SYNTHETIC LINE PROFILES IN EARLY-TYPE STELLAR WINDS. I. H AND He^+

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INTRODUCTION

Statistical equilibrium calculations for the first ten levels of H and He^+ were carried out for several model atmospheres of a star with $T_{eff} = 40,000$ K and $\log g = 3.5$, using the method of Mihalas and Kunasz (1978). Atomic level populations and line profiles were computed for "model C" calculated by Klein and Castor (1978) and for variants of this model in which material density and mass loss rates were scaled down by factors of 2.0, 2.2, 2.5 and 4.0. We will refer to these variant models as D, E, F, and G. The resulting line profiles are discussed. Two variants of the Klein-Castor model C are generally successful and produce He II λ4686 in emission with λ3204 in absorption. All normal Of stars observed with He II λ4686 in emission have λ3204 in absorption. In one of the models, Hα is in emission, while Hβ and the higher Balmer lines remain in absorption, as is commonly observed in Of spectra.

The basic approach to the stellar wind problem taken here is that of semi-empirical modeling, in which empirically required adjustments are made on approximate dynamical models. A sophisticated approach to the multi-level ion statistical equilibrium problem in an early-type atmosphere allows diverse models of such atmospheres to be tested. In the method used here the transfer equation is solved directly in the co-moving frame of the gas, and the approximations of the escape probability technique are not made.

The model hydrogen atom and helium ion make use of the collisional cross sections used by Klein and Castor (1978), and ten bound levels are assumed in each species.

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RESULTS

In models C, D and E λ4686 is a pure emission profile in the sense that although a self-reversal feature grows with decreasing mass-loss rate, it does not lower the intensity below continuum values. Profiles with this shape have been observed in several stars and fall in Beals' (1951) type IV classification. In F and G the absorption feature is stronger than the emission. Hence, finding a model in which λ4686 is in emission and λ3203 is in absorption was possible when the mass-loss rate was reduced, keeping the assumed T(r) and V(r) constant. Model E best satisfies the criterion.

The transition from emission to absorption, which occurs at λ3204 in D and E, occurs at different lines in the series in different models. In model C it occurs at λ2733, λ3204 being in P Cygni emission. In F, λ4686 is a P Cygni line, while λ3204 is in absorption. In G the emission component of λ4686 is just barely visible.

Quantitative comparisons with observations of ζ Puppis (Heap 1972, Morrison 1975) show that λ4686 and λ3203 should be somewhat stronger in emission and absorption, respectively. The effects of Stark broadening, which were not included in the calculation, will be to increase the strength of the absorption lines in the He II spectrum, while leaving the strong emission lines, which are quite broadened by the wind, relatively unchanged.

As model E is the most successful with regard to λ4686 and λ3203, a set of He II profiles for model E is presented in Fig. 1. These profiles are influenced by the effects of both wind velocity and geometric extension of the line-formation region. The higher lines in the various spectral series are relatively narrow because the line-formation zone does not lie in the fast-moving layers, and emission features are absent because this zone does not protrude into the large volume of the extended layers. For the strongest of the lines presented the line-formation zone extends several photospheric radii into the wind. The line-formation zones for the resonance lines, which (being unobservable) are not presented, extend to at least ten photospheres in the models used here.

A series of models with terminal velocities and mass-loss rates identical to those in models C,...,F were tested with a linear velocity law V(r), as applied successfully to P Cygni by Kunasz and Van Blerkom (1978). Very strong and pervasive emission in the He II spectrum proved this law too gradual.

Comparisons with observations indicate that more strength is needed in most of the absorption lines. Application of Stark broadening is likely to correct this deficiency.

Model E is the most successful in the H spectrum as well as in He II. It is the only model of those tested in which Hα is in emission

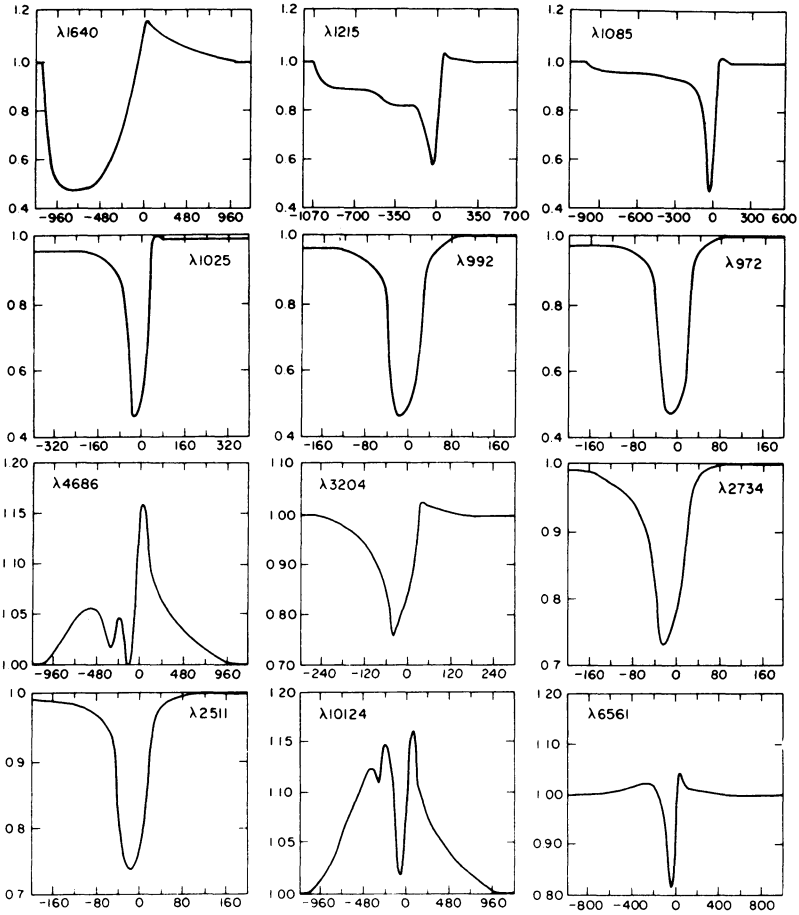

Figure 1

while the higher Balmer lines are in absorption. Further work in which Stark broadening is included and in which other species, such as N III, are treated will put model E to a more rigorous test.

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DISCUSSION FOLLOWING KUNASZ

Snow: The He II λ4686 profiles you calculated in models C and E look very much like the observed profile of this line in ζ Pup, on spectra taken one day apart. Hence your models may indicate that these observations could be explained by significant density fluctuations in the extended atmosphere on a time scale of one day.

Heap: Could you say what it would take to get He II λ1640 fully in emission? My memory of the few UV spectra of Of stars I have seen is that He II λ1640 is an emission line.

Kunasz: λ1640 is not in pure emission in any of the models I have assumed. However, the trend for λ1640 to come more into emission as the atmospheric density (i.e. the mass loss rate) is increased indicates that for an atmosphere with greater mass loss than Castor's model "C", but not a factor two greater, λ1640 will be in emission with no absorption component. Perhaps velocity fields unlike those of Castor, Abbott and Klein, or warm regions in the wind, could enhance emission in λ1640. However we won't know until such structures are modelled.

Stalio: Could you give an interpretation of those whiggles that one sees in your Hα profiles?

Kunasz: In principle they could be a result of the complicated isovelocity surface in an expanding atmosphere. In reality they are probably due to numerical truncation in the "observer's frame step" of the comoving frame calculation.

Hutchings: Is the self-reversal at λ4686 real or computed noise? Is it at zero velocity? It is probably an important diagnostic.

Kunasz: It is due mostly to absorption occurring in low-velocity layers near the photosphere. As the wind is weakened in the sequence of models presented here the absorption feature in λ4686 becomes dominant, and eventually, for the weakest winds, totally dominates the small remaining emission from the expanding envelope. λ4686 is then a pure absorption line.

Vreux: Have you any predictions for Paschen lines? We do observe P6 and P7 in emission in a few O stars.

Kunasz: I have treated a ten-level model of the hydrogen atom. Hence Paschen 6 and 7 were included. They are the transitions 3→9 and 3→10. Since level 10 is poorly determined due to the fact that no higher levels are treated, transitions to level 10 are suspect in the results. To some degree this statement may also apply to level 9. Hence, the two lines were not included in the line-profile step of the calculation.

Noerdlinger: Perhaps the weakness of λ1640 is due to the self-absorption you found in λ4686. This means that trapped radiation depopulates the n=3 state. If you thin out the flow λ1640 may get stronger, to fit the observations in question.

Kunasz: Yes, this is possible.