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ORIGINAL ARTICLE

Investigating the semi-regular light variations of the bright M5 supergiant: α Herculis

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Abstract Analysis of over 15 years of V-band and Wing three filter near-IR photometry of the bright M5Ib-II supergiant has been carried out. Wavelet analysis of these data reveals that the star pulsates with several complicated oscillation modes. Different time scales of variability are identified, and with the aid of discrete Fourier analysis, depending on the filter, up to seven significant pulsation modes are identified and their frequencies and amplitudes extracted. The Long Secondary Period (LSP) with a mean period of ∼1343 d has been identified, as well as other periods of the order of ∼125 d. The longer period appears to be attributed to the radial pulsational mode, while the various peaks near ∼125 d appear to arise from stochastically excited p-modes. After removing the light contribution of the 5th magnitude binary companion and calibrating the intermediate-band photometry to the Wing photometric system, TiO (719 nm) and near-IR (B-C) Wing color indices were formed. These indices have been calibrated with T_{eff}, while the Wing-C bandpass (1025 nm) serves as a proxy for bolometric magnitude and was transformed to approximate m_{bol}. Finally, the derivation of the variations in the star's temperature, luminosity and radius is straightforward.

Keywords Star: α^1 Her · Method: DFT, wavelet · Parameters: temperature, luminosity, radius

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1 Introduction

A long-term photoelectric and spectroscopic monitoring of bright nearby supergiants has been a part of an ongoing project at Villanova University for more than 15 years, and a valuable dataset has developed for the luminous red supergiants α Her, α Ori, α Sco, and TV Gem, and the blue supergiant β Ori. Studying such a dataset helps understanding the growth and decay of pulsation modes in such evolved semi-regular supergiant stars, their chaotic behavior and internal structure. In this paper we present initial results for α Her.

AGB stars are among the most complex stellar systems ever discovered, since they cover more than 10 orders of magnitude in size scale, 30 orders of magnitude in density scale, and 7 orders of magnitude in temperature scale. The LSP which is present in up to 50% of red supergiants (Percy and Sato 2009), and moderate mass loss rates attest α Her to be an AGB star (the surface abundance ratio of $^{12}C/^{13}C$ as a complementary test is not examined here (Lattanzio and Wood 2004). The nature of pulsations of these stars is still the subject of debate in the literature, especially the LSP (Wood et al. 2004; Nicholls et al. 2009). Moreover, Christensen-Dalsgaard et al. (2001) predict beating with solar-type pulsations as the main cause of semi-regularity, since excitation of p-modes is expected from those stars that develop extensive outer convection zones. Bedding (2003) has identified some SRc stars exhibiting non-radial modes from the study of their visual light curves from AAVSO archive. Bedding et al. (2005) have discovered a single mode resolved into multiple peaks under a narrow envelope in the Discrete Fourier Transform (DFT) spectra of L_2 Pup, and verified that it is stochastically excited. In this work we pursue these two aspects.

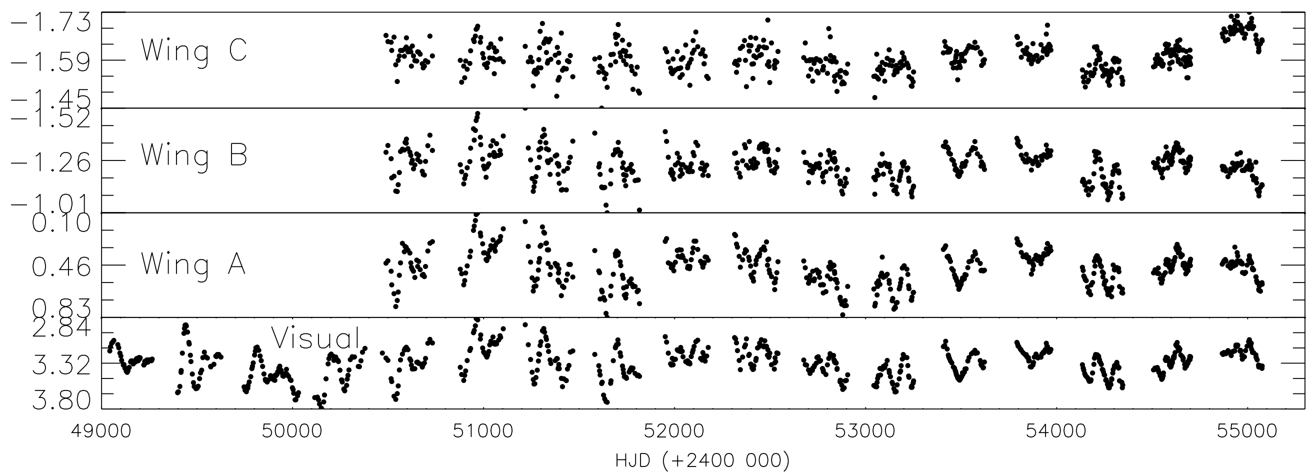

Fig. 1 Observed V-band, TiO, continuum, and near-IR photoelectric light variations of α Her, details of which are addressed in Table 1. The cycle to cycle chaos and irregularity in the *light curve* suggests α Her to be classified as an SRc pulsator

2 Physical properties of α Her

The M5Ib-II supergiant α^1 Her (HD 156014) is the luminous V $\sim$ 3.5 mag component of a triple star system. Its resolved 5.5 mag companion α^2 Her is more than 500 AU distant and this component is itself a close double-line spectroscopic (G5III + F2V) binary. α^1 Her has an Hipparcos parallax (Perryman 1997) of $\pi(\text{Hipp}) = 8.53 \pm 2.80$ mas ($\sim$120 pc). Interferometry of α^1 Her yields an angular diameter of 34 ± 0.8 mas, which, at the assumed Hipparcos distance, corresponds to a radius of $\sim$400 $R_\odot$ (Benson et al. 1991). Photometry of α^1 Her indicates that the star is a semi-regular pulsating light variable of $\sim$0.1 to 0.3 mag with systematic light variations occurring on time scales of months to several years. For α^1 Her, the measured effective temperature is $\log T_{\text{eff}} = 3.52$, bolometric luminosity is $\log L/L_\odot \simeq 3.93$, and $R/R_\odot \simeq 275$ (see Sect. 5). In addition, α^1 Her has a relatively large mass loss rate of $\dot{m} = 3 \times 10^{-8}\ M_\odot/\text{year}$, with an outer dust/gas circumstellar shell expanding with a terminal velocity $\sim$10 km/sec (Deutsch 1956).

3 Observations

The photoelectric monitoring of this star in Johnson V started from late February 1993, and in Wing filters from mid-February 1997, and it is still on-going; the V-band light curve is constituted by 681, and in the other three filters 498 data points. The sampling is uneven with an average time spacing of $\sim$5 days within each observing season. HD 154595 and HD 154143 were used as comparison and check stars, respectively. Figure 1 shows the light curve corrected to yield the standardized apparent magnitudes in all four filters, and Table 1 summarizes the details of our observation.

Table 1 α Her observation details

Filter	wavelength (FWHM) $\sim$Å	max (mag)	min (mag)
Johnson V	5500 (700)	+2.768	+3.624
A (TiO)	7190 (110)	+0.093	+0.817
B (continuum)	7550 (110)	−1.519	−1.012
C (near-IR)	10250 (420)	−1.707	−1.449

4 Fourier and wavelet frequency analysis

Employing Period04 software (Lenz and Breger 2005) each DFT spectra is prewhitened to identify individual modes; mode extraction is curtailed if the signal-to-noise ratio at that specific frequency reaches the value 4. Consequently, eight individual modes are identified in visual, three modes in A filter, six in B filter, and finally four in C filter; the frequencies and the amplitudes are listed in Table 2, with a common 10^{-3} c/d multiplier factored out from all listed frequencies to conserve space, and the amplitudes expressed in mmag (in all four filters, the statistical significance of the fit, χ^2 is at least 5.52e-3, and the uncertainty from least-squares fitting δ is at most 0.37%). The modes denoted by F_i in Table 2 appear to be non-radial low degree high order p-modes, due to the similarity of a hump around the frequency at $\sim 8 \times 10^{-3}$ c/d to those of the Sun and other cool solar-type pulsators. In this respect, this is another example of the detection of stochastically excited modes in M-type supergiants (Christensen-Dalsgaard et al. 2001), Fig. 2.

Employing weighted wavelet Z-transform method (Foster 1996), the time series are divided into bins of $\Delta t = 100$ days; next the profile of period and amplitude within each bin is found; so the time evolution of the star's pulsation can be tracked by joining the results in every bin, sequentially.

Table 2 Summary of the identified pulsation frequencies and amplitudes of modes above 4σ significance limit F_i in the form ν_i, A_i extracted by Period04 in increasing frequency order (except for the LSP). Note that the common factor of 10^{-3} c/d is factored out from all frequencies, and all amplitudes are in mmag

Filter	LSP	F_1	F_2	F_3	F_4	F_5	F_6	F_7
V	0.699, 95	1.64, 35	5.41, 45	5.76, 30	7.48, 26	7.84, 43	7.96, 86	11.17, 40
A	0.748, 107	8.04, 70	8.47, 42					
B	0.785, 53	0.959, 25	8.02, 39	8.20, 39	9.23, 25	11.02, 35		
C	0.747, 20	4.90, 13	5.49, 17	8.05, 13				

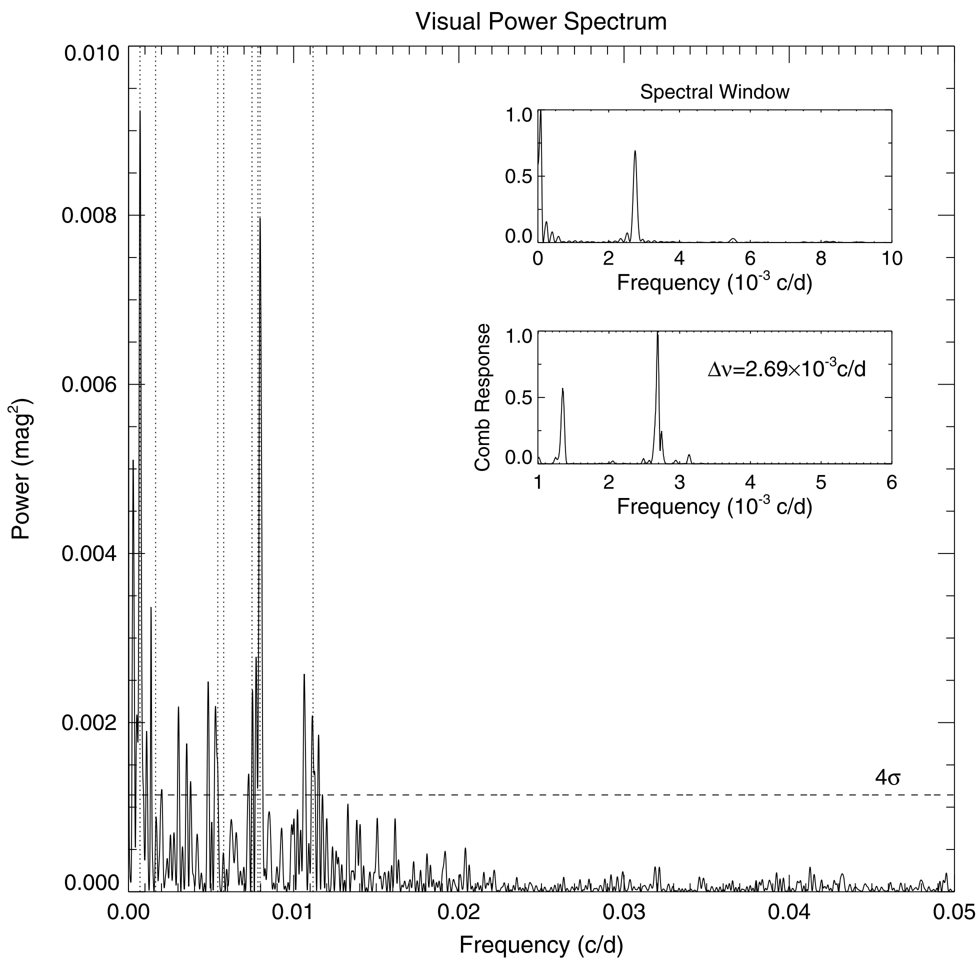

Fig. 2 DFT power spectrum of the *light curve* in Johnson V filter. The *top inset* is the spectral window through which the star was observed, showing two dominant peaks, one very close to zero frequency (due to finiteness of the time series), and another at 2.737×10^{-3} c/d (due to annual gapping in the time series); see Table 2. The high peak at very low frequencies corresponds to the LSP with a period of 1431 days, and the period of the maximum of the solar-type hump is 126 days

Figure 3 is the resulting wavelet plot for the V-band light curve (see bottom panel in Fig. 1).

5 Changes in luminosity, effective temperature, and radius

Calibrating the three Wing filters (Wing 1992), a derivation of the variations of the luminosity $L/L_\odot$, effective temperature $T_{\rm eff}$, and radius $R/R_\odot$ as functions of observation time is straightforward. From the knowledge of the magnitude in the TiO filter A, the magnitude in the continuum band B, and the magnitude in the near-IR band C two color indices γ_1 and γ_2 are defined (Neff et al. 1995), namely

$$\gamma_1 = (\mathrm{B} - \mathrm{C}), \quad \text{TiO-index} \equiv \gamma_2 = \mathrm{A} - \mathrm{B} - 0.13\gamma_1. \qquad (1)$$

Eighteen mid K to late M stars are selected from the Wing standard-star list (Wing 1978) to calibrate TiO-index versus $T_{\rm eff}$; fitting a polynomial of order two to these standard stars and extracting the best fit coefficients yields (Levesque et al. 2005),

$$T_{\rm eff} = 3540 - 690.2\gamma_2 + 498.4\gamma_2^2. \qquad (2)$$

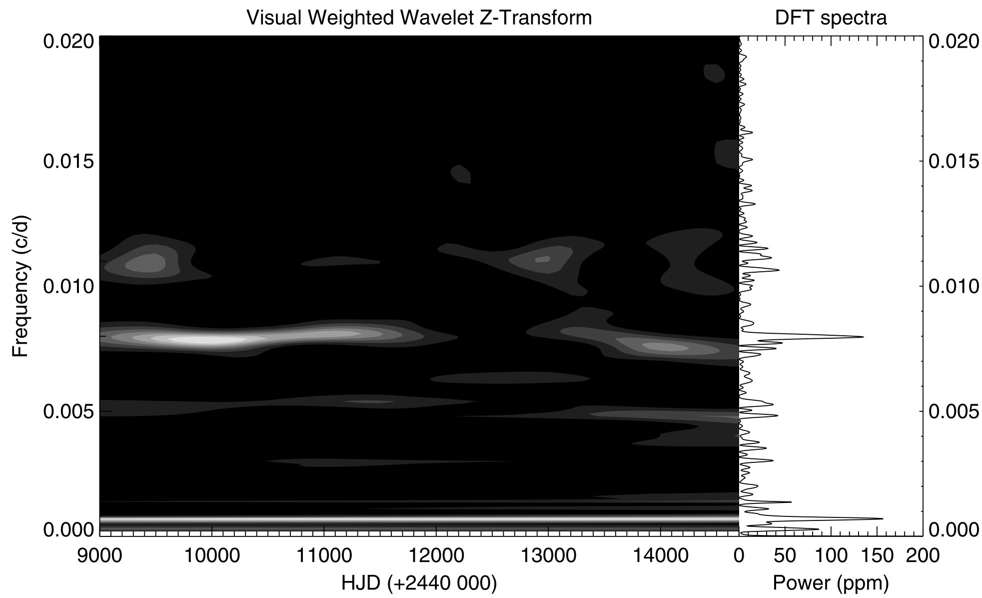

Fig. 3 Weighted wavelet Z-transform according to Foster (1996) for the light curve in the V-band on the left panel. The right panel is the DFT spectrum of the same time series, plotted as a means of comparison

Table 3 The meant extreme measures of $T_{\rm eff}$ (°K), $L/L_\odot$, and $R/R_\odot$ average and extremum values for α Her, found through the calibration with a sample of standard stars. See (1) to (5)

	Mean	Min	Max	|Max – Min|/Mean
$T_{\rm eff}$ (°K)	3350	3315	3415	3.0%
$L/L_\odot$	8600	7450	9500	23.8%
$R/R_\odot$	275	255	295	14.5%

Since absorption in the near-IR filter is not pronounced, the observed magnitude in the C filter can be corrected to yield the bolometric magnitude $m_{\rm bol}$

$$m_{\rm bol} = C + 1.75\,(\pm.07). \tag{3}$$

Owing to the fact that α Her resides 117 ± 28 pc, we can easily compute its absolute bolometric magnitude, and hence its luminosity with respect to the solar luminosity ($L_\odot$)

$$L/L_\odot = 10^{(4.76 - M_{\rm bol})/2.5}, \qquad M_{\rm bol} = m_{\rm bol} - 5.34, \tag{4}$$

where 4.76 is the absolute bolometric magnitude of the Sun. The Stefan law can be finally employed to yield the time variation of the radius

$$R/R_\odot = (L/L_\odot)^{1/2}\,(5779/T_{\rm eff})^2. \tag{5}$$

6 Discussion

Except the LSP which seems coherent in all passbands (see the left panel in Fig. 3), our photometry distinguishes a total of 17 independent pulsation modes with SNR > 4 in four filters. Some frequencies listed in Table 2 are more and less common in other filters, while some other ones are not present. For instance, the identified frequency of LSP varies from 0.699×10^{-3} to 0.785×10^{-3} c/d. Similarly, the maximum of the hump ranges from 7.96×10^{-3} to 8.05×10^{-3} c/d in different filters. The F_7 mode in the V filter appears at another close frequency in the Wing B filter, but has no counterpart in the Wing A and C filters; investigating Table 2 thoroughly gives more examples of this case. Finally, some modes such as F_1 in the V and Wing B filters are unique and are not seen in other bandpasses. This calls for a more detailed analysis of the frequencies to exclude possible false modes. Season-by-season analysis of the light curve (not presented here) justifies the presence of modes with their corresponding periods in the range ∼12–160 d, and with light amplitudes lying in 10–438 mmag interval. This direct evidence from the empirical study of the light curves is good support to identify stochastically excited p-modes predicted by Christensen-Dalsgaard et al. (2001).

As seen in Table 3 the major variations in temperature, luminosity and radius occur at the period of LSP. Yet, no certainty has reached in explaining the mechanism behind the LSP (Kiss and Bedding 2003; Wood et al. 2004; Nicholls et al. 2009), but within all suggestions, binarity seems the least possible guess. The reason is that the orbital parameters of the system (Sect. 2) are well known, and neither the period of the companion around the primary, nor that of two members of companion itself meet the period of LSP. While our ground-based observations is secure enough to study the LSP, the duty cycle is rather poor for the analysis of the non-radial modes, and it calls for uninterrupted space-based observations, to verify if beating with solar-type pulsations is the cause of semi-regularity in pulsating

AGB stars. We hope to receive data from the first year run of BRITE-Constellation (Kaiser et al. 2008).

Not only the internal structure of α Her A as an AGB star is poorly understood, but also its seismic modeling looks challenging. Pulsationally, a glance at the last column of Table 3, and inspection of the light curve within each observation season admits that α Her is a non-adiabatic pulsator, with strong signatures of mode interaction; hence a non-linear non-adiabatic algorithm may be consulted to properly take the mutual role of convection and pulsation into account and match the observed frequencies (Tables 2 and 3).

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