RevMexAA (Serie de Conferencias), **33**, 132–134 (2008)

LBVs AND THE NATURE OF THE S DOR CYCLES: THE CASE OF AG CARINAE

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RESUMEN

Presentamos los resultados de un análisis espectroscópico detallado sobre 20 años de observaciones de AG Carinae, usando el código de transferencia radiativa llamado CMFGEN. Entre las conclusiones de este trabajo, resaltamos la importancia de incluir efectos dependientes del tiempo en el análisis del ciclo completo de S Dor. Hemos obtenido que la tasa de pérdida de masa es aproximadamente constante durante las fases frías, implicando que las erupciones en los objetos de tipo S Dor comienzan bastante más temprano que durante el máximo observado en la curva de luz visual. Hemos determinado además que los ciclos S Dor son, en última instancia, consecuencia de un aumento/disminución del radio hidrostático en combinación con una pseudo-fotosfera.

ABSTRACT

We present the results of a detailed spectroscopic analysis of 20 years of observations of AG Carinae using the radiative transfer code CMFGEN. Among the conclusions of this work, we highlight the importance of including time-dependent effects in the analysis of the full S Dor cycle. We obtained that the mass-loss rate is approximately constant during the cool phases, implying that the S Dor-type eruptions begin well earlier than the maximum seen in the visual lightcurve. We also determined that the S Dor cycles are ultimately a consequence of an increase/decrease of the hydrostatic radius in combination with the formation of a pseudo-photosphere.

Key Words: stars: early-type — stars: individual (AG Car) — stars: mass loss

1. AG CAR IN CONTEXT

The massive star AG Carinae has been the most variable object among the Galactic luminous blue variables during the last 20 years. Dramatic photometric changes of 3 magnitudes in the V band have been recorded, while the stellar spectra have indicated effective temperatures ranging from about 9kK to 25 kK. AG Car is a rare member of the LBV class that shows strong S Dor-type variations and is surrounded by a bipolar nebula.

This work is a result of a monitoring campaign spanning 20 years of observations of AG Car to obtain its stellar and wind parameters for each epoch. The first results were discussed in Groh et al. (2006), highlighting the first observational evidence of fast rotation in LBVs. The evolution of both stellar (effective temperature, radius, luminosity) and wind parameters (mass-loss rate and wind terminal velocity) along the S Dor cycle, and the correlations among them, provide significant insights about the physical processes going on during this short and unstable evolutionary stage.

2. SPECTROSCOPIC MODELING

The physical parameters of AG Car were obtained through spectroscopic modeling using the radiative transfer code CMFGEN (Hillier & Miller 1998), which allows a simultaneous solution of the radiative transfer and rate equations. Spherical geometry and steady state are assumed to solve those equations, while clumping is included using a depth-variable filling factor. Fully-blanketed models were calculated for AG Car, taking into account the presence of over than 50,000 transitions of H, He, C, N, O, Si, P, Na, Mg, Fe, Mn, Co and Ni.

For the first time in the analysis of LBV winds, time-dependent effects were included consistently in the velocity law and density structure of the wind assuming that the mass-loss rate and wind terminal velocity change linearly as a function of time (Groh et al., in prep.). Significant differences can be seen in the fits obtained with a time-dependent model in comparison with a steady-state model, especially in the ultraviolet region (Figure 1).

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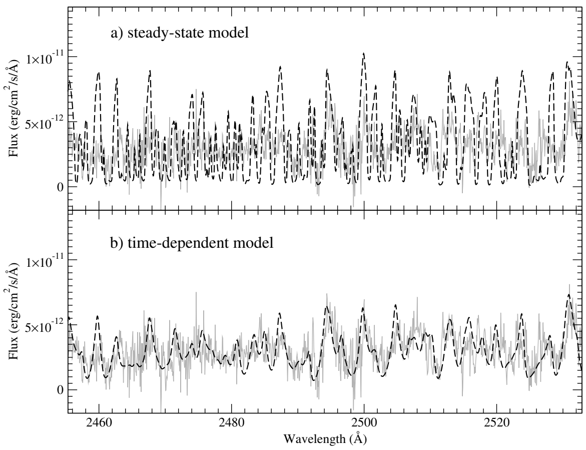

Fig. 1. Comparison between the ultraviolet spectrum of AG Car taken in 1991 October (grey) and a steady-state model (panel *a*, dashed) and a time-dependent model (panel *b*, dashed). The better quality of the time-dependent fits is remarkable.

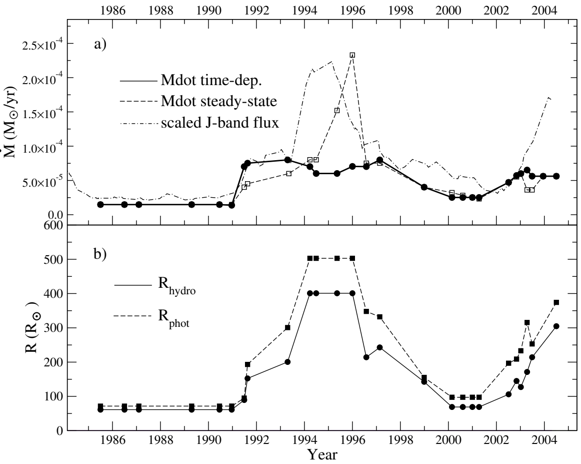

Fig. 2. Evolution of the mass-loss rate (panel *a*) and of the hydrostatic and photospheric radius (panel *b*) of AG Car during the S Dor cycle.

TABLE 1

STELLAR PARAMETERS DURING MINIMUM

Epoch	$R_\star$ $R_\odot$	$T_{\rm eff}$ (K)	$\dot{M}$ ($M_\odot {\rm yr}^{-1}$)	v_∞ (km s^{-1})
1985–1990	62	23,800	1.5×10^{-5}	300
Apr 2001	69	20,500	2.5×10^{-5}	105

3. RESULTS AND CONCLUSIONS

3.1. *Comparison between the minimum epochs*

The stellar and wind parameters are different during consecutive minima as derived from the analysis of spectra taken in 1985–1990 and 2001 (Table 1). During those epochs, a significant difference of ~ 3000 K in $T_{\rm eff}$ is noticed. In addition, a remarkable difference is seen in $\dot{M}$ (which is 2 times higher in 2001 than in 1985–1990) and v_∞ (3 times lower in 2001). We interpret the changes in $\dot{M}$ and v_∞ as a consequence of the bistability of line-driven winds (Lamers et al. 1995). Indeed, there is a change in the iron ionization structure around the sonic point, as predicted by Vink & de Koter (2002). The dominant iron ionization stage below the sonic point (which is around 18 km s^{-1}) changes from Fe^{3+} in 1990 to Fe^{2+} in 2001.

3.2. *The mass-loss rate evolution*

Figure 2 (panel *a*) shows the mass-loss rate evolution along the S Dor cycle obtained from steady-state and time-dependent models. As a result of the large flow timescale ($\sim$ 5 years) during the cool phases, significant differences are derived when time-dependent effects are taken into account. In special, $\dot{M}$ is actually approximately constant during the cool phase (1991–1999), in comparison with a strong increase in $\dot{M}$ around maximum when steady-state models are used. Thus, the results obtained from time-dependent modeling imply that the eruptions during the S Dor cycles begin well earlier than the maximum seen in the visual and near-infrared lightcurve. In addition, it is misleading the idea of an increase in $\dot{M}$ as a consequence of the maximum – actually, the maximum in the lightcurve is a consequence of the increase in $\dot{M}$ which occurred 2 or 3 years ago, in the beginning of the cool phase.

3.3. *Changes in the photospheric and hydrostatic radius*

The evolution of the photospheric and hydrostatic radius of AG Car during the S Dor cycle is presented in the panel *b* of Figure 2. It is apparent to conclude that *the S Dor-type variability is driven mainly by changes in the hydrostatic radius of the star*. Changes in the photospheric radius do occur as a result of the dense wind and variable mass-loss rate, but this change solely is not sufficient to explain the strong temperature changes seen from minimum to maximum.

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DISCUSSION

P. Williams - Do you see changes in the infrared colors which could indicate higher wind contribution when the mass-loss rate is higher?

J.H. Groh - Actually the near-infrared colors are dominated by free-free emission from the wind during the whole cycle. The value of $J-K$ is pretty much constant during the cycle, implying that hot dust formation is negligible during the S Dor cycle.

N. Walborn - Normal OB supergiants already have processed material at their surfaces, which may increase during the LBV phases. The spectra of AG Car and other LBVs change remarkably from light minimum to maximum, from peculiar late-O/early-B (with/without He II 4686 emission) to A like S Doradus. The issue of $M_{\rm bol}$ change or not is very important to the underlying mechanism. It appeared that your minimum model did not fit He II 4686. Might that indicate a higher T and $M_{\rm bol}$, thus less of an increase in the latter to maximum?

J.H. Groh - He II 4686 is very sensitive to the temperature in this regime, which means that a small increase of 500 K in the temperature of the best model is sufficient to fit this line (at the expense of worst fits to other lines). The fits to He II 4686 have a negligible impact on the determination of the bolometric luminosity, as the latter is derived by matching the model and observed flux distributions from the ultraviolet to the near-infrared.

A. Maeder - Do you account for convection in your models since it is normally an unavoidable consequence of a star being close to the $\Omega\Lambda$ limit? A second question: are you able to monitor the evolution of $v\,sin(i)$ during the change of radius of AG Carinae?

J.H. Groh - Convection is not included in the CMFGEN models, and it would be very interesting to explore this possibility in the future. Regarding the evolution of $v\,sin(i)$ as a function of radius during the S Dor cycle, we determined that $v\,sin(i)$ is approximately proportional to ${R_\star}^{-1}$ (Groh et al. 2006).

G. Koenigsberger - What is the timescale for the recurrence of activity? Is there any periodicity or quasi-periodicity?

J.H. Groh - There is a quasi-periodicity of around 10 years for the recurrence of activity, which is typical for strong S Dor-type variability (van Genderen 2001). However, it is important to stress that there are different timescales of outburst/recovery from cycle to cycle.

N. Smith - The original idea for S Doradus-type outbursts of LBVs was that a pseudo-photosphere makes the star look cooler, but then some studies in the past decade or so argued that it was simply an increased radius of the star. Now you are suggesting that it is in fact both. So my question is how much of the apparent ΔT is caused by the radius change and how much by the pseudo-photosphere?

J.H. Groh - The changes in the hydrostatic radius of the star account for most of the temperature changes seen from maximum ($\sim$ 9000 K) to minimum ($\sim$ 25000 K). The formation of a pseudo-photosphere is an unavoidable consequence of the high wind density and variable mass-loss rate. The extension and the decrease in temperature caused by the pseudo-photosphere is variable and depends on the epoch. Typically, $T_{\rm eff}$ decreases by about 2000–3000 K due to the presence of the extended photosphere.