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A METHOD FOR EXTRACTING THE EMISSION COMPONENT IN STELLAR SPECTRAL LINES

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ABSTRACT

This article describes a method for separating the contribution of emission components belonging to the stellar envelope from the contribution of stellar photosphere lines in high-resolution spectrograms obtained at the Tusi-Shamakhy Astrophysical Observatory (ShAO). A polynomial approximation method is proposed to account for the instrumental function. Application of this method allows one to separate the emission component belonging to envelope radiation for different variable stars.

Key words: Stars: atmospheres – Stars: circumstellar matter – Techniques: spectroscopic – Line: profiles.

1 INTRODUCTION

It is well known that in many stars the presence of additional radiation-producing matter in the surrounding environment — such as stellar envelopes and gas–dust discs — is revealed in optical spectra through additional emission components in spectral lines. Since hydrogen constitutes the main fraction of stellar matter (∼75–80 per cent), these emission components are most prominently manifested in the strong photospheric profiles of hydrogen lines.

The study of variability in spectral-line profiles in non-stationary stars is of great importance for understanding the physical processes occurring in their atmospheres. Examples of such objects include young stars of the T Tauri and Herbig Ae/Be types, Be stars, supergiants, flare stars, and symbiotic stars. These objects generally exhibit spectral variability in various forms within their line profiles. In most cases, such variability is attributed to the interaction between the central star and its surrounding environment, particularly gas–dust discs.

As a result, hydrogen lines observed in the spectra of these stars often display, in addition to the normal absorption profile, various types of emission components superimposed on the photospheric profile. In astrophysics, such profiles are commonly classified as P Cygni, inverse P Cygni, double-peaked, or single-peaked profiles (e.g. Sobolev 1985; Huseynov 2010).

A correct estimation of the contribution of the emission component in hydrogen lines is essential for understanding the physical state of the circumstellar matter and the active processes occurring within it. The separation of the emission spectrum from the photospheric radiation, and its subsequent analysis, is based on the theory of stellar atmospheres and radiative transfer — one of the fundamental areas of astrophysics (see e.g. Mihalas 1978; Unsöld 1969). Various approaches to this problem exist, depending on the quality of the observational material and available resources. The simplest method involves obtaining, in addition to the target star spectrum, the spectrum of a standard star with identical fundamental parameters, chemical composition, microturbulent velocity, and projected rotational velocity. The emission contribution can then be derived by subtracting the standard spectrum from that of the target star. However, finding such an identical standard star is extremely difficult, and therefore this method is rarely applied. A generally accepted scheme for accurately separating the emission component in spectral-line profiles has not yet been developed for spectra with resolutions of $R = 28\,000$ and $R = 56\,000$ obtained with the 2-m telescope of the Shamakhy Astrophysical Observatory. Taking this into account, the aim of the present work is to describe a method for separating the emission component in hydrogen lines and determining its spectrophotometric parameters, using Herbig Ae/Be stars as an example.

2 THEORETICAL APPROACH

The observed stellar spectrum (flux) can be expressed as the combined effect of the intrinsic spectral distribution of the star and the transmission characteristics of the telescope and

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spectrograph system (e.g. Allende Prieto 2004; Thorne et al. 1999). Analytically, the observed flux $F_{\rm obs}(\lambda)$ is given by following formula:

$$F_{\rm obs}(\lambda) = \left[F_\star(\lambda)\, T_{\rm atm}(\lambda)\, T_{\rm tel}(\lambda)\right] * {\rm PSF}_{\rm inst}(\lambda) + N(\lambda) \qquad (1)$$

Here $F_{\rm theor}(\lambda)$ denotes the intrinsic spectral flux emitted by the stellar photosphere. In the absence of an additional circumstellar disc, this quantity represents a single component. However, in the presence of a gas–dust disc, the stellar flux can be written as

$$F_\star(\lambda) = F_{\rm theor}(\lambda) + F_{\rm em}(\lambda) \qquad (2)$$

where $F_{\rm theor}(\lambda)$ is the pure photospheric radiation and $F_{\rm em}(\lambda)$ is the additional emission arising from the circumstellar gas disc.

The function $F_{\rm theor}(\lambda)$ is computed using NLTE model atmospheres, taking into account the fundamental stellar parameters: effective temperature $T_{\rm eff}$, surface gravity $\log g$, chemical composition, microturbulent velocity, and projected rotational velocity $v \sin i$.

$T_{\rm atm}(\lambda)$ is the transmission function of the Earth's atmosphere, including telluric absorption lines. $T_{\rm tel}(\lambda)$ represents the efficiency of the telescope and optical system (e.g. mirror reflectivity). $*$ denotes the convolution operator. ${\rm PSF}_{\rm inst}(\lambda)$ is the instrumental profile (point spread function), and $N(\lambda)$ represents the detector noise.

The dark frame is used to correct the observed stellar spectrum for detector noise. By subtracting the dark frame from the observed spectrum, the contribution of $N(\lambda)$ is effectively removed. If all remaining instrumental and observational effects are combined into a single response function $G(\lambda)$, then equation (1) can be rewritten as

$$F_{\rm obs}(\lambda) = F_\star(\lambda)\, T_{\rm atm}(\lambda)\, G(\lambda) \qquad (3)$$

Since in our case

$$F_{\rm obs}(\lambda) = F_{\rm theor}(\lambda) + F_{\rm em}(\lambda) \qquad (4)$$

equation (1) can be rewritten as

$$F_{\rm obs}(\lambda) = \big(F_{\rm theor}(\lambda) + F_{\rm em}(\lambda)\big)\, T_{\rm atm}(\lambda)\, G(\lambda) \qquad (5)$$

Thus, based on the above expressions, the emission component $F_{\rm em}(\lambda)$ can, in principle, be determined. For spectral regions free from significant telluric contamination (e.g. Hβ and Hγ), the atmospheric transmission function can be approximated as $T_{\rm atm}(\lambda) \approx 1$. However, in the H$\alpha$ region ($\lambda = 6563$ Å), this function may introduce noticeable distortions in both the line wings and core.

For stars of spectral type B8Ve–A0Ve, the Hα line is typically very broad, with photospheric absorption widths of approximately 20–50 Å. In such objects, the emission component usually originates from the circumstellar gas disc, filling the central absorption core or producing a double-peaked profile.

A more detailed expression for separating the emission contribution in this wavelength region, including the effects of both the instrumental response $G(\lambda)$ and atmospheric absorption, can be written as

$$F_{\rm obs} = \big(F_{\rm theor} + F_{\rm em}\big)\, T_{\rm H_2O}\, G \qquad (6)$$

where $T_{\rm H_2O}$ is the water vapour transmission function. In conditions of high humidity, this function can reduce the line wings or modify the peak intensity.

To correct for this effect, the observed spectrum is divided by a telluric standard (divisor spectrum) obtained with the same instrumental setup. Thus, we obtain

$$F' \approx \frac{F_{\rm obs}}{T_{\rm H_2O}} \approx \big(F_{\rm theor} + F_{\rm em}\big)\, G \qquad (7)$$

Equation (4) is then used as the working relation for separating the emission component from the observed profile. For spectral lines other than Hα, $T_{\rm H_2O}$ can be safely taken as unity. Before applying equation (4) to the Hα line, the observed spectrum must be divided by a divisor spectrum obtained with the same instrument.

3 METHOD I

Suppose that $F_{\rm obs}$ denotes the observed flux in the stellar spectrum and $F_{\rm theor}$ is the synthetic NLTE (non-local thermodynamic equilibrium) spectrum of the star. In Fig. 1, the upper panel shows the observed Hβ line profile of the spectrum KF1011-12 obtained on 20.05.2017, while the lower panel presents the corresponding synthetic profile of the Hβ line.

The synthetic hydrogen line profiles were calculated using the STAR program (e.g. Menzhevitski et al. 2014). In this code, the synthetic spectra are computed using the fundamental stellar parameters: effective temperature $T_{\rm eff}$, surface gravity $\log g$, microturbulent velocity ($\xi = 2$ km s^{-1}), chemical composition, and projected rotational velocity $v \sin i \approx 236$ km s^{-1} Merín et al. 2004. For the instrumental profile of the spectrograph, a value of 0.15 Å was adopted, Ismailov et al. 2024. For the Herbig Ae/Be star HD 141569, a solar chemical composition was assumed.

Since the Hβ line wings are free from emission, the synthetic profiles were directly compared with the observed profiles of HD 141569.

After subtraction of the detector dark signal $N(\lambda)$ and correction for telluric absorption, equation (1) can be reduced to the simplified form

$$F_{\rm obs} = \big(F_{\rm theor} + F_{\rm em}\big)\, G \qquad (8)$$

Here $F_{\rm theor}$ represents the stellar photospheric radiation, $F_{\rm em}$ is the flux originating from the circumstellar environment, and G is the response function of the observing instrument. To extract the emission component $F_{\rm em}$ from this expression, we use the theoretically calculated line flux $F_{\rm theor}$.

Dividing equation (5) by $F_{\rm theor}$, we obtain

$$D_1 = \frac{\big(F_{\rm theor} + F_{\rm em}\big)\, G}{F_{\rm theor}} \qquad (9)$$

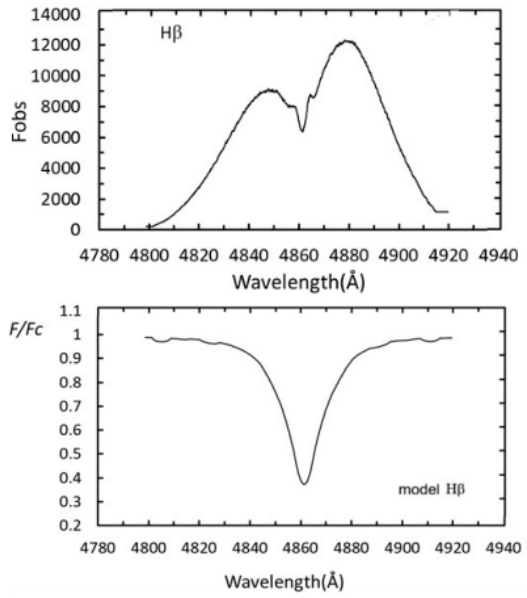

Figure 1. Observational profile (top) and synthetic profile (bottom) for the star HD141569.

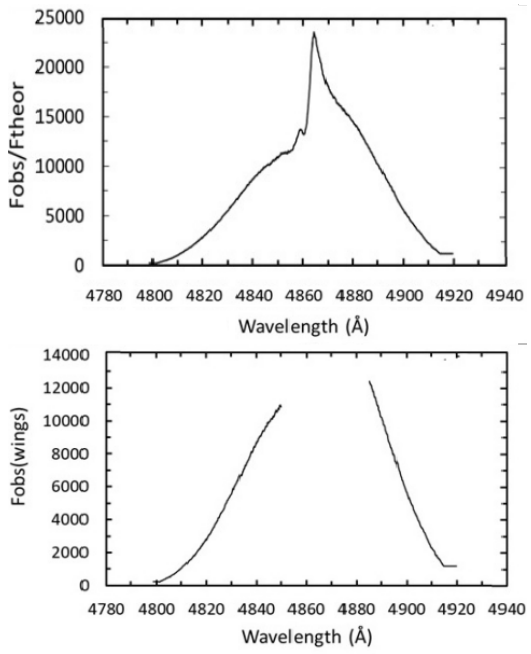

Figure 2. The profile obtained from expression (6) (top) and its case without considering the emission region (bottom).

It is clear that the purely photospheric radiation of the star corresponds to $F_{\rm theor}$, since the synthetic spectrum is calculated based on the known photospheric parameters of the star. The emission peak is clearly visible in the resulting curve obtained after division (see Fig. 2).

We approximate the continuum curve using a polynomial function, excluding the emission region of the line profile (see Fig. 3). The resulting polynomial function is denoted as $F_{\rm pol}$. If we assume $F_{\rm em} = 0$ in equation (2), it follows that $F_{\rm pol} \approx G$. Thus, the instrumental response function can be

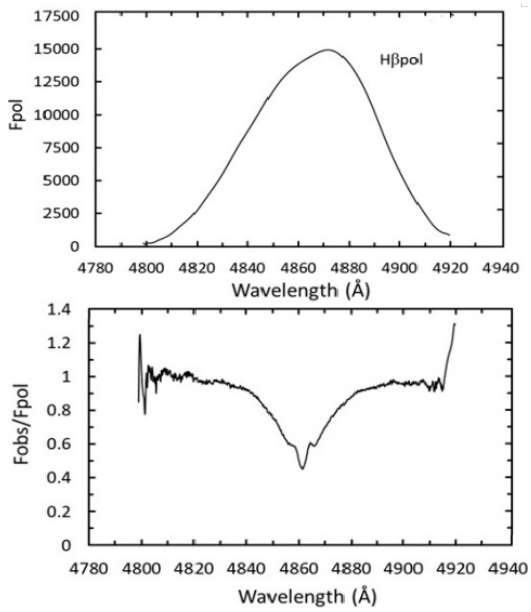

Figure 3. Polynomial distribution constructed after approximation (top). The bottom panel shows the profile obtained from the polynomial division of the observation profile.

represented by a polynomial approximation of the observed continuum (upper panel in Fig. 3).

The polynomial is calculated over the same wavelength range as the observed spectrum, including the line profile region, thereby providing the corresponding values of $F_{\rm pol}$. In the next step, the observed spectrum $F_{\rm obs}$ is divided by the polynomial function $F_{\rm pol}$. As a result, a properly normalized spectral line profile is obtained. After this division, the resulting profile is free from continuum distortions (see Fig. 3, lower panel):

$$\frac{F_{\rm obs}}{F_{\rm pol}} = \frac{(F_{\rm theor} + F_{\rm em})\, G}{G} = F_{\rm theor} + F_{\rm em} \qquad (10)$$

After obtaining this profile, the outer wings are selected and compared with the theoretical profile. In Fig. 4 (upper panel), the cut and normalized observed profile (blue line) and the synthetic profile (red line) of the Hβ line are shown. If the wings of the profiles do not match satisfactorily, the atmospheric parameters of the model must be adjusted. This procedure is repeated until a satisfactory agreement between the observed and theoretical line wings is achieved.

Subtracting $F_{\rm theor}$ from equation (7) yields the emission line profile $F_{\rm em}$ (see Fig. 4, lower panel). By adding unity to the intensity of the resulting residual profile, the emission component is normalized.

The resulting clean emission profile can then be exported as an ASCII file to the DECH program and converted into a FITS file. From this profile, the spectrophotometric parameters of the emission line can be determined.

4 METHOD II

This method is similar to Method I; however, to eliminate the instrumental response function G in equation (1), the observed spectral region is divided by a flat-field (lamp) spectrum obtained with the same instrument setup. The instrumental response function is effectively removed when both spectra are recorded using the same instrumental configuration.

By dividing the observed spectrum by the flat-field spectrum, we obtain the following expression (8), which is analogous to equation (7):

$$F_{\rm obs} = \frac{(F_{\rm theor} + F_{\rm em})\, G}{G} = F_{\rm theor} + F_{\rm em} \qquad (11)$$

The theoretical profile is then subtracted from the obtained normalized profile, yielding the emission component $F_{\rm em}$, which can again be determined using equation (8). The procedure is identical to that described in Method I.

As can be seen, Method II is essentially a continuation of Method I and is based on the use of a synthetic stellar spectrum.

5 CONCLUSIONS

Thus, this paper proposes two different methods for extracting the contribution of the emission component from spectral line profiles containing emission features. Method I is based on a polynomial approximation used to eliminate the instrumental response function. Method II employs flat-field lamp spectra obtained with the same instrumental configuration to correct for the instrumental response.

Both methods were tested using spectra of the Herbig Ae/Be star HD 141569, and satisfactory results were obtained. These approaches can be widely applied in future studies of stars exhibiting emission lines in their spectra.

Using the Hβ spectral line from the observed spectrum KF1011-12 as an example, we demonstrated how to isolate the emission component superimposed on the absorption profile. This procedure was also applied to the remaining Hα–Hδ hydrogen lines for all spectra of the star prepared for publication. As an example, the resulting spectral components for these lines are shown in the Appendix (Fig. A1).

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APPENDIX A: EXTRACTED EMISSION COMPONENTS IN STELLAR SPECTRAL LINES OF THE Hα LINE

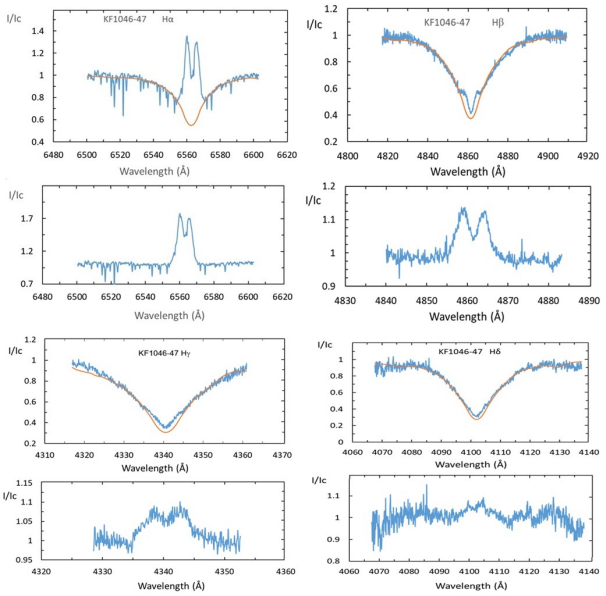

Figure A1: Extracted emission components for the *Hα–Hδ* lines in the KF1046-47 spectra are shown in the lower panels. In the upper panels, the observed line profiles (blue lines) and synthetic spectral lines (red lines) are presented for each transition.