Session V

Pulsation

chair: A. Maeder

https://doi.org/10.1017/S0252921100072171 Published online by Cambridge University Press

Pulsations in O Stars

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Abstract. O stars are located in a domain of the HRD where nonradial pulsations are expected. Photometric surveys did not reveal pulsating O stars, showing that the amplitudes must be very small. Intensive spectroscopic studies yielded pulsation modes for very few O stars only, although many are line-profile variables. Wind contamination of many spectral lines is a major difficulty. Future concentrated spectroscopic efforts will undoubtedly increase the number of pulsating O stars.

The current status of our knowledge of pulsations in these stars is reviewed. From one specific example a critical attitude emerges towards the quantitative results reached so far. We also address the question whether non-radial pulsation can be the cause of the non-spherical time-dependent winds of these stars.

1 Introduction

Pulsating stars are found in nearly every part of the HR diagram. Among O stars, however, only very few pulsators are known. Fullerton et al. (1996) listed 3 confirmed and 6 suspected pulsating O stars and noticed that all of them are located in the instability strip predicted by Kiriadikis et al. (1993).

Besides its asteroseismological potential, the search for nonradial pulsations (NRP) in early-type stars is also motivated by the unknown origin of the widely observed cyclic variability in their winds, notably in the absorption parts of the ultraviolet P Cygni profiles. Most prominent are the migrating discrete absorption components (DACs) with a recurrence time scale that can be interpreted as (an integer fraction of) the stellar rotation period (e.g. Kaper et al. (1998)). The cyclic recurrence of DACs is attributed to corotating wind structures, caused by large-scale inhomogeneities. The unsolved issue is where the modulation comes from. Either magnetic fields or non-radial pulsations could equally provide the required differentiation of the emerging wind (Cranmer & Owocki (1996)). In the first case the number of wind structures matches the number of magnetic footpoints and the modulation comes directly from the stellar rotation, whereas in the case of a single NRP mode the value of the azimuthal number m determines the azimuthal distribution of the wind structures, and the modulation is caused by the traveling speed of the pulsation superposed on the stellar rotation in the observers frame. A third case could also be considered, in which coadding amplitudes of multiple modes may give rise to traveling local perturbations (de Jong et al. (1998b)).

Enhanced equatorial mass loss, to produce disks, as a consequence of sectoral NRP is a third reason for interest in pulsation in these stars.

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2 Non-radial pulsations among O stars

All discoveries of NRP in O stars are based on the recognition of systematic changes in the shape of photospheric line profiles (e.g. Fig. 1). A detailed analysis of the moving features yields, in principle, the pulsation properties. In photometric searches for pulsating O stars, for example by Balona (1992), no new pulsators are found. This shows that the amplitudes must be very small, notably for high-order modes, as expected. A study of HIPPARCOS data by Marchenko et al. (1998) revealed a number of short-term periodicities in O stars, but these could not be associated with pulsations.

A few selected key discovery papers of pulsating O stars are Smith (1978) on 10 Lac, Walker et al. (1979) and Vogt & Penrod (1983) on ζ Oph, Baade (1991) on ζ Pup, and Baade et al. (1990) on the companion of γ^2 Vel. The best suitable lines are those formed deep in the photosphere. Typical lines used are Si IV λ4654, He I $\lambda\lambda$4471, 4713, 5875, 6678, C IV $\lambda\lambda$5801, 5812. Most H and He lines are often confused with variable wind contributions with comparable timescales. Typical periods are between 1 and 12 hours, and $\ell = |m|$ values up to 17. Both prograde and retrograde modes have been reported. The reliability of the pulsation parameters is limited, however (see the caveat in section 4). The systematic survey among 31 O stars by Fullerton et al. (1996) yielded line-profile variations in more than 75% of the sample, most of which are likely due to pulsations, but due to lack of coverage, no parameters could be derived in many cases. There is little doubt that a concentrated effort on such stars will reveal the pulsation properties.

The nine O stars for which pulsations are found or suspected are collected in Table 1. Typical mode properties are listed, together with wind periodicities in the last column. Figure 2 gives their positions in the HR diagram. The sample is the same as in Fullerton et al. (1996), but the number of confirmed pulsators has increased by recent work on ξ Per, λ Cep and ζ Pup.

To compare the occupied domain in the HRD with the predicted location of strange-mode occurrence in these massive stars (Kiriadikis et al. (1993), Glatzel & Mehren (1996)) a conversion from [M_V, Sp. type] to [L, $T_{\rm eff}$] is needed. The uncertainties in this conversion inhibit, however, a firm conclusion regarding the evolutionary and pulsational status of the sample stars.

Table 1. O stars with confirmed or suspected pulsations

Name	HD	Sp. Type	$v\sin i$ (km/s)	$P_{\rm NRP}$(h)	Mode($\ell = \|m\|$)	$P_{\rm DAC}$(d)
ζ Pup	66810	O4I(n)f	208	8.4, 4.3	2, 4	0.8
λ Cep	210839	O6I(n)fp	214	12.3	3	1.3:
	34656	O7II(f)	106	8.2	–	1.1
ξ Per	24912	O7.5III(n)((f))	200	3.5	3	2.0
γ^2 Vel	(WR 11)	O9I	200	8.4 - 43	6	
10 Lac	214680	O9V	32	4.9	2	7:
α Cam	30614	O9.5Ia	85	–	–	
	93521	O9.5V	400	1.8, 2.9	9	
ζ Oph	149757	O9.5Vne	400	1.1, 1.3	4 - 17	0.9

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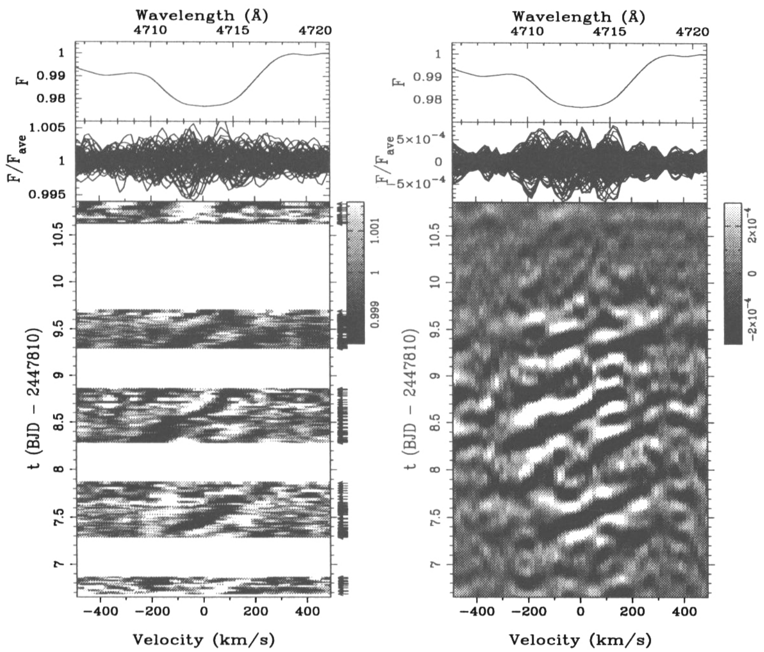

Fig. 1. Dynamic quotient He I spectra of λ Cep, along with the inverse Fourier transform of a selected frequency range, showing moving features attributed to NRP. The top panel shows the average profile. (From de Jong et al. (1998b))

3 Mode identification techniques

Since the early atlas of predicted line-profile variations as a function of pulsation parameters by Kambe & Osaki (1988), a number of powerful methods have been developed to retrieve periodicities and modes from spectroscopic time series. We mention the moment method by Balona (1986) and Aerts et al. (1992), the wavelet analysis by Townsend (1997), cross-correlation techniques by Howarth et al. (1998) and several methods based on Fourier analysis in various forms (Gies & Kullavanijaya (1988), Kambe et al. (1990), Telting & Schrijvers (1997), Kennelly et al. (1998)), each method having their own advantages and specific requirements regarding data quality and coverage. Temperature effects have been considered e.g. by Gies (1991), Lee et al. (1992) and Schrijvers & Telting (1998). Extensive applications to generated data and their success rate for mode retrieval are often included. Most, but not all these methods can be applied to O stars.

An interesting feature emerging of some of these studies is that if $\ell \neq m$, it is the value of ℓ (rather than m) that can be determined, and an additional study of the relative amplitude and phase behavior of the first harmonic frequency is needed to determine m (see Telting & Schrijvers (1997)).

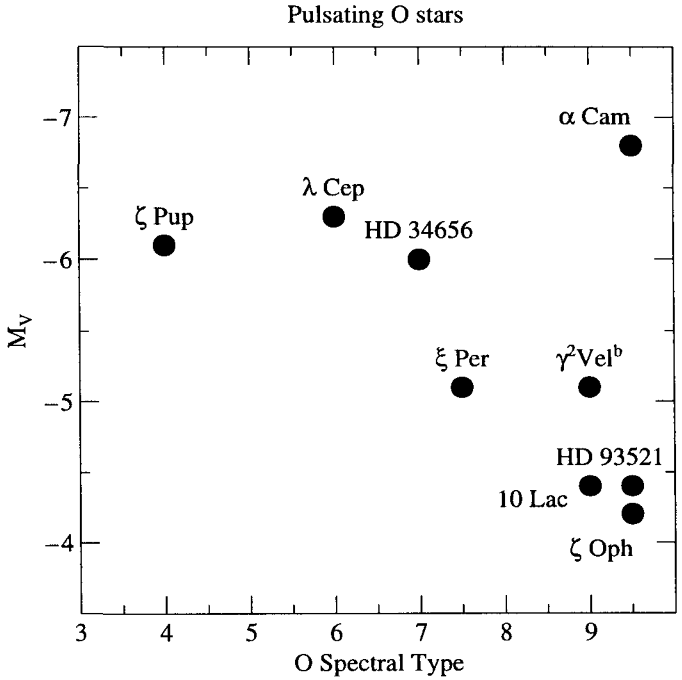

Fig. 2. The nine presently known pulsating O stars in the HR diagram. The stellar parameters are from Puls et al. (1996)

4 Multiplicity of modes: a caveat

The derived pulsation properties are limited by the signal-to-noise ratio and sampling of the dataset. Higher quality data and/or denser coverage will undoubtedly reveal more accurate values, and multiple modes, if present. As an illustration we summarize the evolving knowledge of the well studied O9.5Ve star ζ Oph during the past five years. The two main periodicities in the line profiles at 3.33 h and 2.43 h are considered as $\ell(=-m) = 4$ and 7 respectively by Kambe et al. (1993), but 4 and '5 or 6' by Reid et al. (1993) based on 360 spectra during 10 days, whereas Kambe et al. (1997) find '4 or 5', and '7 or 8', for these modes, respectively. In contrast, a recent study by Jankov et al. (1998) based on 242 spectra during 3 days yields $\ell(=-m)$ $= 5$ for the first mode, and resolves the second mode into 4 other pulsation modes with small differences in period. In the latter study modes up to $\ell \approx$ 17 and periods down to 1 h were identified. This example of the best studied O star so far clearly demonstrates that our present quantitative knowledge of pulsation modes should be considered as fragmentary in all cases of Table 1. This inhibits a fair comparison with theoretical models and shows that any asteroseismological attempt will be premature at present.

5 Wind – NRP connection?

An important question is whether non-radial pulsation can be the origin of the cyclical wind variability in O stars (Henrichs (1984), Abbott et al. (1986)). It appears in several cases that the pattern speed of the waves of a single mode running around the star superposed on the rotation is too high (usually a factor of 5 to 10, see Table 1) to be compatible with the observed wind periods in the DACs. This will be probably true for most short-period single mode pulsations, since for most O stars the rotation rate is much slower than in these examples. As discussed by de Jong et al. (1998b)), the presence of multiple modes could be relevant for the origin of cyclical wind variability. Consider for example a case with two different sectoral modes, traveling around the star with different frequencies. Matching crests with coadding amplitudes above some threshold to generate wind differentiation will appear at different longitudes and epochs. The occurrence of these cyclical surface perturbations is related to the relative traveling speeds and relative m values of the NRP waves. The temporal consequences for the wind behavior will therefore depend on the superposed rotation rate. The simultaneous presence of more than two modes will increase the complexity even more. This means that in order to match the observed periods of wind variability a fine tuning of the pulsation parameters is required in each individual case. This is not obvious because the cyclical wind periods are found to scale with the rotation periods among O (and B) stars, and this is not easily expected for a sample of different stars with a range of different pulsation parameters, but we cannot exclude this on the basis of the presently very small sample. We therefore think that the best candidate for the cause of the cyclical wind variability still remains the presence of weak magnetic fields on the surface, corotating with the star. A proof has to wait for a systematic deep survey of these fields. Preliminary upper limits on the magnetic field strength of ξ Per were presented by Henrichs et al. (1998).

6 Summarizing remarks

The evidence for the presence of pulsations in O stars has substantially increased during the last decade. In this strongly data-limited problem it can be expected that every attempt to detect pulsations in a given O star will be awarded, provided the signal to noise ratio and the time coverage are sufficient. An increase of the quality of the data will undoubtedly reveal many more details of the pulsation properties, in particular the presence of multimodes. From the timescales of the O stars studied so far, it is unlikely that pulsations alone can cause the observed cyclic wind variability. Clearly, much more studies are needed before asteroseismology can be seriously attempted.

Acknowledgments
I am very grateful to Coen Schrijvers, Jeroen de Jong, John Telting and Lex Kaper for their deep insight, continuous support and never-ceasing efforts.

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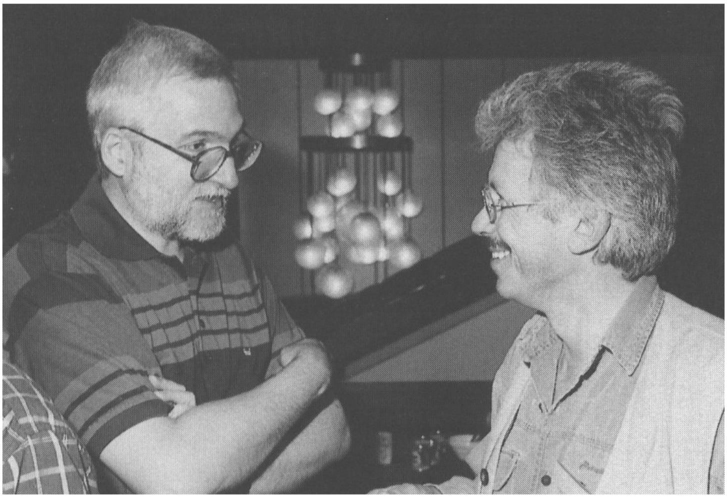
Discussion

P. Petrenz: Is there any chance to infer constraints on the absolute rotation rate by a comparison of NRPs of rotating and non-rotating stars?
H. Henrichs: If one finds different modes caused by rotational m-splitting, one can directly derive the rotation rate. This has been done for β Cep, for instance, but not for O stars yet, mainly because the data are not good enough to resolve the splitting. In principle, precise values can be derived, since the discrete nature of l and m constrain the allowed range strongly.

S. Shore: What happens in the case of a rotation law that is not a rigid one?
H. Henrichs: A good point: I am not aware of any line profile calculations for pulsating massive stars that take differential rotation into account, but it could be done. It would be interesting to compare such calculations with the standard ones for the purpose of diagnosing non-rigid rotation.

I. Appenzeller: What are the velocity amplitudes found in the O stars of your list and what is the present velocity detection limit?
H. Henrichs: Velocity amplitudes of pulsation are derived using a model and depend rather strongly on the model parameters (in particular the assumed inclination). Nevertheless, most amplitudes are found in the range from 5 to 10 km/s. The detection limit depends on the S/N of the spectra and is in the range of a few km/s.



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