An asteroseismic study of the $\beta$ Cephei star $\theta$ Ophiuchi: photometric results

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ABSTRACT

We have carried out a three-site photometric campaign for the $\beta$ Cephei star $\theta$ Oph from April to August 2003. 245 hours of differential photoelectric uvby photometry were obtained during 77 clear nights. The frequency analysis of our measurements resulted in the detection of seven pulsation modes within a narrow frequency interval between 7.116 and 7.973 cd$^{-1}$. No combination or harmonic frequencies were found. We performed a mode identification of the individual pulsations from our colour photometry that shows the presence of one radial mode, one rotationally split $\ell = 1$ triplet and possibly three components of a rotationally split $\ell = 2$ quintuplet. We discuss the implications of our findings and point out the similarity of the pulsation spectrum of $\theta$ Oph to that of another $\beta$ Cephei star, V836 Cen.

Key words: stars: variables: other -- stars: early-type -- stars: oscillations -- stars: individual: $\theta$ Oph -- techniques: photometric

1 INTRODUCTION

Two recent groundbreaking studies have opened up the class of the $\beta$ Cephei pulsators for asteroseismic investigations. For the star V836 Cen, Aerts et al. (2003, 2004a) acquired and analysed 21 years of time-resolved Geneva photometry. They identified the six detected pulsation modes with their pulsational quantum numbers (the radial fundamental mode, an $\ell = 1$ triplet and two components of a rotationally split $\ell = 2$ mode). Consequent seismic modelling (Dupret et al. 2004) allowed the derivation of constraints on the star’s position in the HR diagram and its convective core size plus demonstrated that its interior rotation is not rigid.

A second $\beta$ Cephei star, $\nu$ Eri, was studied with large photometric and spectroscopic multisite campaigns (Handler et al. 2004, Aerts et al. 2004b), yielding a total of almost 1200 hours of measurement. The nine modes detected for this star were identified with the radial fundamental mode, two $\ell = 1$ triplets, one $\ell = 1$ singlet and one $\ell = 2$ mode (De Ridder et al. 2004). Seismic modelling (Pamyatnykh, Handler & Dziembowski 2004, Ausseloos et al. 2004) demonstrated that the pulsation spectrum of $\nu$ Eri cannot be reproduced with standard models, some convective core overshooting may be required and again non-rigid interior rotation must be present (with the edge of the convective core rotating about 3 times faster than the outer layers, consistent with the findings for V836 Cen). The seismic results indicate that it is possible that the interior chemical composition of the star is not homogeneous.

After some 15 years of frustration, asteroseismology of opacity-driven main sequence pulsators has thus finally become reality. The reasons why some $\beta$ Cephei stars are the first such objects to be studied may be summarised as follows: their pulsational mode spectra are sufficiently simple that few possibilities for erroneous or ambiguous mode identifications occur, yet the observed spectra are fairly complete; radial modes have been detected for the two above-mentioned stars (substantially reducing the number of possible seismic models); finally, the applied mode identification methods do work (e.g. see Handler et al. 2003).

The general astrophysical implications of seismic studies of the $\beta$ Cephei stars are also highly interesting. Since these objects are main sequence stars between 9 and 17 $M_\odot$ (Stan­kov & Handler 2005), they are progenitors of Type II supernovae, which in turn are largely responsible for the enrichment of the interstellar medium and thus for the chemical evolution of galaxies. Consequently, if we can trace the evolution of $\beta$ Cephei stars by sounding their interiors in different evolutionary states, we are not only able to calibrate stellar structure and evolution calculations, but could put constraints on the modelling of extragalactic stellar sys-

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tems. Therefore it is highly desirable to determine the interior structure of several β Cephei stars.

One of the objects that seems well suited for an asteroseismic study is θ Oph. The variability of this bright \( V = 3.27 \) mag object has been known for a long time (Henroteau 1922), and the corresponding period determinations in the literature are partly controversial. Several authors (van Hoof & Blaauw 1958, van Hoof 1962, Briers 1971, Heynderickx 1992) noted variable shapes of their radial velocity and light curves, indicating multiperiodicity. However, no consensus on the values of possible secondary and tertiary periods was reached.

Together with the presence of archival high-resolution spectroscopy (to be analysed in a companion paper by Briquet et al. 2005), the findings mentioned above made θ Oph an attractive target for a multisite study. Consequently, we have carried out a photometric campaign on this star in mid 2003.

2 OBSERVATIONS AND REDUCTIONS

We acquired single-channel differential photoelectric photometry through the Strömgren \( uvy \) filters with three telescopes on three continents during the months of April to August 2003. The measurements of θ Oph were obtained with respect to two comparison stars, 44 Oph (HD 157792, A3m, \( V = 4.17 \)) and 51 Oph (HD 158643, A0V, \( V = 4.81 \)). Owing to the brightness of all three objects, some neutral density filters were applied to avoid damage of the photomultipliers. A short summary of the observations is given in Table 1. The total time base of our measurements is 124 days.

Data reduction was started by correcting for coincidence losses, sky background and extinction. Nightly extinction coefficients were determined with the Bouguer method or with the differential technique from the comparison stars (neither showed any variability during our measurements). As the comparison stars are considerably cooler than the variable, second-order colour extinction coefficients were also determined. We found colour extinction corrections to be necessary for the \( u \) data from SSO and the APT and applied them correspondingly.

We then determined the mean \( u, v, y \) zeropoints between the comparison star magnitudes and used them to combine the measurements of 44 and 51 Oph to a curve that was assumed to reflect the effects of transparency and detector sensitivity changes only. Consequently, these combined time series were binned into intervals that would allow good compensation for the above mentioned nonintrinsic variations in the target star time series and were subtracted from the measurements of θ Oph. The binning minimises the introduction of noise in the differential light curve of the target.

The timings for this differential light curve were heliocentrally corrected as the next step. Finally, the photometric zeropoints of the different sites, which may not be quite the same because of slightly different wavelength responses of the individual instrumental systems combined with the different colours of the variable and the comparison stars, were set to zero. The resulting final combined time series was subjected to frequency analysis; we show some of our light curves of θ Oph in Fig. 1. We note that the amplitude of the light variation is modulated, but its shape is not; it is always sinusoidal.

3 FREQUENCY ANALYSIS

Our frequency analyses were performed with the program PERIOD 98 (Sperl 1998). This package applies single-frequency power spectrum analysis and simultaneous multi-frequency sine-wave fitting, and also includes advanced options.

We started by computing the Fourier spectral window of the final light curves in each of the filters. It was calculated as the Fourier transform of a single noise-free sinusoid with a frequency of 7.116 cd\(^{-1}\) (the strongest pulsational signal of θ Oph) and an amplitude of 10 mmag sampled in the same way as were our measurements. The upper panel of
Table 1. Log of the photometric measurements of θ Oph. Observatories are ordered according to geographical longitude.

| Observatory                                      | Longitude | Latitude | Telescope | Amount of data | Observer(s) |
|--------------------------------------------------|-----------|----------|-----------|----------------|-------------|
| South African Astronomical Observatory (SAAO)     | +20°49'   | −32°22'  | 0.5m      | 9              | 135 TM      |
| Fairborn Observatory                              | −110°42'  | +31°23'  | 0.75m APT | 44             | 662 --      |
| Siding Spring Observatory (SSO)                   | +149°04'  | −31°16'  | 0.6m      | 24             | 506 RRS     |
| **Total**                                        |           |          |           | 77             | 1303        |

Table 2. Multifrequency solution for our time-resolved photometry of θ Oph. The signals are ordered according to their frequencies, but labelled in the order of detection. Formal error estimates (following Montgomery & O’Donoghue 1999) are listed for the individual frequencies; formal errors on the amplitudes are ±0.20 mmag in \( u \), ±0.18 mmag in \( v \) and ±0.16 mmag in \( y \). The S/N ratio quoted is for the \( y \) filter data.

| ID | Freq. (cd\(^{-1}\)) | \( u \) Ampl. (mmag) | \( v \) Ampl. (mmag) | \( y \) Ampl. (mmag) | S/N |
|----|---------------------|----------------------|----------------------|----------------------|-----|
| \( f_1 \) | 7.11600 ± 0.00008 | 12.7 | 9.2 | 9.4 | 41.4 |
| \( f_2 \) | 7.2881 ± 0.0005 | 2.1 | 1.5 | 1.4 | 6.4 |
| \( f_3 \) | 7.3697 ± 0.0003 | 3.6 | 2.9 | 2.4 | 10.8 |
| \( f_4 \) | 7.4677 ± 0.0003 | 4.7 | 2.4 | 2.3 | 10.2 |
| \( f_5 \) | 7.7659 ± 0.0003 | 3.4 | 2.3 | 2.1 | 9.7 |
| \( f_6 \) | 7.8742 ± 0.0005 | 2.3 | 1.8 | 1.3 | 5.8 |
| \( f_7 \) | 7.9734 ± 0.0005 | 2.4 | 1.6 | 1.2 | 5.6 |

Fig. 2 contains the result for the \( y \) data. Any alias structures that would potentially mislead us into incorrect frequency determinations are reasonably low in amplitude due to our multisite coverage.

We proceeded by computing the amplitude spectra of the data itself (second panel of Fig. 2). The signal designated \( f_1 \) dominates. We prewhitened it by subtracting a synthetic sinusoidal light curve with a frequency, amplitude and phase that yielded the smallest residual variance, and computed the amplitude spectrum of the residual light curve (third panel of Fig. 2).

This resulted in the detection of a second signal (\( f_2 \)). We then prewhitened a two-frequency fit from the data using the same optimisation method as before, and continued this procedure (further panels of Fig. 2) until no significant peaks were left in the residual amplitude spectrum.

We consider an independent peak statistically significant if it exceeds an amplitude signal-to-noise ratio of 4 in the periodogram (see Breger et al. 1993). The noise level was calculated as the average amplitude in a 5 cd\(^{-1}\) interval centred on the frequency of interest; the final detection limit corresponding to \( S/N = 4 \) is shown as a significance curve in the second lowest panel of Fig. 2.

We repeated the prewhitening procedure with the \( u \) and \( v \) data independently and obtained the same frequencies within the observational errors. We then determined final values for the detected frequencies by averaging the values from the individual filters. The pulsational amplitudes were then recomputed with those frequencies. We regard this solution as representing our data set best; the result is listed in Table 2.

\( \theta \) Oph has also been observed by the HIPPARCOS satellite (ESA 1997). We reanalysed the corresponding photometry of the star and find a main frequency of 7.11605 ± 0.00002 cd\(^{-1}\) in these measurements, consistent with the result from our data within the errors. An analysis of our measurements combined with those by HIPPARCOS allows us to refine the value of the dominant frequency to 7.116015 ± 0.000002 cd\(^{-1}\); aliases are outside the quoted errors for each individual determination. No amplitude variations of the strongest mode seem to have occurred between the HIPPARCOS measurements and ours; the other signals are not detected in the space-based photometry.

The residuals from the multifrequency solution in Table 2 were searched for additional candidate signals that may be intrinsic. We have first investigated the residuals in the individual filters, then analysed the averaged residuals in the three filters (whereby the \( u \) data were divided by 1.5 to scale them to amplitudes and rms scatter similar to that in the other two filters), and found no evidence for additional significant periodicities in any case. The residuals between light curve and fit are 5.2, 4.6 and 4.1 mmag per single \( u \), \( v \), \( y \) point, respectively and are thus somewhat higher than the accuracy of the differential comparison star data, suggesting that additional, presently undetected, frequencies could be present.

We can now confront the results of our frequency analysis with those in the literature. The frequency of the dominant signal is consistent with all the earlier studies except Henroteau (1922), taking into account some slight (evolutionary?) frequency variability with respect to Brier’s (1971) study. Concerning the remaining frequencies, we note that the resonance period of 0.137255 d found by van Hoof (1962) is consistent with our signal \( f_3 \). On the other hand, none of the secondary or harmonic frequencies claimed by Huynderickx (1992) can be reconciled with our data. We suspect this is due to the small amount of data available to this author. Finally, we note that the \( y \) amplitude of our analysis is consistent with that in Huynderickx’ (1992) Walraven V data, i.e. no amplitude variations seem to have occurred between the years 1987 and 2003.

4 MODE IDENTIFICATION

Our three-colour photometry gives us the possibility of deriving the spherical degree \( \ell \) of the individual pulsation modes from an analysis of the colour amplitudes. This involves a comparison of the observed amplitudes with those predicted by models and first requires knowledge of the star’s position in the HR diagram.

However, \( \theta \) Oph is not a single star. Besides its low-mass
spectroscopic companion discovered by Briquet et al. (2005), it is also a Speckle binary (McAlister et al. 1993). Shatsky & Tokovinin (2002) determined a $K$ magnitude difference of 1.09 mag between the two components and argued that the companion to the $\beta$ Cephei star (hereinafter called $\theta$ Oph A) is physical. From the standard relations by Koornneef (1983) we can infer that the Speckle companion (hereinafter called $\theta$ Oph B) is 1.33 mag fainter in $V$ and must thus be a B5 main sequence star.

To determine the effective temperature and luminosity of $\theta$ Oph A, we must take the contribution of $\theta$ Oph B to the total light into account. We use the standard Strömgren photometry by Crawford, Barnes & Golson (1970), and adopt the mean $V$ magnitude from the Lausanne Photometric data base [http://obswww.unige.ch/gcpd/gcpd.html] $V = 3.266$ for the system, and then reproduce it and the Strömgren $c_1$ index, which is a measure of the stars’ effective temperatures, with the help of the standard relations by Crawford (1978), and after dereddening. The results are shown in Table 3.

The observations are reasonably well matched, with the exception of the luminosity sensitive $\beta$ parameter. However, this is not a severe problem as we will derive the star’s luminosity from its parallax. We also note that $\beta$ measurements by other authors are closer to our calculated results as the results from Crawford et al. (1970).

The calibration by Napiwotzki, Schönberner & Wenske (1993) applied to the Strömgren indices listed in Table 3 then results in $T_{\text{eff}} = 22900 \pm 900$ K and $M_v = -2.5 \pm 0.5$ for $\theta$ Oph A, and in $T_{\text{eff}} = 18400 \pm 700$ K and $M_v = -1.3 \pm 0.5$ for $\theta$ Oph B. The analysis of IUE spectra by Niemczura & Daszyński-Daszkiewicz (2004) yielded $T_{\text{eff}} = 22200 \pm 850$ K (consistent with the combined contribution of both system components) $\log g = 3.77$ and $[M/H] = -0.15 \pm 0.12$. Finally, the HIPPARCOS parallax of the system $(5.79 \pm 0.69$ mas) results in $M_v = -2.6 \pm 0.3$ for $\theta$ Oph A and $M_v = -1.3 \pm 0.3$ for $\theta$ Oph B, respectively, consistent with the result from Strömgren photometry. The tables by Flower (1996) then yield bolometric corrections of $-2.2$ and $-1.7$ mag, respectively, and thus $M_{\text{bol}} = -4.8 \pm 0.5$ for $\theta$ Oph A as well as $M_{\text{bol}} = -3.0 \pm 0.4$ for $\theta$ Oph B. We show the positions of the $\theta$ Oph components in the HR diagram derived in this way in Fig. 3. It becomes clear that the observed pulsations must originate from $\theta$ Oph A only.

To derive mode identifications for the pulsations of $\theta$ Oph A, we have computed theoretical colour amplitudes for modes of $0 \leq \ell \leq 4$ for models with masses between 8.5 and 10 $M_{\odot}$ (in steps of 0.5 $M_{\odot}$), effective temperatures in the range of 4.34 $\leq \log T_{\text{eff}} \leq$ 4.38 and $Z = 0.015$. We first computed stellar evolutionary models by means of

![Figure 2. Amplitude spectra of $\theta$ Oph. The uppermost panel shows the spectral window of the data, followed by the periodogram of the data. Successive prewhitening steps are shown in the following panels; note their different ordinate scales. The second lowest panel contains a significance curve; any peak to be regarded as real by us must exceed it. The lowest panel shows the residual amplitude spectrum in a wider frequency range, containing no evidence for further periodicities in our data.](image-url)

| $V$  | $b - y$ | $m_1$ | $c_1$ | $\beta$ |
|------|---------|-------|-------|---------|
| Observed | 3.266 | -0.092 | 0.089 | 0.104 | 2.617 |
| Dereddened | 3.223 | -0.102 | 0.092 | 0.102 | 2.617 |
| $\theta$ Oph A | 3.546 | -0.109 | 0.080 | 0.074 | 2.640 |
| $\theta$ Oph B | 4.876 | -0.089 | 0.095 | 0.25 | 2.684 |
| Combined | 3.266 | -0.104 | 0.083 | 0.105 | 2.650 |

Table 3. Johnson V magnitude and Strömgren colour indices of the $\theta$ Oph system.
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Figure 3. The position of θ Oph A and θ Oph B in the theoretical HR diagram. Some stellar evolutionary tracks labelled with their masses (full lines) and the theoretical borders of the β Cephei star instability strip (Pamyatnykh 1999, dashed lines) are included for comparison. All the theoretical results are for a metal abundance of Z = 0.015. θ Oph A is located within the instability strip, whereas θ Oph B is not.

the Warsaw-New Jersey evolution and pulsation code (described, for instance, by Pamyatnykh et al. 1998). Then we derived the pulsational amplitudes of such models in the parameter space constrained above following Balona & Evers (1999). A range of theoretical frequencies of $6.5 \text{ cd}^{-1} \leq f \leq 8.5 \text{ cd}^{-1}$ was examined to allow for some nonradial mode splitting. Phase shifts between the light curves in the individual filters were not considered, as no such shifts were observationally found significant even at the 2σ level. We show a comparison of the observed and theoretical amplitude ratios of three modes in Fig. 4.

We note that we took the contribution of θ Oph B to the total light of the system into account when determining the observed amplitude ratios; we found that θ Oph B contributes some 23% to the total flux in Strömgren y, 22% in v and 19% in u.

The reliability of the mode identifications in Fig. 4 are not easy to judge. Whereas the modes $f_3$ and $f_4$ can be identified with $\ell = 0$ and $\ell = 1$, respectively, the situation is less clear for mode $f_1$ (upper panel of Fig. 4) where the $u/v$ amplitude ratio points towards an $\ell = 1$ mode, but the $u/y$ amplitude ratio suggests $\ell = 2$. Similar problems have been found for other modes that are not shown in this figure. We believe that the reason for these problems is a combination of several factors, for instance possible systematic errors in the determination of some of the pulsational amplitudes (which would be particularly severe in u), the uncertainties of the star’s position in the HR diagram, its poorly constrained surface metallicity (see Dupret et al. 2004 for a discussion of the latter), and the influence of the light of θ Oph B.

We have therefore chosen an alternative approach that appears more objective. We calculated the ratio of the individual $u, v, y$ amplitudes with respect to their mean with the hope of compensating largely for systematic errors in the amplitude determinations. Then we compared these ratios to the theoretical ones treated in the same way by means of a $\chi^2$ analysis, similar to Balona & Evers (1999) and Daszyńska-Daszkiewicz, Dziembowski & Pamyatnykh (2003), but disregarding the pulsational phases since they do, in our case, contain no information on the type of the modes as argued before. The behaviour of $\chi^2$ depending on $\ell$ computed this way is shown in Fig. 5 for all modes.

Because of the systematic errors that may affect our mode identification, we believe that we cannot interpret the results in Fig. 5 in a strict statistical sense (i.e. by comparing...
we can rule out that $f_3$ ratio of these two modes (i.e. neglecting effects of the Coriolis force and possible differential internal rotation), we derive a rotation period of 9.6 days. The absolute magnitude and effective temperature of the star, as determined at the beginning of

Table 4. Possible $\ell$ identifications of the individual modes of $\theta$ Oph A from our $\chi^2$ analysis.

| ID | Freq. (cd$^{-1}$) | $\ell$ |
|----|------------------|-------|
| $f_1$ | 7.11600 | 2 or 1 |
| $f_5$ | 7.2881 | 2, 1 or 3 |
| $f_2$ | 7.3697 | 3, 2 or 1 |
| $f_3$ | 7.4677 | 0 |
| $f_4$ | 7.7659 | 1 |
| $f_6$ | 7.8742 | 3 or 1 |
| $f_7$ | 7.9734 | 0, 1 or 3 |

larger than any period ratio of low-order radial modes in a $\beta$ Cephei star can be.

Secondly, Heynderickx, Waenkens & Smeyers (1994) have identified $f_1$ as an $\ell = 2$ mode from their Walraven photometry. We have checked this identification with our method (again taking the contribution of $\theta$ Oph B to the total light into account) and also find $\ell = 2$ to be clearly the best match between observed and theoretical colour amplitude ratios. Thirdly, Dzsynska-Daszkiewicz et al. (2002) demonstrated that modes of odd $\ell$, starting with $\ell = 3$, suffer heavy geometric cancellation in photometric observations of $\beta$ Cephei stars using filters. For instance, an $\ell = 3$ mode of the same intrinsic amplitude as an $\ell = 2$ mode will have only $\sim 1/10$ of its photometric amplitude in the $u, v, y$ filters. We therefore disregard all the possible $\ell = 3$ identifications in Table 4 as well.

Thus we have arrived at unique $\ell$ identifications for five of the seven modes we detected: $f_1$ is $\ell = 2$, $f_3$ is radial, and $f_4, f_6, f_7$ are all $\ell = 1$. $f_2$ and $f_5$ can be either $\ell = 1$ or 2. As the last step, we examine the frequency spectrum of $\theta$ Oph A (schematically plotted in Fig. 6) for the presence of structures that may be useful for further constraining the mode identifications.

Indeed, some interesting features can be discerned. The $\ell = 1$ modes $f_4, f_6$ and $f_7$ form a frequency triplet that is almost equally spaced. However, there is a slight asymmetry, and it is exactly in the sense expected for nonradial $m$-mode splitting due to the second-order effects of rotation. We therefore believe that $f_4, f_6$ and $f_7$ are indeed a rotationally split triplet of $\ell = 1$ modes.

The remaining four modes are also grouped together. Intriguingly, the spacing between $f_2$ and $f_5$ is approximately half the frequency difference of $f_3$ and the $\ell = 2$ mode $f_1$. Again, the asymmetry of this hypothesised $f_1, f_5, f_2$ multiplet is consistent with the second-order effects of rotation. $f_3$ does not fit this pattern, but this is not surprising as we have already identified it as a radial mode. The first-order rotational splitting obtained from the $f_1, f_5, f_2$ multiplet is very similar to the splitting of the $f_4, f_6$ and $f_7$ triplet. Thus we suspect that $f_1, f_5$ and $f_2$ are part of a rotationally split $\ell = 2$ quintuplet with two components yet undetected.

Assuming that the mean splitting of the $\ell = 1$ triplet is a good approximation of the surface rotation frequency of $\theta$ Oph A (i.e. neglecting effects of the Coriolis force and possible differential internal rotation), we derive a rotation period of 9.6 days. The absolute magnitude and effective temperature of the star, as determined at the beginning of
this section, result in a radius of $5.2 \pm 1.3 \, R_\odot$, and hence in a surface rotation velocity of $27 \pm 7 \, \text{km/s}$. As the measured projected rotational velocity of $\theta$ Oph A is about $30 \, \text{km/s}$ (e.g. Abt, Levato & Grosso 2002), there is a chance that we see the star close to equator-on.

5 AN ECLIPSING BINARY?

If we indeed saw $\theta$ Oph A equator-on, it can be suspected that the spectroscopic companion discovered by Briquet et al. (2005) may cause eclipses. The binary orbit derived by these authors leads to an ephemeris for the times of primary and secondary minimum, respectively. M. Briquet (private communication) predicts

\begin{align*}
t_1 &= HJD 2451811.002 + i \times 56.712 \\
t_{11} &= HJD 2451834.599 + i \times 56.712
\end{align*}

where $i$ is the number of orbital revolutions since epoch zero. Given the total mass of the spectroscopic binary system ($\sim 10 \, M_\odot$), the orbital period and the radius of the primary determined above, we can also estimate the maximum duration of a possible eclipse, amounting to $17 \pm 4 \, \text{h}$.

Although we found no obvious evidence for eclipses in our photometric measurements, we folded our data according to this ephemeris and searched them again for possible eclipses. As it turns out, we have no measurements whatsoever during or even near the predicted times of primary minimum, which is not surprising given that our orbital coverage is only $17 \%$. We do have data around the expected times of secondary eclipse, but none is found, which is also not a surprise since the secondary of the spectroscopic binary would much less luminous than $\theta$ Oph A if we see the orbital plane (close to) edge-on, and consequently the depth of a secondary eclipse would be too small to be detected. We again conclude that there are no eclipses in our photometry of the $\theta$ Oph system.

6 DISCUSSION

Our photometric multisite campaign on the $\beta$ Cephei star $\theta$ Oph resulted in the detection of seven independent pulsation modes. Our colour photometry that was intended for mode typing only resulted in two firm identifications, but we believe that this is mostly due to the small photometric amplitudes of all but one of the pulsation modes. However, also the strongest mode could not be unambiguously identified from our data; we had to invoke literature results.

Mode identification from colour photometry of $\beta$ Cephei stars primarily rests on the amplitudes determined in the blue and ultraviolet ($\lambda < 4200 \, \text{Å}$). We have used a subset of the Strömgren filter system for our measurements as a compromise between wide availability and mode identification potential, with the drawback that the identifications critically depend on the results in the $u$ filter, which may be hard to verify. Consequently, any systematic error in the $u$ measurements can heavily compromise the mode identifications.

The Walraven or the Geneva photometric systems would provide a solution to this dilemma, but they are unsuitable for multisite work since few observatories are equipped for their use. However, the pulsation spectrum of $\theta$ Oph A is reasonably simple and the range of excited frequencies is less than $1 \, \text{cd}^{-1}$, so that an extensive singlesite study of this star in one of these photometric systems should be sufficient to check the mode identifications we finally arrived at by adding further constraints to the colour amplitude analysis.

We believe that our suggestion that $f_1$, $f_5$ and $f_2$ are part of a rotationally split $\ell = 2$ quintuplet can also be checked by theoretical model calculations. Since the asymmetry of the hypothesised multiplet due to the second-order effects of rotation has been measured to good relative accuracy, and since the rotation rate of the star is constrained by the $f_4$, $f_6$, $f_7$ triplet splitting, pulsational models should be able to reproduce the observed asymmetries if our identification of $f_1$, $f_5$ and $f_2$ is correct.

To perform a detailed asteroseismic study, one more ambiguity must then still be overcome: if $f_1$, $f_5$ and $f_2$ are $\ell = 2$ quintuplet members, their $m$ values must be determined. From photometry alone, we cannot distinguish if they correspond to $m = (-2, 0, 1)$ or $m = (-1, 1, 2)$. However, the analysis of archival spectroscopy by Briquet et al. (2005) solves this ambiguity.

It is interesting to note that we found evidence that $\theta$ Oph A is seen close to equator-on (a result corroborated by Briquet et al. 2005). In such a configuration, the $m = 0$ component of $\ell = 1$ modes as well as the $|m| = 1$ components

![Figure 6. Schematic amplitude spectrum of $\theta$ Oph. The frequency differences between some of the modes are indicated.](image)
of $l = 2$ modes should suffer heavy geometric cancellation. However, such modes are apparently observed.

In any case, a seismic investigation of $\theta$ Oph A is possible. We note that we would not expect its outcome to be as fruitful as that for $\nu$ Eri (Pamyatnykh et al. 2004, Ausseloos et al. 2004) since fewer radial overtones of modes are excited, but the general applicability of earlier results could be tested. In addition, the detection of a possible eclipse of the primary would help to constrain the system parameters even tighter, which can in turn assist the seismic modelling.

Finally, we would like to point out that the frequency structure of $\theta$ Oph A is remarkably similar to that of V836 Cen (Aerts et al. 2004a): a radial mode close to an incomplete $l = 2$ multiplet of somewhat lower frequency and a complete $l = 1$ triplet of higher frequency, and all modes are contained in a very narrow frequency interval (which is of extremely similar size in the co-rotating frame). The only differences are the somewhat higher pulsation frequencies of $\theta$ Oph A and its faster rotation. We thus speculate that once more pulsation spectra of $\beta$ Cephei stars become known in detail, important clues on mode excitation can be gathered.

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