ON THE INTERPRETATION OF EMISSION WINGS OF BALMER LINES IN LUMINOUS BLUE VARIABLES

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ABSTRACT

We discuss Hα line profiles calculated with plane-parallel, hydrostatic NLTE model atmospheres. In our lowest log g models the profiles show extended emission wings. Qualitatively, these wings are similar to the extended wings generated by electron scattering of line photons in the stellar wind. We propose that the line wings observed in luminous blue variables may be due to a combination of the NLTE effect discussed here and the traditional scattering mechanism.

Key words: luminous blue variables—Hα—NLTE line transfer—stellar atmospheres—stellar winds

1. Introduction

The optical spectra of luminous blue variables (LBVs) are characterized by strong Balmer emission lines. In many cases, P Cygni profiles having emission components with linewidths (FWHM) of less than ~ 300 km sec\(^{-1}\) show extended emission wings reaching up to ~ 1000 km sec\(^{-1}\). A large number of examples of such profiles have been published by Stahl et al. (1985). Since the outflow velocities in these stars are well below ~ 400 km sec\(^{-1}\) (see, e.g., Lamers 1986), these wings cannot be interpreted in terms of macroscopic Doppler broadening. Bernat and Lambert (1978) attributed the broad wings observed in P Cyg to incoherent electron scattering of line photons in the outer layers of the extended envelope. Electron scattering had previously been proposed as a contributor of broad wings to the emission lines of Be stars (Marlborough 1969) and Wolf-Rayet stars (Castor, Smith, and Van Blerkom 1970).

Since then the electron-scattering mechanism provided a satisfactory explanation for the extended wings observed in LBV line profiles. Several authors (e.g., Wolf et al. 1981; Stahl and Wolf 1982; Wolf and Stahl 1982) estimated the electron-scattering optical depth from the strength of the observed wings and derived mass-loss rates. In this paper we discuss an alternative mechanism which may partly contribute to the observed line wings.

2. The Model Atmosphere

Our computations are based on the program TLUSTY (Hubeny 1988). This program computes model atmospheres assuming a plane-parallel, horizontally homogeneous atmosphere in radiative and hydrostatic equilibrium and allowing for departures from local thermodynamic equilibrium (LTE). In this paper we consider only hydrogen and helium, with H/He = 0.1.

We are well aware of the fact that LBVs have photospheric scale heights which are not insignificant with respect to the stellar radius. Their near-infrared continuum-energy distribution and Balmer discontinuity can only be understood in terms of spherically-extended model atmospheres. On the other hand, the effect discussed here originates in very deep photospheric layers where sphericity effects are of less importance. Nevertheless, we emphasize that the models presented here are intended to show the qualitative effect only and should not be used to derive physical parameters of LBVs.

3. The Temperature Structure and the Influence of Gravity

As a representative example, we discuss a model with \(T_{\text{eff}} = 15,000\) K which is a typical value observed in LBVs. The lowest gravity for which a stable model exists is \(\log g = 1.65\). Figure 1 shows the run of temperature well known in NLTE atmospheres (e.g., Mihalas 1978). For comparison we included an LTE model with the same \(T_{\text{eff}}\) and \(\log g\). The temperature decreases monotonically with mass density in the LTE case. An NLTE model which includes continua only (NLTE-C) shows an increase of \(T\) with respect to the LTE model at \(\log m = -2\) due to increased heating in the Balmer continuum.

If the hydrogen lines Hα, Hβ, Hγ, Pa, Pβ, and Bo are included (NLTE-L), an additional temperature rise occurs due to even higher heating in the Balmer continuum. In this case, the Balmer lines open an efficient channel to populate the \(n = 2\) level and a distinct temperature minimum at \(\log m = -1\) is formed. The temperature

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minimum remains unaffected when the cooling effect of the Lyman lines $\lambda\alpha$, $\lambda\beta$, $\lambda\gamma$, and $\lambda\delta$ is included in the models. Our forthcoming discussion will be based on the NLTE-L model without Lyman lines.

The influence of $\log g$ on the resulting temperature structure is illustrated in Figure 2. The temperature minimum is shifted deeper in the atmosphere as the gravity decreases. This behavior can be understood in terms of

**Fig. 1**—Comparison of the temperature structure of different models with $T_{\text{eff}} = 15,000$ K and $\log g = 1.65$.

**Fig. 2**—The influence of $\log g$ on the temperature structure of the computed NLTE atmospheres. The three models drawn with solid lines show the influence of $\log g$; the dash-dotted line illustrates the cooling effect of the Lyman lines.
lower gas pressure at a given \( \log m \) resulting from lower gravity. A lower pressure is associated with lower number densities and, thus, lower opacity so that optical-depth unity in the relevant transitions occurs at higher column density. This was first noted by Auer and Mihalas (1970), and Abbott and Hummer (1985) discussed an analogous effect for O stars.

4. Balmer Line Profiles

Figure 3 shows the resulting \( \text{H}\alpha \) profiles of the three NLTE models with \( \log g = 2.5, 2.0, 1.65 \), and, for comparison, of a \( \log g = 1.65 \) LTE model. The lowest-gravity NLTE model shows pronounced emission wings extending a few hundred km sec \(^{-1} \) to each side of the line center. They are due to an NLTE coupling of the Balmer continuum and the Balmer lines. Extended emission wings also arise in higher Balmer lines, but they rapidly decrease in strength as compared with \( \text{H}\alpha \).

The formation mechanism of the emission wings is explained in Figure 4. The wings are formed at the region of the temperature minimum for all gravities. At the temperature minimum one finds \( b_3 = 1 \) and \( b_2 < 1 \) for all models (\( b_3 \) and \( b_2 \) are the departure coefficients for the third and the second level of hydrogen, respectively). The reason for \( b_2 < 1 \) is not due to the transfer in the Balmer lines but due to the transfer in the Balmer continuum causing a higher rate of photoionizations than of recombinations. Hubeny (1986) discussed several examples of NLTE effects in the continuum; the present effect is an example of C-type effect in his terminology. Since optical depth unity in the Balmer continuum occurs deeper in the atmosphere where the radiation field is higher, as \( \log g \) decreases (cf. Fig. 2), the \( n = 2 \) level of hydrogen is even more depopulated for lower gravity.

The source function of \( \text{H}\alpha \) can be approximated as
\[
S_v(\text{H}\alpha) = (b_2/b_3) B_v.
\]
From the above discussion it follows that \( S_v(\text{H}\alpha) > B_v \) at the temperature minimum. The difference between \( S_v(\text{H}\alpha) \) and \( B_v \) is greater at lower gravi-

![Fig. 3—NLTE Ha profiles for different values of log g. For comparison, the corresponding LTE profile is also shown. The dashed lines are rotationally broadened profiles with \( v \sin i = 50 \text{ km sec}^{-1} \).](image-url)
ties so that the mean intensity in the wings eventually becomes higher than the mean intensity in the continuum.

Auer and Mihalas (1970) found an analogous effect for higher gravities, namely, an enhancement of the Hα wing flux with respect to the LTE flux. In fact, the effect discussed above represents a continuation of their effect toward lower gravities, where the flux enhancement eventually becomes a genuine emission. Finally, Peterson (1969) also discussed a similar effect using, however, cruder model atmospheres.

5. Conclusions

The emission wings in Hα produced by a hydrostatic, plane-parallel, low-gravity NLTE atmosphere are in qualitative agreement with the observations although they are still weaker. For even lower log g values (which are derived in LBVs), however, the emission wings can be expected to strengthen considerably. In realistic models (including the photosphere and the stellar wind), the traditional electron-scattering mechanism and the effect discussed here will operate. A determination of wind properties assuming the emission wings are purely due to electron scattering may, therefore, be misleading.

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