Time-dependent effects in the wind of Luminous Blue Variables

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Abstract

Luminous blue variable (LBV) stars are characterized by strong photometric and spectroscopic variability on timescales from days to decades, arising from changes in stellar and wind parameters. Therefore, the common assumption of a steady-state outflow is invalid for LBVs. We present a newly-developed method to include the effects of time variability in the radiative transfer code CMFGEN. We found that time-dependent effects significantly change the velocity law and density structure of the wind, affecting the derivation of the mass-loss rate, wind terminal velocity, temperature, radius and luminosity. The results of our work are applicable to all active LBVs in the Galaxy and in the LMC, such as AG Car, HR Car, S Dor, and R 127, and could likely result in a revision of their stellar and wind parameters.

Introduction

The remarkable photometric variability of LBVs ($\Delta m_V > 3$ mag) have attracted the attention of astronomers since the photometric outbursts detected in P Cygni in the 1600s and η Car in the 1840s. Those events are currently understood as the ejection of several solar masses during a very short time interval of a few years (Humphreys & Davidson 1994; Smith 2006), and the physical mechanism which drives the ejection is still under debate.

LBVs also present strong photometric ($\Delta m_V \sim 1-3$ mag) and spectroscopic variability on timescales from days to decades, the so-called S-Dor type variability, which arises from changes in stellar and wind parameters (Humphreys & Davidson 1994; van Genderen 2001; Groh et al. 2007). The relationship (if any) between the giant outbursts *à la* η Car and the S-Dor type variability is yet unknown, and might provide key insights on the nature of LBVs.

In order to analyze the complex winds of those massive stars major improvements, such as the inclusion of wind clumping and a consistent treatment of line blanketing, have been incorporated into radiative transfer codes during the last decade (e.g. Hillier & Miller 1998; Gräfener et al. 2002; Puls et al. 2005). However, a steady-state outflow is still assumed by the models. While this is probably valid for single Wolf-Rayet and O-type stars, it is invalid for LBVs. A careful evaluation of the wind timescales, and how they compare to the variability timescale, is required to quantify the impact of time-dependent effects in the spectroscopic analysis of LBVs.

The flow timescale

The flow timescale ($t_{\rm flow}$) is the time required for the material ejected from the surface of the star ($R_\star$) to reach a distance r in the wind. Thus, a lower limit can be estimated as $(r - R_\star)/v$, where v is the wind velocity at r. Since the wind of LBVs usually have a beta-type velocity law, a more realistic $t_{\rm flow}$ can be obtained by integrating the inverse of the velocity law.

LBVs show a wide range of physical parameters, and the value of $t_{\rm flow}$ can vary significantly from minimum (i.e. hot) to maximum (i.e. cool) phases. We present in Figure 1 the flow timescale and the line formation region calculated for models assuming the physical parameters found in LBVs at minimum (panels a and b, respectively) and maximum phases (panels c and d, respectively).

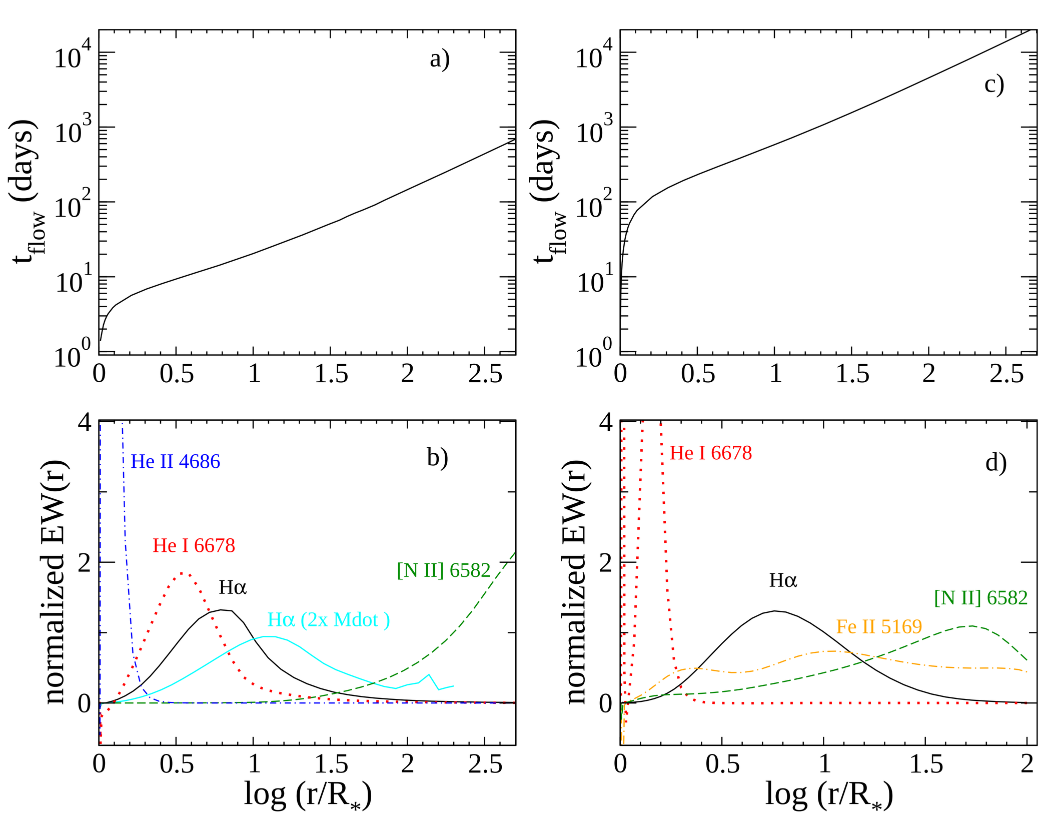

Figure 1: Flow timescale as a function of distance in the wind for minimum (i.e. hot) epochs (panel a) and maximum (i.e. cool) epochs (panel c). The formation region of the strongest diagnostic lines present in LBVs during minimum and maximum epochs are shown in panels b and d, respectively. Notice that the flow timescale can be large for Hα even during minimum.

At minimum phases, $t_{\rm flow}$ is less than a 100 days for distances up to 100 $R_\star$. All the diagnostic lines typically used in the spectroscopic analysis (e.g. He II 4686, Hα, He I 6678) are formed in the inner 100 $R_\star$ region, which translates into a small impact of time-dependent effects. During maximum phases, however, $t_{\rm flow}$ increases dramatically, as the wind terminal velocity is typically 4 times lower than during minimum, and the stellar radius is increased by a factor of 8 (Stahl et al. 2001; Groh et al. 2007). Therefore, it is anticipated that most diagnostic lines will be affected by time-dependent effects. Moreover, physical parameters obtained through steady-state models will be significantly biased. As can be seen in the right panels of Figure 2, time-dependent effects are especially crucial to model Hα, which has an extended line formation region, yielding a large flow time of $t_{\rm flow} = 300 - 1000$ days.

It is important to point out that, as LBV stars have very dense winds, the recombination timescale is very short (few days) for distances smaller than $\sim 500\ R_\star$. Typically, $t_{\rm flow}$ is at least one or two orders of magnitude larger than the recombination timescale, and hereafter we neglect the latter. The recombination timescale, however, is important to study the radio-wavelength formation region ($\sim 1000 R_\star$).

Including time-dependent effects in the radiative transfer code CMFGEN

The long flow timescales found for LBVs will change significantly the wind density structure, and the velocity field. We developed a code to obtain a realistic description of $v(r)$ and $\rho(r)$, and use them as an input to the radiative transfer code CMFGEN (Hillier & Miller 1998). The main steps involved in our implementation are:

1. We consider two epochs: epoch 1 (initial), and epoch 2 (final), which are separated in time by Δt days. We assume that the physical parameters of the star are known for epoch 1, while they will be determined for epoch 2 accounting for time-dependent effects.
2. We obtain rough values for the wind terminal velocity and stellar radius for epoch 2, using a CMFGEN steady-state model. The refined values are determined later through a detailed spectroscopic analysis.
3. We determine the flow timescale for epoch 2:
$$t_{flow}(r) = \int_{R_\star}^{r'} (v_\infty - v_0)^{-1} (1 - R_\star/r)^{-\beta}\, dr' \ .$$
4. Using $t_{\rm flow}$, we calculate how the wind "terminal velocity" and $\dot{M}$ change as a function of r. We assume both vary linearly as a function of time:
$$v_\infty(r) = v_{\infty,i} + \frac{(v_{\infty,f} - v_{\infty,i})[\Delta t - t_{flow}(r)]}{\Delta t} \ ,$$
$$\dot{M}(r) = \dot{M}_i + \frac{(\dot{M}_f - \dot{M}_i)[\Delta t - t_{flow}(r)]}{\Delta t} \ .$$
5. The velocity field is then obtained, assuming a beta-type law at each point and a constant value of $v_0 = 5.0\ \mathrm{km\,s^{-1}}$:
$$v(r) = v_0 + [v_\infty(r) - v_0][1 - R_\star(r)/r)^\beta] \ .$$
For $v < v_0$, the beta-type law is smoothly connected to a hydrostatic structure.
6. Finally, the density structure, which includes the effects of clumping through a volume filling factor $f(r)$, is derived using the equation of mass continuity:
$$\rho(r) = \frac{\dot{M}(r) f(r)^{-1/2}}{4\pi r^2 v(r)} \ .$$

Effects in the spectrum

Whenever the stellar parameters present strong variability, such as in LBVs, the spectrum computed by CMFGEN under the assumption of a steady-state outflow will be significant different compared to the spectrum generated by time-dependent models. This happens due to the large changes in the density structure and velocity law of the wind. Figure 2 illustrates how dramatic those changes can be, showing the case of an LBV star evolving from a minimum state towards a maximum state. The stellar parameters change from $T_\star = 26500\,\mathrm{K}$, $R_\star = 56 R_\odot$, $L = 10^6 L_\odot$, $\dot{M} = 1.5 \times 10^{-5} M_\odot \mathrm{yr}^{-1}$, $v_\infty = 312\mathrm{km\,s^{-1}}$ during minimum to $T_\star = 13800\,\mathrm{K}$, $R_\star = 172 R_\odot$, $L = 10^6 L_\odot$, $\dot{M} = 6.5 \times 10^{-5} M_\odot \mathrm{yr}^{-1}$, $v_\infty = 115\mathrm{km\,s^{-1}}$ towards maximum, after a time interval of Δt=230 days.

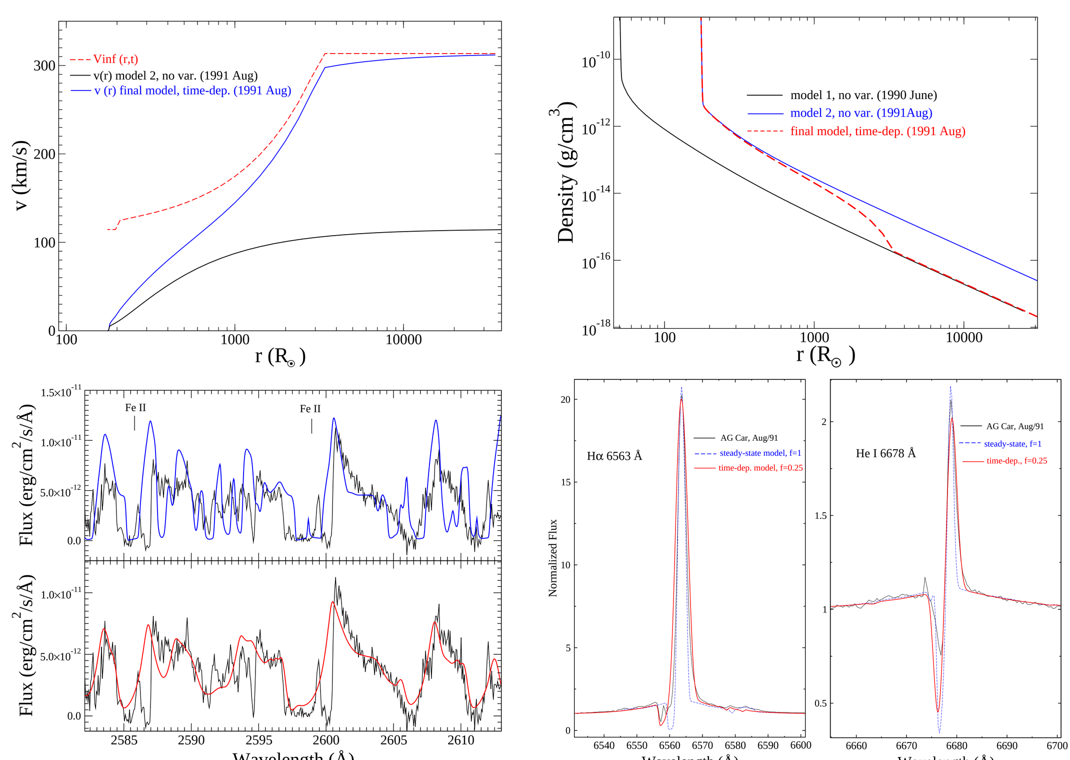

Figure 2: Comparison between the velocity structure (top-left) and density structure of the wind (top-right) obtained with steady-state and time-dependent models. The bottom row shows the comparison of the ultraviolet (bottom-left) and the optical spectrum (bottom-right) of the LBV AG Carinae with synthetic spectra calculated by the radiative transfer code CMFGEN. The use of time-dependent models improves significantly the fit, especially in the ultraviolet region.

Several striking features present in the spectrum of LBVs can be explained by time-dependent effects (Groh et al. 2008, in prep.), such as the constant presence of a high-velocity P-Cygni absorption component in the ultraviolet lines of some LBVs (e.g. AG Car, Leitherer et al. 1994). We suggest this is due to the presence of a fast fossil wind ($v_\infty \sim 300\mathrm{km\,s^{-1}}$) from the previous minimum phase, located at distances of hundreds of stellar radii, which absorbs stellar radiation in the resonance lines. This phenomenon is illustrated in Figure 2 (bottom-left panel).

Results: the case of AG Carinae

We analyzed the 20-year spectroscopic and photometric evolution of AG Carinae, which has been the most variable LBV in the Galaxy in the last decades (van Genderen 2001). We obtained the stellar parameters using CMFGEN, taking into account the time-dependent effects in the velocity field and density structure as outlined above. Further details about the observational data, technique, and results can be found in Groh et al. 2007, Groh 2007, and Groh et al. 2008, in preparation.

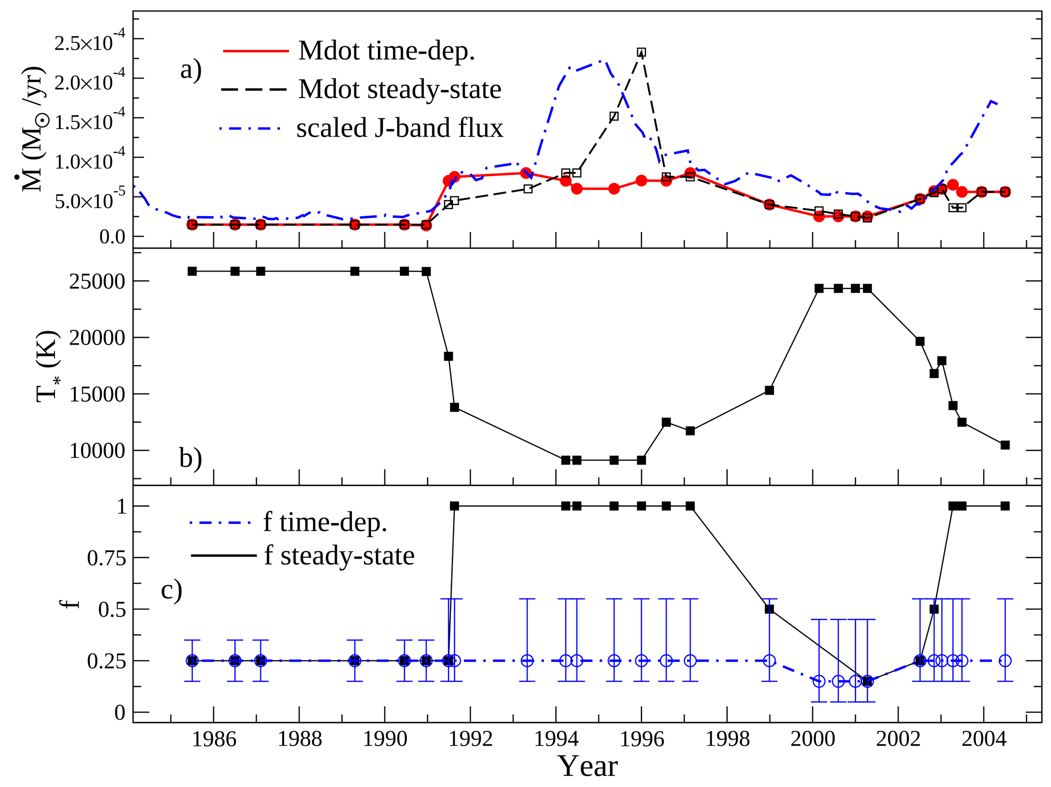

Figure 3: Evolution of the mass-loss rate (panel a), stellar temperature (b) and volume filling factor (c) during the last 20 years for AG Car.

To highlight the need for time-dependent models, we show in Figure 3 (panel a) the evolution of the mass-loss rate of AG Car during the last 20 years, comprising two full S-Dor cycles, obtained from our CMFGEN modeling. The J-band lightcurve is also shown as a reference for the maximum and minimum phases. Striking differences are seen in the results obtained by steady-state models and time-dependent models. The steady-state models predict an increase in the mass-loss rate from minimum to maximum, with a peak of very high mass-loss rate around the lightcurve maximum.

However, when time-dependent effects are taken into account, the mass-loss rate still increases from minimum to maximum, but without a peak of very high mass-loss rate around maximum. Instead, the mass-loss rate reaches approximately a constant value during the maximum phase. Indeed, the apparent peak in the mass-loss rate during maximum obtained by steady-state models is an artifact caused by the neglecting the time-dependent effects in the density structure. Those effects have a key impact in the formation of Hα and other strong emission lines which are formed by recombination and thus are density-squared dependent. As Hα and other strong hydrogen lines are usually the main diagnostics for the mass-loss rate, *extreme* caution is neeeded if they are used to derive the mass-loss rate for active LBVs, such as AG Car, and S Dor.

AG Car is a special laboratory to study the behavior of the wind clumping as a function of temperature, since $T_{\rm eff}$ changes from $\sim 8000\,\mathrm{K}$ to $\sim 26000\,\mathrm{K}$. While at minimum the volume filling factor is typically 0.15–0.25 (Figure 3), the derivation of f during maximum is more complicated, since a reasonable knowledge of the wind density structure is required. We found out that the assumption of a steady-state outflow is invalid and will provide biased results.

Summary & Conclusions

The inclusion of time-dependent effects in the radiative transfer codes is required to obtain reliable stellar and wind parameters for active LBVs, as shown here for AG Car. Ongoing work by our group might lead to significant revision of stellar and wind parameters of those active LBVs, and might provide key insights on the evolution during the LBV phase. The long flow timescales of LBVs have a significant impact on the density structure and velocity law of their wind, which makes steady-state models usually invalid for active LBVs. We conclude that the strongest lines present in the spectrum of LBVs, such as Hα, Hβ, Paβ, and Brγ, will be the most affected by time-dependent effects. Therefore, the stellar parameters obtained from those lines obtained when assuming a steady-state outflow will be biased. Especially, the derivation of the mass-loss rate will be strongly affected, since the aforementioned recombination lines are proportional to the square of the density. Our implementation is also especially useful to derive the mass-loss rate of the most distant LBVs, and of the so-called *Supernova impostors*, where usually only Hα or other strong hydrogen line can be observed.

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