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Investigating a Chromosphere Plus Disk-wind Scenario for the Hot Gas Component of β-Pictoris, as Revealed by FUSE

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Abstract. The FUSE satellite revealed the first emission line spectrum of β Pictoris. Broad emission lines due to highly ionized species, C III and O VI, are well detected above the very low continuum level. The mere presence of such lines in β Pictoris spectrum is evidence of a complex stellar environment, including dense and hot regions, within a few stellar radii of the photosphere. Based on the intepretation of the apparent structure of the lines profiles, it has been concluded that accretion and solar-like activity are the most likely processes for the gas heating. We present the results we obtained with a model including a solar-like extended chromosphere-corona complex and a weak wind.

1. Introduction

β Pictoris is a young main-sequence A5 star, 20 ± 10 Myr old (Barrado y Navascués et al. 1999) and located 19.3 pc from the Sun. Past work on the β Pic system has focussed on the unique and exciting circumstellar (CS) disk, which is believed to contain millions of planetesimals, and possibly young planets (Vidal-Madjar et al. 1998). The star itself has been little studied, understandably, as stars of this spectral type are not supposed to show any of the activity seen in later-type stars like the Sun. Standard stellar models predict that stars like β Pic should not have convective envelopes which could drive magnetic dynamo action and produce strong stellar activity like high temperature chromospheric or coronal emissions. Until recently, β Pic has appeared to be well behaved, showing no emission lines or wind signatures in any previous observations.

2. The Data

β-Pic was observed with FUSE on March 1 and 3, 2001, with a total exposure of 28 ksec, using the low resolution apertures ($30'' \times 30''$). The data have been processed with the CALFUSE v1.8.7 software and rebinned to a constant wavelength step of 0.1 Å. The absolute wavelength scale was set by comparing the photospheric absorption lines in the spectrum to a Kurucz stellar atmosphere model (T_{eff} = 8200 K, $log\ g$ = 4.25), yielding an uncertainty on the abso-

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lute wavelength of less than 40 km s^{-1}. Strong emission lines of highly ionized species, are clearly visible in the spectrum.

The C III resonance line at 977 Å appears as a broad, non Gaussian, emission feature, with a total width of about 1000 km s^{-1} (Fig. 1a). One can not exclude, at first, that the profile is in fact a broad single-peaked emission, on which absorption components, hypothetically from the disk, are superimposed. More likely, it could be made either of two components or even three. In the first case, it consists of a double-peaked emission, on the blue side of which an additional component is superimposed; the deep central depression is broad (0.2 Å) and redshifted by 55 km s^{-1}, with respect to the stellar velocity. Measuring the separation between the two most intense peaks, we found $\Delta v = 205$ km s^{-1}. In the second case, the line profile is made of three distinct components, formed at different projected radial velocities.

The C III UV4 multiplet (λ 1175.711) is well detected, with a large blueshift of about 200 km s^{-1} relative to the star (Fig. 1b), and a Gaussian-like shape.

A Gaussian fit was made for the components of the O VI resonance doublet, with the λ 1037 line scaled by the doublet ratio to the λ 1032 line (Fig. 1c). The lines are redshifted by about 46 km s^{-1} relative to the star. The blue wing of the λ 1037 line is blended with a weak emission line identified as the C II resonance line at 1036.3 Å.

These line profiles remain stable in the spectra recorded 2 days apart.

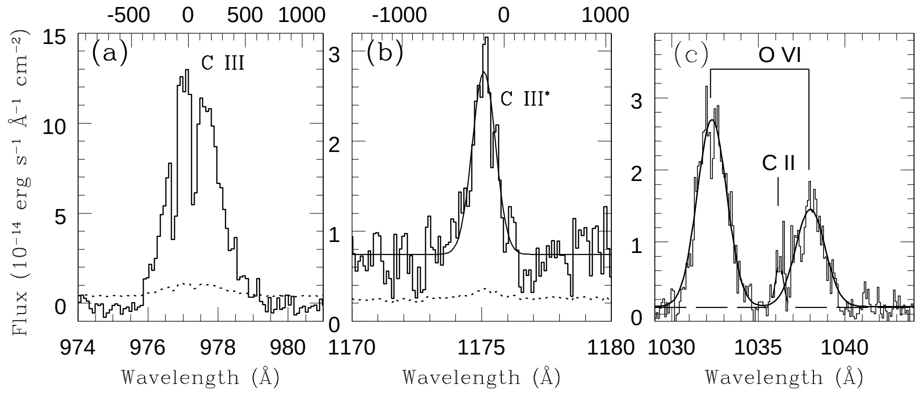

Figure 1. FUSE spectrum of β-Pic showing (a) C III, (b) C III* and (c) the O VI resonance doublet, in emission. The upper x-axis shows velocities (in km s^{-1}) with respect to the stellar heliocentric velocity. Gaussian fits are overplotted with a thick line. C II emission is present at 1036.3 Å(dashed line). From Deleuil et al. 2001.

3. Origin of the Highly Ionized Emissions

The high temperature species observed by FUSE cannot be produced by photoionization in the CS environment of an A5 V star like β-Pic, as there is far too little stellar FUV flux to ionize large numbers of atoms into such high ionization states. Only collisional processes can produce these ions, implying relatively high densities in the line formation regions.

Previous observations of highly ionized species in β-Pic disk (Al III and C IV) were attributed to shocks in star-grazing comet comae that are very close to the star (Beust & Tagger 1993). In this framework, emission lines should all be redshifted by several hundreds of km s^{-1}, should vary rapidly (within hours) and should be weak. None of these predictions is compatible with our observations.

On the other hand C III and O VI emission lines are observed in the spectra of other A-type stars and the Sun at similar strength (Simon & Landsman 1997; Simon & Ayres 1998) and are produced in the transition zone (TZ) between the chromosphere and the corona. We used spectral line modeling to investigate how this formation scenario is applicable to β-Pic case.

4. Models

The model for the envelope of β-Pic is inspired from those developed to study the activity of Herbig Ae/Be stars (Bouret & Catala 2000). The star is simulated by a classical photosphere Kurucz model, on the top of which a model for the circumstellar envelope is appended, including an extended heated region. By analogy with the solar case, we refer to the different parts of this region as chromosphere and transition zone, respectively. This region is completed by a temperature plateau, extending on a few tenths of stellar radii. Line profiles are calculated with the ETLA code, which solves the radiative transfer equation in the comoving frame of the gas, in the equivalent two level atom formulation, taking into account NLTE effects (Bouret & Catala 2000). Doppler profiles were assumed for the lines.

5. Results

We found that temperatures ranging from 20,000K at the bottom of the chromosphere up to 3×10^5K in the higher transition region are needed to obtain emission lines whose profiles are similar to the observed ones. These values are similar to those measured for the Sun. The models we considered span densities from about $2. \times 10^{-16}$ to about $2. \times 10^{-7}$ g.cm^{-3} in the lines formation regions. Only those within the range 8.6×10^{-14} to 1.2×10^{-12} g.cm^{-3} give line profiles whose morphology is similar to the observed ones. In terms of electron densities, this translates into $n_e \approx 10^9$ cm^{-3} in the TZ, slightly smaller than solar values. Quite remarkably, this is consistent with the electron density derived from the observed line flux ratio f_{1176}/f_{977} (Bhatia & Kastner 1993), although in β-Pic, these lines probe different regions on the stellar environment, with very different physical properties.

On the other hand, whatever the temperature law, line profiles are never as broad as observed. We had to convolve these profiles by rotation velocities as high as 3 times the stellar rotation velocity, which is ≈ 130 km s^{-1}, to match the observations, indicating a "super-rotational" broadening. This suggests that β-Pic is indeed surrounded by an extended hot magnetosphere that traps and heats gas out in co-rotation lobes.

Searching for the model that best fit the observed profiles, we derived the parameters listed in table 1. The intensity, width, and velocity shift of the synthetic O VI lines profiles are in very good agreement with the observed ones. On the other hand, none of our models can account for the deep central absorption trough, in the C III line profile. Such components have been seen in FUSE spectra of late-type stars with bright C III emissions and have been found to be of interstellar origin. However, the wavelength calibration we achieved precludes any precise interpretation in terms of an ISM contribution; besides, the non-detection of C III in the MDRS aperture data also rules out an interstellar origin for these lines. The model produces a weak C III* line in emission and redshifted by about 50 $\mathrm{km\,s^{-1}}$. An unsufficient resolving power, together with blends with the red side of the C III* blueshifted emission component (see Fig. 1b) and a potential absorption line redward of the latter ($\lambda\lambda$ 1176.5; see Fig. 1b), prevents any realistic fitting atempt with our code.

Table 1. Parameters for the model illustrated in Fig. 2. T_{chrom} and T_{flat} are the temperatures reached at the external border of the chromosphere and in the temperature plateau, respectively. R_{chrom}, R_{TZ} and R_{flat} are the radial size of the deep chromosphere, the transition region and the temperature plateau, respectively. The radii are given in stellar units.

T_{chrom}	R_{chrom}	R_{TZ}	T_{flat}	R_{flat}
40,000	0.1	0.06	260,000	0.5

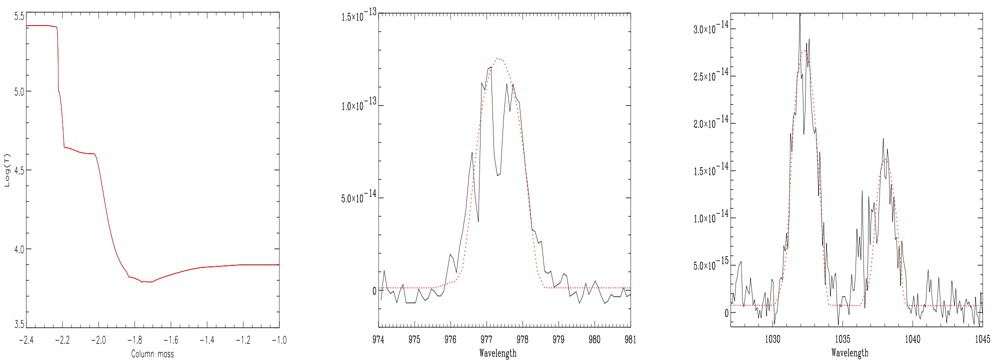

Figure 2. *Left*: Temperature law for table 1 model. X-axis is log of column mass, for the sake of clarity. *Middle and Right*: C III and O VI line profiles (respectively) for this model. Line profiles are convolved with $v\sin i$=400 km $\mathrm{s^{-1}}$.

6. A Two-component Model

The observed blueshift of C III* and C II implies that these lines are formed in a fast moving medium, where velocities projected on the line of sight can be as high as 200 km s^{-1}. The asymmetric emission component seen on the blueside of the C III line profile may as well originate from this region. On the other hand, if it exists, this medium is not hot enough to ionize O V into O VI, since no blueshifted component are detected for the O VI resonance doublet.

We assumed that a thin, moderately warm wind is escaping from the circumstellar disk of β-Pic. No physical assumptions were made for this disk-wind. We restricted ourselves to a semi-empirical model, searching for conditions in which C III* line may form with the observed profile. We focussed on this ion rather than C II because of the blend of the latter with the blue component of the O VI resonance doublet which makes any fitting atempt more difficult.

We first built a spherically symmetric model of wind. Afterwards, we solved for the radiative transfer with the ETLA code, in the comoving frame of the flow. Finally, we calculated the line profiles in the observer's frame. For this step, we selected only impact parameters intercepting the stellar disk, i.e, we only took into account regions of high projected velocities on the line of sight.

A canonical mass loss rate of $\dot{\mathrm{M}}=10^{-10}\mathrm{M}_{\odot}.\mathrm{yr}^{-1}$ is assumed, compatible with the non detection of usual wind indicators (e.g Hα) in β-Pic. Temperature laws were adapted from those of Herbig Ae/Be stars winds (Bouret & Catala 2000). We found that "moderate" temperatures of about 15,000 K are required for the C III* line to appear in emission, and blueshifted (fi. 3a).

Taking the contribution of the chromosphere-TZ model into account, we generated a composite profile for the C III 977 Åline (Fig. 3b), using a method exposed in Bouret & Catala (2000). The black line is a profile obtained with a chromosphere-TZ model while the red one corresponds to the line profile from the model producing the C III* line shown in figure 3a. The presence of two different regions, each of them producing a specific line profile allows a three peaks profile to form, whose global shape is roughly similar to what is observed.

7. Conclusions

Our preliminary modeling shows that the presence of FUV emission lines from C III and O VI can be explained by the presence of a chromosphere-TZ region surrounding the star. This region seems to have solar-like temperature structure and electron density in the TZ.

An additional disk-wind component (see Fig. 4) is however required to explain the observed blueshifted lines (C III*, C II) and potentially the actual structure of the C III resonance line.

Further tests of this framework are now required. We intend to model N V, C IV or Mg II resonance line profiles as well as many other C II lines in the HST/STIS bandpass, to test our interpretation and derive new constraints on the hot gas component of β-Pic.

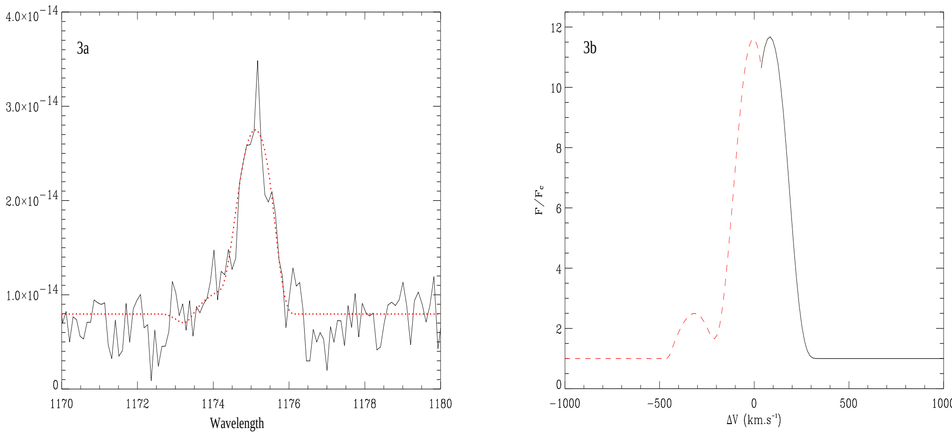

Figure 3. *Left:* C III* profile, from disk-wind model with a maximum temperature of T_{max}=15,000K in the wind. A terminal velocity of 300 km s^{-1} was used.*Right:* Composite profile for C III 977 Å, from a two-components model as discussed hereabove.

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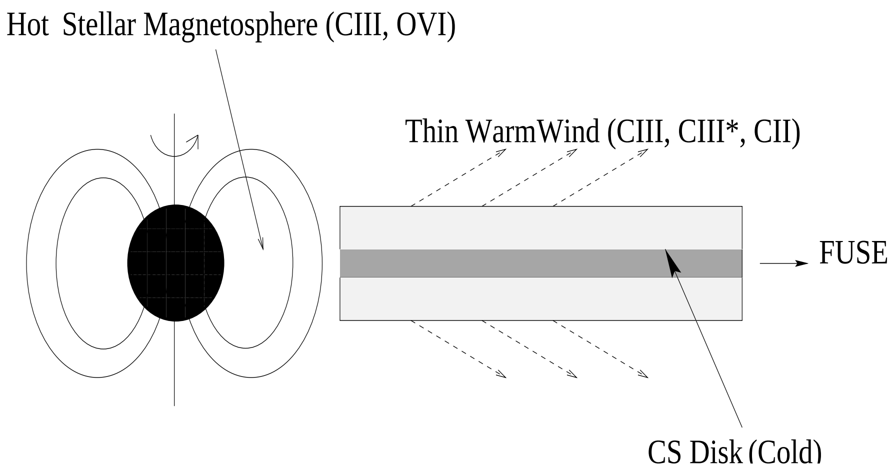

Figure 4. A schematic diagram of the configuration we considered