*Clumping in Hot Star Winds*
*W.-R. Hamann, A. Feldmeier & L.M. Oskinova, eds.*
*Potsdam: Univ.-Verl., 2008*
*URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981*

# Mass-loss rate and clumping in LBV stars: the impact of time-dependent effects

**J.H. Groh** [1], **D.J. Hillier**[2] **& A. Damineli**[3]
[1] *Max-Planck-Institut für Radioastronomie, Germany*
[2] *University of Pittsburgh, USA*
[3] *Universidade de São Paulo, Brazil*

This paper outlines a newly-developed method to include the effects of time variability in the radiative transfer code CMFGEN. It is shown that the flow timescale is often large compared to the variability timescale of LBVs. Thus, time-dependent effects significantly change the velocity law and density structure of the wind, affecting the derivation of the mass-loss rate, volume filling factor, wind terminal velocity, and luminosity. The results of this work are directly 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 result in a revision of stellar and wind parameters. The mass-loss rate evolution of AG Car during the last 20 years is presented, highlighting the need for time-dependent models to correctly interpret the evolution of LBVs.

## 1 Introduction

In order to analyze the complex winds of 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 el 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 LBV stars.

LBVs are characterized by strong photometric and spectroscopic variability on timescales from days to decades, arising from changes in stellar and wind parameters (Humphreys & Davidson 1994; van Genderen 2001). 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.

## 2 The flow timescale

The flow timescale ($t_{\text{flow}}$) 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 $r$. As the wind of LBVs usually have a beta-type velocity law, a more realistic $t_{\text{flow}}$ can be obtained by integrating the inverse of the velocity law.

As LBVs show a wide range of physical parameters, the value of $t_{\text{flow}}$ 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).

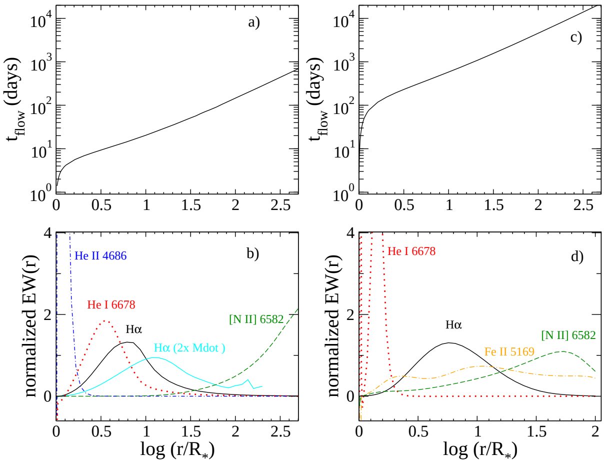

Figure 1: Flow timescale as a function of distance in the wind for minimum phases (panel *a*) and maximum phases (panel *c*). The formation region of the strongest diagnostic lines used to analyze minimum and maximum phases is also shown in panels *b* and *d*, respectively. Notice that the flow timescale can be large for H$\alpha$ 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 used in the spectroscopic analysis (e.g. He II 4686, H$\alpha$, He I 6678, etc.) are formed in the inner 100 $R_\star$ region, which translates to 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 1, time-dependent effects are especially crucial to model H$\alpha$, which has an extended line formation region, with $t_{\rm flow} = 300 - 1000$ 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.

## 3 Including time-dependent effects in 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 code are:

1. We consider two epochs: epoch 1 (initial), and epoch 2 (final), which are separated in time by $\Delta t$ 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 $v_0 = 5.0$ 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 continuity:

$$\rho(r) = \frac{\dot{M}(r) f(r)^{-1/2}}{4\pi r^2 v(r)} \ .$$

## 4 Results: 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. 2006, Groh 2007, and Groh et al. 2007.

### 4.1 Mass-loss rate evolution

To highlight the need for time-dependent models, we shown in Figure 2 (panel *a*) the evolution of the mass-loss rate of AG Car during the last 20 years, comprising two full S-Dor cycles. 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. This is qualitatively similar to the results obtained by Stahl et al. 2001, besides quantitative differences due to the inclusion of clumping and full line blanketing in our models.

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 H$\alpha$ and other strong emission lines which are formed by recombination and thus are density-squared dependent. As H$\alpha$ and other strong hydrogen lines are usually the main diagnostics for the mass-loss rate, *extreme* caution has to be used if they are used to derive the mass-loss rate for active LBVs, such as AG Car, HR Car, R127 and S Dor.

### 4.2 How clumpy are LBV winds?

Another interesting result obtained from the analysis of the AG Car spectra is the evolution of the volume filling factor $f$ during the S-Dor cycle, which is shown in Figure 2 (panel *c*). As the physical parameters of the star and the wind are very different from minimum to maximum, AG Car is an ideal laboratory to study how of the wind clumping changes as a function of the stellar temperature (panel *b* of Fig.2), for instance.

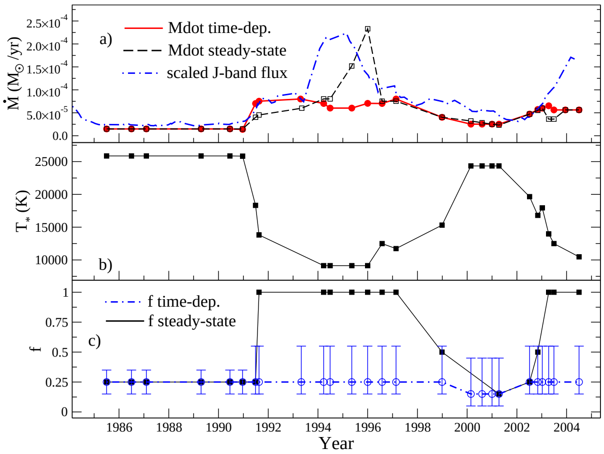

Figure 2: Evolution of the mass-loss rate (panel *a*), stellar temperature (*b*) and volume filling factor (*c*) during the last 20 years for AG Car.

The results obtained using steady state models show that $f$ increases from 0.25 during minimum (high $T_{\rm eff}$) to 1.0 during maximum (low $T_{\rm eff}$). This happens because the electron-scattering wings become very strong during maximum, and they are used to constrain the value of $f$. However, the change in $f$ occurs in a short timescale of 3 months, which is difficult to be explained.

When time-dependent models are used, the changes in $f$ as a function of time are small or none at all. The changes compared to the steady-state results are due to a modified density structure due to the long flow timescale of the wind (order of a few years). Therefore, because the density structure of the wind is modified compared to the steady-state models, strong electron-scattering wings are present for smaller values of $f$ in time-dependent models.

Moreover, we assume for simplicity that the mass-loss rate and wind terminal velocity change linearly as a function of time. Different variations as a function of time also produce changes in the electron-scattering wings, which can account for the observed line profiles. Clearly, time-dependent models are required to derive the volume filling factor of LBV winds.

## 5 Summary and Conclusions

The long flow timescales of LBVs have a significant impact in the density structure and velocity law of the wind, which makes steady-state models usually invalid for active LBVs.

Strong hydrogen recombination lines such as H$\alpha$, H$\beta$, Pa$\beta$, and Br$\gamma$ are formed through a large volume of the wind, and are the most affected by time-dependent effects. Therefore, physical parameters obtained using those lines will be biased, especially the mass-loss rate, and the aforementioned emission lines are proportional to the square of the density.

The inclusion of time-dependent effects in the radiative transfer codes is required to obtain reliable stellar and wind parameters for such 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.

## References

Gräfener, G., Koesterke, L., & Hamann, W.-R. 2002, A&A, 387, 244

Groh, J. H. 2007, PhD Thesis, Universidade de São Paulo (Brazil)

Groh, J. H., Hillier, D. J., & Damineli, A. 2006, ApJL, 638, L33

Groh, J. H., Damineli, A., & Hillier, D. J. 2007, astro-ph/0702612

Hillier, D. J. & Miller, D. L. 1998, ApJ, 496, 407

Humphreys, R. M. & Davidson, K. 1994, PASP, 106, 1025

Puls, J., Urbaneja, M. A., Venero, R., et al. 2005, A&A, 435, 669

Stahl, O., Jankovics, I., Kovács, J., et al. 2001, A&A, 375, 54

van Genderen, A. M. 2001, A&A, 366, 508

**Najarro:** The radio variability of LBVs is usually explained in terms of changes of ionization rather than to flow of the material, due to the short time scale of the variability. Have you checked the effects of ionization fronts associated with your radial dependent mass loss?

**Groh:** The recombination time scale is an order of magnitude lower than the flow time scale, therefor I think that, even for the radio emission, the long-term variability will be dominated by changes in the $\dot{M}$ and $v_\infty$. But you are right, the ionization fronts will dominate the radio variability on shorter time scales of days to months.

**Smith:** If a slightly faster wind is overtaking a slow wind, and the flow time scale is comparable to the variability time scale, you may expect hydrodynamic instabilities to develop in the slower shell that may induce large scale clump formation. Have you considered this?

**Groh:** No. Right now I only consider changes in the velocity law and density structure as a function of time. The faster wind will only overtake the slow wind during minimum, and for those epochs I use lines formed in the inner wind as diagnostics for the stellar parameters. As the interaction between fast and slow wind will produce a non-monotonic velocity field, I cannot deal with that in the radiative transfer at the moment.