The ultraviolet study of B[e] stars: evidence for pulsations, LBV-type variations, and processes in envelope

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ABSTRACT
Stars with B[e] phenomenon comprise a very diverse group of objects in a different evolutionary status. These objects show common spectral characteristics, including presence of Balmer lines in emission, forbidden lines, and strong infrared excess due to the dust. The observations of emission lines indicate the illumination by ultraviolet ionizing source, which is a key part to understand the elusive nature of these objects. We study the ultraviolet variability of many B[e] stars to specify the geometry of the circumstellar environment and its variability. We analyse massive hot B[e] stars from our Galaxy and from Magellanic Clouds. We study the ultraviolet broad-band variability derived from the flux-calibrated data. We determine variations of individual lines and its correlation with the total flux variability. We detected variability of the spectral energy distribution and of the line profiles. The variability has several sources of origin, including the light absorption by the disk, pulsations, LBV-type variations, and eclipses in the case of binaries. The stellar radiation of most of B[e] stars is heavily obscured by circumstellar material. This suggests that the circumstellar material is not present only in the disk but also above its plane. The flux and line variability is consistent with a two-component model of circumstellar environment composed of the dense disk and ionized envelope. The observations of B[e] supergiants show that many of these stars have nearly the same luminosity of about $1.9 \times 10^5 \, L_\odot$ and similar effective temperature.

Key words: stars: early-type – stars: emission-line, Be – stars: variables: general – stars: winds, outflows – stars: oscillations

1 INTRODUCTION
B[e] stars form a very diverse group of stars that share common spectroscopic properties, however their astrophysical nature is very different. Among the typical spectroscopic properties of B[e] stars belong strong Balmer lines in emission, presence of low excitation permitted emission lines as well as forbidden emission lines, and infrared excess (Allen & Swings 1976). Despite their spectral similarities, the astrophysical nature of stars showing B[e] phenomenon is diverse. The group of B[e] stars contains stars in different evolutionary stages (pre-main sequence B[e] stars vs. B[e] supergiants), stars with different initial mass (massive B[e] supergiants vs. compact planetary nebulae), and binary status (including symbiotic binaries). Besides these classes of stars showing B[e] phenomenon summarized by Lamers et al. (1998) also presumably unevolved B[e] stars may appear (Miroshnichenko 2007).

The variability observed in the optical photometry (e.g., Sitko et al. 1994, de Winter & van den Ancker 1997, van Genderen & Sterken 1999) and spectroscopy (e.g., Borges Fernandes et al. 2012, Polster et al. 2012, Kucerová et al. 2013) indicates a possibility of ultraviolet (UV) variability. Although the UV flux variability was indeed found in some B[e] stars (Savage et al. 1978, Shore 1990, Sitko et al. 1994), there is no detailed systematic study of UV variability of B[e] stars according to our knowledge.

The study of UV variability of B[e] stars is especially relevant because hot stars emit most of their radiation in the UV domain. Consequently, the UV variability may shed some light on the elusive nature of many of these objects. The circumstellar environment of B[e] stars is combined from an ionized hot envelope and cool dusty material (Shore & Sanduleak 1983). While the presence of ionized envelope can be naturally explained by radiatively driven stellar wind, which is common in luminous stars of spectral type B (Vink et al. 2000, Crowther et al. 2006, Markova & Puls 2008), the origin of a cool dust containing envelope is unclear. The cool envelope is likely shaped in the form

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of a disk (Zickgraf et al. 1985, Schulte-Ladbeck & Clayton 1993) whose inner parts may be relatively hot and shield the remaining cooler parts (e.g., Kraus & Lamers 2003, Zsargó et al. 2008).

The geometry of the circumstellar environment may therefore to some extent resemble classical Be stars (see Rivinius et al. 2013, for a review of Be phenomenon). Classical Be stars may contain a viscous disk that is fed as a result of angular momentum loss from near critically rotating star (Lee et al. 1991, Okazaki 2001, Krtička et al. 2011, Kürþrst et al. 2014). The origin of the disk is still a matter of debate in Be stars as well as in B[e] stars. The near critical rotation in these stars may possibly be induced either by evolutionary spin up (Granada et al. 2013) or by a binary interaction (Bogomazov & Tutukov 2009). The later hypothesis may be more likely in B[e] supergiants because the evolutionary models show strong decrease of the rotational velocity in the supergiant phase (Ekström et al. 2012).

The merger origin of B[e] stars was proposed by, e.g., Podsiadlowski (2010). The flow during such event is complex and may involve outflows as well as inflows (e.g., Pejcha et al. 2016). The merger scenario may be supported by the presence of extended envelopes that surround some B[e] stars (e.g., HD 34664, Chu et al. 2003, HD 38489, Kastner et al. 2010). Some B[e] stars are spectroscopic binaries (e.g., Djurašević et al. 2008, Marchiano et al. 2012).

In the following paper, we analyse the archival IUE data available for B[e] stars to better understand the geometry of the circumstellar environment around these stars and to describe its variability in detail. Because the group of B[e] stars is very diverse, we focus on the stars that may share some common characteristics and exclude pre-main sequence stars, planetary nebulae, and symbiotic binaries from our analysis. We study mostly unevolved and evolved hot massive stars that display the B[e] phenomenon.

2 METHODS

We downloaded the far-UV 1150–1900 Å (SWP camera) and near-UV 2000–3300 Å (LWP and LWR cameras) low-dispersion large-aperture fluxes of B[e] stars from the INES database using the SPLAT-VO package (Draper 2014, Škoda et al. 2014). We selected only B[e] stars with multiple IUE observations that are suitable for the analysis of variability. The list of all used IUE observations is given in Appendix A.

Motivated by the success in detection and modelling of the flux variability of chemically peculiar stars from IUE spectra (e.g., Krtička et al. 2012, Krtička et al. 2015), we selected the same approach to study the variability of B[e] stars. We constructed the broad-band fluxes

\[ F_\lambda = \int_0^\infty \phi_\lambda(\lambda) F(\lambda) \, d\lambda \]

from the UV fluxes \( F(\lambda) \) observed by IUE. Here \( \phi_\lambda(\lambda) = \left(\sqrt{\pi}\sigma\right)^{-3} \exp\left[-(\lambda - c)^2/\sigma^2\right] \) is a Gauss function centered on the wavelength \( c \). The central wavelengths of individual Gauss filters were selected to describe the individual regions of UV spectra. We focused on the regions without strong emission lines. We selected \( c = 1500 \) Å to describe the flux in far-UV regions, \( c = 2175 \) Å which selects the flux in the region of carbon opacity bump, and \( c = 2500 \) Å for near-UV region (see Fig. 1). The filters centered on different wavelength regions allow us to study the variations of temperature. Moreover, the regions of \( c = 1500 \) Å and \( c = 2500 \) Å are affected by the interstellar reddening by nearly the same amount (Fitzpatrick & Massa 2007). We selected \( \sigma = 100 \) Å to cover a broader region of the stellar flux distribution. However, our tests showed that the selection of central wavelengths and the dispersion does not significantly affect final results. The variations are plotted as a function of modified Julian date (MJD), MJD = JD − 2400000. The derived values together with their mean uncertainties (in the same units) are given also in Tables A1–A13. We used our results for the comparison of individual fluxes and for the study of general relationships between them.

The emission lines in the spectra of B[e] stars also clearly show variability (e.g., Sanduleak 1978, Kučerová et al. 2013). However, their study is more problematic, because there is no clear continuum in UV region, and the true continuum may lie significantly above the anticipated level. To overcome this problem, we constructed a pseudocontinuum in each spectrum and subtracted the pseudocontinuum flux from observed flux to derive the total flux in individual lines (see Fig. 2). The pseudocontinuum was created by hand using the SPLAT-VO\(^1\) package taking into account the flux distribution of stars without B[e] phenomenon. We used the spline function to connect the points corresponding to the pseudocontinuum. In other words, a similar procedure is typically applied as when normalizing a spectrum. To describe the variations of the emission and absorption lines as a whole, we integrated the flux above and below the pseudocontinuum in the region 1250–1900 Å to derive the total flux in the emission lines \( F_{\text{em}} \) and line absorption \( F_{\text{abs}} \) as shown in Fig. 2. The fluxes in individual strong lines and the total line fluxes are plotted in graphs

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\(^1\) http://star-www.dur.ac.uk/~pdrafter/splat/splat-vo/
and also listed in Tables A1–A13. The uncertainties are given in the same units as individual fluxes.

During the construction of the pseudocontinuum, we focused our attention to a precise and homogeneous processing of all spectra. The repeated processing of selected spectra showed that we are able to reliably reproduce the derived results. Consequently, the line fluxes \( F_{\text{em}} \) and \( F_{\text{abs}} \) reflect the changes in the spectral properties of individual stars and enable the mutual comparison between studied stars. Moreover, the comparison with literature data shows that our emission line fluxes agree typically within 10–20% with that given in Shore & Sanduleak (1983) for HD 38489 (see Table A7) and in Shore et al. (1987) for LHA 115-S 18 (Table A1).

We also tested the dependence of the flux on the position angle of the slit to reveal large nebula around the star or nearby stellar object. We have not detected any such dependence for all stars except one. We found the dependence of the flux on the position angle for LHA 115-S 18, however, we interpret this dependence as coincidental.

Our additional aim was the determination of the temperature of the stellar envelope. We fitted the observed spectra by theoretical spectral energy distribution. We selected the spectra for which nearly simultaneous observations are available in far-UV and near-UV regions. The spectra were fitted by ATLAS9 fluxes\(^2\) (Kurucz 2005, Castelli 2005) calculated assuming LTE, which cover the studied temperature interval. We selected solar chemical composition for the Galactic stars and \([\mathrm{M}/\mathrm{H}]\) = −0.5 for stars from the Magellanic Clouds. The spectra were attenuated by the extinction curve \( k(\lambda - V) \) of Fitzpatrick & Massa (2007),

\[
F_\lambda = F_0(\lambda) \times 10^{-\alpha(k(\lambda - V))},
\]

where \( F_0(\lambda) \) is unattenuated flux and \( \alpha \) is a free parameter of the fit. The other fit parameters are the model effective temperature and surface gravity. For normal stars without circumstellar envelope, the model effective temperature corresponding to the best fit of the UV flux distribution is equal to the effective temperature of the star. For the stars with opaque circumstellar environment, the stellar effective temperature may be different, and consequently we denote the temperature corresponding to the best fit of UV spectra as \( T_{\text{UV}} \). This temperature corresponds to the temperature of the circumstellar envelope. Because the fluxes are rather insensitive to the surface gravity, we do not provide its final value. B[e] stars typically show infrared excess due to the dust. Consequently, part of the dust absorption accounted for by Eq. (2) may originate in circumstellar environment of given star. However, because infrared dust emission traces large volumes of the circumstellar medium, while the dust absorption is given just by the dust particles intersecting the line of sight, we expect that the interstellar contribution may dominate in Eq. (2). Anyway, both contributions are accounted for in Eq. (2) because our approach does not assume any particular spatial distribution of the dust. We fitted just the normalized fluxes.

### 3 UV Variability of Individual Stars

We searched the IUE archive for the observations of B[e] stars with multiple IUE spectra. Basic properties of studied stars are given in Appendix A and are summarized in Table 1 including the temperature \( T_{\text{UV}} \) derived from the spectral energy distribution fit. We provide range of temperatures for the stars that show variability of \( T_{\text{UV}} \). We have not found any clear variations of the dust absorption parameter \( \alpha \) Eq. (2) in any star.

#### 3.1 LHA 115-S 18

The star LHA 115-S 18 shows a prominent UV flux variability (Fig. A1). This variability is caused mostly by emission lines, whereas the continuum varies only weakly (Shore et al. 1987). In accordance with Shore et al. (1987), we detected line variability in \( \text{N} \text{v} \) 1245 Å, \( \text{O} \text{i} \) 1302 Å, \( \text{C} \text{iv} \) 1550 Å, and \( \text{He} \text{ii} \) 1640 Å lines (Table A1). The total emission line flux

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**Table 1.** Basic properties and temperatures \( T_{\text{UV}} \) (see Sect. 2) of studied stars. Here "sg" denotes supergiant, "b" binary, "eb" eclipsing binary and "H" Herbig Ae/Be star.

| Star Location Type       | Location | Type | \( T_{\text{UV}} \) [K] |
|--------------------------|----------|------|------------------------|
| LHA 115-S 18 (AeV 154)   | SMC      | sg   | 9100 ± 100             |
| LHA 115-S 65 (Sk 193)     | SMC      | sg   | 18800 ± 300            |
| HD 129-S 12 (Sk -67 23)  | LMC      | sg   | 9500 – 10500           |
| HD 34664 (LHA 120-S 22)  | LMC      | sg   | 12800 ± 400            |
| HD 37974 (LHA 120-S 127) | LMC      | sg   | 16900 ± 1000           |
| HD 45677 (FS CMA)        | Gal.     | b    | 14100 – 16300          |
| HD 50138 (V743 Mon)      | Gal.     | b    | 11700 ± 200            |
| HD 87643 (V640 Car)      | Gal.     | b    | 10900 – 11700          |
| HD 94878 (GG Car)        | Gal.     | eb   | 27800 ± 700            |
| HD 100546 (KR Mus)       | Gal.     | H    | 12000 ± 200            |
| HD 169515 (RY Sct)       | Gal.     | eb   | 35000 ± 1000           |

\(^2\) http://www.oact.inaf.it/castelli/
and the total line absorption flux vary (Table A1). The typical timescale of the variability (about four years) is longer than the most prominent cycle of optical variations, which is about 440 days (Clark et al. 2013). We have not fitted the spectrum of this star, because the continuum is relatively weak.

3.2 LHA 115-S 65

All IUE observations of LHA 115-S 65 were obtained in two different epochs. Consequently, we calculated just mean values of individual fluxes in both epochs (Table A3). While the fluxes at 1500 Å and 2500 Å do not change within the errors, there may be a decrease of the flux at 2175 Å. This may indicate increased dust absorption by intervening circumstellar material.

3.3 LHA 120-S 12

The IUE observations of LHA 120-S 12 are scarce. However, the wind line profiles show variability. The most prominent is the increase of the wind terminal velocity apparent in the C IV 1548 Å line profile from 1400 ± 200 km s\(^{-1}\) to 2300 ± 200 km s\(^{-1}\) (see Fig. 3) during roughly 11 years. Similar changes are present also in Si IV 1393 Å line, albeit with a lesser extent. While the total line absorption and the total emission line flux do not change substantially, the fluxes in Si IV doublet and in C IV line increase (Table A4). If the fitted temperature \(T_{\text{UV}} = 18\,800 \pm 300\) K corresponds to the effective temperature of the star, then the change of the wind terminal velocity can be explained as a result of bistability (Pauldrach & Puls 1990). This effect appears close to \(T_{\text{eff}} \approx 20000\) K and leads to the modification of the wind terminal velocity (Lamers et al. 1995, Crowther et al. 2006) and possibly also of the mass-loss rate as a result of sensitivity of wind ionization to the effective temperature of the star (Vink et al. 1999, Petrov et al. 2016).

3.4 HD 34664

The flux variations of HD 34664 in Fig. 4 show a strong decrease of the flux between MJD 45000 and 48000 detected by Shore (1990). The decrease of the flux is stronger in far-UV band centered at 1500 Å than in near-UV bands centered at 2175 Å and 2500 Å. This shows that the most likely cause of the light variability is the change of the effective temperature of the star. Such changes, which are typical for LBV S Doradus variables, were detected in HD 34664 by van Genderen & Sterken (1999) and Sterken (2011) from optical data. In accordance with this interpretation, van Genderen & Sterken (1999) detected optical reddening of this star over roughly the same period covered by IUE data.

The variations of the total absorption and the total emission line fluxes in Fig. 5 show linear decrease in both
3.5 HD 37974

The flux variations of HD 37974 in Fig. A2 can be interpreted as the flux decrease during MJD 43 000 – 46 000 and slight brightening in the period MJD 48 000 – 50 000. Additional variations may be connected with complex long-term (hundreds of days) and short-time (tens of days) optical light variability (van Genderen & Sterken 2002).

The variations of O I 1302 Å emission line in Fig. A2 as well as the total emission line flux in Fig. 6 show similar trends as F$_{1500}$ fluxes, that is decrease during MJD 43 000 – 46 000 and increase of the later phases. The total line absorption decreased during the whole observational period (Fig. 6).

3.6 HD 38489

The IUE spectra of HD 38489 secured between MJD 44 800 – 49 200 show nearly constant flux$^3$ (Shore & Sanduleak 1983) with dispersion of about 2%. Also the optical observations do not show any strong variability (Zickgraf et al. 1986). Despite this, the star shows emission line variability. He II 1640 Å (Shore & Sanduleak 1983) emission line flux increased during the period of IUE observation (Table A7). On the other hand, O III line at 1665 Å and N III line at 1752 Å show decrease followed by increase of the flux (see Fig. 7). The similarity of O III and N III emission line flux variations supports the idea that these lines originate in the same region, which is different from the region where He II line originates (Shore & Sanduleak 1983). Neither the total emission nor line absorption show a strong variability as a result of differing trends in the variability of individual lines.

3.7 HD 45677

The UV flux variations of HD 45677 in Fig. 8, which show increase of the flux from MJD of about 44 000 to 48 000, are correlated with visual light variations (Sitko et al. 1994).

$^3$ The observations at about MJD=49 250 show flux dip, but we regard this just as an instrumental feature, because a similar dip is present in observations of HD 34664 (see Fig. 4).
Slightly decreasing trend between MJD 48 000 – 50 000 may be connected with reprocess from the visual light maximum that appeared at about MJD 48 700 (Sitko et al. 1994). The maximum is visible also in the Hipparcos data (ESA 1997).

The total emission flux, 1641 Å O I emission line flux (see Fig. 9), and the 1745 Å N I (Sitko & Savage 1980, Brown et al. 1995) line flux show a similar behaviour as the total absorption and broad-band fluxes. This indicates that the corresponding processes are connected.

The temperature $T_{UV}$ decreased from about 16 300 ± 500 K in MJD 43 000 – 45 000 to 14 100 ± 300 K in MJD 48 000 – 49 000. The fluxes do not change significantly below about 1300 Å, but significantly increase above 1300 Å in later epochs. Moreover, the flux maximum shifts from 1300 Å to about 1400 Å, causing the mentioned decrease of $T_{UV}$.

### 3.8 HD 50138

The IUE observations of HD 50138 cover two epochs with MJD of about 43 800 – 45 000 and 48 600 – 49 800. The stellar flux systematically decreased during MJD 43 800 – 45 000 in all bands studied here, but the short-term variations are also significant during that epoch (see Fig. 10). These short term variations are apparent in the Hipparcos photometry (ESA 1997) and possibly also in the visual photometry (Halbedel 1991). The flux reached original level during MJD 48 600 – 49 800. The long-term variations could be probably explained by increasing obscuration by the matter expelled during outburst (Hutsemekers 1985), which was already dispersed in the second epoch.

We used Period04 (Lenz & Breger 2005) to analyse the $F_{2175}$ and $F_{2500}$ data in the epoch MJD 49 400 – 49 800 yielding the detection of the period 1.194 ± 0.006 d. A similar frequency is present also in the $F_{1500}$ data albeit with much larger uncertainty. All variations can be nicely fitted by simple sinusoidals (see Fig. 10). We have checked the data from MJD 43 800 – 45 000 and data from Hipparcos (taken in MJD 47 900 – 49 100) and we have not found any reasonable periodicity.

The total emission and absorption line fluxes also show strong variations for MJD 43 800 – 45 000 (see Fig. A3). The inspection of the total line absorption in the epoch MJD 49 400 – 49 800 also shows possible periodicity, but with relatively large scatter. However, the total emission line fluxes show steady increase for MJD 49 400 – 49 800 when the periodical photometric variations are detected.

The stochastic variations during MJD 43 800 – 45 000 may be the consequence of the outburst that appeared in 1978–1979 (Hutsemekers 1985). Borges Fernandes et al. (2012) attributed the detected photospheric variations to pulsations. If this model is correct, then the fact that the pulsations are detectable only during the epoch when the star does not show stochastic variations likely means that either the pulsations are triggered by stochastic variations or are hidden in these variations. Kraus et al. (2015) suggested that pulsations in a blue supergiant 55 Cygni can lead to phases of enhanced mass loss. In HD 50138, this could be possibly connected to the increase of the total...
emission line flux (Fig. A3). The pulsational period is close to that found in main-sequence stars with similar spectral type (Diago et al. 2009, Neiner et al. 2009) indicating that HD 50138 is still main-sequence star (in agreement with Borges Fernandes et al. 2009).

For MJD$>49,000$ the observations possibly evince the phase variability of $T_{\text{UV}}$ from about $11,800 \pm 200$ K to about $11,400 \pm 200$ K. The region close to the Ly$\alpha$ line shows a relatively broad (at about $1150 - 1250$ Å) flux minimum, which is connected with low $T_{\text{UV}}$.

3.9 HD 87643

The IUE observations of HD 87643 in Fig. 11 covering the period of MJD 44 000 – 50 000 show an overall decrease of the flux with possibly additional stochastic variations. We fitted the flux variations with linear function $F_l(\text{MJD}) = a_l(\text{MJD} - \text{MJD}) + b_l$, where MJD is the mean MJD for each observational set. The wavelength dependence of $a_l$ and $b_l$ can be explained by the variations of either dust absorption or temperature. The decrease of the broad-band fluxes is accompanied by the decrease of the total and 1730 Å emission line fluxes (see Fig. 12). A similar decrease appears in 1590 Å emission line flux. The total line absorption varies between MJD 44 000 and MJD 49 800 with the maximum roughly in the middle of the time interval and with the minima at the beginning and the end of the observational time period (Table A10).

The fitting of the flux reveals a possible increase of the $T_{\text{UV}}$ during the studied period from about $10,900 \pm 200$ K to $11,700 \pm 800$ K.

3.10 HD 94878

Despite the binary nature of the object, HD 94878 does not show any clear periodicity of UV fluxes. Even the phase diagram based on the ephemeris of Marchiano et al. (2012) does not show any clear trend in any colour. This is probably connected with low amount of data and with the fact that the visual light variations show a large scatter (Gosset et al. 1984, van Leeuwen et al. 1998) possibly as a result of the intrinsic variability of a component. This component likely dominates in UV making the binary lightcurve undetectable. The broad-band photometry does not show any long-term variability in the studied time interval.

Despite the lack of clear flux variability, the absorption lines show variability which may be orbitally modulated. The C ii 1335 Å (Brandi & Gosset 1987) line absorption is variable (see Table A11) with possible minimum around the phase 0.3 of Marchiano et al. (2012). On the other hand, the C iv absorption line at 1548 Å does not evince orbitally modulated variability. The total emission and absorption fluxes suggest variability (Table A11). The broad-band flux $F_{2175}$ is relatively low compared to other fluxes, which is caused by the dust absorption.

3.11 HD 100546

The UV spectrum of HD 100546 does not show any clear flux variability. A small dispersion of UV flux of about 6% is consistent with small amplitude of optical variability (van den Ancker et al. 1998). There may be increase of the flux in the emission line at 1779 Å and the total emission line flux from MJD=48 000 to 50 000 (Table A12). There may be also some variability in 1657 Å Fe ii absorption line. Other absorption lines as C ii 1335 Å and the total line absorption do not show any variability (Table A12).

3.12 HD 169515

The stellar spectral energy distribution of HD 169515 evince strong influence of the dust absorption on $F_{2175}$ fluxes, which are by order of magnitude lower than $F_{2500}$ fluxes. We have not detected any clear long term flux variability of this star, however, we are able to detect the 11.1 d orbital period (Kreiner 2004) from the 1500 Å and 2500 Å flux data.

The total emission and absorption fluxes do not show any strong phase dependence, but there may be long-term variations of the total fluxes. The decrease of the
total emission line flux during the observational period is shown in Fig. 13. The total line absorption displays slightly downward trend during the observational period. Individual lines show phase dependence. The Fe\textsc{ii} absorption line at 1658 Å (Sahade et al. 2002) is the weakest during visual eclipses (using ephemeris of Kreiner 2004). We have not detected any phase variability of C\textsc{i}v emission lines at 1550 Å (Sahade et al. 2002), but all studied lines evince variability, which means Si\textsc{iv} 1402 Å emission line, C\textsc{iv} 1550 Å emission line, and Fe\textsc{ii} 1658 Å absorption line (Table A13).

4 GENERAL RELATIONS BETWEEN INDIVIDUAL FLUXES

Fig. 14 shows that there is correlation between the far-UV broad band fluxes and the total emission line fluxes for the stars from the Magellanic Clouds. The emission line flux depends on the amount of ionizing radiation and therefore on the stellar effective temperature and radius. However, these parameters can not be the cause of the relationship in Fig. 14, because in limit of zero broad-band flux $F_{1500}$ the emission line flux $F_{\text{em}}$ does not approach zero. Consequently, it is more likely that the relationship results from geometrical reasons, i.e., from varying inclination or radius of the disk. The origin of continuum and some emission lines is different. Therefore, the relationship in Fig. 14 could be possibly explained assuming that with larger disk column density (or with higher disk inclination, i.e., for disks seen edge-on) the flux gets more absorbed and therefore $F_{1500}$ becomes lower. However, some parts of the envelope are visible even for high inclinations or large disk radii, consequently, $F_{\text{em}}$ is nonzero for very low $F_{1500}$. Because the amount of ionizing radiation depends mainly on the effective temperature, a relatively tight correlation of $F_{1500}$ and $F_{\text{em}}$ fluxes indicates that the supergiant B[e] stars in the Magellanic Clouds come from a relatively narrow range of the stellar parameters.

With exception of HD 37974, the ratio of far-UV and near-UV broad band fluxes for stars from the Magellanic Clouds depends on the far-UV flux (see Fig. 15). We have not included LHA 115-S 18 in the plot, because the star does not show a strong continuum. The variations in Fig. 15 show a tight linear trend for all stars except HD 37974 despite complicated flux variations in individual stars. The relation can be fitted using model atmospheres emergent fluxes $f_{1500}$ and $f_{2500}$ (Kurucz 2005) assuming constant luminosity of B[e] stars and variable UV temperature and radius $R_{\text{UV}}$, as $L \sim R_{\text{UV}}^2 T_{\text{eff}}^{14}$. From this follow relationships $f_{1500}/T_{\text{UV}}^4 \sim f_{2500}$ or $f_{1500} \sim T_{\text{eff}}^{-14} R_{\text{UV}}^{-2} f_{2500}$ for the model atmosphere fluxes, or (multiplying by $R_{\text{UV}}^{-2}$) $f_{2500} \sim f_{1500}/f_{2500}$. The flux $f_{1500}$ in Fig. 15 was linearly scaled to fit the observed relation and $T_{\text{eff}}$ is the effective temperature corresponding to model atmosphere flux. These results show that a large group of B[e] supergiants has the same luminosity of about $(1.9 \pm 0.4) \times 10^5 L_\odot$ from the model atmospheres, assuming the LMC distance 50 kpc (de Grijs et al. 2014), and correcting for mean extinction derived here. This can provide the possibility to reveal the origin of B[e] supergiant stars. Moreover, with a proper calibration, the relationship in Fig. 15 could be used for distance estimation.

Fig. 16 shows that there is not a clear correlation between the emission line flux and the ratio of $F_{1500}/F_{2500}$, which is a temperature indicator. The lack of correlation supports a general picture that the continuum flux observed
in the UV region does not originate in the stellar atmosphere.

The total line absorption is strongly correlated with the \( F_{1500} \) flux for the stars from the Magellanic Clouds (see Fig. 17). The \( F_{1500} \) flux increases with increasing temperature of the circumstellar envelope, consequently, from the nonlinearity of the relationship in Fig. 17 follows that the absorption lines become relatively stronger for higher temperature of the envelope.

5 DISCUSSION AND CONCLUSIONS

We studied the UV variability of B[e] stars in individual lines and in broad-band fluxes. From the observed flux distribution, we calculated the broad-band variations using artificial photometric filters centered on selected wavelengths. We evaluated the total emission and absorption line fluxes and studied their variability, which originates in the stellar envelope, disk, and the star alone. The observed spectral energy distributions were fitted with atmosphere flux attenuated by the dust absorption.

The UV domain provides wealth of information about the variability of B[e] stars. The multi-colour photometry centered ideally in the far-UV and near-UV regions is able to detect long-term variability (in LHA 115-S 18, HD 37974, HD 45677, HD 50138, and HD 87643) and the S Doradus type variability (in the case of HD 34664). The detected eclipses in HD 169515 may help to constrain the nature of companions. Some stars also show irregular short-term variability (HD 94878). In HD 50138, we also detected pulsations, which are relatively rare among B[e] stars. The derived pulsation period in HD 50138 is 1.194 d. This is the first unambiguous detection of the pulsation and measurement of its period in this star. Some B[e] stars do not show any strong flux variability (LHA 115-S 65, HD 38489, and HD 100546).

The line variability is typically connected with the flux variability. In HD 34664 the decrease of the flux (and the estimated temperature) is correlated with the decrease of the line fluxes. A similar correlation is also found in HD 37974, HD 45677, and HD 87643. LHA 120-S 12 shows wind line profile variability that corresponds to the wind bistability jump. In HD 169515 we have found variability of absorption lines during the eclipses.

We found striking differences in the ratios of the total emission line flux to the total line absorption among studied stars perhaps as a consequence of envelope properties. The stars with high total emission line flux are LHA 115-S 18, LHA 115-S 65, HD 34664, HD 38489, HD 45677, HD 50138, HD 87643, and HD 169515. This group of stars shows the ratio of the total emission line flux to the total line absorption \( F_{\text{em}}/F_{\text{ab}} \) in the range 1.1–23.5. The predominance of emission line flux is typical for these stars. On the contrary, the stars LHA 120-S 12, HD 37974, HD 94878, and HD 100546 show low ratio of the total emission line flux to the total line absorption and the spectra evince more absorption lines than emission lines. We specify the ratio \( F_{\text{em}}/F_{\text{ab}} \) in the range 0.46–1.37 for these stars.

In many B[e] stars, the temperature obtained from the fitting of UV flux distribution is significantly lower than 20 Kk. This is too low to cause a significant Hα emission. This indicates that many B[e] stars are enshrouded by optically thick envelope, and a significant part of UV radiation does not originate on the surface of B[e] stars, but in their disk. The stellar radiation is heavily obscured in such stars, and the temperature derived from fitting corresponds to the temperature of the circumstellar environment. This conclusion is further supported by the relation between the broad-band fluxes and total emission line flux. Possibly, the absorbing material appears also above the disk.

The fitted amount of the dust absorption derived from the 2175 Å opacity bump does not vary with time in majority of stars. This indicates the interstellar origin of this feature in many stars.

The fluxes from the Magellanic Cloud stars show that many B[e] stars evince the same luminosity of about \( 1.9 \times 10^5 L_\odot \) and similar effective temperature. This indicates that the long-term broad-band variability of B[e] stars is most likely caused by the changes in the envelopes of these stars. Moreover, this puts strong constraints on the models of evolution of these stars and possibly establishes distance indicator.
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APPENDIX A: BASIC PROPERTIES OF STUDIED B[e] STARS, LISTS OF THE IUE OBSERVATIONS USED IN THE PAPER AND DERIVED BROAD-BAND AND LINE FLUXES, AND SUPPLEMENTARY FIGURES

Here we summarize the basic properties of studied B[e] stars.

**LHA 115-S 18** The forbidden emission lines in the spectra of SMC star LHA 115-S 18 (AzV 154) were detected by Azzopardi et al. (1981). Besides the prominent variability of He II 4686 Å emission line (Sanduleak 1978) and many UV lines (Shore et al. 1987), the star also shows optical variability on different time scales (van Genderen 2001, van Genderen & Sterken 2002, Clark et al. 2013). A two-component model for the LHA 115-S 18 outflow consisting of fast radiatively driven wind and slow outflowing disk was proposed by Zickgraf et al. (1989). The star shows a strong infrared excess due to the dust (Kastner et al. 2010). The optical spectra of the star shows Raman-scattered lines (Torres et al. 2012), Clark et al. (2013) proposed a binary nature of the object based on the detection of X-ray emission (Antoniou et al. 2009).

**LHA 115-S 65** In the case of SMC B[e] supergiant LHA 115-S 65 (CPD-75° 116, RCM 50, Sk 193) any variability from IUE spectra has not been found (Shore & Sanduleak 1984). The profiles of emission lines of this star are consistent with their origin in Keplerian disk (Kraus et al. 2010, Aret et al. 2012).

**LHA 120-S 12** The LMC blue supergiant star LHA 120-S 12 (Sk-67 23) shows Hα emission and dust envelope (Stahl et al. 1984). The detected polarization signature (Magalhães 1992) points to the presence of non-spherical envelope. Measurement of $^{13}$C relative abundance in the infrared spectra of this star provided support for the evolved nature of the object (Liermann et al. 2010).

**HD 34664** The B[e] supergiant HD 34664 (LHA 120-S 22, MWC 105) is a member of NGC 1871 association in the LMC and shows forbidden emission lines (Fehrenbach 1971). The IUE spectra of this star were studied by Bensammar et al. (1983). The polarimetry and spectropolarimetry revealed the existence of a disk around this star (Magalhães 1992, Schulte-Ladbeck & Clayton 1993). The nebula around the supergiant, which is visible in the optical, Hα, and infrared wavelengths, reflects the Hα line of the star (Chu et al. 2003). The structure of the nebula around the star is especially complex in the IRAC observations of SPITZER.

**HD 37974** The IUE spectra of the LMC B[e] supergiant HD 37974 (LHA 120-S 127) show very strong resonance lines (Shore & Sanduleak 1984). This star, which is viewed pole-on, displays signatures of the dusty disk in infrared and numerous Fe II emission lines in near-UV (Zickgraf et al. 1985, Aret et al. 2012). The total mass of the dusty disk is estimated to be $3 \times 10^{-3}$ $M_\odot$ from SPITZER (Kastner et al. 2006).

**HD 38489** The detailed study of IUE spectra (Shore & Sanduleak 1983) of LMC supergiant HD 38489 (LHA 120-S 134) revealed presence of the stellar wind from P Cygni lines (Shore & Sanduleak 1983). Stahl et al. (1984) detected the infrared dust emission in the photometry of this star. Infrared observations also show a nebula around the star (Kastner et al. 2010). Some emission lines display double peaked shapes indicating their origin in rotating disk (Aret et al. 2012). The infrared spectra of the star show CO emission (McGregor et al. 1988, Oksala et al. 2013).

**HD 45677** Although HD 45677 (FS CMa) is classified as a B[e] star, its luminosity class is not in agreement with the supergiant characteristics (Cidale et al. 2001). The UV energy distribution shows signatures of dust absorption in HD 45677 (Savage et al. 1978, Sitko & Savage 1980). The UV spectropolarimetry of this star obtained during space shuttle mission (Schulte-Ladbeck et al. 1992) revealed a bipolar reflection nebula consistent with dusty disk. Grady et al. (1993) interpreted available observations concluding that HD 45677 is a Herbig Be star in the phase of circumstellar material accretion. This was questioned by Miroshnichenko (2007), partly due to the missing pre-stellar objects in the neighborhood. The infrared properties of the star are also different from pre-main sequence objects (Lee et al. 2016). Sitko et al. (1994) interpreted the observed UV, optical, and infrared variability as a result of variable dust extinction. The UV flux variations show increase from MJD of about 44 000 to 48 000 discussed by Sitko et al. (1994). This corresponds to the recovery from a deep visual minima, that occurred around 1980 (de Winter & van den Ancker 1997, Patel et al. 2006) and is accompanied by the decrease of thermal emission in infrared (Sitko et al. 1994). These variations are interpreted as a result of decreasing obscuration by circumstellar dust, which was possibly ejected after an explosive event around 1950 (Sitko et al. 1994, de Winter & van den Ancker 1997).

**HD 50138** The UV observations of HD 50138 (V743 Mon) star were described by Sitko et al. (1981). The disk of the star was resolved using spectropolarimetry (Bjorkman et al. 1998) and interferometry (Borges Fernandes et al. 2011, Ellerbroek et al. 2015). The star shows complex line profile variations that were attributed to the pulsations with period significantly shorter than the rotational period of about 3.6 d (Borges Fernandes et al. 2012). The UV variability of this star was reported by Savage et al. (1978) based on the observations of the ANS satellite. Hutsemekers (1985) provide evidence of outburst in 1978–1979 from IUE line data. The photometric monitoring has not revealed a significant optical variability (Ponomareva 1981, Halbedel 1991).
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Figure A1. Variation of LHA 115-S 18 broad-band fluxes with time.

Figure A2. Variation of HD 37974 with time. Left panel: Broad-band fluxes. Right panel O I 1302 Å emission line flux.

**HD 87643** The southern emission line star HD 87643 (V640 Car) is a member of a wide binary (Millour et al. 2009), resides close to the H ii region RCW 47 (Crampton 1971), and is accompanied by a reflection nebula clearly visible in the optical images (Surdej et al. 1981). HD 87643 is one of the stars whose observations led to the definition of the B[e] phenomenon (Swings 1974, Allen & Swings 1976). IUE observations of HD 87643 show strong lines of Fe ii (de Freitas Pacheco et al. 1982). The spectropolarimetric observations (Oudmaijer et al. 1998) revealed the existence of the disk around HD 87643. The star shows irregular light variations (Greaves 2005).

**HD 94878** The eclipsing binary of β Lyrae type HD 94878 (GG Car, Marchiano et al. 2012) shows infrared excess (Allen & Swings 1976). The UV spectrum displays numerous lines of ions with low ionization potential (Brandi & Gosset 1987, Brandi et al. 1987). The polarimetric properties of the star indicate the presence of multicomponent envelope (Gnedin et al. 1992). The H α spectropolarimetry reveals the presence of the disk (Pereyra et al. 2009), which rotates with Keplerian velocity (Kraus et al. 2013). The new data from GAIA DR1 (Lindegren et al. 2016), which give the distance \( r > 2 \) kpc, agree with other studies (e.g., Marchiano et al. 2012) and confirm luminous nature of the source.

**HD 100546** HD 100546 (KR Mus) is classified as a Herbig Ae/Be star (Hu et al. 1989). The star hosts a protoplanetary disk (Garufi et al. 2016).

**HD 169515** The double-lined eclipsing binary HD 169515 (RY Sct) consists of mass losing O9.7 Ibep supergiant accompanied by massive companion (Antokhina & Kumsashvili 1999, Grundstrom et al. 2007, Djurasevic et al. 2008). The binary interaction provides a natural explanation of the H α emission line and other spectral features connected with the B[e] phenomenon. The observed ring structure of the circumstellar medium indicates possible discrete mass ejection phases (Men'shchikov & Miroshnichenko 2005, Smith et al. 2011). The IUE spectrum of HD 169515 was extensively studied by Sahade et al. (1984, 2002), who provide also identification of many UV lines.

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Figure A3. Variation of HD 50138 total emission line fluxes (left panel) and total line absorption (right panel) with time.

Table A1. List of the IUE observations and fluxes of LHA 115-S 18. The units of broad-band flux $F_{1500}$ are $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of broad-band fluxes $F_{2175}$ and $F_{2500}$ are $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The units of $F_{\text{em}}$ (for individual lines and the total flux) and $F_{\text{ab}}$ (total) are $10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$ N$\text{v}$ 1245 Å | $F_{\text{em}}$ O$\text{i}$ 1302 Å | $F_{\text{em}}$ C$\text{iv}$ 1550 Å | $F_{\text{em}}$ He$\text{ii}$ 1640 Å | $F_{\text{em}}$ total | $F_{\text{ab}}$ |
|--------|-------|-------------|------------|-----------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------|-------------|
| SWP    | 14463 | 2,400,000.5+ | 1.91       | 170                               | 17                              | 42                              | 140                            | 530            | 61          |
| SWP    | 15122 | 44798.59642  | 2.88       | 240                               | 30                              | 88                              | 220                            | 680            | 69          |
| SWP    | 19371 | 45395.84036  | 3.55       | 150                               | 20                              | 62                              | 200                            | 690            | 30          |
| SWP    | 25789 | 46182.47697  | 1.72       |                                   |                                  |                                 |                                 |                 |             |
| mean uncertainty | 0.7 | 30 | 6 | 18 | 15 | 160 | 13 | |

Camera Image Julian date $F_{2175}$ $F_{2500}$ mean uncertainty

| LWR    | 11058 | 44798.64322 | 9.90 | 17.2 |
| LWP    | 05836 | 46182.55200 | 12.9 | 11.3 |
| mean uncertainty | 12 | 4 | |

Table A2. List of the IUE observations and fluxes of LHA 115-S 65. The units of broad-band flux $F_{1500}$ are $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and the units of broad-band fluxes $F_{2175}$ and $F_{2500}$ are $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{2175}$ | $F_{2500}$ |
|--------|-------|-------------|------------|------------|------------|
| SWP    | 10990 | 44611.36670 | 9.97       | 1.12       | 1.29       |
| SWP    | 13503 | 44678.88659 | 9.80       | 1.24       | 1.39       |
| SWP    | 13504 | 44678.94138 | 10.6       | 1.37       | 1.38       |
| SWP    | 15121 | 44876.38932 | 10.4       | 1.26       | 1.35       |
| SWP    | 43360 | 48601.44294 | 9.77       | 1.04       | 1.23       |
| SWP    | 48257 | 49196.52540 | 11.3       | 1.10       | 1.32       |
| mean uncertainty | 1.4 | | | | |

| LWR    | 09659 | 44611.38731 | 1.12       | 0.3        | 0.1        |
| LWR    | 10146 | 44678.91174 | 1.24       | 0.3        | 0.1        |
| LWR    | 11057 | 44798.54116 | 1.37       | 0.3        | 0.1        |
| LWR    | 11638 | 44876.40194 | 1.26       | 0.3        | 0.1        |
| LWP    | 21992 | 48601.73820 | 1.04       | 0.3        | 0.1        |
| LWP    | 26031 | 49196.49965 | 1.10       | 0.3        | 0.1        |
| mean uncertainty | 0.3 | | | | |
Table A3. Mean LHA 115-S 65 broad-band fluxes

| Julian date | $F_{1500}$ | $F_{2175}$ | $F_{2500}$ |
|-------------|------------|------------|------------|
| 2,400,000+  | [10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}] |            |            |
| 44730       | 1.02 ± 0.04 | 1.25 ± 0.09 | 1.35 ± 0.04 |
| 48900       | 1.05 ± 0.13 | 1.07 ± 0.06 | 1.28 ± 0.08 |

Table A4. List of the IUE observations and fluxes of LHA 120-S 12. The units of broad-band flux $F_{1500}$ are $10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, units of broad-band fluxes $F_{2175}$ and $F_{2500}$ are $10^{-14} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, the units of $F_{\text{ab}}$ (Si iv 1393 Å, C iv 1548 Å) are $10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$, the units of $F_{\text{em}}$ (total) are $10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$, and the units of $F_{\text{ab}}$ (total) are $10^{-11} \text{erg s}^{-1} \text{cm}^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{ab}}$ Si iv | $F_{\text{ab}}$ C iv | $F_{\text{em}}$ total |
|--------|-------|-------------|------------|----------------------|---------------------|---------------------|
| SWP    | 14450 | 44796.80990 | 1.70       | 2.4                  | 1.6                 | 3.9                 | 1.1                |
| SWP    | 36709 | 47727.7732  | 1.64       | 2.7                  | 1.1                 | 3.6                 | 1.1                |
| SWP    | 38434 | 47978.5226  | 1.77       | 3.2                  | 1.5                 | 5.1                 | 1.3                |
| SWP    | 38435 | 47978.58015 | 1.76       | 3.2                  | 1.6                 | 5.3                 | 1.4                |
| SWP    | 44666 | 48756.5182  | 1.72       | 3.6                  | 2.2                 | 6.0                 | 1.3                |
|        | mean uncertainty | 0.1          | 0.1          | 0.2                  | 0.3                 | 0.1                |

Table A5. List of the IUE observations of HD 34664. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, the units of $F_{\text{em}}$ (O i 1302 Å) are $10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$, the units of $F_{\text{em}}$ (total) are $10^{-11} \text{erg s}^{-1} \text{cm}^{-2}$, and the units of $F_{\text{ab}}$ (total) are $10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$ O i 1302 Å | $F_{\text{em}}$ total |
|--------|-------|-------------|------------|-----------------------------|---------------------|
| SWP    | 07634 | 44250.42995 | 2.71       | 9.2                         | 2.1                 | 2.6                |
| SWP    | 07881 | 44276.32869 | 2.74       | 8.2                         | 1.9                 | 1.3                |
| SWP    | 15035 | 46678.98535 | 2.70       | 11.2                        | 1.9                 | 1.9                |
| SWP    | 14449 | 44796.73076 | 2.75       | 6.5                         | 1.8                 | 2.0                |
| SWP    | 15114 | 44875.47450 | 2.63       | 7.4                         | 1.4                 | 3.7                |
| SWP    | 38609 | 47996.73495 | 1.42       | 7.6                         | 1.2                 | 1.4                |
| SWP    | 38667 | 48004.95577 | 1.35       | 9.8                         | 1.0                 | 1.4                |
| SWP    | 38668 | 48005.02173 | 1.39       | 8.4                         | 1.1                 | 0.8                |
| SWP    | 40926 | 48311.45845 | 1.32       | 8.9                         | 1.2                 | 0.9                |
| SWP    | 43125 | 48577.25947 | 1.30       | 6.5                         | 1.0                 | 1.1                |
| SWP    | 43349 | 48599.47516 | 1.26       | 9.1                         | 1.2                 | 1.2                |
| SWP    | 43350 | 48599.53042 | 1.25       | 8.2                         | 1.0                 | 1.2                |
| SWP    | 44160 | 48693.90032 | 1.31       | 7.0                         | 1.2                 | 0.9                |
| SWP    | 45246 | 48831.59244 | 1.35       | 6.2                         | 0.9                 | 1.4                |
| SWP    | 46592 | 48982.96380 | 1.29       | 5.4                         | 1.0                 | 1.2                |
| SWP    | 48202 | 49190.30118 | 0.995      | 5.2                         | 0.8                 | 0.8                |
| SWP    | 48709 | 49253.41809 | 1.05       | 5.3                         | 1.0                 | 1.3                |
| SWP    | 50703 | 49478.58207 | 1.30       | 6.2                         | 1.0                 | 0.9                |
| SWP    | 50711 | 49479.45130 | 1.36       | 5.9                         | 1.0                 | 1.0                |
| SWP    | 53169 | 49710.28760 | 1.12       | 5.6                         | 0.9                 | 1.3                |
| SWP    | 54482 | 49829.01160 | 1.30       | 5.8                         | 0.9                 | 0.9                |
|        | mean uncertainty | 0.1          | 1.2          | 0.1                      | 0.2                |

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LWR 11639 44876.51574 10.4 8.48
LWR 17633 47978.54468 11.0 9.59
mean uncertainty 2.4 1.0

LWR 06629 44250.44821 1.73 1.72
LWR 06868 44276.30139 1.69 1.72
LWR 06868 44276.35351 1.70 1.74
LWR 10147 44678.99903 1.77 1.74
LWR 11631 44875.49513 1.89 1.73
LWR 17753 47996.70867 1.25 1.39
LWR 17803 48004.97747 1.26 1.40
LWR 19825 48311.47734 1.35 1.45
LWR 21760 48577.28020 1.28 1.40
LWR 21979 48599.49844 1.19 1.39
LWR 21980 48599.78824 1.36 1.19
LWR 22578 48693.92689 1.36 1.42
LWR 23595 48831.55923 1.27 1.35
LWR 24599 48982.92294 1.27 1.36
LWR 26436 49252.35258 0.932 1.07
LWR 28072 49479.38554 1.33 1.44
LWR 29749 49710.25062 1.27 1.38
mean uncertainty 0.3 0.1

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Table A6. List of the IUE observations of HD 37974. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{em}}$ (O i 1302 Å) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{em}}$ (total) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and the units of $F_{\text{ab}}$ (total) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. We have not used LWP spectra 17752 and 26022 for our analysis, because their flux around 2000 Å does not correspond to the SWP spectra taken roughly at the same time.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$(O i 1302 Å) | $F_{\text{em}}$(total) | $F_{\text{ab}}$(total) |
|--------|-------|-------------|------------|-----------------------------|------------------------|------------------------|
| SWP    | 01402 | 43620.84477 | 7.19       | 3.5                         | 3.1                    | 2.8                    |
| SWP    | 16617 | 45052.96092 | 6.75       | 2.5                         | 2.4                    | 2.4                    |
| SWP    | 21142 | 45660.65824 | 6.44       | 1.8                         | 2.2                    | 2.3                    |
| SWP    | 36705 | 47726.43124 | 6.32       | 1.5                         | 2.0                    | 2.2                    |
| SWP    | 38466 | 47979.76919 | 6.58       | 2.7                         | 2.3                    | 2.3                    |
| SWP    | 44640 | 48752.84347 | 6.79       | 3.1                         | 2.6                    | 2.4                    |
| SWP    | 46715 | 48999.78725 | 6.65       | 2.9                         | 2.6                    | 2.1                    |
| SWP    | 48224 | 49192.51418 | 6.85       |                             |                        |                        |
| SWP    | 53170 | 49710.35884 | 6.62       | 3.3                         | 2.7                    | 2.0                    |

mean uncertainty 0.4 0.6 0.2 0.2

Table A7. List of the IUE observations of HD 38489. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{em}}$ (He ii 1640 Å, O iii 1665 Å, and N iii 1752 Å) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{em}}$ (total) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and the units of $F_{\text{ab}}$ (total) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$(He ii 1640 Å) | $F_{\text{em}}$(O iii 1665 Å) | $F_{\text{em}}$(N iii 1752 Å) | $F_{\text{ab}}$(total) |
|--------|-------|-------------|------------|------------------------------|-------------------------------|-------------------------------|------------------------|
| SWP    | 14447 | 44796.61089 | 3.00       | 1.1                          | 2.0                           | 3.1                           | 2.0                    |
| SWP    | 15117 | 44875.62457 | 3.02       | 1.0                          | 2.0                           | 3.1                           | 1.5                    |
| SWP    | 25790 | 46182.62654 | 2.93       | 0.97                         | 1.8                           | 2.4                           | 1.7                    |
| SWP    | 38464 | 47979.62477 | 2.91       | 1.7                          | 2.5                           | 2.5                           | 1.9                    |
| SWP    | 44163 | 48694.08755 | 2.86       | 1.5                          | 2.6                           | 2.9                           | 2.0                    |
| SWP    | 46714 | 48999.73408 | 3.06       | 1.7                          | 2.3                           | 3.0                           | 2.2                    |
| SWP    | 48223 | 49192.46920 | 3.06       | 1.3                          | 2.4                           | 3.1                           | 2.0                    |

mean uncertainty 0.2 0.4 0.3 0.4 0.2 0.4

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Table A8. List of the IUE observations of HD 45677. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are \(10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\), the units of $F_{\text{em}}$(O\,i 1641 Å) are \(10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\), the units of $F_{\text{em}}$(N\,i 1745 Å) are \(10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\), and the units of $F_{\text{em}}$ (total) and $F_{\text{ab}}$ (total) are \(10^{-10}\) erg s\(^{-1}\) cm\(^{-2}\).

| Camera | Image | Julian date 2,400,000.5+ | $F_{1500}$ | $F_{\text{em}}$ O\,i | $F_{\text{em}}$ N\,i | $F_{\text{em}}$ total | $F_{\text{ab}}$ total | $F_{2175}$ | $F_{2500}$ |
|--------|-------|--------------------------|------------|----------------|----------------|----------------|----------------|------------|------------|
| SWP    | 01388 | 43617.91900              | 7.98       |                |                |                |                |            |            |
| SWP    | 02707 | 43771.73863              | 8.62       |                |                |                |                |            |            |
| SWP    | 02772 | 43777.64468              | 8.86       |                |                |                |                |            |            |
| SWP    | 04340 | 43926.86856              | 1.5        | 2.4            | 1.8            |                |                |            |            |
| SWP    | 04761 | 43959.28757              | 1.4        | 2.6            | 1.6            |                |                |            |            |
| SWP    | 06569 | 44135.58933              | 7.78       |                |                |                |                |            |            |
| SWP    | 08006 | 44290.99348              | 8.14       |                |                |                |                |            |            |
| SWP    | 10648 | 44564.23906              | 8.18       |                |                |                |                |            |            |
| SWP    | 10652 | 44564.46919              | 20         | 1.2            | 2.6            | 1.1            |                |            |            |
| SWP    | 11230 | 44639.19581              | 8.14       |                |                |                |                |            |            |
| SWP    | 15991 | 44978.02437              | 14         | 1.3            | 3.2            | 1.4            |                |            |            |
| SWP    | 15992 | 44978.12183              | 8.86       |                |                |                |                |            |            |
| SWP    | 40272 | 48230.26057              | 24         | 1.6            | 3.6            | 1.9            |                |            |            |
| SWP    | 44033 | 48673.17445              | 14.4       |                |                |                |                |            |            |
| SWP    | 44069 | 48679.02518              | 13.6       |                |                |                |                |            |            |
| SWP    | 46547 | 48978.12535              | 28         | 1.9            | 3.9            | 2.2            |                |            |            |
| SWP    | 46548 | 48978.23332              | 33         | 1.5            | 4.1            | 2.1            |                |            |            |
| SWP    | 46549 | 48978.34512              | 12.7       |                |                |                |                |            |            |
| SWP    | 48869 | 49268.38414              | 34         | 1.7            | 4.8            | 1.8            |                |            |            |
| SWP    | 50020 | 49397.96430              | 40         | 1.7            | 5.6            | 2.0            |                |            |            |
| SWP    | 50021 | 49398.00809              | 12.5       |                |                |                |                |            |            |
| SWP    | 50042 | 49400.11357              | 11.6       |                |                |                |                |            |            |
| SWP    | 52074 | 49605.35304              | 33         | 2.0            | 4.7            | 2.2            |                |            |            |
| SWP    | 52075 | 49605.40010              | 12.6       |                |                |                |                |            |            |
| SWP    | 53046 | 49698.45771              | 47         | 1.9            | 4.8            | 3.1            |                |            |            |
| SWP    | 55972 | 49980.35381              | 35         | 1.5            | 3.7            | 1.9            |                |            |            |
| SWP    | 55973 | 49980.40276              | 13.5       |                |                |                |                |            |            |

mean uncertainty 0.5 1.8 0.2 0.2 0.1
Table A9. List of the IUE observations of HD 50138. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}\text{erg s}^{-1}\text{cm}^{-2}\text{Å}^{-1}$, the units of $F_{\text{em}}$ (1530 Å) are $10^{-11}\text{erg s}^{-1}\text{cm}^{-2}$, and the units of $F_{\text{em}}$ and $F_{\text{ab}}$ (total) are $10^{-10}\text{erg s}^{-1}\text{cm}^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$ | $F_{\text{em}}$ | $F_{\text{ab}}$ |
|--------|-------|-------------|------------|----------------|----------------|--------------|
| SWP 03663 | 43863.62772 | 2.19 |              |                |                |              |
| SWP 04294 | 43922.93508 | 1.92 |              |                |                |              |
| SWP 04295 | 43923.02686 | 1.81 | 4.9 | 13.2 | 3.2 |              |
| SWP 04557 | 43941.29904 | 2.36 | 5.8 | 10.5 | 5.9 |              |
| SWP 04947 | 43978.87895 | 2.40 |              |                |                |              |
| SWP 08007 | 44291.06204 | 2.08 | 3.2 | 10.1 | 4.7 |              |
| SWP 08008 | 44291.10022 | 2.20 |              |                |                |              |
| SWP 10649 | 44564.30298 | 1.40 | 4.1 | 8.6 | 4.4 |              |
| SWP 10650 | 44564.33850 | 1.46 |              |                |                |              |
| SWP 11231 | 44639.24050 | 1.83 |              |                |                |              |
| SWP 15993 | 44978.17375 | 1.75 | 2.9 | 9.9 | 3.2 |              |
| SWP 15994 | 44978.22819 | 1.89 |              |                |                |              |
| SWP 16017 | 44981.10741 | 2.81 |              |                |                |              |
| SWP 50023 | 49398.12077 | 2.61 | 4.1 | 10.2 | 5.7 |              |
| SWP 50024 | 49398.16796 | 2.87 |              |                |                |              |
| SWP 52169 | 49616.47436 | 2.62 | 9.0 | 12.0 | 6.3 |              |
| SWP 53047 | 49698.53272 | 2.25 | 6.3 | 12.7 | 4.8 |              |
| SWP 54035 | 49780.85206 | 2.10 | 4.4 | 13.8 | 5.5 |              |

Mean uncertainty 0.09 0.5 0.5 0.2

| Camera | Image | Julian date | $F_{2175}$ | $F_{2500}$ |
|--------|-------|-------------|------------|------------|
| LWR 02499 | 43780.64124 | 1.50 | 1.26 |
| LWR 03226 | 43863.52685 | 1.35 | 1.11 |
| LWR 03247 | 43865.44774 | 1.44 | 1.31 |
| LWR 03794 | 43922.92648 | 1.17 | 1.04 |
| LWR 03796 | 43923.01449 | 1.17 | 1.05 |
| LWR 03967 | 43941.27313 | 1.47 | 1.24 |
| LWR 04276 | 43978.86907 | 1.37 | 1.14 |
| LWR 06958 | 44289.23593 | 1.00 | 0.847 |
| LWR 06967 | 44291.02461 | 1.00 | 0.929 |
| LWR 06968 | 44291.05943 | 1.21 | 0.985 |
| LWR 09358 | 44564.27408 | 0.585 | 0.574 |
| LWR 09359 | 44564.33405 | 0.789 | 0.680 |
| LWR 09851 | 44639.23849 | 0.908 | 0.724 |
| LWR 12310 | 44978.19663 | 0.814 | 0.738 |
| LWR 12311 | 44978.23478 | 0.962 | 0.821 |
| LWR 12322 | 44980.15007 | 0.894 | 0.740 |
| LWR 21563 | 48559.04685 | 0.980 | 0.801 |
| LWR 22631 | 48699.68528 | 1.02 | 0.824 |
| LWR 27421 | 49398.06091 | 1.50 | 1.37 |
| LWR 27422 | 49398.09727 | 1.46 | 1.26 |
| LWR 27423 | 49398.14733 | 1.53 | 1.33 |
| LWR 27430 | 49400.06514 | 1.33 | 1.19 |
| LWR 29213 | 49616.44913 | 1.43 | 1.11 |
| LWR 29691 | 49698.49794 | 1.24 | 1.12 |
| LWP 30154 | 49780.82694 | 1.19 | 1.01 |
| LWP 30121 | 49879.48141 | 0.995 | 0.942 |
| LWP 30125 | 49879.91653 | 1.09 | 0.989 |
| LWP 30130 | 49900.05439 | 1.19 | 0.986 |
| LWP 30136 | 49910.10010 | 1.22 | 1.01 |
| LWP 30123 | 49920.03470 | 1.28 | 1.07 |
| LWP 30128 | 49920.28557 | 1.13 | 0.942 |
| LWP 30129 | 49921.02873 | 1.02 | 0.880 |
| LWP 30125 | 49945.95547 | 1.15 | 1.04 |
| LWP 30126 | 49955.81162 | 1.17 | 1.01 |
| LWP 30128 | 49966.82841 | 1.32 | 1.06 |
| LWP 30120 | 49979.91027 | 1.20 | 1.08 |
| LWP 30129 | 49979.02828 | 1.46 | 1.26 |
| LWP 30127 | 49980.10454 | 1.21 | 0.970 |
| LWP 30129 | 49980.52721 | 1.16 | 0.933 |
| LWP 30130 | 49981.08013 | 1.30 | 1.06 |
| LWP 30131 | 49982.84345 | 1.35 | 1.10 |
| LWP 30136 | 49983.82111 | 1.24 | 1.06 |

Mean uncertainty 0.2 0.07
Table A10. List of the IUE observations of HD 87643. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{em}}$ (1730 Å) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{em}}$ (total) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and $F_{\text{ab}}$ (total) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date 2,400,000.5+ | $F_{1500}$ | $F_{\text{em}}$ 1730 Å | $F_{\text{em}}$ total | $F_{\text{ab}}$ |
|--------|-------|--------------------------|------------|----------------------|---------------------|--------------|
| SWP    | 05838 | 44071.98731              | 3.56       | 2.9                  | 5.0                 | 2.9          |
| SWP    | 05889 | 44076.10701              | 3.53       | 3.0                  | 4.2                 | 7.7          |
| SWP    | 09166 | 44391.17960              | 3.83       |                      |                     |              |
| SWP    | 13760 | 44714.20766              | 3.48       | 2.6                  | 4.3                 | 3.5          |
| SWP    | 25996 | 46208.58548              | 3.07       | 2.4                  | 3.5                 | 3.1          |
| SWP    | 26040 | 46216.42460              | 3.54       | 2.5                  | 4.0                 | 4.8          |
| SWP    | 28309 | 46564.78045              | 2.43       | 2.6                  | 4.2                 | 4.8          |
| SWP    | 36803 | 47744.58941              | 4.01       | 2.4                  | 4.3                 | 6.1          |
| SWP    | 46913 | 49029.08163              | 3.09       | 2.2                  | 3.4                 | 5.2          |
| SWP    | 50710 | 49479.33012              | 2.21       | 1.9                  | 2.4                 | 5.0          |
| SWP    | 53842 | 49754.11026              | 2.17       | 2.1                  | 2.5                 | 4.6          |
|        | mean uncertainty       |             | 0.2        | 0.3                  | 0.4                 | 0.5          |

Table A11. List of the IUE observations of HD 94878. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{ab}}$ (C II 1335 Å and C IV 1548 Å) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{em}}$ and $F_{\text{ab}}$ (total) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date 2,400,000.5+ | $F_{1500}$ | $F_{\text{ab}}$ C II | $F_{\text{ab}}$ C IV | $F_{\text{em}}$ total | $F_{\text{ab}}$ (total) |
|--------|-------|--------------------------|------------|----------------------|----------------------|---------------------|------------------------|
| SWP    | 02685 | 43769.84366              | 19.4       | 9.2                  |                      |                     |                        |
| SWP    | 02686 | 43769.89388              | 21.2       | 8.8                  | 9.6                  | 13.0                | 9.7                    |
| SWP    | 05679 | 44054.14513              | 26.5       | 3.5                  | 9.2                  | 13.0                | 8.8                    |
| SWP    | 06737 | 44149.71582              | 21.2       | 3.3                  | 7.8                  | 10.0                | 6.5                    |
| SWP    | 08936 | 44365.16023              | 19.6       |                      |                      |                     |                        |
| SWP    | 09399 | 44408.86859              | 26.1       | 7.2                  | 11                   | 3.7                 | 7.3                    |
| SWP    | 18555 | 45287.70249              | 23.1       | 7.4                  | 12                   | 3.7                 | 8.1                    |
|        | mean uncertainty       |             | 1.1        | 1.6                  | 2.0                  | 0.3                 | 0.5                    |
Table A12. List of the IUE observations of HD 100546. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{ab}}$ (C ii 1335 Å and Fe ii 1657 Å) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{em}}$ (1779 Å + 1784 Å) are $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, and the units of $F_{\text{em}}$ and $F_{\text{ab}}$ (total) are $10^{-10}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{ab}}$ | $F_{\text{em}}$ | $F_{\text{em}}$ | $F_{\text{ab}}$ |
|--------|-------|-------------|------------|----------------|----------------|----------------|----------------|
| SWP    | 30712 | 48160.68056 | 2.15       | 5.2            | 1.9            | 0.76           | 1.9            |
| SWP    | 47481 | 49091.17277 | 2.07       | 5.1            | 0.75           | 0.96           | 2.6            |
| SWP    | 54065 | 49783.82326 | 2.05       | 5.4            | 3.1            | 1.1            | 2.7            |
| SWP    | 54658 | 49849.02155 | 2.26       |                |                |                |                |
| SWP    | 54753 | 49862.71465 | 2.38       |                |                |                |                |
| SWP    | 54754 | 49862.79287 | 2.18       | 5.1            | 1.2            | 1.2            | 3.4            |

mean uncertainty: 0.07, 0.5, 0.3, 0.5, 0.1, 0.2

| Camera | Image | Julian date | $F_{2175}$ | $F_{2500}$ |
|--------|-------|-------------|------------|------------|
| SWP    | 16052 | 47740.75450 | 1.06       | 0.913      |
| SWP    | 16075 | 47744.03140 | 1.06       | 0.904      |
| SWP    | 30679 | 49849.01533 | 1.14       | 1.00       |
| SWP    | 30770 | 49862.70994 | 1.12       | 0.959      |
| SWP    | 30771 | 49862.76354 | 0.984      | 0.842      |

mean uncertainty: 0.2, 0.06

Table A13. List of the IUE observations of HD 169515. The units of broad-band fluxes $F_{1500}$, $F_{2175}$, and $F_{2500}$ are $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the units of $F_{\text{em}}$ (C iv 1550 Å) are $10^{-13}$ erg s$^{-1}$ cm$^{-2}$, the units of $F_{\text{ab}}$ (Fe ii 1658 Å) are $10^{-13}$ erg s$^{-1}$ cm$^{-2}$, and the units of $F_{\text{em}}$ and $F_{\text{ab}}$ (total) are $10^{-12}$ erg s$^{-1}$ cm$^{-2}$.

| Camera | Image | Julian date | $F_{1500}$ | $F_{\text{em}}$ | $F_{\text{ab}}$ | $F_{\text{em}}$ | $F_{\text{ab}}$ |
|--------|-------|-------------|------------|----------------|----------------|----------------|----------------|
| SWP    | 01543 | 43642.75860 | 8.14       | 3.0            | 2.3            | 10.2           | 5.1            |
| SWP    | 05830 | 44071.39234 | 8.71       | 4.8            | 0.9            | 4.9            | 2.6            |
| SWP    | 05831 | 44071.47761 | 10.6       | 4.6            | 1.0            | 6.3            | 2.6            |
| SWP    | 06614 | 44139.72653 | 13.0       | 7.7            | 3.1            | 4.4            | 2.5            |
| SWP    | 08938 | 44365.53453 | 7.90       | 6.9            | 1.4            | 3.4            | 1.0            |
| SWP    | 17386 | 45159.00706 | 12.7       | 8.9            | 2.8            | 4.5            | 1.7            |
| SWP    | 17408 | 45161.95042 | 10.5       | 5.9            | 2.2            | 2.3            | 2.0            |
| SWP    | 18009 | 45236.89806 | 12.4       | 6.2            | 2.9            | 3.4            | 2.4            |
| SWP    | 33431 | 47283.76895 | 13.0       | 5.7            | 2.7            | 3.0            | 2.1            |

mean uncertainty: 1.5, 3, 0.9, 0.6, 0.3

| Camera | Image | Julian date | $F_{2175}$ | $F_{2500}$ |
|--------|-------|-------------|------------|------------|
| SWP    | 01493 | 43642.72896 | 0.706      | 5.30       |
| SWP    | 05078 | 44071.38159 | 0.172      | 6.19       |
| SWP    | 05079 | 44071.41798 | 0.456      | 6.68       |
| SWP    | 05672 | 44139.69677 | 0.594      | 8.16       |
| SWP    | 05673 | 44139.74953 | 0.528      | 8.02       |
| SWP    | 07686 | 44365.56572 | 0.175      | 4.51       |
| SWP    | 13161 | 47283.82920 | 0.753      | 8.02       |
| SWP    | 13636 | 45158.93463 | 0.572      | 7.52       |
| SWP    | 13658 | 45161.90118 | 0.426      | 6.30       |
| SWP    | 13659 | 45161.99969 | 0.634      | 6.56       |
| SWP    | 14249 | 45236.92795 | 0.643      | 7.63       |

mean uncertainty: 1.7, 1.2