipolar wind models (Figure ??), the position of the wind absorption moves toward the line centre as *beta* becomes larger. The morphology of the profiles are similar to that of observations.

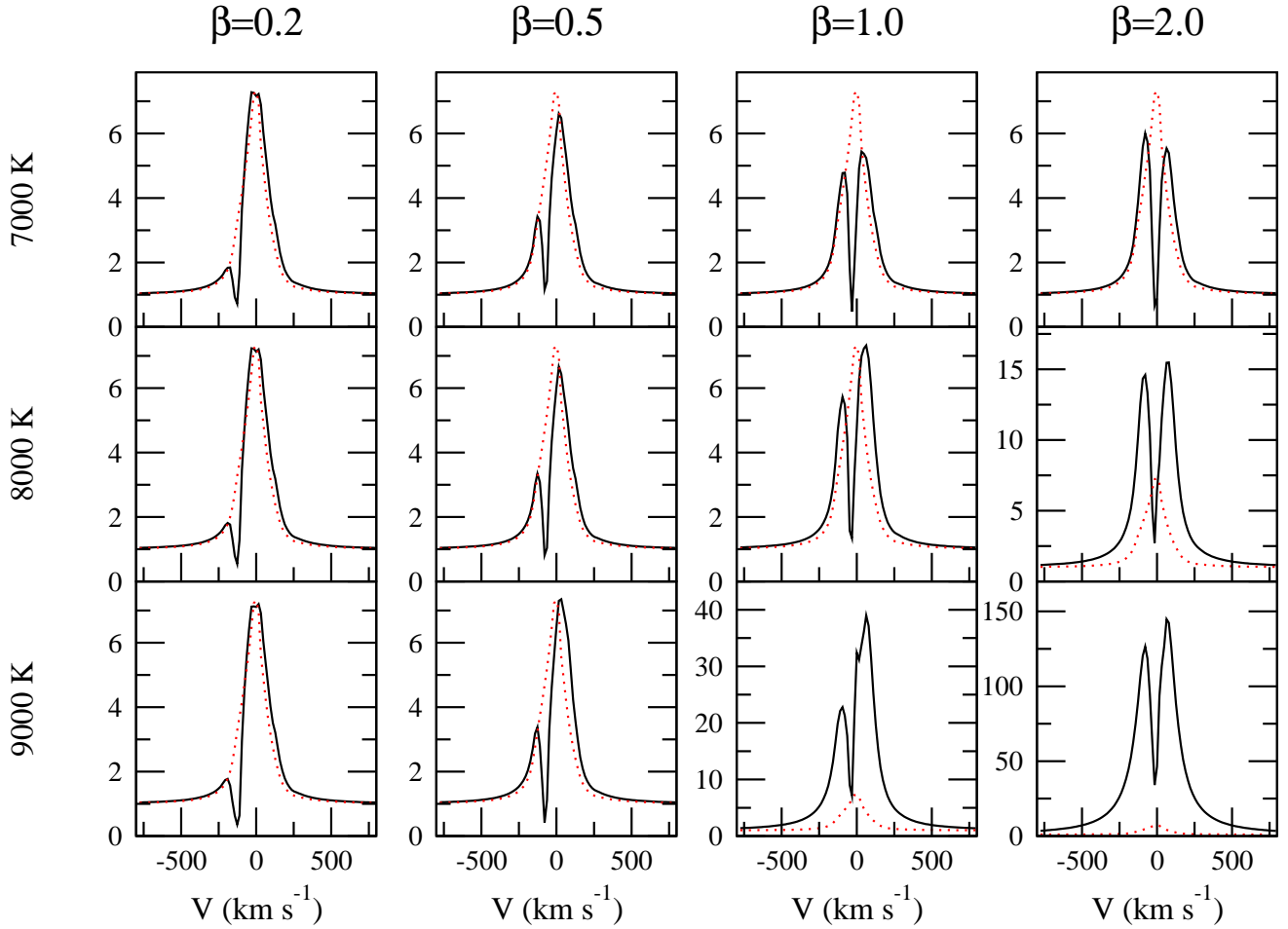
of H $\alpha$  emission profiles of T Tauri stars and Herbig Ae/Be stars. Their classification scheme contains four classes (I, II, III and IV) differentiated by the ratio of the secondary-to-primary emission components in the profiles. Each classes are divided into two subclasses (B and R) which depends whether the absorption component is on the blue or red side. Readers are referred to Fig. 4 of their paper. Figure 17 shows the sample model profiles which are classified according to the definition of Reipurth et al. (1996). The combination of the disc wind, magnetospheric accretion, and accretion disc can reasonably reproduce all the classes of the profiles seen in observations. Similar profiles can be reproduced if the bipolar wind is used instead of the disc wind, but the wind absorption at a given velocity location occurs at a different inclination angles when the wind type is switched from the bipolar wind to the disc wind. The corresponding model parameters used to reproduce the profiles in the figure are given in Table 4 along with brief comments on possible physical conditions which leads to the profiles in each class.

Using the samples of H $\alpha$  from 43 CTTS, Reipurth et al. (1996) found the most common (33 per cent) type of the profile is Type III-B. Interestingly, the most common profile type seen in the profiles from both the bipolar wind, disc and magnetosphere hybrid model

(Figure 14) and the disc-wind and the magnetosphere hybrid model (Figure 16) are Type III-B profiles. In this type of profiles, the main emission comes from the magnetosphere, and the profile shape is altered a slightly blue-asymmetric one to a slightly red-asymmetric one via the wind absorption in the blue wing. The second most common profile (26 per cent)

Type I (symmetric around line centres) is mainly produced in the magnetosphere. Although not shown here, this type of profile can be reproduced with the disc-wind, magnetosphere hybrid mode with pole on configuration. Since there is not material in the polar region in the disc wind model, the observer can look the magnetosphere almost directly for high inclination cases, provided that wind temperature is low enough so that the wind emission is negligible. Type II-R and Type II-B can be produced in a similar physical conditions (e.g. in a slow accretion and low temperature wind plus a magnetosphere). Main difference is between the two is in their inclination angles. The former is more likely seen with high inclination.

Type III-R is the least common type of the observed profile (2 per cent) according to Reipurth et al. (1996). Incidentally, we also had a hard time to reproduce this type of profile since this can be achieved only at narrow range of parameter space (very high



**Figure 16.** The disc-wind, magnetosphere hybrid model. Same as Figure 15, but these models (solid) also include the magnetosphere accretion flow ( $T_{\max} = 7500$  K and  $\dot{M}_{\text{acc}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ ). While the emission from the magnetosphere dominates for the models with smaller  $\beta$  and  $T_{\text{dw}}$  (the faster accretion and the colder wind models), the emission from the wind dominates for the models with larger  $\beta$  and  $T_{\text{dw}}$  (the slower accretion and the hotter models). For a comparison, the profile computed with only the magnetospheric accretion flow (dotted) is overlaid. The model profiles are very similar to the observed profiles influenced by the wind outflow.

inclination angle with disc wind model,  $T_{\max} \sim 8300$  K, and  $\dot{M}_{\text{acc}} 10^{-8} M_{\odot} \text{ yr}^{-1}$ .

Similarly the Type IV-R is the second least common type of observed profile (5 per cent) which shows the inverse P-Cygni profile shape. This can be understood since the magnetospheric accretion model of Hartmann et al. (1994) predicts that the redshifted absorption can occur at a limited range of inclination angle with which the hot continuum flux from the footprint of the magnetosphere is seen through relatively fast moving gas in the accretion stream. Finally Type III-R profile is very similar to Type II-R, but the wind in this type of profile may be accretion faster than that in Type II-R.

## 5.2 An example model fit of T Tau

As a demonstrative purpose, we present a model fit of  $H\alpha$  observation of a classical T Tauri star (T Tau) obtained by Vink et al. (2005). T Tau is known to be a triple system (e.g. Koresko 2000). One of the star in the system T Tau N (a prototype for T Tauri stars) is dominating in optical (e.g. Calvet et al. 1994). The rotational velocity and the rotational period of the star found by Herbst et al. (1987) are  $v \sin i = 19.5 \pm 2.5 \text{ km s}^{-1}$  and 2.80 d respec-

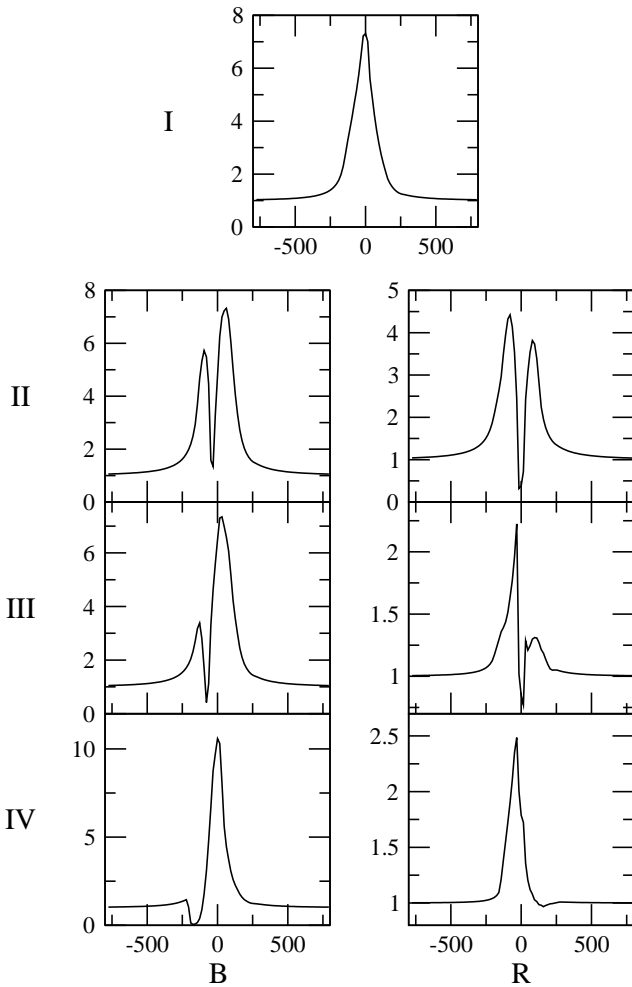
tively. The inclination of the disc is known to be relatively small (e.g.  $i = 29^\circ$ , Akeson et al. 2002). There is a rather large scatter in the previously estimated the accretion rates e.g.  $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  (Johns-Krull et al. 2000) and  $(3.1 - 5.7) \times 10^{-8} M_{\odot} \text{ yr}^{-1}$  (Calvet et al. 2004).

For the photospheric model, the following parameters from Calvet et al. (2004) are adopted:  $T_{\text{eff}} = 5500$  K,  $M_* = 1.9 M_{\odot}$  and  $R_* = 2.9 R_{\odot}$ . The standard geometry for the magnetosphere ( $R_{\text{mi}} = 2.2 R_*$  and  $R_{\text{mo}} = 3.0 R_*$ ) and the bipolar wind configuration (Table 1) are used for simplicity. Again, our purpose here is not to obtain the best fit parameters, but rather it is to examine if the model is capable of reasonably reproducing the data from a real object, in this case, T Tau N. The main parameters here (1) the temperature of the magnetospheric accretion flow ( $T_{\max}$ ), (2) the mass-accretion rate ( $\dot{M}_{\text{acc}}$ ), (3) the temperature of the wind ( $T_{\text{wind}}$ ), and (4) the wind mass-loss rate ( $\dot{M}_{\text{wind}}$ ). The inclination angle is simply adopted from Akeson et al. 2002 i.e.  $i = 29^\circ$ .

Figure 18 shows the result of a model fit. The amount of veiling near  $H\alpha$  is very small ( $< 0.01$ ) for T Tau, according to Basri & Batalha (1990); hence, the observation is not corrected for veiling. The model consists of the magnetosphere, the bipolar wind, and the

Class	$i$	$\dot{M}_{\text{acc}}$	$T_{\text{max}}$	$\dot{M}_{\text{dw}}$	$T_{\text{dw}}$	$\beta$	Comment
I	55	$10^{-7}$	7.5	—	—	—	Accretion dominated possibly without the wind. Mid inclination.
II-B	55	$10^{-7}$	7.5	$10^{-9}$	8.0	1.0	Wind, disc and magnetosphere. Wide range of wind acceleration rate. Mid-high inclination
III-B	55	$10^{-7}$	7.5	$10^{-9}$	9.0	0.5	Wind, disc and magnetosphere. Fast-mid wind acceleration rate. Mid inclination
IV-B	55	$10^{-7}$	7.5	$10^{-8}$	9.0	0.5	Wind, disc and magnetosphere. Fast wind acceleration rate. Mid inclination
II-R	80	$10^{-7}$	7.5	$10^{-9}$	7.0	2.0	Wind, disc and magnetosphere. Slow wind acceleration rate. High inclination
III-R	85	$10^{-8}$	8.2	$10^{-9}$	6.0	1.0	Wind, disc and magnetosphere. Mid wind acceleration rate. Very high inclination
IV-R	55	$10^{-9}$	9.5	—	—	—	Accretion dominated. Low mass-accretion rate. Mid inclination.

**Table 4.** The summary model parameters for the profiles in Figure 17 and brief comments. The temperatures are in  $10^3$  K.  $\dot{M}_{\text{acc}}$  and  $\dot{M}_{\text{dw}}$  are in  $M_{\odot} \text{ yr}^{-1}$ .



**Figure 17.** Sample H $\alpha$  model profiles which characterize the classification by Reipurth et al. (1996). The combination of magnetospheric accretion flow, the accretion disc, and the disc wind model can reasonably reproduce wide ranges of H $\alpha$  profiles seen in observations. Similar results can be obtained if the disc wind is replaced by the disc wind. The model parameters and short comments are summarised in Table 4. The horizontal axes are velocities in  $\text{km s}^{-1}$ , and the vertical axes are normalized fluxes.

accretion disc (with a large hole i.e.  $\sim 5$  AU). The parameters used for the model fit are:  $T_{\text{max}} = 22000$  K,  $T_{\text{wind}} = 8000$  K,  $\dot{M}_{\text{acc}} = 1.1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ , and  $\dot{M}_{\text{wind}} = 2.0 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ . The temperature of the magnetosphere is relatively high compared to the standard cases (e.g. Figure 5; also Muzerolle et al. 2001). Note

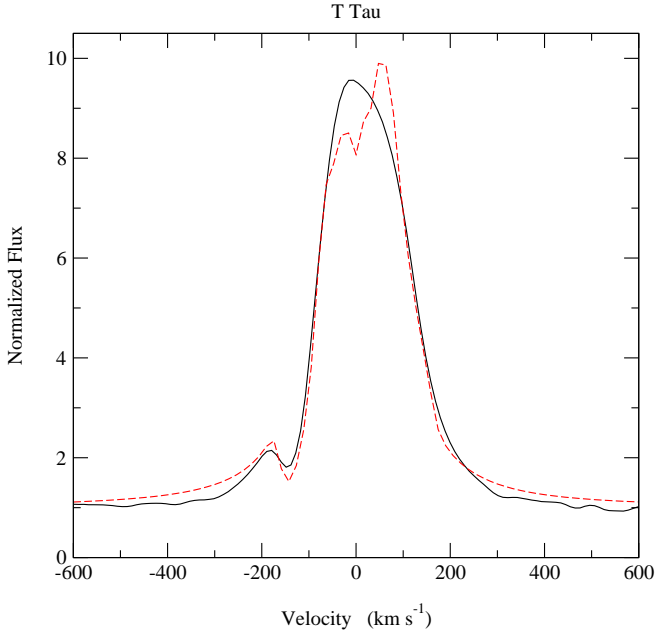
that the estimated value of  $T_{\text{max}}$  depends on the adopted values of  $L_*$  (or  $M_*$  and  $T_{\text{eff}}$ ) for the photospheric continuum model. If a lower value of  $L_*$  is adopted,  $T_{\text{max}}$  value would become smaller in order to match the line strength which is mainly determined by the emission from the magnetosphere, in this case. For example, if the photospheric continuum is 3 times smaller than the one used here, one finds  $T_{\text{max}} \sim 9600$  K which is more similar to that of the standard cases. The figure shows that the agreement between the model and the observation is quite reasonable although the line wings are slightly stronger in the models. In this example, the main profile feature is defined by the emission from the magnetosphere, but the blue side of the profile is affected by the absorption by the wind. The mass-loss to mass-accretion rate  $\mu = 0.18$  which is similar to the value predicted by observations and MHD simulations i.e.  $\sim 0.1$  (Königl & Pudritz 2000). Compared our mass-accretion rate estimate is much less than that of (Johns-Krull et al. 2000), and slightly smaller than that of (Calvet et al. 2004) (see above).

Although not shown here for clarity, the peak flux near the line centre is also affected by the wind absorption (causing about 10 per cent reduction) compared to the profile computed with magnetosphere only model (similar effect also seen in Figure 14). If the fit was performed by ignoring the wind, the temperature and the mass-accretion rate of the magnetospheric accretion flow will be underestimated. A better approach to a model fit is a simultaneous fitting of multiple lines. For example, the near-infrared lines such as Pa $\beta$  and Br $\gamma$  should be used to determine the mass-loss rate since these lines are much less affected by the wind. Using the mass-loss rate from these lines, H $\alpha$  can be used to determine the wind mass-loss rate.

### 5.3 Which wind model?

In the previous sections, two possible geometrical configurations for the wind from CTTS were considered: 1. the bipolar wind, and 2. the disc wind. While the material more concentrated toward the polar regions for a given radius in the first case, the material is more concentrated toward the equatorial plane in the second case. As mentioned earlier, the bipolar wind model resembles the density distribution of the jet MHD simulation of e.g. Krasnopolsky et al. (2003) in large scale ( $> 10$  AU), and the disc wind model resembles that in smaller scale ( $< 10$  AU).

The distinct difference in the density dependency on the polar angles in two models should be apparent in the inclination angle dependency on the shapes of the line profiles. Figure 19 shows the H $\alpha$  profiles computed for 1. the disc, bipolar-wind, accretion hybrid model (section 4.4) and 2. the disc-wind, magnetosphere hybrid model (section 4.5) at inclination angles  $i = 10^\circ, 55^\circ, 80^\circ$ . Both models include the magnetospheric accretion component



**Figure 18.** Comparison of the observed  $H\alpha$  profile of T Tau and the profile computed with the hybrid model, which consist of the magnetosphere, the collimated wind, and the accretion disc (with a large hole i.e.  $\sim 5$  AU). The inclination angle  $29^\circ$  is used. The maximum temperature of the magnetosphere ( $T_{\text{max}}$ ) and the isothermal wind temperature used here are 22000 K and 8000 K respectively. The mass-accretion rate ( $\dot{M}_{\text{acc}}$ ) and the mass-loss rate ( $\dot{M}_{\text{wind}}$ ) are  $1.1 \times 10^{-8} M_\odot \text{ yr}^{-1}$  and  $2.0 \times 10^{-9} M_\odot \text{ yr}^{-1}$  respectively ( $\mu = \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}} = 0.18$ )

with the same parameters used as in sections 4.4 and 4.5 i.e.  $T_{\text{max}} = 7500$  K and  $\dot{M}_{\text{acc}} = 1 \times 10^{-7} M_\odot \text{ yr}^{-1}$ .

Mainly because of the geometrical configuration, the P-Cyg absorption feature weakens as the inclination increases for the model with the bipolar wind. The optical depth to an observer is higher (from the wind emission region) for with a lower inclination angle with this geometry. Although not shown here, this tendency of the inclination dependency holds for the models with bipolar wind models for wide ranges of  $\beta$  and  $T_{\text{wind}}$ . For the model with the disc wind, the absorption becomes stronger as the inclination becomes larger. The optical depth to an observer becomes larger as the inclination increases in this geometry.

Similarly, the line equivalent width increases as the inclination angle increases for the model with the bipolar wind, it decreases as the inclination angle increases for the model with the disc wind. With the models with only magnetosphere (section 4.1), we have also found that the line equivalent width decreases as the inclination increases in those models (see Figure 7). Interestingly, the observational study of Appenzeller et al. (2005) showed that the  $H\alpha$  line equivalent width of CTTS increases as the inclination angle increases. Only the models with the bipolar wind agree with the trend seen in their observation. Although the uncertainty in the inclination angles of the observed object might be large, a larger sample in addition to that of Appenzeller et al. (2005) for further investigation of the inclination dependency on the line profile will be extremely useful for finding a possible wind configuration of CTTS.

Despite the inclination angle dependency of the observed  $H\alpha$  favouring the models with bipolar wind, there are two main aspects of this model are not quite consistent with the magneto-centrifugal launched jet numerical models (e.g. Krasnopolsky et al. 2003). First,

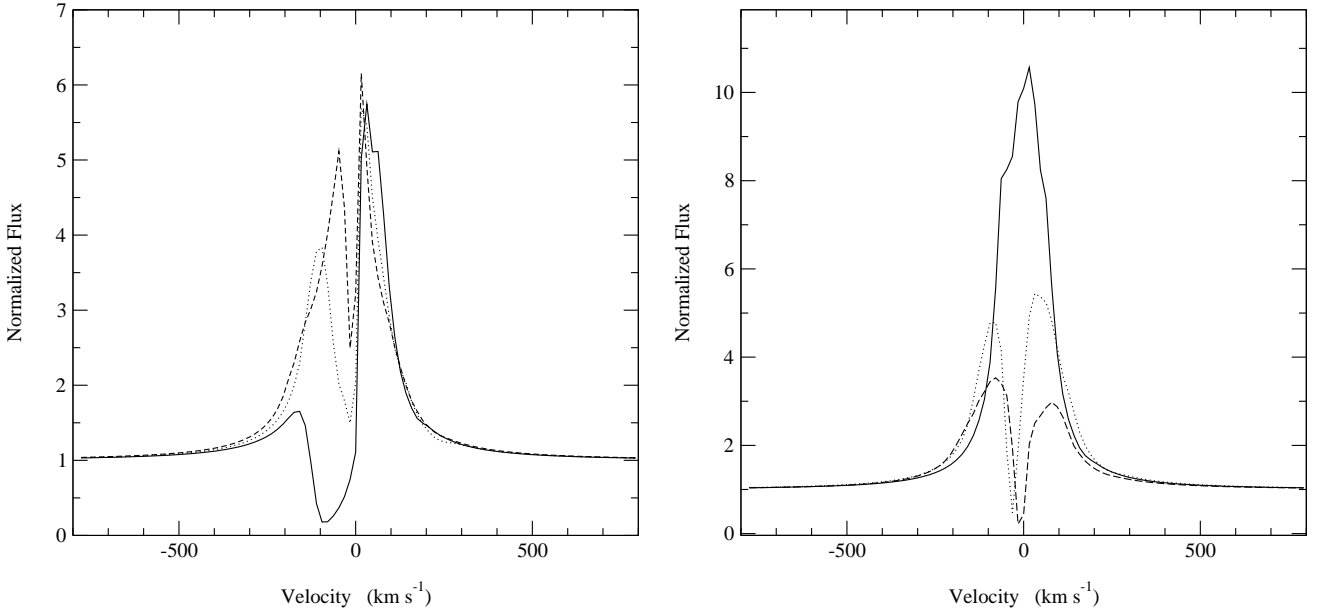
in section 4.4, we found that the ratio of the mass-loss to mass-accretion rates needed to be rather small ( $\mu < \sim 0.025$ ), in order not to have an unrealistically strong P-Cyg absorption component, compared to the MHD simulations suggested (Königl & Pudritz 2000) i.e.  $\mu \approx 0.1$ . In the model fit of T Tau observation (section 5.2), we found much larger value of the ratio  $\mu = 0.18$ . Considering large uncertainty in MHD theories and observational measurements ( $\dot{M}_{\text{acc}}$ ,  $\dot{M}_{\text{wind}}$  and  $B$ ), the wide range of the mass-loss to mass-accretion ratio (e.g.  $0.025 < \mu < 0.18$ ) may be still reasonable. On the other hand, the models with the disc wind (section 4.5) using  $\mu = 0.1$  reproduces the profiles (Figure 16) similar to that seen in observations. Second, the MHD models predict that the wind/jet becomes collimated well above the disc plane ( $> 10$  AU), but our bipolar wind model are collimated (density enhanced toward in the polar direction) from right outside of the magnetosphere. Unless the origin of the wind is from the central star itself, the density distribution used for the bipolar wind is not quite consistent with the near field of the MHD jet models, considering that the most of the  $H\alpha$  emission occurs within a few to a several radii of the magnetosphere (Figure. 11). The density structure used for the disc wind model, however, is very similar to that of MHD simulations in the near field where the most of the  $H\alpha$  wind emission occurs. Interestingly, however, the recent study of Matt & Pudritz (2005) showed the possibility that the stellar wind along the open magnetic field originating from the star can cause significant spin-down torque on the star, provided that mass-loss rate is high enough. Considering the issues mentioned above, it is not possible to favour the bipolar wind model to the disc wind model without further observational constraints. In reality, two types of the winds (bipolar wind and disc wind) may co-exists similar to that seen in e.g. Drew et al. (1998) and Matt & Pudritz (2005). In these models, the fast stellar wind is present in the polar directions, and at the same time the slower disc wind is present near the equatorial plane.

## 6 CONCLUSIONS

We have presented the disc-wind-magnetosphere hybrid radiative transfer models for classical T Tauri stars, and detailed studies of the  $H\alpha$  formation from their complex to circumstellar environment and to understand the wide variety emission line profiles seen in observations. The two types of wind models considered are (1) the bipolar wind model in the wind is originated from the star itself (section 2.3; Figure 1), and (2) the disc-wind model in which the wind originates from the inner part of the accretion disc (section 2.5; Figure 3). We found that both wind models combined with the magnetospherical accretion flow reproduces the wide variety of  $H\alpha$  profiles (Figures 14 and 16) seen in the observations.

The inclination dependency of the line equivalent width predicted by the bipolar wind model agree with trends seen in the observation, but the disc-wind model does not. With the standard magnetospherical configuration (Table 1), the ratio of the mass-loss to mass-accretion rates ( $\mu$ ) used in the bipolar wind was set to be 4–10 times smaller than that predicated by magneto-hydrodynamical (MHD) calculations (c.f.  $\mu \sim 0.1$ ; Königl & Pudritz 2000) to avoid the blue-shifted absorption component becoming unrealistically too strong; however  $\mu$  used in the disc-wind models are consistent with MHD calculations.

Using the model results, we examined the  $H\alpha$  spectroscopic classification proposed by Reipurth et al. (1996), and discuss the basic physical conditions that reproduce the profiles in each classified type. Using the hybrid model, we also fit the observed  $H\alpha$  from



**Figure 19.** Dependency on the inclination angle of the  $H\alpha$  model profiles. The profile computed at  $i = 10^\circ$  (solid),  $55^\circ$  (dot) and  $80^\circ$  using 1. the disc, bipolar-wind, accretion hybrid model (left panel; c.f. section 4.4) and 2. using the disc-wind, magnetosphere hybrid model (right; c.f. section ??) are shown for a comparison. The parameters used for the magnetosphere are same for the both models, i.e.  $T_{\max} = 7500$  K and  $\dot{M}_{\text{acc}} = 10^{-7} M_{\odot} \text{ yr}^{-1}$ . The isotherma wind temperature and the wind accretion parameter used both models are  $T = 7000$  K and  $\beta = 1.0$  respectively. All the other parameters are same as in sections 4.4 and 4.5. While the line equivalent width increases as the inclination angle increases for the former model configuration, it decreases as the inclination angle increases for the latter. Only the former agrees with the tendency seen in the observational study of Appenzeller et al. (2005) who showed that the  $H\alpha$  line equivalent width of CTTS increases as the inclination angle increases.

the optical component of T Tau triple system (T Tau N). The agreement between the model and the observation is excellent; however, we could not confirm the uniqueness of the fit. The ratio of the mass-loss to mass-accretion rate was found to be  $\sim 0.18$ .

Although not attempted in this paper, a better approach for determining the mass-loss and mass-accretion rate consistently is to model multiples lines simultaneously. For example, the mass-accretion rate of an object can be determined more easily by modelling  $\text{Pa}\beta$  and  $\text{Br}\gamma$  since there is no/little wind effect seen in these lines. The mass-accretion rate then can be used to model  $H\alpha$  to find the wind mass-loss rate.

Similar model configurations used here may be also applicable to Herbig Ae/Be and brown dwarfs since their  $H\alpha$  observations also exhibit evidences of the outflow and inflow (e.g. Finkenzeller & Mundt (1984); Muzerolle et al. 2005), but no model has been developed to explain the phenomenon. Further investigation on the possibility of applying our model to these objects are needed.

Future works should include the followings: (1) Improving the wind models. The parametrisation of the wind density structure should be changed to follow more closely that of MHD simulations. The wind temperature structure should be calculated self-consistently (c.f. Hartmann et al. 1994; Martin 1996). (2) Computing the line profiles using the density structure from MHDs directly. Check the consistency, and give feedback to the MHD models which are needed to be tested against observational data. (3) Spectropolarimetric study to explore the geometry and the rotation of the disc (e.g. Vink et al. 2005). (4) Modelling of the extended  $H\alpha$  and spectro-astrometric observations (c.f. Takami et al. 2003; Appenzeller et al. 2005). (5) Line variability study using a 3D radiative transfer model (e.g. Symington et al. 2005; Kurosawa et al. 2005) to probe the geometrical structure.

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## References

- Akeson R. L., Ciardi D. R., van Belle G. T., Creech-Eakman M. J., 2002, *ApJ*, 566, 1124
- Alencar S. H. P., Basri G., 2000, *AJ*, 119, 1881
- Alencar S. H. P., Basri G., Hartmann L., Calvet N., 2005, *A&A*, 440, 595
- Anders E., Grevesse N., 1989, *geochim. cosmochim. acta*, 53, 197
- Appenzeller I., Bertout C., Stahl O., 2005, *A&A*, 434, 1005
- Appenzeller I., Mundt R., 1989, *A&AR*, 1, 291
- Basri G., Batalha C., 1990, *ApJ*, 363, 654
- Basri G., Bertout C., 1989, *ApJ*, 341, 340
- Bertout C., Basri G., Bouvier J., 1988, *ApJ*, 330, 350
- Blandford R. D., Payne D. G., 1982, *MNRAS*, 199, 883
- Burrows C. J., Stapelfeldt K. R., Watson A. M., Krist J. E., Ballester G. E., Clarke J. T., Hester J. J., Hoessel J. G., Holtzman J. A., Mould J. R., Scowen P. A., Trauger J. T. and Westphal J. A., 1996, *ApJ*, 473, 437
- Calvet N., Basri G., Kuhl L. V., 1984, *ApJ*, 277, 725
- Calvet N., Hartmann L., Hewett R., 1992, *ApJ*, 386, 229
- Calvet N., Hartmann L., Kenyon S. J., Whitney B. A., 1994, *ApJ*, 434, 330
- Calvet N., Muzerolle J., Briceño C., Hernández J., Hartmann L., Saucedo J. L., Gordon K. D., 2004, *AJ*, 128, 1294
- Castor J. I., Abbott D. C., Klein R. I., 1975, *ApJ*, 195, 157

- Castor J. I., Lamers H. J. G. L. M., 1979, *ApJS*, 39, 481
- Chiang E. I., Goldreich P., 1997, *ApJ*, 490, 368
- Collier Cameron A., Campbell C. G., 1993, *A&A*, 274, 309
- Cotera A. S., Whitney B. A., Young E., Wolff M. J., Wood K., Povich M., Schneider G., Rieke M., Thompson R., 2001, *ApJ*, 556, 958
- Decampli W. M., 1981, *ApJ*, 244, 124
- Draine B. T., Lee H. M., 1984, *ApJ*, 285, 89
- Drew J. E., Proga D., Stone J. M., 1998, *MNRAS*, 296, L6+
- Edwards S., Cabrit S., Strom S. E., Heyer I., Strom K. M., Anderson E., 1987, *ApJ*, 321, 473
- Edwards S., Hartigan P., Ghandour L., Andrulis C., 1994, *AJ*, 108, 1056
- Finkenzeller U., Mundt R., 1984, *A&AS*, 55, 109
- Frank J., King A., Raine D. J., 2002, *Accretion Power in Astrophysics: Third Edition*. Cambridge Univ. Press, Cambridge, p. 398
- Ghosh P., Pethick C. J., Lamb F. K., 1977, *ApJ*, 217, 578
- Grevesse N., Noels A., 1993, in *Origin and Evolution of the Elements*, N. P., E. V.-F., M. C., eds., Cambridge Univ. Press, Cambridge, p. 15
- Guenther E. W., Emerson J. P., 1996, *A&A*, 309, 777
- Gullbring E., Hartmann L., Briceno C., Calvet N., 1998, *ApJ*, 492, 323
- Hanner M., 1988, in *NASA Conf. Pub. 3004*, 22, Vol. 3004, p. 22
- Harries T. J., 2000, *MNRAS*, 315, 722
- Hartigan P., Edwards S., Ghandour L., 1995, *ApJ*, 452, 736
- Hartmann L., Avrett E., Edwards S., 1982, *ApJ*, 261, 279
- Hartmann L., Hewett R., Calvet N., 1994, *ApJ*, 426, 669
- Herbig G. H., 1962, *Advances in Astronomy and Astrophysics*, 1, 47
- Herbst W., Booth J. F., Koret D. L., Zajtseva G. V., Shakhovskaya H. I., Vrba F. J., Covino E., Lines R., Barksdale W., 1987, *AJ*, 94, 137
- Hillier D. J., 1991, *A&A*, 247, 455
- Johns-Krull C. M., Valenti J. A., Hatzes A. P., Kanaan A., 1999, *ApJ*, 510, L41
- Johns-Krull C. M., Valenti J. A., Linsky J. L., 2000, *ApJ*, 539, 815
- Kenyon S. J., Hartmann L., 1987, *ApJ*, 323, 714
- Kenyon S. J., Hartmann L., Hewett R., Carrasco Cruz-Gonzalez I., Recillas E., Salas L., Serrano A., Strom K. M., Strom S. E., Newton G., 1994, *AJ*, 107, 2153
- Kim S., Martin P. G., Hendry P. D., 1994, *ApJ*, 422, 164
- Klein R. I., Castor J. I., 1978, *ApJ*, 220, 902
- Knigge C., Woods J. A., Drew E., 1995, *MNRAS*, 273, 225
- Königl A., 1991, *ApJ*, 370, L39
- Königl A., Pudritz R. E., 2000, *Protostars and Planets IV*, 759
- Koresko C. D., 2000, *ApJ*, 531, L147
- Krasnopolsky R., Li Z.-Y., Blandford R. D., 2003, *ApJ*, 595, 631
- Kuhi L. V., 1964, *ApJ*, 140, 1409
- Kurosawa R., Harries T. J., Bate M. R., Symington N. H., 2004, *MNRAS*, 351, 1134
- Kurosawa R., Harries T. J., Symington N. H., 2005, *MNRAS*, 358, 671
- Kurosawa R., Hillier D. J., 2001, *A&A*, 379, 336
- Kurucz R. L., 1979, *ApJS*, 40, 1
- , 1993, *VizieR Online Data Catalog*, 6039, 0
- Kwan J., Tademaru E., 1995, *ApJ*, 454, 382
- Long K. S., Knigge C., 2002, *ApJ*, 579, 725
- Luttermoser D. G., Johnson H. R., 1992, *ApJ*, 388, 579
- Malbet F., Benisty M., De Wit W. J., Kraus S., Meilland A., Millour F., Tatulli E., Berger J., Chesneau O., Hofmann K., Isella A., Natta A., Petrov R., Preibisch T., Stee P., Testi L., Weigelt G., AMBER Collaboration, 2005, *ArXiv Astrophysics e-prints*
- Martin S. C., 1996, *ApJ*, 470, 537
- Mathis J. S., Rimpl W., Nordsieck K. H., 1977, *ApJ*, 217, 425
- Matt S., Pudritz R. E., 2005, *ApJ*, 632, L135
- Mihalas D., 1978, *Stellar atmospheres*, 2nd edn. W. H. Freeman and Co., San Francisco
- Muzerolle J., Calvet N., Hartmann L., 2001, *ApJ*, 550, 944
- Muzerolle J., Luhman K. L., Briceño C., Hartmann L., Calvet N., 2005, *ApJ*, 625, 906
- Ouyed R., Pudritz R. E., 1997, *ApJ*, 482, 712
- Pudritz R. E., Banerjee R., 2005, *ArXiv Astrophysics e-prints*
- Ray T. P., Mundt R., Dyson J. E., Falle S. A. E. G., Raga A. C., 1996, *ApJ*, 468, L103+
- Reipurth B., Pedrosa A., Lago M. T. V. T., 1996, *A&AS*, 120, 229
- Rybicki G. B., Hummer D. G., 1978, *ApJ*, 219, 654
- Shakura N. I., Sunyaev R. A., 1973, *A&A*, 24, 337
- Shang H., Glassgold A. E., Shu F. H., Lizano S., 2002, *ApJ*, 564, 853
- Shu F. H., Najita J., Ostriker E., Wilkin F., Ruden S., Lizano S., 1994, *ApJ*, 429, 781
- Steinacker J., Henning T., Bacmann A., Semenov D., 2003, *A&A*, 401, 405
- Symington N. H., Harries T. J., Kurosawa R., 2005, *MNRAS*, 356, 1489
- Takami M., Bailey J., Chrysostomou A., 2003, *A&A*, 397, 675
- Uchida Y., Shibata K., 1985, *PASJ*, 37, 515
- Ustyugova G. V., Koldoba A. V., Romanova M. M., Chechetkin V. M., Lovelace R. V. E., 1995, *ApJ*, 439, L39
- Vernazza J. E., Avrett E. H., Loeser R., 1973, *ApJ*, 184, 605
- Vink J. S., Drew J. E., Harries T. J., Oudmaijer R. D., Unruh Y., 2005, *MNRAS*, 359, 1049
- Walker C., Wood K., Lada C. J., Robitaille T., Bjorkman J. E., Whitney B., 2004, *MNRAS*, 351, 607
- Whitney B. A., Wood K., Bjorkman J. E., Wolff M. J., 2003, *ApJ*, 591, 1049
- Wolf S., Henning T., Stecklum B., 1999, *A&A*, 349, 839
- Wood K., Wolff M. J., Bjorkman J. E., Whitney B., 2002, *ApJ*, 564, 887