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A Model of the Circumstellar Envelope of Luminous Blue Variables

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Abstract The continuum energy distributions of the luminous blue variables R127 and R110 in the outburst phase are fitted with a circumstellar envelope model. Both stars show two peaks in their continuum, one near 1250Å and the other in the optical band. We suggest that their UV and optical fluxes may have different origins: the UV flux comes from the central star while the optical flux comes from an expanding circumstellar envelope. We construct a model for LBVs consisting of two LTE atmosphere models with different temperatures, and find it to be in agreement with the observed spectral energy distributions of R127 and R110. According to our numerical experiments, R127's continuum is composed of fluxes from a circumstellar envelope of $T_{\rm eff} = 8000\,{\rm K}$, $R = 485R_\odot$, and log $g = 1$, and from a central star of $T_{\rm eff} = 17\,000\,{\rm K}$, $R = 135R_\odot$, and log $g = 2.5$ with a permeating factor $f = 0.5$; while R110's continuum can be fitted by a circumstellar envelope of $T_{\rm eff} = 7000\,{\rm K}$, $R = 350R_\odot$, and $\log g = 0.5$, and a central star of $T_{\rm eff} = 25\,000\,{\rm K}$, $R = 27R_\odot$, and log $g = 3.0$ with a permeating factor $f = 0.65$. Both models show that the non-spherically symmetric, optically thick regions are formed surrounding the central star in the outburst phase. The light of the central star is shielded by the circumstellar envelope so that the visual brightness increases with the decrease/increase of the temperature/radius of the optically thick regions.

Key words: stars: variables: LBVs -stars: continuum spectrum -stars: mass loss

1 INTRODUCTION

Luminous blue variables (LBVs) are a separate class of massive stars. They are very evolved post main sequence stars or post red supergiants. Their most distinct character is irregular variations of brightness on various timescales. LBVs could undergo three types of variations: micro-variations of less than a few tenths of a magnitude on the timescale of weeks or months, moderate variations of 1 to 2 magnitudes on timescales of years to a decade, and giant eruptions with increases of more than 3 magnitude that may last for decades to hundred years[1](Bohannan 1997; van Genderen 2001). A general discussion of the LBV phenomenon can be found in Nota & Lamers (1997). While LBVs at the quiescent phase occupy a wide temperature range, the eruptive LBVs are located almost in a vertical strip on the HR diagram (Wolf 1989). Their continuum radiation at the minimum or quiescent phase shows the spectrum of hot supergiants. During the visual maximum period, the atmosphere of an LBV resembles a much cooler supergiant of spectral type A or F (Humphreys & Davidson 1994). Recent investigations focus on the instability of the moderate variations characterized by visual magnitude changes of 1 to 2 mag and timescales from years to decades.

On the basis of the opaque-wind model, Davidson (1987) predicted that a sudden increase in the mass loss rate could result in a 'photosphere' formed at several stellar radii with temperature at the maximum phase around 8000 K. This explains successfully the phenomenon that the temperatures of eruptive LBVs are all alike (around 8000 K) and that almost all eruptive LBVs lie in a vertical strip. However, some LBVs show that the visual brightness varies at a constant or even a lower $\dot{M}$ (Leitherer 1997). Thus, sure observational evidence for a general correlation between $\dot{M}$ and the brightness variation has not been forthcoming. de Koter et al. (1996) adopted an expanding atmosphere model and found that a drastic increase in the mass loss rate could not form a 'pseudo-photosphere' in the wind. They suggested that the variation of the visual magnitude occurring at a roughly constant luminosity was originated below the stellar photosphere. In their model a visual brightness variation might result from the expansion and contraction of the stellar envelope, and a high mass loss might not always result in optically thick regions. However, their model assumed $\dot{M}$ to be constant and isotropic throughout the atmosphere and ignored variable and anisotropic mass loss from the star, which could result in the formation of clump structure or shells in the wind. Therefore, the formation of optically thick regions in the wind is still not clear and should be checked in detail.

Investigations on the continuum spectra of LBVs are rare but desirable, because they may provide indications of their basic configuration and physical conditions. Stahl et al. (1983, 1990), Shore et al. (1996), and Szeifert et al. (1993) have studied R127, R110, R40 and AG Car. Their results hint at a general feature, namely the brightness variations in the UV and optical bands are anti-correlated. An increase of the brightness in the optical band is accompanied by a decrease in the UV band in the eruptive phase. However, an important feature of the continuum spectra of R127 and R110, namely the over-luminous component in the short-wavelength range (SWP, 1150–1980 Å) at the maximum phase, has not provoked enough interest of investigators up to now. Figure 1 shows the continuum energy distributions of R127 and R110 during the maximum phase. Stahl et al. (1990) suggested that this over-luminous UV component was most likely due to contamination of a faint and hot companion star. In their work the UV continuum of R110 was recovered by first assuming that the contaminating companion is an early B type star, then fitting a low temperature model of 7600 K to the observed continuum. In particular, their model could only fit the optical spectrum well, because the UV band was not real.

On the other hand, Nota et al. (1992) confirmed the presence of highly axial-symmetric features in the nebulosity of AG Car. Leitherer et al. (1994) also detected two wind components in AG Car; of these one is slow and dense and the other is fast but less dense. Schulte-Ladbeck et al. (1993) identified an equatorial circumstellar disk from the spectropolarimetry measurements of R127. These results imply that the wind of some LBVs might not be spherically symmetric. It is usually assumed that deposition of matter can form optically thick regions (Davidson 1987), but optically thin regions can also be formed simultaneously if the wind is anisotropic and/or if there is mass ejection. It shows that an asymmetric mass loss can result in the coexistence of optically thin and thick regions around the star, which allows the radiation from the star

[1] not all LBVs have giant eruptions

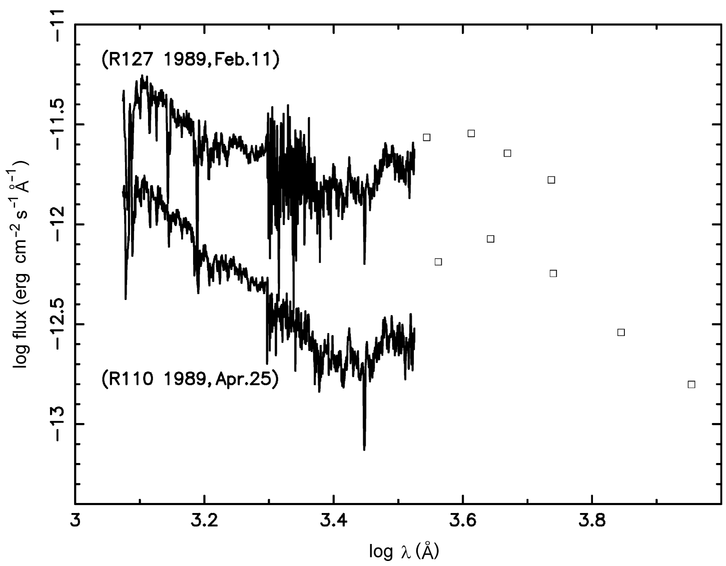

Fig. 1 Dereddened continuum energy distributions of R127 and R110 in the eruptive phase.

to be seen by observers. We suggest that the over-luminous continuum in the SWP range could be a part of the radiation from the central star. The radiation from the optically thick regions induced by the asymmetric mass loss is concentrated in the optical band, because these regions are far from the central star and therefore have lower temperatures. The combination of both radiation components may reproduce the observed continuum energy distributions. So, we decided to fit the observed continuum spectra of LBVs during the maximum phase with a model of two stellar atmospheres, one pertaining to the central star and the the other, to optically thick regions formed around the central star by an anisotropic mass loss.

In this paper, we concentrate on the LMC LBVs, R127 and R110, which have been studied by Stahl & Wolf (1986), Stahl et al. (1983, 1990) and Van Genderen et al. (1996). Their optical spectra during the maximum phase show the characters of middle A or early F stars (even early G). By comparing the photometric history of R127 in the published literature (Spoon et al. 1994; Stahl et al. 1983), we inspect two continuum spectra in the UV and optical bands: one belonging to the maximum state around 1990 and the other lying in a visual magnitude dip in 1983. The observed data of R110 are so sparse that a complete photometric history from the minimum to the maximum could not be obtained. So we only chose the data near the maximum state.

The rest of this paper is organized as follows: In Sect. 2 the observed data are summarized and in Sect. 3 the properties of the continuum spectra and the physical considerations are presented. In Sect. 4 we give a discussion on the results. Our conclusions are shown in Sect. 5.

2 OBSERVATIONS

2.1 Photometry

The UBV photometry of R127 (=HDE 269858) has been published and summarized by Stahl et al. (1983) and Spoon et al. (1994). In addition, R127 and R110 are included in a long-term project originated by Sterken (1983) of monitoring slow variations (LTPV) in the Strömgren uvby-system. The early data show that R127 attained a visual magnitude of 11.6^{m} in 1969 (Mendoza 1970). In the early 1980's the magnitude showed a fluctuation around 10^{m}. After 1983 the light curve of R127 climbed from the visual minimum in 1983 to the visual maximum around 1990. Afterwards the visual magnitude decreased slowly. The rising branch lasted approximately 1000 days during which the visual magnitude slowly increased from 10.2^{m} to 8.8^{m} (Spoon et al. 1994). In addition, the LTPV data were obtained on Nov. 30, 1988. Through the photometric history of R127 the maximum phase should be around 1990, but the minimum state cannot be accurately identified. Considering the visual magnitude vacillating around 10^{m} since 1980, we chose 1983 as a minimum despite this phase might just be a relative minimum over a limited period. In Table 1 we summarize these observational data. Regarding R110, the photometric history is not so clear. The visual magnitude increased from 10.4^{m} to 9.99^{m} during 1983–1989. Stahl et al. (1990) referred to an increase of the visual brightness by about 0.5^{m} in the last ten years and obtained UBVRI and JHK photometry in January 1989. The spectrum of R110 in the optical band was also similar to an F-type supergiant in 1989. We reviewed the data from LTPV and found that, from 1989 to 1992, the y band magnitude hovered around 9.9^{m} with a maximum amplitude of 0.1^{m}. van Genferen et al. (1996) found that R110 reached maximum with $V_J \sim 9.7$ in early 1993, which could indicate that the star was then in the eruptive state. An exact time of the minimum of R110 cannot be estimated from the published data. So, we just considered January 1989 as an outburst phase, and did not consider minimum state. The photometric history of R110 is summarized in Table 2.

Table 1 The photometric data of R127

Data	System	U	B	V	J	H	K	L	State	Ref.
Dec. 1969	$BVRI$			11.16					min	Mendoza (1970)
Feb. 16, 1983	UBV	9.21	10.23	10.13	9.76	9.58	9.4	8.850	min*	Stahl et al. (1983)
		u	v	b	y					
Nov. 30, 1988	$uvby$	9.82	9.36	9.10	8.84				max	LTPV

* a relative minimum during the interval of 1983–1992.

Table 2 The photometric data of R110

Data	System	U	B	V	R	I	J	H	K	State	Ref.
Jan. 1989	UBV	10.26	10.34	9.99	9.77	9.53	9.28	9.19	9.07	max	Stahl et al. (1990)
		u	v	b	y						
Sep. 26, 1990	$uvby$	12.31	10.90	10.27	9.91					max	LTPV

2.2 Spectral energy distributions from IUE

All spectra discussed in this paper were obtained from the database of the IUE satellite. The data consisted of a short-wavelength part (SWP, 1150–1980 Å) and a long-wavelength part (LWP and LWR, 1850–3350 Å) in low ($R = 300$) and high ($R = 10\,000$) resolution modes. All raw data have been reduced by the NEW SPECTRAL IMAGE PROCESSING SYSTEM (ref. IUE NEWSIPS manual, Nichols & Linsky 1996). We chose the spectral data around the maximum (1989) and minimum (1983) of R127. Considering our focus was on the continuum radiation, the low resolution spectra were preferred. We adopted the format of MXLO. The observations on R110 were very sparse. We chose the spectra on April 25, 1989 as an example of the maximum state. In Table 3 we collect the observed time, data format, exposure time, and so on.

Table 3 IUE Observations of R127 and R110

Object	Date	Camera	Aperture[a]	Dispersion[b]	Exposur time[min]	Image number	State
R127	1989 Feb.11	LWP	L	L	3	15013	max
	1989 Feb.11	SWP	L	L	15	35533	max
	1983 Mar.02	SWP	L	L	10	19372	min
	1983 Mar.02	LWR	L	L	6	15407	min
	1983 Feb.18	SWP	L	L	15	19287	min
	1983 Feb.18	SWP	L	L	15	19288	min*
R110	1989 Apr.25	LWP	L	L	30	15404	max
	1989 Apr.25	SWP	L	L	75	36088	max

[a] Aperture: L=Large; [b] Dispersion: L=Low; * include companion.

3 CONTINUUM ENERGY DISTRIBUTIONS

The ground based photometric data combined with the IUE data were used to make up the continuum energy distributions. We corrected the observed IUE spectra for interstellar reddening using the interstellar law of Savage & Mathis (1979) and Nandy et al. (1981) for the galactic foreground extinction and the absorption within the LMC. Considering that both stars are in the LMC, the same value of the interstellar extinction was used. The standard value $E(B-V)=0.05$ was used for the galactic foreground extinction, and the value E(B-V)=0.10 was used for the LMC. The photometric data were dereddened using the reddening law of Code et al. (1976) and Leitherer & Wolf (1984) for the visual and infrared bands, respectively. For the Strömgren uvby measurements an absolute calibration was carried out by Gray (1998). The conversion factors for $u=v=b=y=0.0$ mag are C_u=1.172 10^{-8}, C_v=8.66 10^{-9}, C_b=5.89 10^{-9}, C_y=3.73 10^{-9} in units of erg s^{-1} cm^{-2} $\mathrm{Å}^{-1}$. The corresponding wavelengths were adopted as the normal values.

3.1 R127

Figure 2 shows a minimum state spectral energy distribution of R127 (March 2, 1983). We fitted the continuum energy distribution with an LTE atmosphere model of $T_{\rm eff}=17\,000\,\mathrm{K}$, $R=135R_\odot$ and $\log g=2.5$, which is almost identical with the result of Stahl et al. (1983). This shows also that the calibration between the optical photometric data and UV spectral data is reasonable. Actually, for R127, the continuum spectrum could not define an absolute minimum because the V magnitude reached $11.16^{\rm m}$ in 1969 (Mendoza 1970), it just expresses a relative minimum from 1982 to 1992 (Spoon et al. 1994). Subsequently, the star entered a period of outburst until 1989 during which the visual brightness increased slowly while the UV flux decreased. The continuum energy distributions in the two states (cf. Fig. 2) are similar in the short wavelength part, which could mean a correlation between the quiescent and outburst states. Evidently, no atmosphere model can fit the essential feature of the continuum in the

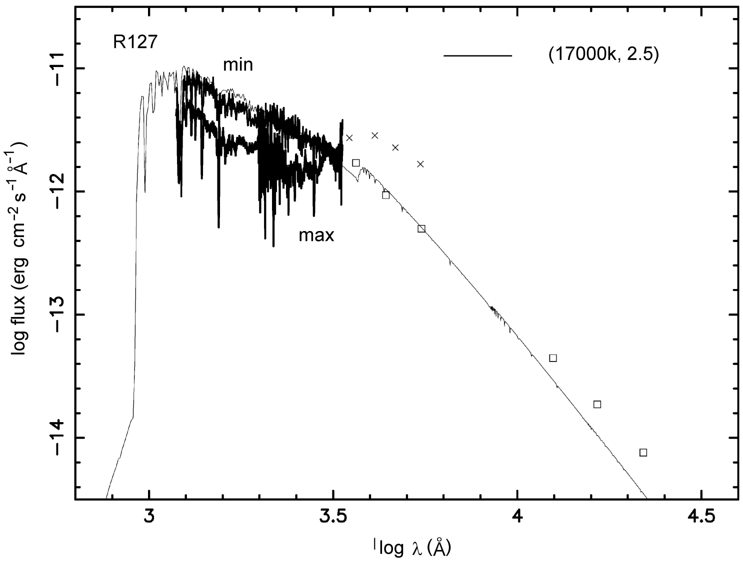

Fig. 2 Spectral energy distributions of R127 at the minimum (UV: Mar. 2, 1983; optical: Feb. 16, 1983) and maximum (UV: Feb. 11, 1989; optical: Nov. 30, 1988) states. The crosses are the photometric data at the maximum state, the diamonds, those at the minimum state.

outburst phase of having two peaks. The first peak, located at about 1250 Å, is a feature of B-type stars, the second peak that emerges around the Strömgren u band is a normal feature of A-type stars. Therefore, the observed continuum energy distribution of R127 in its outburst phase could come from two origins: the UV part originates mainly from a B-type star (R127 itself) and the optical flux, from an A-type star (the optically thick regions in the wind).

We have already stated that the flux in the SWP is higher at the minimum state than the maximum state, so the overall continuum energy distribution at the maximum state can be constructed with a permeating factor f, which measures how much light from the central star gets through the optically thin regions in the wind and eventually arrives at the observer. We simply multiply the model in the quiescent state by the factor f (less than 1) to account for the observed SWP continuum in the outburst phase, because we are not so clear about the process of radiative transfer through the optically thin regions or the configuration of the optically thick regions. Finally, the model at the outburst phase is constructed by adding the model of an A-type star to the modified minimum model of the central star (multiplied by factor f). We fitted the profile of the optical spectrum at the outburst phase with a model of $T_{\rm eff} = 8000\,{\rm K}$, $R = 485R_\odot$ and $\log g = 1$, which are the average physical parameters for the optically thick regions (strictly speaking, the optically thick parts should be defined by unit optical depth at the different wavelengths). In our numerical experiments, we found that a permeating factor $f = 0.5$ was appropriate to recover most of the observed features of R127. The fitted result is shown in Fig. 3, which shows satisfactory agreement with the observations. Comparing with Fig. 2 we find that the energy distribution at the minimum phase can be well fitted by using just one single atmosphere model, while in the outburst phase two atmosphere models with different temperatures are required.

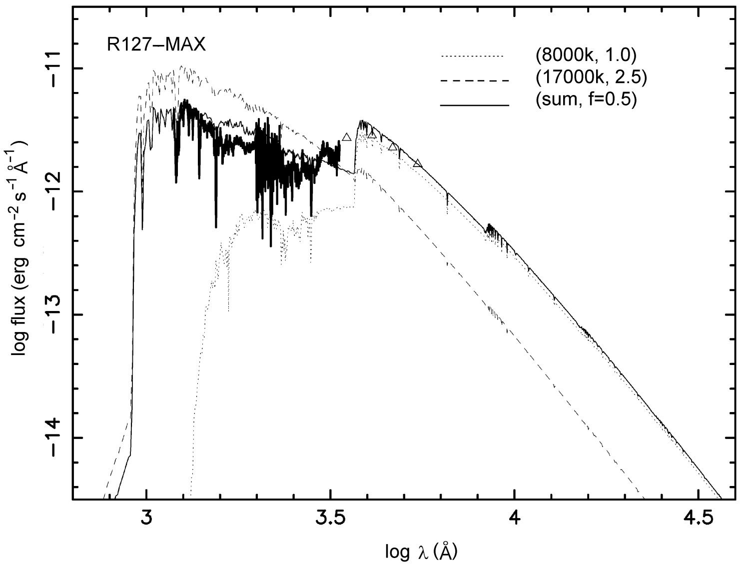

Fig. 3 Model of the circumstellar envelope of R127 at the outburst phase. The continuum energy distribution (UV: Feb. 11, 1989; optical: Nov. 30, 1988) is fitted by two atmosphere models of $T_{\rm eff} = 8000\,{\rm K}$ (dotted line) and $T_{\rm eff} = 17\,000\,{\rm K}$ (dashed line), and $f = 0.5$. The dereddened absolute fluxes at the effective wavelengths of the Strömgren uvby filters are marked by triangles.

The model detailed above has the disadvantage that the free parameters are not uniquely determined. A fluctuation of 1000 K is permitted due to the insensitivity of the continuum to temperature. Rather than attempting to explore the parameter space, the observations of the spectral lines during the maximum and minimum phases (Stahl et al. 1983; Stahl & Wolf 1986; Stahl et al. 1990) do indicate that the temperature and $\log g$ of our model are suitable.

We noticed that the Balmer jump is not as sharp as in normal supergiants, rather, it is very broad and flat, and our model cannot give it a good fit. The absence of the Balmer jump in the maximum phase has also been noticed in other LBVs, such as R40 (Szeifert et al. 1993).

3.2 R110

R110 increased its visual brightness by 0.5 mag from 1980 to 1989 (Stahl et al. 1990). However, the physical parameters in the minimum phase are not known clearly because the observations are too sparse. Around 1989 R110 attained the maximum phase during which the continuum energy distribution resembled R127's (cf. Fig. 4). Therefore, we fitted its continuum spectrum with the same technique used for R127. Over the visual spectral range a model of $T_{\rm eff} = 7000\,{\rm K}$, $R = 350R_\odot$ and $\log g = 0.5$ was applied. The parameters are comparable with the parameters derived by Stahl et al. (1990). For the whole continuum, including the UV and visual bands, we adopted a second component of $T_{\rm eff} = 25\,000\,{\rm K}$, $R = 27R_\odot$ and $\log g = 3.0$ with a permeating factor of 0.65. The result, shown in Fig. 4, can be seen to be consistent with the observations. The component of 25 000 K has not appeared in the published literature. Sanduleak (1969) derived a B6 type star for R110. However, the poor observations of R110 result in great uncertainties

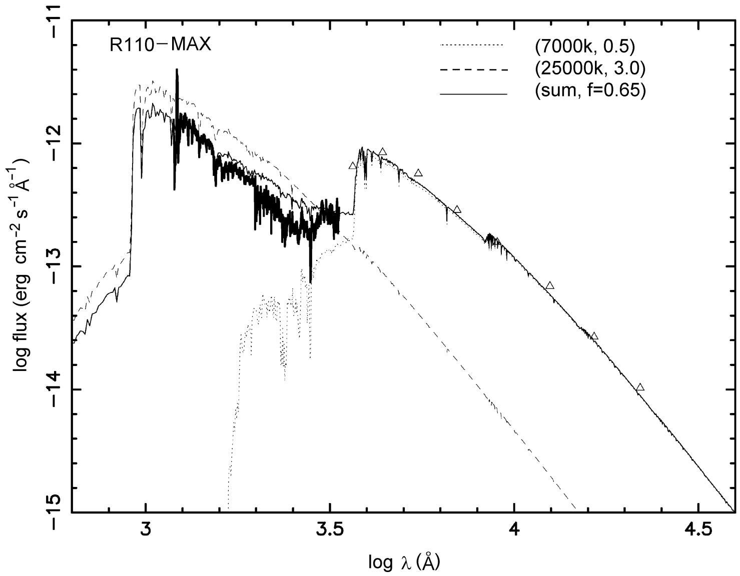

Fig. 4 Model of R110 at the maximum phase. The continuum energy distribution (UV: Apr. 25, 1989; optical: Jan. 1989) is fitted by two atmosphere models of $T_{\rm eff} = 7000\,$K (dotted line) and $T_{\rm eff} = 25\,000\,$K (dashed line), and $f = 0.65$.

on the determination of the minimum state. Moreover, the observations in the UV band are also very sparse for R110. Thus one cannot ignore the possibility of R110 being an early B star at the minimum phase.

4 DISCUSSION

Stahl et al. (1983, 1990) already referred to the possibility that the over-luminous component in the SWP of the continuum energy distribution could be the result of contamination by a hot nearby (non-physical) companion. In their papers it was shown that the IUE spectrum SWP No. 19287 (Feb. 18, 1983) of R127 avoided the contamination of the companion, and SWP No. 19288 (Feb. 18, 1983) included the companion. Thus the difference of the two spectra should roughly characterize the continuum spectrum of the companion in the SWP range. In addition, they derived a flux ratio of $F_{\rm R127}/F_{\rm companion}$ of 13 to 16 in the optical range. According to this result we can have a rough reconstruction of the continuum of the hot companion. As shown in Fig. 5, the continuum can be fitted by a model of $T_{\rm eff} = 20\,000\,$K. According to the argument of Stahl et al. (1990) the sum of the fluxes of the companion and the model of 8000 K (see Sect. 3.1) should explain the observed continuum of R127 in the maximum phase, because the model of 8000 K fits the optical band well.

However, such a view is not in agreement with the observations. The observed flux is much higher than the flux of the model involving a companion (cf. Fig. 5). To match the observations, a model of a higher temperature ($T_{\rm eff} \sim 10\,000\,$K) for the optical continuum of R127, or a more luminous companion with the flux increased by a factor of 2-3, is required. It has been known that the temperature of the optical continuum of R127 at the maximum phase is around 8000 K (van Genderen 2001), thus the first possibility is eliminated. In addition, the temperatures of

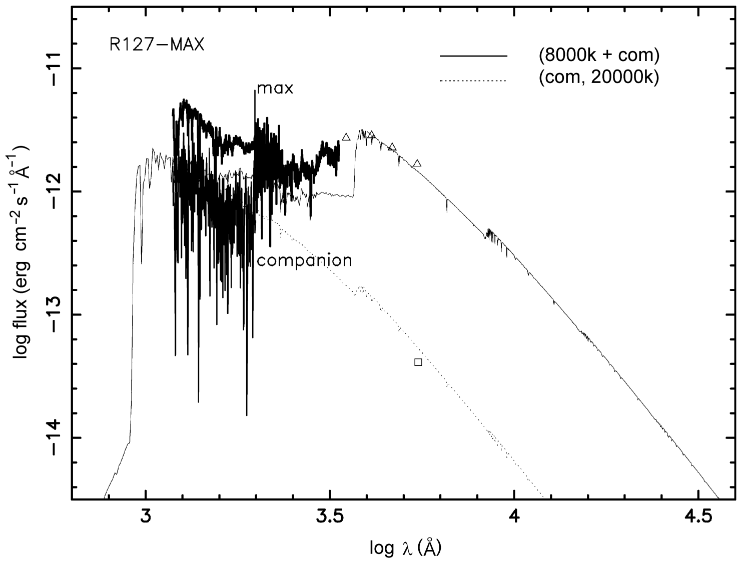

Fig. 5 Continuum energy distributions for a possible companion and R127 at the maximum state. The upper spectrum shows the outburst of R127, and the lower expresses the continuum of the companion. A fit has been made for the companion (dotted line). The sum of the fluxes of the companion and the model of 8000 K is shown by the solid line.

the LBVs at the maximum phase are considered to be fairly low, which means that their radiation fluxes are concentrated in the optical band and that they should be very faint in the UV band. This hints that almost all the observed UV flux comes from the companion if the companion contaminates the UV continuum. This requires that the companion is so luminous that its flux in the UV band is comparable to R127's at the minimum phase, which means that the companion should be a luminous supergiant instead of a faint star. Hence, the probability of contamination by a faint and hot companion is low. However, direct measurements of the companion in the UV band are difficult and unavailable; thus the possibility of contamination by the companion cannot be totally eliminated.

On the other hand there is some evidence that the wind in LBVs could not be spherically symmetric. Observations of R127 have revealed a red-shifted absorption component in singly ionized metallic lines after the photometric maximum, which seems to indicate the beginning of an envelope contraction episode. Surprisingly the IUE spectra taken during this phase do not show any significant variation (Wolf 1992). Szeifert et al. (1996) referred to a He I emission line appearing during the maximum phase of Var B in M33. These pieces of evidence seem to indicate that a non-spherically symmetric envelope surrounds the star and the variations of the UV and optical spectra come from different sources. Therefore, we suggest that an outburst in the LBV can form a non-homogeneous envelope in the extended atmosphere or wind, which is not optically thick in all directions, and radiation from the central star can leak out through the optically thin part of the envelope. The observed spectral energy distribution comes from the central star as well as the optically thick part of the envelope. By comparing Fig. 5 with Fig. 3 we see that our LBV model with a central star and a circumstellar envelope (composed of optically thin and thick regions, and not related to the circumstellar nebulae that are always observed around LBVs, farther away from the central star) can explain the over-luminous SWP continuum better than a single star or the contaminated model, so we consider the circumstellar envelope model to be a better model for explaining the outburst of LBVs. The mechanism of its formation could be the ram pressure formed equatorial excretion disk (Bjorkman & Cassinelli 1993), or the decoupling of gas and radiation field in the wind (Poter & Skouza 1999).

In addition, we see in Fig. 3 that the Balmer jump is not so conspicuous as in normal stars. A possible explanation is a decrease of neutral hydrogen due to collisions in the dense wind, or a release of the energy due to the recombination of hydrogen. In addition, the LBVs have more extended atmospheres in which the velocity field changes with the radius and the lines of the Lyman series could be spread out. Many broad lines on top of one another can also lead to a flat and broad Balmer jump. In fact, the model of hydrodynamic atmosphere combined with the process of radiation transfer is more suitable for the LBVs.

5 CONCLUSIONS

In this paper we discuss the continuum energy distributions of R127 and R110. The over-luminous continuum in the SWP range was previously regarded as the contamination by a faint companion. However, irregular mass ejection could form a non-stationary and non-continuous envelope, leading to appearance of clump structures in the wind. It is not appropriate for those models to apply a constant $\dot{M}$ and a smooth velocity law and to determine whether a pseudo-photosphere can form in the wind at the outburst phase of the LBVs. We point out an alternative possibility, namely, the over-luminous continuum in the SWP range is a contribution from the central star itself because the matter external to the star is asymmetric. The light emitted from the central star leaks out through the optically thin regions of the non-homogeneous circumstellar envelope. Our circumstellar envelope model explains the observations better than the contamination model. Based on the detailed research we conclude that the continuum spectra of both stars at the outburst phase are composed of radiation fluxes from the central star and the optically thick matter around the star, respectively engendering the observed UV and optical continuum spectra.

In our model the optically thick regions are far away from the central star. The ratio of the radius of the optically thick region to that of the central star is 3.6 for R127 and 13.0 for R110. The time interval between the maximum and the minimum of R127 is about 6 years, which means the average expanding velocity of the optically thick region is of the order of a few kilometers per second. This is less than the local sound speed ($\sim 10\,\mathrm{km\ s^{-1}}$), thus an obvious conjecture is that the expansion resembles a quasi-stationary process. Therefore, a possible evolutionary scenario is as follows. At the beginning of the outburst the star runs into some unstable process due to some physical instabilities which could have resulted in a variation of mass loss, for example, appearance of asymmetric mass loss or variation in the mass loss rate, and then the optically thick regions are formed surrounding the central star. These regions expand with a slow velocity outward ($\sim$1km $\mathrm{s^{-1}}$) and the average temperature decreases as they move away from the central star. During this process the visual brightness increases with the decrease of the temperature of the optically thick regions. Meanwhile the flux of the UV band decreases as well with the development of the optically thick regions, but it can maintain a considerable level due to the central star's flux escaping through the optically thin regions. The circumstellar envelope can be kept optically thick until around 8000 K when the opacity declines quickly due to recombination of hydrogen. Afterwards, the central star gradually emerges from the circumstellar envelope, the optically thick regions fade out, and the LBV goes back to the quiescent state.

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