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Macroclumping, Magnetic Fields, and X-Rays in Massive Stars

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Abstract. Modern stellar wind models should account for new effects that were traditionally ignored in classical model atmospheres. Among these effects are stellar magnetic fields, X-ray emission, and wind clumping. The X-rays strongly affect the ionization structure of the winds. In O-type supergiants, clumping must be accounted for in the models to derive correct stellar parameters from X-ray or UV spectroscopy.

1. Magnetic Early B-Type Stars

In Oskinova et al. (2011b) we investigated the X-ray emission and wind properties of magnetic early B-type stars. Dedicated observations with *XMM-Newton* were performed for ξ^1 CMa, V2052 Oph, and ζ Cas. We found that the X-ray emission from magnetic stars does not significantly differ from the X-ray spectra of stars where magnetic fields have not been found (e.g. Raassen et al. 2005). B-type stars with magnetic fields have diverse X-ray properties: while some stars are hard and luminous X-ray emitters, others are soft and rather faint. We conclude that strong, hard, and variable X-ray emission may be a sufficient attribute of magnetic massive stars, but it is not a necessary one.

To obtain the parameters of stellar winds in our sample stars, we analyzed their spectra by means of non-LTE state-of-the-art stellar atmosphere code PoWR. The X-rays were included in the models at the observed fluxes and temperatures. The PoWR models accurately fit the stellar photospheric spectra and also accurately reproduce the spectral energy distribution from the X-ray to the IR band. The mass-loss rates were empirically obtained from the analysis of resonance doublets in stellar UV spectra. The PoWR model of the Si IV line in the spectrum of β Cep is shown in Figure 1. The inferred mass-loss rates are significantly lower than the theoretically expected (Abbott 1982). Our models show that the X-rays strongly affect the ionization structure in the wind. Despite of this, their effect does not reduce the total radiative acceleration enough to explain the low mass-loss rates deduced from the modeling of the UV lines.

2. X-Ray Spectra of O Stars

The high-resolution X-ray spectra of O-type stars present an interesting problem: how the shape of the X-ray emission lines and their similarity across the spectrum can be explained? As possible solutions, the reduction of the wind absorption column density (e.g. Waldron & Cassinelli 2001; Kramer, Cohen, & Owocki 2003; Owocki & Co-

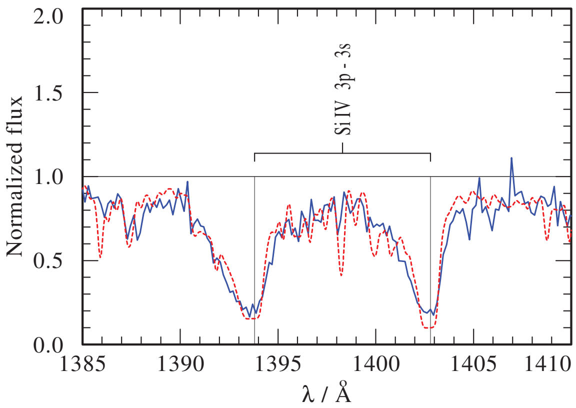

Figure 1. Observed Si IV $\lambda\lambda$1393.8, 1402.8 doublet in the IUE spectrum of β Cep (solid blue) and PoWR model spectrum with $\log(\dot{M}\,[\mathrm{M}_\odot\,\mathrm{yr}^{-1}]) = -9.3$ (dashed red). Model spectrum includes X-ray emission with observed L_X and T_X.

hen 2006) and the correct accounting for the wind clumping (Feldmeier, Oskinova, & Hamann 2003) were suggested.

Microclumping approximation is based on the assumption that the wind clumps are small compared to the mean free path of the photons. However, clumps with realistic sizes can be optically thick and affect the formation of the X-ray lines. Lets consider the O4 I star ζ Pup. From an analysis of its UV spectrum, Oskinova, Hamann, & Feldmeier (2007) obtained $\dot{M} = 2.5 \times 10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. In such wind, a clump with the size of $\sim 0.01\,R_*$ located at $2\,R_*$ will be optically thick for the X-ray radiation at 19 Å (Oskinova et al. 2011a). Since there are no observational constraints that rule out clumps of such size, the macroclumping formalism has to be applied to avoid spurious results. Figure 2 illustrates that using smooth/microclumping wind approximation for modeling line profiles results in a poor fit. Correct accounting for wind clumping allows to explain the observed X-ray spectra with realistic mass-loss rates.

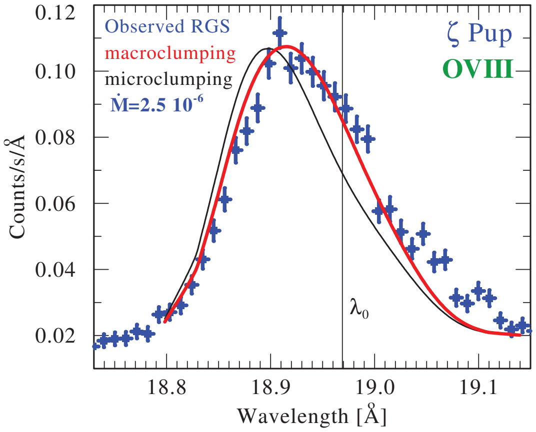

Figure 2. O VIII λ18.97 line in the XMM spectrum of ζ Pup (blue crosses). A clumped wind model line with 9×10^5 clumps (thick red) and a microclumping model line (thin black) are shown.

3. The Mass-Loss Rate Diagnostics Based on UV Resonance Lines

In Oskinova et al. (2007) we generalized our macroclumping formalism for the effective opacity to apply it for the line radiative transfer. It allowed us to include macroclumping in the non-LTE stellar atmosphere PoWR model and obtain model spectra that were compared to the observed ones.

We modeled the emergent spectrum of hot massive stars and demonstrated the influence of macroclumping on the mass-loss diagnostic lines Hα and P v. By comparing the modeled and observed spectra we showed that wind porosity affects the P Cygni profiles from resonance lines (see Fig. 3), but does not influence the optically thin recombination lines. This resolves the reported discrepancies between resonance-line and recombination-line diagnostics. It was shown that when macroclumping is accounted for, the empirically deduced mass-loss rates are factor of 3-5 lower than those obtained using unclumped models.

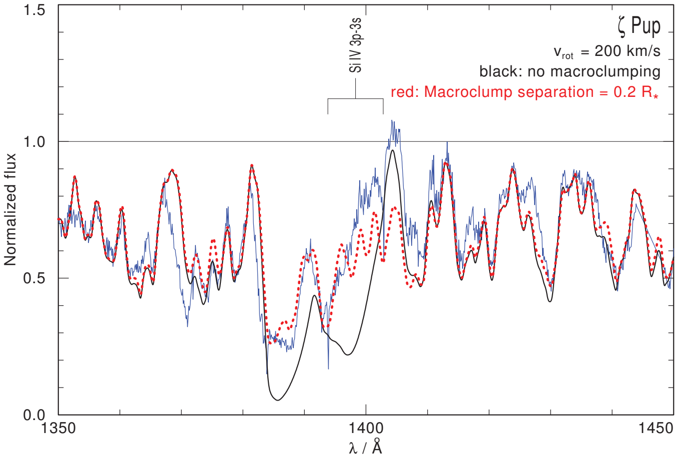

Figure 3. Observed Si iv $\lambda\lambda$1393.8, 1402.8 doublet in the UV spectrum of ζ Pup (blue). Two wind models computed with the PoWR code using the same mass-loss rate are shown: microclumping model (blue thin) and macroclumping model (red dotted).

Later works suggested that some additional effects such as non-empty interclump medium or large scale velocity jumps in the wind might improve the model fits (Sundqvist, Puls, & Feldmeier 2010). New fully 3-D models that include all these effects will allow to gain deep insights into the structure of stellar winds and obtain reliable mass-loss rates (Šurlan *et al.,* these proceedings).

4. Conclusions

Strong, hard, and variable X-ray emission may be a sufficient attribute of magnetic massive stars, but it is not a necessary one.

The microclumping/smooth wind approximation puts strong constraints on the size of the clumps and is valid only for unrealistically small clumps. The macroclumping formalism allows clumps of any size, easy to use, and yields reliable results.

Mass-loss rates inferred from optically thin emission, such as the Hα line in O stars, are not influenced by macroclumping. The strength of optically thick lines, however, is reduced because of the macroclumping. These effects have to be taken into account in stellar wind modeling to obtain empirically correct mass-loss rates (Oskinova et al. 2007) .

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