

# Tracking Live Evolution of Semiregular Pulsators

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## Abstract

Cool, massive, evolved stars known as red supergiants show light variations on time scales of the order of months to years. Their variability corresponds to different phenomenon, most prominent of which is extensive surface convection. After distinguishing two different variability time scales, which must cautiously be called eigenperiods, the change in period and amplitude of pulsations of  $\alpha$  Her over time is shown as an example of such stars through wavelet analysis, and some open questions are introduced.

## Introduction

Seismic modeling of massive evolved stars is yet an uncertain issue in astrophysics, and the study of such stars will bring a wealth of information on some yet undiscovered aspects such as rotational mixing, meridional circulation, semi-convection, strong convective overshooting, and mass loss, involved in the structure of red supergiants. This uncertainty rises from the lack of precise and uninterrupted photometric and spectroscopic observations, and can be pursued in two ways. The first reason is due to the patience required in monitoring light variations in such long-period pulsators, and the second comes from the saturation problem of observing instruments. Owing to the fact that the variability amplitude in some red pulsators is several magnitudes, they sometimes do not fit within observing capabilities of most instruments. That's why some bright red pulsators in the night sky are not studied in detail. Long-term photoelectric and spectroscopic monitoring of bright nearby supergiants have been pursued at Villanova University and with such data sets that span more than a decade, we are able to track the growing and decaying pulsational modes in such stars. Supergiants are classified due to their amplitude of oscillations and the degree of regularity in their light curves into SRa, SRb, and SRc, in order of increase in chaotic behavior in light curves. Among several datasets at our disposal, V-band photometric data of  $\alpha$  Her is selected as a means to find period and amplitude variations throughout the time.

According to the modeling by Ostlie and Cox (1986), the corresponding radial oscillations of such stars are heat-driven in partial ionization zones of H I-II II and He I-He II. With very extensive atmosphere, there is a strong (and yet unsecure) correlation between the convection and pulsation in SRc stars. Under recent consideration by Wood *et al.* (2004) is the origin of the second long period pulsation and low degree  $g$ -mode oscillations combined with large-scale spots offering the most likely interpretation. There is no global agreement on classification of red variables as SRa/b/c/d and this notion is poorly defined, Mattei *et al.* (1997). Two key ideas to help differentiate between semi-regular subclasses are the small difference in chemical composition resulting in different mass loss efficiencies, and the existence of quasi-periodic cycles due to the formation of shock waves and the propagation of such shocks in the dilute outer atmospheres of evolved supergiants. Christensen-Dalsgaard (2001) proposes beating with solar-like oscillations (with longer periods than the main sequence stars) which is confirmed by Kiss and Bedding (2003) after studying OGLE database, as the cause of semi-regularity. The reason can be traced to the development of large outer convection envelopes, see Lebzelter and Hron (2008). If such a prediction becomes confirmed observationally, then red supergiants will attract much attention, and provide a great potential to study the complex interior of red supergiants at their late stages of evolution through asteroseismology.

An interesting issue in such red supergiant pulsators- like  $\alpha$  Her - is the presence and the question of nature of the secondary long-period component in their light curves. Percy (2007). After frequency analysis of 48 red pulsators, Percy (2009) shows that about one third of such variables show this secondary companion. His analysis also reveals that this two time scales are an order of magnitude different.

## Physical properties of $\alpha$ Her

The bright (2.7 - 3.6 mag) red supergiant M5 Iab star,  $\alpha$  Hercules (HD 156014), is the most massive member of a triple star system (consisting of G5 III and F2 V components). This red supergiant is the brightest star in the Hercules constellation, with 2000.0 coordinates  $\alpha = 17h 14m 38.8s$ ,  $\delta = +14^{\circ} 23' 25.2''$ . This evolved, cool red supergiant has the following properties:  $M/M_{\odot} \sim 14$ ,  $R/R_{\odot} \sim 400$ ,  $T_{\text{eff}} = 3200$  K. As reported by Hipparcos (1997), its measured parallax is  $\pi'' = 8.53$  mas (120 pc).  $\alpha$  Her is a close neighbor of the Mira on the upper right portion of instability strip in the HR diagram. It is important to understand evolved massive red supergiants such as  $\alpha$  Her because this star (along with Antares and Betelgeuse) are nearest Type II SN progenitors.

## Observations

Our photometry (with HD 154595 as the comparison star, and HD 154143 as the check star, Wasatonic(1997)) carried out over the last 15 years indicates the star to be an SRc semi-regular pulsator with visual magnitude that varies from  $m_V = 2.7$  to 3.6 mag, see also Percy (2001). The photometry is carried out in three other filters too, as TiO band -on line/ off line at 7190 Å at a continuum band of 7550 Å (off TiO in a line-free region) and an approximately line-free near-IR band at 10250 Å. The V-band data for a M5 star that pulsates tracks mainly temperature changes since the V-band is full of TiO bands that get stronger with decreasing  $T_{\text{eff}}$ . The 10,250 Å filter measures luminosity. All of these can be used to measure and analyze  $L$ ,  $T_{\text{eff}}$ , and radius changes. Such data sets are also available for other semiregulars. Table 1 summarizes the detail of our observation.

Table 1.  $\alpha$  Her observation details.

Filter	wavelength Å	FWHM ~Å	Starting Time <sup>b</sup>	Ending Time <sup>b</sup>	$N^a$	min (mag)	max (mag)
V	5500	700	9043	14701	681	2.768	3.624
TiO	7190	100	10489	14701	498	.093	.817
continuum	7550	100	10489	14701	498	-1.519	-1.012
near-IR	10250	300	10489	14701	498	-1.707	-1.449

<sup>a</sup> This is the total number of observation point available in the specified filter.

<sup>b</sup> All values are in HJD, and a common factor of +2440000 is subtracted from this column.

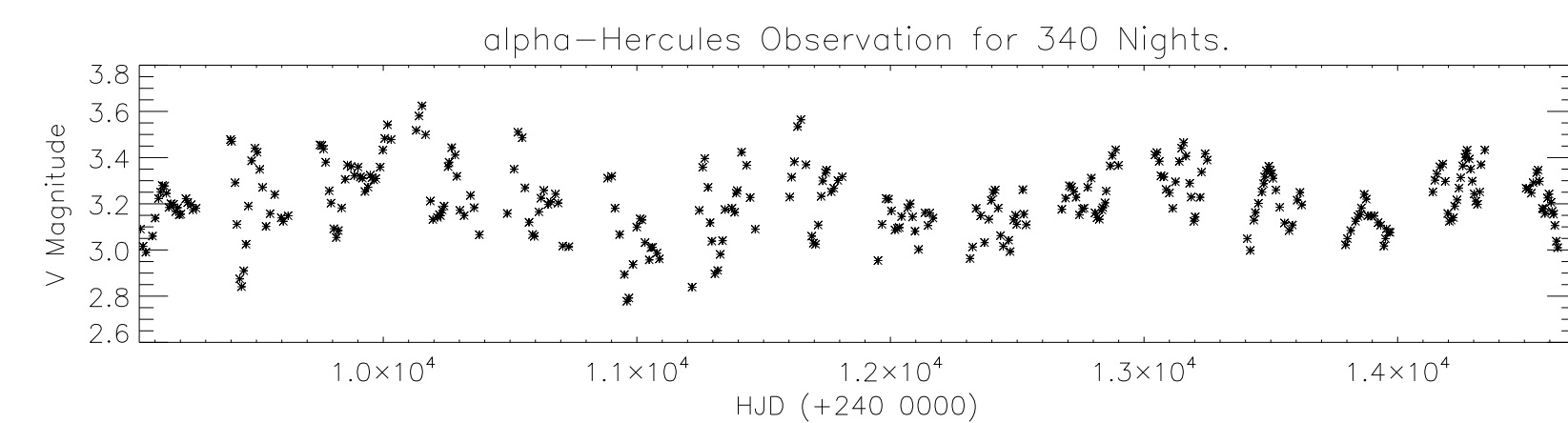


Figure 1. Observed V-band photoelectric light variations of  $\alpha$  Her from HJD 2449043 to 2454701. The cycle to cycle chaos and irregularity in the light curve suggests  $\alpha$  Her to be classified as an SRc pulsator. The average spacing between successive data points-ignoring large (6 month) gaps- is an order of a week. While Fourier based frequency analysis methods suffer from aliasing due to the presence of gaps, the wavelet transform survives from this issue.

## Variability

As a semi-regular pulsator, we expect  $\alpha$  Her to switch between modes throughout the time, and one may track the live evolution of such stars depending on the ratio of the mode life time  $\tau$  and observation time span  $T$ . Consider a mode with frequency  $\nu_0$

$$m(t) = a \cos(2\pi \nu_0 t + \delta), \quad (1)$$

and then, the power spectrum, after carrying out a Fourier transform to frequency space, and multiplying the result by its complex conjugate, is found to be the sinc function

$$\bar{m}(\omega) = \int dt m(t) e^{-i\omega t}; \quad P(\omega) = |m(\omega)|^2, \quad (2)$$

where  $\omega$  is the frequency. Plotting  $P(\omega)$  as a function of  $\omega$  reproduces the classical Lomb-Scargle periodogram. The presence of nightly and annual gaps complicates the power spectrum, and makes the analysis difficult. The case gets more complicated when the pulsation mode has a decaying constant  $\eta = 1/\tau$ , then the visual magnitude of the target varies over time as

$$m(t) = a \cos(2\pi \nu_0 t + \delta) \exp(-\eta t), \quad (3)$$

with a Lorentzian power spectrum

$$P(\nu) = \frac{a^2}{4(\nu - \nu_0)^2 + \eta^2}, \quad (4)$$

which is the expected character of stochastically excited modes. However, the case is more sophisticated if the amplitude  $a$  and frequency  $\nu_0$  are not stationary and are time-varying parameters. Such a star can oscillate at each cycle with an amplitude and frequency that can be slightly (or severely) different from those of the previous and future cycles. What we are interested in, for semi-regular pulsators, is to know the amplitude and frequency of the pulsations as a function of time.

Generally, one's approach to analyze any variable star's light curve lies in one of the following categories:

- If  $T \gg \tau$ , then one can observe the growing and decaying modes in the power spectrum of the star. In this case, the Fourier-based algorithms fail to deduce the true frequency and amplitude of the modes, unless our time series is binned into parts that we know it had a constant period/amplitude. A wavelet analysis is the best tool at hand to fulfil our demand in this case, Foster (1996).
- In the opposite sense, if  $T \ll \tau$ , then the mode can be assumed stationary, and a Fourier-based method such as CLEANest works well, Foster (1995).

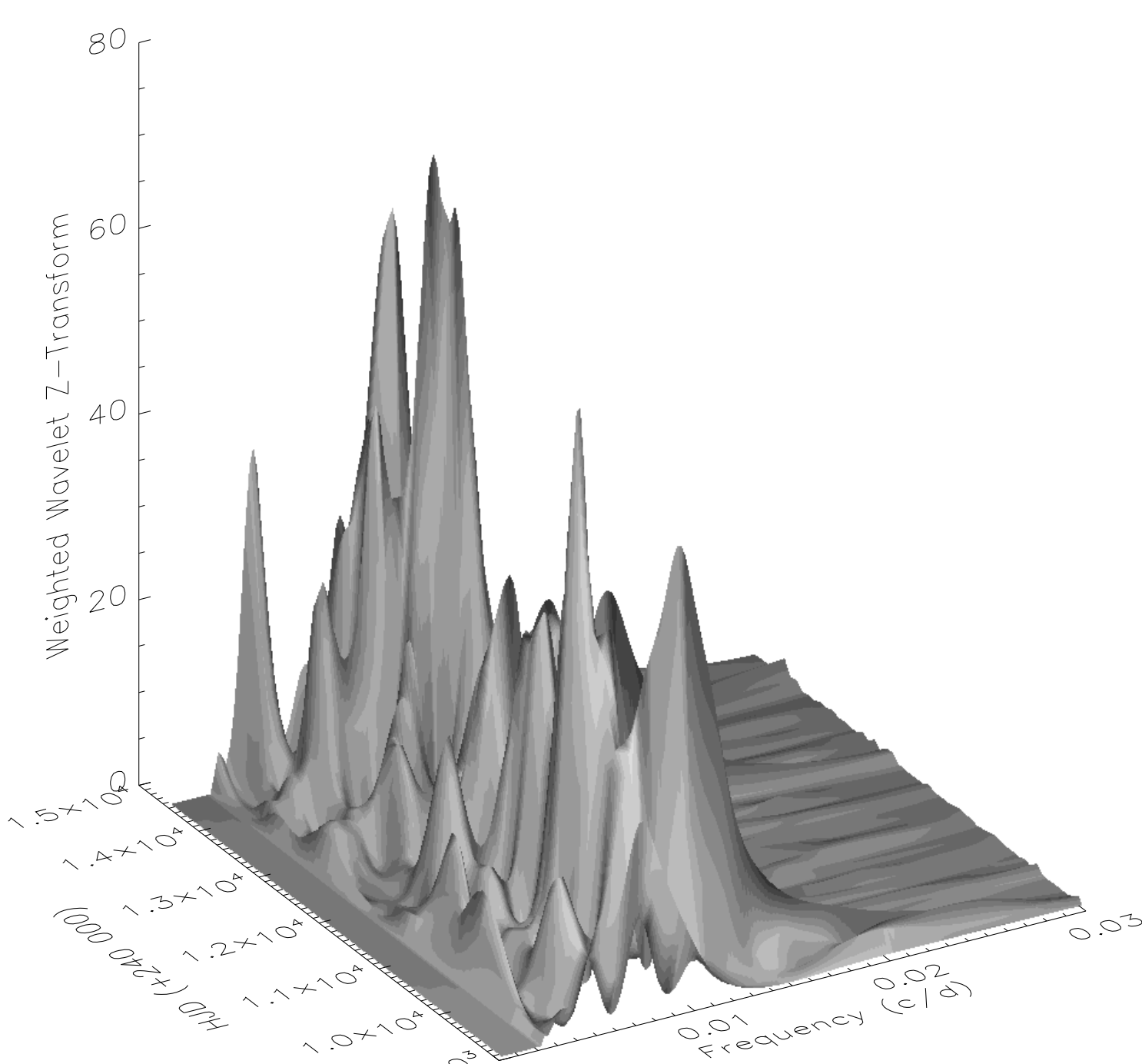


Figure 2. Surface plot of weighted wavelet z-transform (WWZ) as a function of observation time (+240000 HJD) and test frequencies  $\nu = [2 \times 10^{-4} : 3 \times 10^{-2}] \text{ d}^{-1}$  with the frequency mesh  $\delta\nu = 2 \times 10^{-4} \text{ d}^{-1}$ . The x-axis is the observation time in HJD averaged every  $\Delta t = 100$  days, and the y-axis is the frequency grid examined to find periodicity. The z-axis is what G. Foster (1996) calls the WWZ, and is approximately the F-statistic. It can be interpreted as the relative probability of occurrence for a mode of any frequency at any time. The peaks at different times can be used to extract the dominant pulsation frequency during those observation times. The definition of the WWZ includes a constant which specifies the tradeoff between time resolution and frequency resolution, here taken to be  $1/8\pi^2 \approx .0125$ . The dominant peaks of every time bin is extracted and plotted as a function of time in figure 4a.

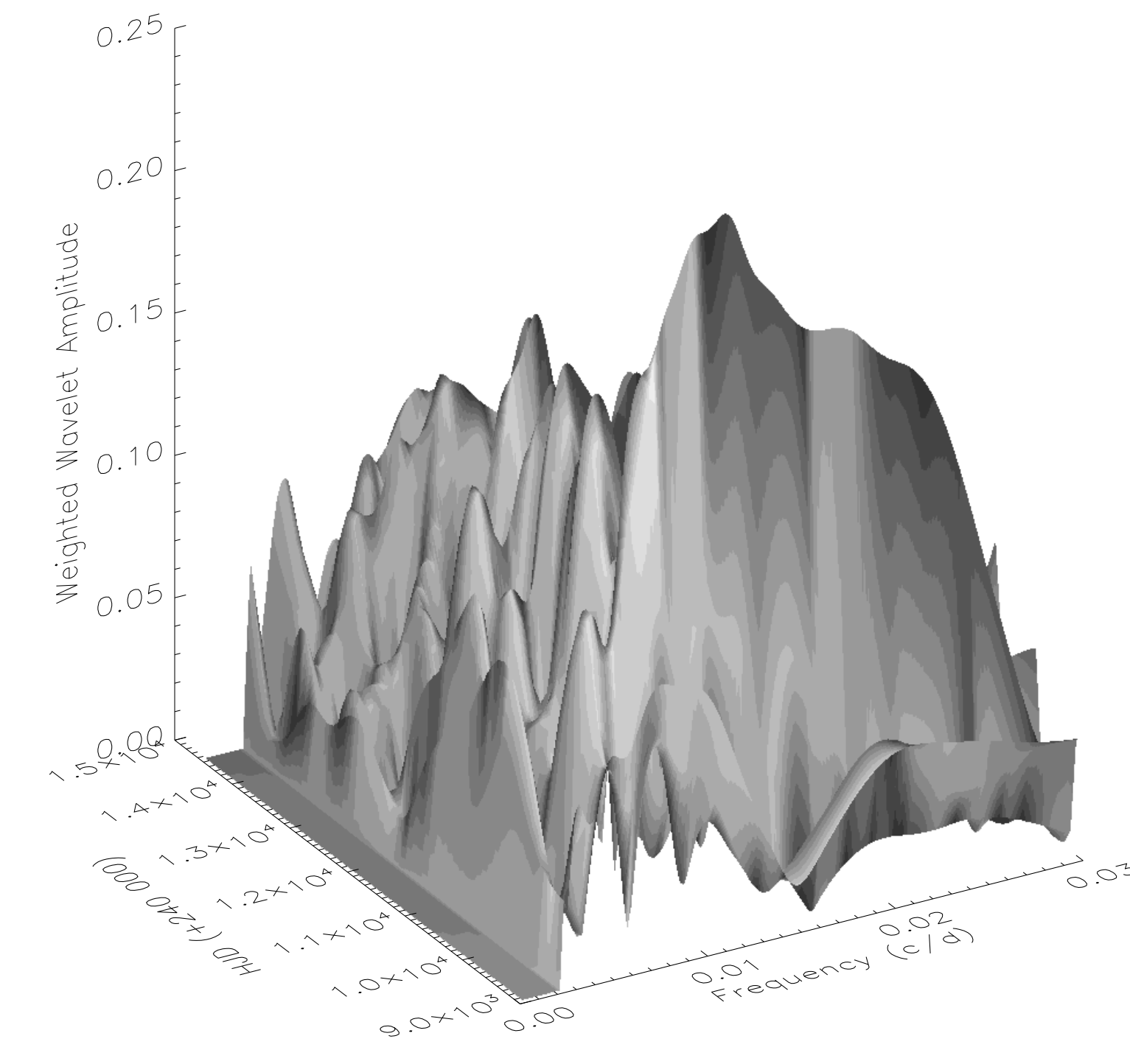


Figure 3. Surface plot of weighted wavelet amplitude (WWA) of  $\alpha$  Her. The axis details and wavelet parameters are the same as figure 2, except the z-axis which depicts the amplitude of oscillations in every time bin of size  $\Delta t = 100$  d. The maxima in every bin is extracted and plotted as a function of time in figure 4b.

## Results

Employing Foster (1996) wavelet analysis method which is tuned best to suit long-period variable stars with unevenly spaced data sets we, at the first step, have found out that just a wavelet analysis must be trusted, for the case of  $\alpha$  Her. If we divide the time series into bins of  $\Delta t = 100$  days, and find the profile of period/amplitude within each bin, then the time evolution of the star's pulsation can be tracked by joining the results in every bin, sequentially. This generates a 3D plot as depicted in figures 2 and 3 which reveals the presence of two dominant modes. Furthermore, the dominant period/amplitude within each bin can be extracted to demonstrate the time dependence of period/amplitude of variability, as presented in figure 4. The long-term component  $\tau_2$  gradually decreases its period from approximately 1710 d to 1220 d. The short-term component  $\tau_1$  is turned on whenever  $\tau_2$  is momentarily inactive.  $\tau_1$  has a varying period of 94, 104, and 131 d over the course of time, the mean of which is 112 days. The ratio of periods  $\tau_2/\tau_1$  decreases from about 15 to 11, if we use the averaged period for  $\tau_1$ . Figures 4a and 4b best reflect this fact.

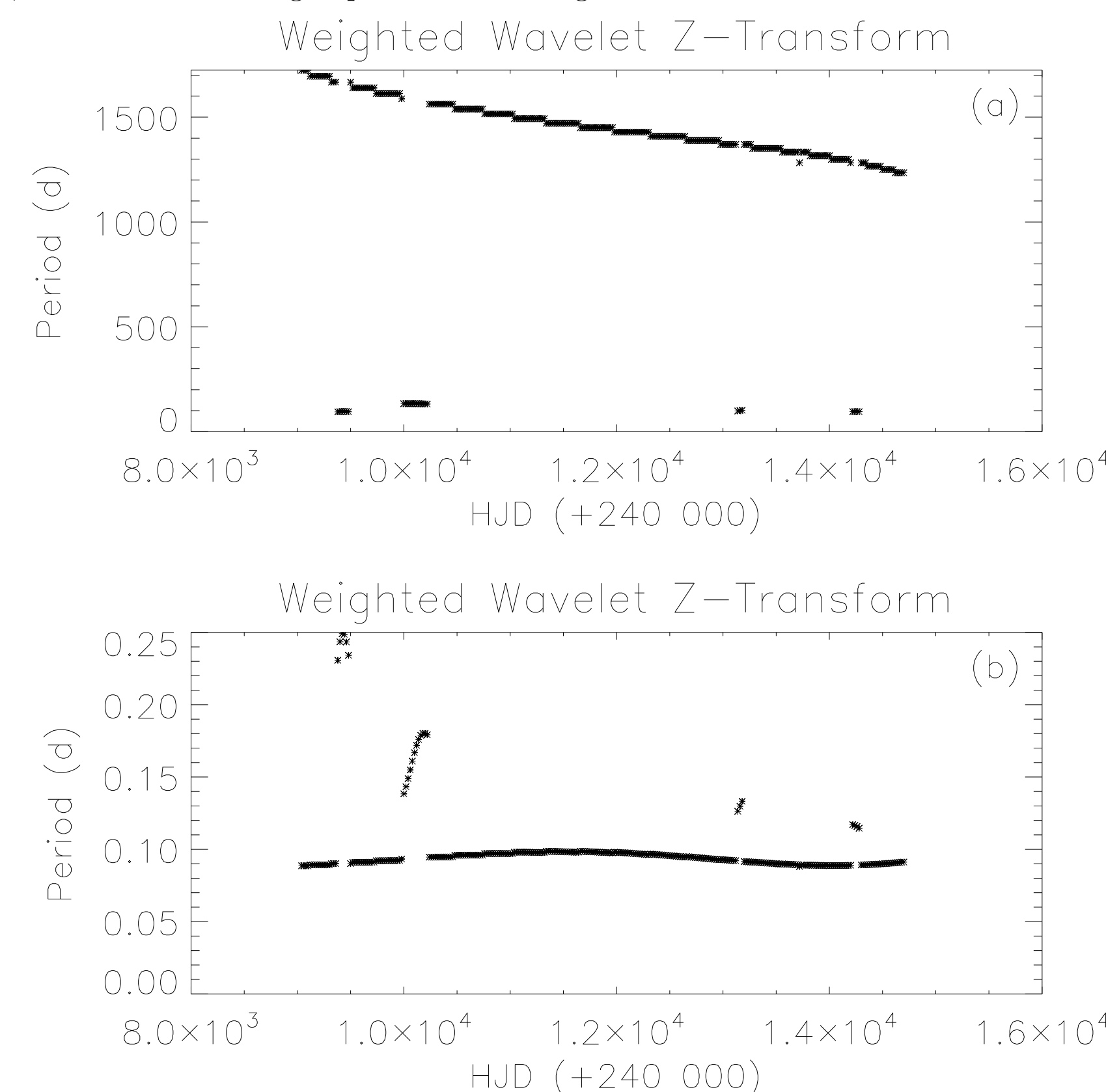


Figure 4. Time evolution of period (a) and that of amplitude (b) as functions of observation time in HJD. The period axis is in days, and the amplitude axis is in magnitude units.

The amplitude evolution plot is more scattered, and a much denser time series could make it more continuous. However, the eye catching feature of figure 4b is a trend in amplitude of  $a_v \sim 0.1$  mag, with some occasions of  $0.1 < a_v < .25$  mag.

## Discussion and some open questions

A word of comparison between Fourier methods and wavelets for supergiants is worthwhile. While Fourier based methods suffer from false (alias) peaks when dealing with gapped time series, Foster's wavelet analysis method, however, survives this problem, see Foster (1996). As a result, a great degree of certainty is involved in interpreting the oscillation frequencies as the intrinsic changes of the target star, not arising from aliases, as shown in figures 2 and 3. Furthermore, CLEANing according to Foster (1995) results in two modes, one with a period of 125 days (what Percy *et al.* (2001) report as 128 d) and another companion with a period of 1410 day. But, a quick glance at figure 4a rejects the stationarity assumption implied in CLEANing, and the two reported periods seem to be time averaged values of  $\tau_1$  and  $\tau_2$ . In this way, Fourier based methods are not reliable.

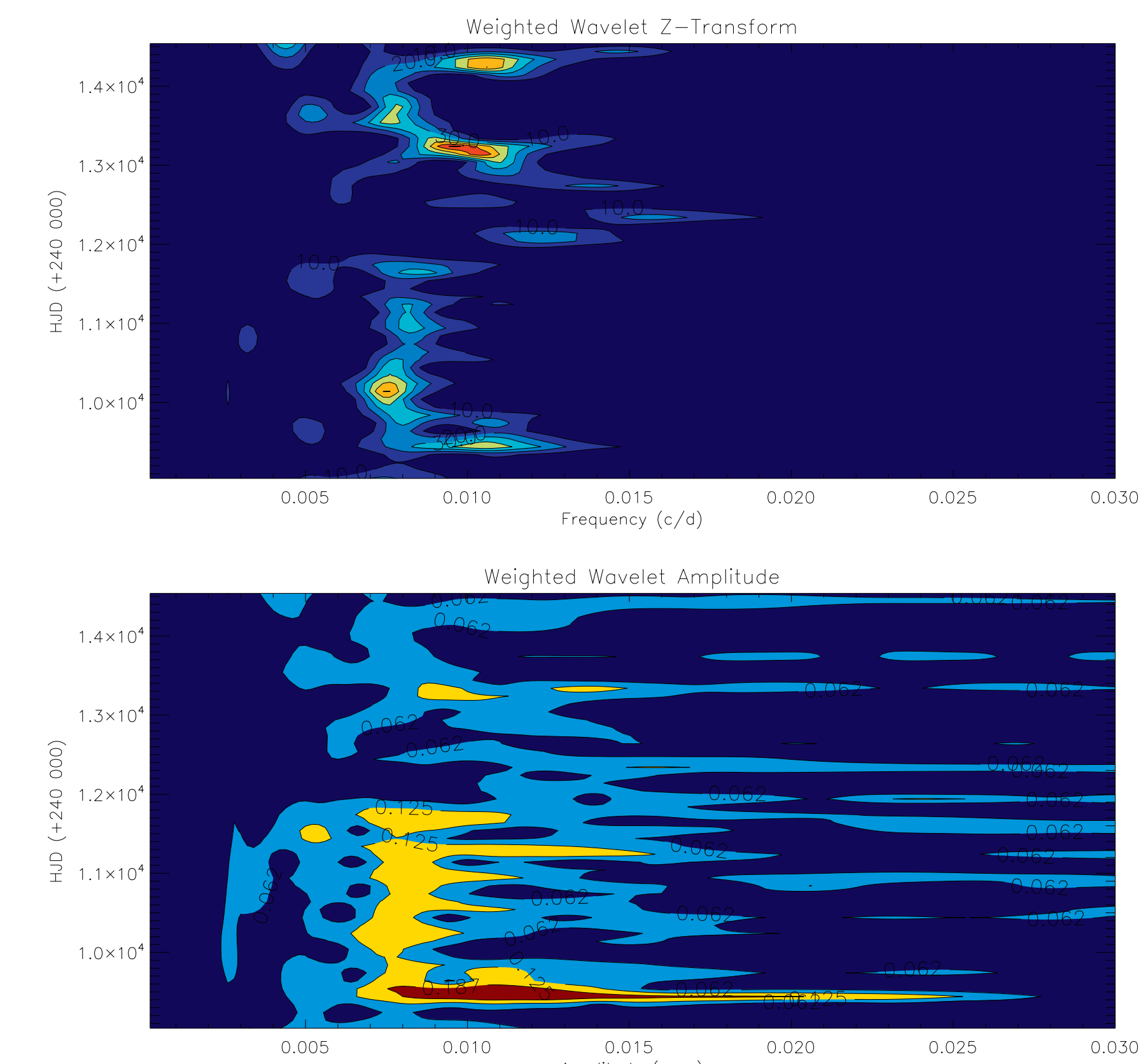


Figure 5. Contour plot of WWZ (top) in the time-frequency plane. Different colors depict different WWZ powers. The same kind of plotting for WWA (bottom). The axis are similar to figure 2.

Empirically, red supergiants show either one, or two pulsational modes, and in some few cases three modes, the longest of which is the fundamental mode ( $\tau_1$  in our case), and the others are the overtones. Thus, we have to settle this issue for  $\alpha$  Her, and identify which phenomenon each time scale is related to. We refer to figure 2 to see what number of peaks (assigned simultaneously to them two different frequencies) can be found in the WWZ surface plot, at each moment of observation. If more than one peak is located at the same instant, then the star is a multiperiodic pulsator, otherwise, a single mode one. To acquire a better insight into this issue, a contour plot of WWZ/WWA is very practical, as seen in figure 5. Evidently, no two peaks take place at the same time, and  $\alpha$  Her is, as a result, a single mode pulsator.

Two different time scales are interesting in live evolution of red supergiants. First, is a long-term instability, with a time scale in the range of years, and an amplitude of .2 to .4 mag, and its period is of the same order, as the surface convective cell's life times. Second, is the short-term pseudo-periodic semiregular component, whose period is typical of fundamental (radial) modes in such supergiants, and ranges from 19 to 120 days. It affects the light curve more chaotically. For a detailed discussion of this issue see Johnson and Quercy (1986).

Our study lacks space based, more precise multi-band photometry and spectrometry with time between exposures around an hour, to study in detail, the convection in  $\alpha$  Her's atmosphere, and discover whether the short-term variability is periodic, quasi-periodic or quite chaotic, in nature. This can also give us clues if the variability is caused by semi-convection or large hot spots on the photosphere.

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## References

### REFERENCES

- Christensen-Dalsgaard J., Kjeldsen H., and Mattei J. A. 2001, *ApJ*, 562L, 141
- Foster G. 1995, *AJ*, 109, 1889
- Foster G. 1996, *AJ*, 112, 1709
- Johnson H. R. and Quercy F. R. 1986, *The M-type stars*, NASA SP-492.
- Kiss L. L. and Bedding T. R. 2003, *MNRAS*, 343L, 79
- Lebzelter b. and Hron J. 2008, *CoAst*, 152, 178-181
- Mattei J. A. *et al.* 1997, *ESASP*, 402, 269
- Ostlie D. A. and Cox A. N. 1986, *ApJ*, 311, 864
- Percy J. R. and Wilson J. B. 2001, *PASP*, 113, 983
- Percy J. R. 2007, *Understanding Variable Stars*, Cambridge University Press
- Percy J. R. and Sato H. 2009, *JRASC* (in preparation)
- Perryman M. A. C. *et al.* 1997, *A&A*, 323L, 49
- Wasatonic R. 1997, *JAAVSO*, 26, 1
- Weiss W. W. 2008, *CoAst*, 152, 89-93
- Wood P. R., Olivier E. A. and Kawaler S. D. 2004, *ApJ*, 604, 800

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Table 1:

<sup>a</sup>  
This is the total number of observation point available in the specified filter.

<sup>b</sup>  
All values are in HJD, and a common factor of +2 440 000 is subtracted from this column.

Fig. 1.—

Fig. 2.—

Fig. 3.—

Fig. 4.—

Fig. 5.—