Multi-site, multi-year monitoring of the oscillating Algol-type eclipsing binary CT Her*, **

P. Lampens1, A. Strigachev2, S.-L. Kim3, E. Rodriguez4, M.J. López-González4, J. Vidal-Sainz5, D. Mkrtichian6,7,8, J.-R. Koo3,9, Y. B. Kang3,9, P. Van Cauteren10,11, P. Wils11, Z. Kraicheva2, D. Dimitrov2, J. Southworth12, E. García Melendo5, and J.M. Gómez Forellad5

1 Koninklijke Sterrenwacht van België, Ringlaan 3, 1180 Brussels, Belgium
2 Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72 Tsarigradsko Chosse Blvd., 1784 Sofia, Bulgaria
3 Korea Astronomy and Space Science Institute (KASI), Daejeon 305-348, Korea
4 Instituto de Astrofísica de Andalucía, CSIC, P.O. Box 3034, E-18080 Granada, Spain
5 Grup d’Estudis Astronòmics, Apdo. 9481, 08080 Barcelona, Spain
6 Astrophysical Research Center for the Structure and Evolution of the Cosmos, Sejong University, Seoul, Korea
7 Astronomical Observatory, Odesa National University, Odesa, 650014 Ukraine
8 Crimean Astrophysical Observatory, Nauchny, 98409 Crimea, Ukraine
9 Department of Astronomy and Space Science, Chungnam National University, Daejeon, 305-764, Korea
10 Beersel Hills Observatory (BHO), Beersel, Belgium
11 Vereniging voor Sterrenkunde (VVS), Oostmeezers 122 C, 8000 Brugge, Belgium
12 Astrophysics Group, Keele University, Newcastle-Under-Lyme ST5 5BG, United Kingdom

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ABSTRACT

We present the results of a multi-site photometric campaign carried out in 2004-2008 for the Algol-type eclipsing binary system CT Her, the primary component of which shows δ Scuti-type oscillations. Our data consist of differential light curves collected in the filters B and V which have been analysed using the method of Wilson-Devinney (PHOEBE). After identification of an adequate binary model and removal of the best-matching light curve solution, we performed a Fourier analysis of the residual B and V light curves to investigate the pulsational behaviour. We confirm the presence of rapid pulsations with a main period of 27.2 min. Up to eight significant frequencies with semi-amplitudes in the range 3 to 1 mmag were detected, all of which lie in the frequency range 43.5-53.5 d^{-1}. This result is independent from the choice of the primary’s effective temperature (8200 or 8700 K) since the light curve models of the binary are very similar in both cases. This is yet another case of a complex frequency spectrum observed for an accreting δ Scuti-type star (after Y Cam). In addition, we demonstrate that the amplitudes of several pulsation frequencies show evidence of variability on time scales as short as 1-2 years, perhaps even less. Moreover, our analysis takes into account some recently acquired spectra, from which we obtained the corresponding radial velocities for the years 2007–2009. Investigation of the O-C diagram shows that further monitoring of the epochs of eclipse minima of CT Her will cast a new light on the evolution of its orbital period.

Key words. stars: binaries: eclipsing – stars: oscillations – stars: fundamental parameters – stars: individual: CT Her

1. Introduction

Asteroseismology aims to understand the pulsation physics in order to probe the interior parts of all kinds of stars. Among the classical pulsators, δ Scuti stars are rather common and are located at the intersection of the Cepheid instability strip and the main sequence. They pulsate primarily in low overtone radial and non-radial acoustic modes with periods between 30 min and 6 hr. Some may also pulsate in gravity modes (Kurtz 2000). Their excitation mechanism, i.e. the κ-mechanism active in the partial ionisation zones of He I and He II, is well-understood. However, still now, unknown amplitude limiting and mode selection mechanisms are operating in these pulsators. Only a fraction of the theoretically predicted modes are observed, which results in (too) many free parameters in the pulsation models. It is indeed primordial to collect knowledge on the fundamental stellar properties of the pulsator independently.

One way is to study the pulsating components of binary (multiple) systems in great detail, since binary (multiple) systems with well-characterized components supply additional constraints for a more reliable modelling. The posi-
tions in the H-R diagram and therefore the components’ evolutionary statuses can be more accurately determined than in the case of single stars, e.g. for those δ Scuti stars that are at the (very) end of their H-core burning phase. The complexity of having to deal with additional components does generally not weigh against the scientific return, although observations spread over even longer time-scales may be necessary to disentangle both phenomena.

About seventy percent of all stars of the Solar neighborhood are members of binary or multiple systems (67% for G-M stars, Mayor et al. 2001; 75% for O-B stars, Mason et al. 2001). Yet, these facts are usually ignored in the study of stellar pulsation. There is, however, strong evidence that duplicity affects the pulsation properties in specific cases (e.g. the eccentric binaries HD 177863 (De Cat & Aerts 2002) and HD 209295 (Handler et al. 2002)). This is also predicted from a theoretical point-of-view (Witte & Savonije 1990). It is thus essential to understand the possible link(s) between binarity and pulsation(s) and to observe whether or not - under given circumstances - the internal structure and the pulsating properties of such stars might be different from those of the single pulsators (Lampens 2006).

Detached and semi-detached eclipsing binaries (EBs) are particularly powerful tools in astrophysics: their accurate observation enables to derive the fundamental properties (masses, radii, luminosities) of each component. EBs also provide the component’s effective temperatures, as well as the distance if stellar atmosphere models are used (Maceroni 2006).

We present a detailed photometric study of the Algol-type binary CT Her, an eclipsing binary of mag 11-12 and spectral type A3V+[G3IV] with an orbital period of 1.7863748 days (Samus et al. 2009). Radial velocity measurements have also been collected, but due to its faintness, high-quality spectra are not easily acquired. CT Her belongs to the group of oscillating Algol-type (oEA) stars comprising 35 known members. Up to now, a few members of this group only have been investigated thoroughly: RZ Cas has been observed photometrically as well as spectroscopically over almost a decade (Lehmann & Mkrtichian 2004; Rodriguez et al. 2005; Soyudgan et al. 2006; Lehmann & Mkrtichian 2008) while a very detailed photometric study of Y Cam was recently finished (Rodriguez et al. 2010). TW Dra is another case for which a large spectroscopic observational effort was carried out (Lehmann et al. 2009; Tkachenko et al. 2010). Its (O-C) diagram shows a slow orbital evolution (Kreiner et al. 2001). The primary component displays oscillations of type δ Scuti with a (main) pulsation period of 0.46 hr (≈28 min) and a total amplitude of about 0.02 mag (Kim et al. 2001). Among the currently known oEA stars, it has one of the shortest orbital periods and the highest ratio $P_{\text{obs}}/P_{\text{puls}}$ (about 95).

The oEA stars are former secondarys of evolved, semi-detached eclipsing binaries which are (still) undergoing mass transfer and form a recently detected subclass of pulsators close to the main sequence (Mkrtichian et al. 2002, 2004). Searches for new oscillating Algols have been performed by Kim et al. (2004a, 2004b) and Mkrtichian et al. (2005, 2006). Pigulski & Michalska (2007) and Michalska & Pigulski (2008) looked for them in the ASAS-3 and the OGLE-II public databases. A search using the NSVS database has also been on-going at the Institute of Astronomy of the Bulgarian Academy of Sciences (Dimitrov et al. 2003a, 2003b, 2003c, 2003d). Their general characteristics and pulsational properties have been summarized by Mkrtichian et al. (2005). Such oEA stars are, indeed, excellent laboratories for investigating the effects of mass accretion events as well as of tides onto the pulsation properties. Changes of these properties (amplitudes, modes and/or phases) due to mass accretion episodes have been observed (e.g. in RZ Cas where strong modal amplitude variations followed an abrupt change of its orbital period; Rodriguez et al. 2003; Mkrtichian et al. 2005). Their pulsational frequencies could be tidally split (in KW Aur, Fitch 1976) and/or there may be some coupling between the pulsation and the orbital frequency due to some resonance mechanism (Mkrtichian et al. 2005). Their very different evolutionary history is a challenge for stellar evolution modelling. For example, in order to reproduce the gainers of RZ Cas, KO Aql and S Equ through conservative binary evolution, large initial mass ratios (typically > 3) would be necessary. But the corresponding high mass loss rates in the beginning of the Roche Lobe overflow stage result in radii larger than the Roche radii. Hence, a non-conservative approach is needed, in which processes are considered that enhance the period without losing too much mass (De Grève et al. 2009). Such studies have not yet been attempted. Detailed and multi-year studies of more oEA stars are essential in order to provide solid grounds for their (future) asteroseismic modelling.

2. Observations and data reduction

2.1. The multi-site campaign

High-precision light curves of CT Her (GSC 01509-1142, $V = 11.347, B - V = 0.203$) were collected in the framework of a 5-yr long multi-site campaign set up with the purpose to study its pulsational behaviour. A logbook of the observations is given in Table 1. We observed in a differential mode from late spring till late summer of the years 2004-2008. The original observations which led to its discovery as an oEA star (Kim et al. 2001a) were also included. The following comparison stars were used: C1=GSC 01509-1140 ($V = 10.951, B - V = 1.414$); C2=GSC 01509-1052 ($V = 11.405, B - V = 0.779$); C2’=GSC 01509-1130 ($V = 12.02$); C3=GSC 01509-0901 ($V = 12.30, B - V = 0.78$) and C4=GSC 01509-1000 ($V = 10.75, B - V = 0.48$).

The characteristics of the various CCD cameras are the following ones:

- at the Skinakas Observatory of the University of Crete, Greece. The camera is a Photometrics 1024×1024 with a SITE SITe SI003B chip of grade 1 and a pixel size of 24 µm corresponding to a scale of 0.78″ on the sky. The field-of-view is 8″ × 8.5″ (Papadakis et al. 2003).
- at the Sobaeksan Optical Astronomy Observatory of the Korea Astronomy and Space Science Institute (KASI), South-Korea. The camera has a 2048×2048 SITE chip with a pixel size of 24 µm corresponding to a scale of 0.60″ on the sky. The field-of-view is 20.5″ × 20.5″.
- at the Observatory of Mt. Lemmon, Arizona, operated by KASI. The camera has a 2084×2084 Kodak chip with a pixel size of 24 µm corresponding to a scale of 0.64″ on the sky. The field-of-view is 22.2′ × 22.2′ large.
– at the Observatorio de Monegrillo, North of Spain. The camera is a SX Starlight CCD with a Sony ICX027BL chip (cooled to about -25°C) and a pixel size of 12.7 \( \mu \times 16.6 \mu \) corresponding to 1.80" \( \times \) 1.38". The field-of-view covered a sky region of 11.5° \( \times \) 7.7°. The reduction was done using a software package called LAIA (Laboratory for Astronomical Image Analysis) developed by Joan A. Can.

– at the Beersel Hills Observatory, Belgium. The camera is a SBIG ST10XMe with a chip of grade 1 and a pixel size of 6.8 \( \mu \) corresponding to a scale of 1.43" on the sky (2x2 binning). The field-of-view is 17.5° \( \times \) 26° on the sky. The reduction was done using the Mira AP (v.7) package.

– at the Observatorio Sierra Nevada, South of Spain. The camera has a 2k x 2k chip with a pixel size of 13.5 \( \mu \) corresponding to a scale of 0.23" on the sky (2x2 binning). The field-of-view is 7.92" \( \times \) 7.92" large.

– at the National Astronomical Observatory (NAO) Rozen, Bulgaria. The CCD is a VersArray 1330B with a 1340 \( \times \) 1300 E2V CCD36-40 chip of grade 2 and a pixel size of 20 \( \mu \) corresponding to a scale of 0.258" on the sky. The field-of-view is 5.76" \( \times \) 5.95" large.

Photoelectric photometric data on CT Her were also acquired in the four Strömgren passbands uvby at the Observatorio Sierra Nevada between 2008 March, 31 and 2008 April, 13. The comparison stars were K1 = HD 145122, K2 = HD 146101, K3 = HD 145549, CT Her, AO Ser, CT Her, AO Ser... because both oEA stars are close enough in the sequence Sky, K1, K2, CT Her, AO Ser, K1, K3, CT Her, AO Ser... because both oEA stars are close enough to one another on the sky. Unfortunately, the orbital period was not fully covered during the additional observations.

2.2. Observational technique

CT Her was observed using the standard (Johnson) filters B (mostly) and V (less frequently). At the Beersel Hills Observatory (BHO), we follow the specifications for the filters of Bessell (1995). C1 is the principal comparison star which was commonly used at every observatory. We adopted the filter B as the main filter because of its higher signal-to-noise ratio and the larger amplitudes of pulsation expected. Typical exposure times for the B filter were set between 15 s (e.g. Sierra Nevada) and 60 s (e.g. Skinakas). Typical exposures for the V filter were 20-30 s (e.g. BHO and Skinakas). All observers followed the standard calibration procedure: a set of biases (resp. darks) was taken regularly during each night and a set of 5 to 6 flat-fields per filter was obtained during evening and/or morning twilights.

As an example, we describe the full reduction procedure used for images collected at the Skinakas Observatory. All the primary reduction steps were performed using standard ESO-MIDAS routines. The frames were processed as follows: subtraction of the residual bias pattern using a median master bias frame, flat-fielding using a median master flat-field frame, and median cosmic ray cleaning. Since the field is not crowded, the technique of aperture photometry was applied to extract the differential magnitudes. The fixed aperture photometry was performed using DAOPHOT (Stetson 1987). CT Her and the comparison stars C1, C2 and C3 were measured using an aperture size as close as possible to the value providing the highest signal-to-noise ratio (Strigachev 2009). The data consist of differential photometry of the variable star in the sense (CT Her - C1) and of the check stars in the sense (C2' - C1) and (C3 - C1).

CT Her was also observed in the BVR filters together with standard fields (Landolt 1992). We performed all-sky photometry up to an airmass of 2 at the Skinakas Observatory on Aug. 2005, 1. The coordinates, calibrated magnitudes and colours of the target and comparison stars are listed in Table 2.

3. Photometric data – time series

The influence of interstellar and atmospheric extinction may be crucial when constructing light curves of eclipsing binaries (Prša & Zwitter 2005a). This is generally the case when matching data from different sites and campaigns but it may also be valid when using data from a single site. Observations from different nights and/or sites do usually not match - their mean level may be shifted, and there may also a correlation with airmass during some nights. In this case, differential corrections associated with the second-order coefficient of the atmospheric extinction (k") were needed since the colours of the comparison star (C1) and the variable star are not the same (see Table 2). These corrections were mainly needed for the data acquired in the filter B because of the dependence in wavelength and the greater inhomogeneity of the B-data sets collected over a longer period and at a larger number of sites equipped differently.

To correct for this influence, we first computed the magnitude of CT Her based on the magnitude of C1 in Table 2 and the differential values (CT Her - C1). Next, we adopted a preliminary model light curve based on known and fitted parameters for the V light curve obtained during the 2005 & 2008 runs at the Observatory of Monegrillo, Spain (cf. Table 2). This was possible because the V light curve is less dependent on these corrections. In general, a clear dependence of the residuals in magnitude difference with the airmass per night was found, which we modelled using linear regression. The correction involved the zero-point shift due to interstellar and atmospheric extinction and the slope due to the term associated to the second-order atmospheric extinction. At any given site with the same instrument and filter, this slope was assumed constant. Where relevant, we applied the correction. Remark that the effect is systematically smaller in the V-band than in the B-band. The resulting differential magnitudes of every night were concatenated per filter to produce the overall corrected B and V data sets. These data are presented in Tables 3 and 4. The full tables are available in electronic form only. Table 3 also lists the numbers of observations collected at each observatory. In the subsequent analysis, more than 7900 and 2100 data points, respectively in the filters B and V, were treated.

4. Simultaneous modelling of the light curves

The B- and V-data sets were used to plot the respective light curves phased against the orbital period of 1.786374885656.
Table 1. Campaigns and instrumentation. Total number of useful observations and hours.

| Year | Site        | Country | Tel. | Period (Obs.) | Nights | Hours | Filter | CODE |
|------|-------------|---------|------|---------------|--------|-------|--------|-------|
| 2004 | Skinakas    | Crete   | 1.3-m| Jun-July (AS) | 4      | 573   | B      | SKB1  |
| 2004 | Sobaeksan   | Korea   | 0.61-m| March (SLK)  | 3      | 379   | B      | KRB1  |
| 2005 | Skinakas    | Crete   | 1.3-m| May-Aug (AS)  | 6      | 1091  | B      | SKB2  |
| 2005 | Mt. Lemmon  | Arizona | 1.0-m| Jun-July (SLK)| 5      | 643   | B      | KRB2  |
| 2005 | Monegrillo  | Spain   | 0.4-m| Jun-July (JV) | 15     | 1208  | V      | SPV1  |
| 2005 | Beersel     | Belgium | 0.4-m| Jun-July (PVC)| 5      | 430   | B      | BHOB  |
| 2005 | Beersel     | Belgium | 0.4-m| Jun-July (PVC)| 2      | 517   | V      | BHOV  |
| 2006 | Skinakas    | Crete   | 1.3-m| Jun-July (AS) | 9      | 1427  | B      | SKB3  |
| 2006 | Sierra Nevada| Spain  | 1.5-m| Aug (ER+MLG) | 9      | 835   | B      | SPB1  |
| 2007 | Sierra Nevada| Spain  | 1.5-m| Mar-May(ER+MLG)| 8     | 2158  | B      | SPB2  |
| 2007 | Monegrillo  | Spain   | 0.4-m| March (PVC)  | 1      | 83    | V      | BHOV  |
| 2008 | NAO Rozhen  | Bulgaria| 2.0-m| June-July (AS)| 2      | 358   | B      | ROZB  |
| 2008 | Monegrillo  | Spain   | 0.4-m| June-July (JV) | 3      | 372   | V      | SPV2  |
| 2004-08 | All      | —       | —    | —             | —      | 2180  | —      | ALL   |
| 2004-08 | All      | —       | —    | —             | —      | 7960  | —      | ALL   |

Table 2. Coordinates and standard system calibrated magnitudes with their errors for the target and comparison stars.

| Ident | GSC | RA   | DEC   | B      | V      | R      | B − V  | B − R  |
|-------|-----|------|-------|--------|--------|--------|--------|--------|
| CT Her| GSC01509-1142 | 16 20 26.57 | +18 27 16.9 | 11.33±0.03 | 11.12±0.03 | 11.00±0.03 | 0.21±0.04 | 0.12±0.04 |
| C1    | GSC01509-1140 | 16 20 33.89 | +18 27 18.5 | 12.40±0.03 | 12.40±0.03 | 12.40±0.03 | 0.69±0.04 |
| C2    | GSC01509-1130 | 16 20 18.61 | +18 27 32.6 | 13.41±0.03 | 13.41±0.03 | 13.41±0.03 | 0.52±0.04 |
| C3    | GSC01509-0901 | 16 20 43.00 | +18 30 53.2 | 13.18±0.03 | 13.18±0.03 | 13.18±0.03 | 0.29±0.04 |

Notes:
- C1 was also used by Kim et al. (2004a)
- C2’ is not the same star as C2 (Kim et al. 2004a)

Table 3. CT Her B light curve (first three lines, table available in electronic form).

| HJD    | B    | Code | Year |
|--------|------|------|------|
| 2453954.47391 | 11.460156 | SPB1 | 2006 |
| 2453954.47529  | 11.462120 | SPB1 | 2006 |
| 2453954.47609  | 11.460165 | SPB1 | 2006 |

Table 4. CT Her V light curve (first three lines, table available in electronic form).

| HJD    | V    | Code | Year |
|--------|------|------|------|
| 2453557.38196 | 11.958390 | SPV1 | 2005 |
| 2453557.38406 | 11.938400 | SPV1 | 2005 |
| 2453557.38617 | 11.921600 | SPV1 | 2005 |

We performed a simultaneous modelling of the B and V light curves of CT Her using the light-curve fitting programme PHOEBE, version 0.31a, in Mode 5, which corresponds to a semi-detached binary configuration in which the secondary component fills its limiting lobe, as required for the oEA stars. PHOEBE (Prša & Zwitter 2005b) is a package which enables to compute models of eclipsing binaries based on observed photometric and radial velocity data. It relies on the 2003-version of the widely used Wilson-Devinney code (Wilson & Devinney 1971, Wilson 1979, 1990). First, we employed the almost complete and homogeneous V-light curve obtained by one of us (JVS) during the years 2005 and 2008 to compute an initial model; next, using this initial model, we corrected the individual B and V data sets (where needed) for the differential effects of atmospheric extinction as explained in Sect. 3 Only then did
we compute a best-fitting solution for the combined data series.

Since CT Her is classified as an A3V star (Kuznetsova & Svechnikov 1990), we initially adopted 8700 K as the surface temperature of the primary component. Except for the orbital ephemeris, all other parameters were set as adjustable parameters during the minimization procedure: this concerns the secondary star’s surface temperature, \(T_2\), the inclination, \(i\), the mass ratio, \(q\), the dimensionless potential, \(\Omega\), and the fractional luminosities of the primary component, \(L_1\), in \(B\)- and \(V\)-light (6 free parameters). We adopted the roughly determined absolute photometric and geometric elements (Svechnikov & Kuznetsova 1990) as starting values (e.g. \(i = 82\degree\) for the inclination and \(q = 0.27\) for the mass ratio), together with an estimate of the secondary component’s surface temperature, \(T_2 = 5800\) K, corresponding to a spectral type of G3IV. Other parameters such as the gravity darkening coefficients \(g_1\) and \(g_2\) and the albedos \(A_1\) and \(A_2\) were set to the theoretical values corresponding to a radiative atmosphere (\(A_1 = 1.0\) and \(A_1 = 1.0\)) in the case of the primary component and to a convective atmosphere (\(g_2 = 0.32\) and \(A_2 = 0.5\), Rucinski 1969) in the case of the secondary component. The limb darkening coefficients in the \(B\)- and \(V\)-bands were taken from the tables by Van Hamme (1993). In all the runs, convergence was achieved after only two or three iterations using the differential correction method.

By scanning the distribution of the function to be minimized, \(\chi^2\), as a function of both \(T_1\) and the mass ratio, \(q\), we found two regions of possible solutions: one region near \(T_1 = 8700\) K and another one near \(T_1 = 8200\) K. Fig. 3 illustrates the evolution of \(\chi^2\) as a function of the parameters \(T_1\) and \(q\). Thus, we considered two equivalent solutions in the subsequent analysis: one solution associated with \(T_1 = 8700\) K (model 71) and one associated with \(T_1 = 8200\) K (model 72), with their corresponding values of \(T_2\) and \(q\). The latter value of \(T_1\) corresponds to a spectral type of A5V and to a colour index \((B-V) = 0.15\) assuming zero reddening (cf. also the observed colour index \((B-V)\) in Table 2). The resulting parameter values and their formal uncertainties are listed in Table 3. Both models fit the observed \(B\) and \(V\) light curves very well, as evidenced by the small values of the \(\chi^2\) function and the 1-2\%-level scatters of their residual data sets. The synthetic (and observed) light curves corresponding to the first model are illustrated by Figs. 1 and 2. The synthetic light curves corresponding to the alternative model are indistinguishable.

The main difference between both models is the surface effective temperature of the secondary component, \(T_2\), which is shifted by about 200 K. The largest changes with respect to the initial values are found in the parameters \(T_2\) and \(q\): both are smaller than their adopted first guesses (respectively 5800 K and 0.27). The mass ratio is significantly smaller than previously assumed (i.e. \(q < 0.20\)). Nonetheless, even though the components’ effective temperatures are different, both models are obviously similar since their derived physical parameters lie very close to one another (cf. the masses, gravities and radii of Table 1).

From here on, even though the values of the \(\chi^2\) function are slightly smaller in the former case (cf. Table 3), we will adopt the solution derived with \(T_1 = 8200\) K (model 72), the reason being that we obtained a better fit with this temperature to a few observed regions of the spectrum of CT Her (Sect. 6). We will furthermore show that the frequency-analysis of the corresponding residuals is independent of the choice of either one of the two proposed models (Sect. 5).

5. Frequency analysis of the residual light curves

The light curve model with \(T_1 = 8200\) K was subsequently subtracted from the original light curves of CT Her to search for short-period pulsations in the residual data. The phased residual light curves are plotted in Figs. 4 and 5, respectively in the filters \(V\) and \(B\). The adjustment is excellent for the \(B\)-data set (without a primary minimum) and fair for the \(V\)-data set. Weights were associated based
on the overall standard deviations of the (CT Her - C1) differential B-magnitudes computed night by night; while 1.0 was adopted in most cases, some sets with higher noise were allocated a relative weight of 0.2. This is the case for a few nights at the Beersel Hills Observatory (2005) and two nights at the Observatory of Sierra Nevada (2007).

We restricted the residual data to the orbital phase bins between 0.05-0.95 in order to omit the phase of primary minimum (sparsely covered by our V-observations). The fact that various outliers were found close to a primary minimum indicates that it is hard to model both effects simultaneously during this phase of rapid and steep light variation. On the other hand, the outliers are only associated to partially observed eclipses, whereas the fully observed primary eclipse of 2008 shows normal residuals. Such small effects might also have been introduced by the airmass-dependent corrections (since more prominent at the beginning/end of the night). After the removal of a few outliers larger than or equal to 0.02 mag, the remaining standard deviations are 6.4 mmag in the V-band (with 1958 residual data points) and 6.3 mmag in the B-band (with 7625 residual data points).

5.1. Results from the B-data

We performed Fourier analyses with PERIOD04 (Lenz & Breger 2005). Fig. 6 illustrates the frequency search in the range $0-80$ d$^{-1}$ for the larger residual data set (B-band): the spectral window is shown in the top panel while the following panels show the initial periodogram and the periodograms successively prewhitened of the strongest signal from each previous run. The last panel shows the residual periodogram with the mean noise level computed for frequency bins of width 5 d$^{-1}$. We identified fifteen frequencies with an amplitude-to-noise ratio larger than or equal to 4.0 (the empirical criterion introduced by Breger et al. [Breger et al. 1993]). The frequencies, amplitudes, residual standard deviations, signal-to-noise ratios and the removed fraction of the initial variance, $1 - R = (\sigma_{\text{init}}^2 - \sigma_{\text{res}}^2)/\sigma_{\text{init}}^2$, obtained from a multi-parameter fit of the residuals to a solution with fifteen frequencies, are listed in Table 5. The errors on the frequencies and the amplitudes were computed using 120 Monte Carlo simulations of PERIOD04. The signal-to-noise ratios are based on the mean noise levels of the periodograms of the residuals. Remark that eight frequencies are concentrated in the range 43.5 - 53.5 d$^{-1}$. The main frequency of 52.93664 d$^{-1}$ has a semi-amplitude of 3.3 mmag in B. This frequency corresponds to a periodicity of 27.2 min, and is the one found by Kim et al. (2014a). A few oEA stars have even shorter main pulsation periods: e.g. RZ Cas ($f_1 = 64.1935$ d$^{-1}$, Rodriguez et al. 2004) and AS Eri ($f_1 = 59.03116$ d$^{-1}$, Mkrtichian et al. 2014).

All seven frequencies in the range $f < 5$ d$^{-1}$ are caused by small imperfections linked to the reduction, extraction of the orbital variations and statistical fluctuations in the data sets. Since they are irrelevant for our study, we kept them fixed during the Monte Carlo simulations. Some of the other eight frequencies found are affected by the 1 d$^{-1}$ aliasing phenomenon: they are flagged in Table 3. At this point, we conclude that eight (pulsation) frequencies are found to be significant. After prewhitening for the multi-frequency solution, the remaining standard deviation in the B-band equals 4.3 mmag, removing 53% of the initial variance. High-quality residual B-band light curves are presented in Fig. 7, demonstrating a good agreement between the residuals and the proposed solution.

5.2. Results from the V-data

Likewise, the complete set of the V-band residual data was analysed. Since these data are less numerous and more noisy, less significant results were found. We identified ten frequencies with an amplitude-to-noise ratio larger than 4.0, six of which are located in the range 43.5 - 53.5 d$^{-1}$. The frequencies, amplitudes, residual standard deviations, signal-to-noise ratios and the removed fraction of the initial variance, 1 - R, resulting from a multi-parameter fit of the V-band residual data set to a solution with ten frequencies, are listed in Table 4. All errors were computed using 120 Monte Carlo simulations of PERIOD04. Apart from the fre-
Fig. 6. Periodograms of CT Her computed during successive frequency analyses (filter B).

5.3. Variability of the pulsation amplitudes

The full analyses in the B and V-bands were repeated after subtraction of the alternative model using $T_1 = 8700$ K (model 71). In the range above 24 d$^{-1}$, the frequencies listed in Tables 6 and 7 were confirmed, though with slight modifications in the order of their appearance. This shows that the results of the Fourier analyses are perfectly independent of the adopted choice for the binary model (owing to a) the fact that the binary models are almost identical and b) the different time scales involved).

It would also seem that the results of the frequency analyses in both filters tend to a common solution, were it not for the presence of F3 (Table 6) and G4 (Table 7). In addition, the order in which the frequencies were detected in the respective data sets is not identical. Therefore, we investigated whether patterns could be found in the pulsation amplitudes assuming that the frequency content is stable. All eight frequencies from Table 6 located in the range 43.5 – 53.5 d$^{-1}$ were adopted to represent the frequency content of CT Her. Preference was given to the results from the B-band analysis because the aliasing is much stronger in the V-band data (particularly the 1 d$^{-1}$ and the 0.0018 d$^{-1}$ aliasing effects). Next, we computed the multi-parameter solutions with the amplitudes and the phases as free parameters on a yearly basis.

| ID | Frequency (± error) d$^{-1}$ | Amplit. (± 0.1) mmag | $\sigma_{res}$ mmag | S/N | 1 - R |
|----|-----------------------------|----------------------|------------------|-----|-----|
| F1 | 52.93664 (± 0.8)           | 3.3                  | 5.9              | 12.7|     |
| F2 | 0.97682 (fixed)           | 2.8                  | 5.6              | 11.4|     |
| F3 | 47.59996 (± 2)            | 1.8                  | 5.4              | 7.2 |     |
| F4 | 49.20822 (± 2)            | 1.8                  | 5.3              | 6.6 |     |
| F5 | 2.37738 (fixed)           | 2.0                  | 5.1              | 8.1 |     |
| F6 | 45.69130 (± 3)*           | 1.3                  | 5.0              | 6.2 |     |
| F7 | 1.00032 (fixed)           | 2.1                  | 4.9              | 8.4 |     |
| F8 | 45.44028 (± 2)*           | 1.4                  | 4.8              | 6.8 |     |
| F9 | 3.44103 (fixed)           | 1.1                  | 4.7              | 4.3 |     |
| F10| 53.23474 (± 2)            | 1.2                  | 4.6              | 4.8 |     |
| F11| 4.08614 (fixed)           | 1.1                  | 4.5              | 4.4 |     |
| F12| 0.61211 (fixed)           | 1.2                  | 4.5              | 4.7 |     |
| F13| 4.16902 (fixed)           | 1.1                  | 4.4              | 4.3 |     |
| F14| 43.76799 (± 3)            | 1.1                  | 4.4              | 5.4 |     |
| F15| 45.56395 (± 4)*           | 1.0                  | 4.3              | 4.6 | 0.53|

*: possibly affected by the 1 d$^{-1}$ aliasing
Fig. 7. Sample figures of the $B$-band residual data set and corresponding multi-frequency model.

Table 7. $V$-band frequency-analysis of the residuals (model 72)

| ID  | Frequency ($\pm$ error) $d^{-1}$ | Amplit. ($\pm$ 0.2) mmag | $\sigma_{rca}$ | S/N | 1 - R |
|-----|----------------------------------|---------------------------|---------------|-----|------|
| G1  | 52.93762 ($\pm$ 5)$^c$         | 2.2                       | 6.4          | 7.4 |
| G2  | 0.56716 (fixed)                | 2.2$^e$                   | 6.1          | 6.4 |
| G3  | 49.20636 ($\pm$ 6)$^\#$       | 1.8                       | 5.9          | 6.8 |
| G4  | 49.49661 ($\pm$ 7)            | 1.6                       | 5.6          | 6.2 |
| G5  | 3.68294 (fixed)               | 1.9                       | 5.5          | 5.6 |
| G6  | 45.43726 ($\pm$ 479)$^e$     | 1.1                       | 5.4          | 5.3 |
| G7  | 0.38478 (fixed)               | 2.3                       | 5.3          | 6.8 |
| G8  | 2.08342 (fixed)               | 1.6                       | 5.2          | 4.7 |
| G9  | 43.76975 (± 22)               | 1.1                       | 5.3          | 5.4 |
| G10 | 48.06813 (± 125)$^*$          | 1.1                       | 5.2          | 4.4 |

$^c$: (possibly) affected by the 1 $d^{-1}$ aliasing
$^e$: the error is ± 0.2 mmag
$^\#: $ is the 0.00095 $d^{-1}$ alias frequency of 5.90664 $d^{-1}$ (F1, Tab. 6)
$^e$: is the 0.0018 $d^{-1}$ alias frequency of 49.20822 $d^{-1}$ (F4, Tab. 6)

Table 8. Semi-amplitudes of the pulsation frequencies ($B$-band)

| ID  | Amp. 2004 ($\pm$ 0.3) mmag | Amp. 2005 ($\pm$ 0.2) mmag | Amp. 2006 ($\pm$ 0.1) mmag | Amp. 2007-2008 ($\pm$ 0.1) mmag |
|-----|---------------------------|---------------------------|---------------------------|--------------------------------|
| G1  | 3.0                       | 3.2                       | 3.4                       | 3.2                            |
| F3  | 2.2 ($\pm$ 0.4)           | 1.1                       | 2.2$^a$                   | 1.6$^a$                        |
| F4  | 2.4                       | 2.1                       | 1.3                       | 2.0$^a$                        |
| F6  | 2.2                       | 1.7                       | 0.7$^a$                   | 1.7                            |
| F8  | 0.9                       | 0.6                       | 1.4$^a$                   | 2.2                            |
| F10 | 1.8                       | 1.2                       | 1.2                       | 1.8                            |
| F14 | 0.2                       | 1.0                       | 1.5                       | 0.8                            |
| F15 | 1.3 ($\pm$ 0.5)           | 0.5 ($\pm$ 0.5)           | 1.2$^b$                   | 1.2$^b$                        |

$^a$: the error is ± 0.2 mmag

The results of the computations are shown in Table 8 and illustrated in Fig. 10. While the amplitude of the frequency $F1$ can be considered to be stable over the entire observing season, this is not true for all the frequencies. The frequencies $F4$ and $F6$ behave similarly (first decreasing in amplitude until 2006 and then increasing), whereas the frequencies $F3$ and $F8$ show a maximum of their amplitude, respectively in 2006 and 2007. In contrast, the frequencies $F14$ and $F6$ show variability of their amplitude which occurs in anti-phase. This behaviour explains why the frequencies detected in Sect. 5.1 and 5.2 are not identical: the detection of $G1 = F1$, $G3 = F4$ and $G4 = F8$ may be understood in the light of the 2005 (partially supplemented by the 2007-2008) $B$-band semi-amplitudes. In conclusion, the amplitudes of these pulsation frequencies show evidence of variability on time scales of 1-2 years, perhaps even less, with the exception of the most dominant frequency which has a stable amplitude.
6. Radial velocities

High-resolution spectra of CT Her were gathered with the 2-m telescope of the NAO, Rozhen, and the Coudé spectrograph equipped with an AT200 Photometrics camera (with a Site SL003AB chip and pixel size of 24 μm), and a spectral resolution of 0.19 Å/pixel. Three regions were observed: $H_3$ and the regions around MgII ($\lambda = 4481$ Å) and FeI ($\lambda = 5455$ Å). Forty-seven spectra were collected during 17 nights: 5 nights in May-July 2007, 5 nights in April-June 2008, as well as 7 nights in April-July 2009. Typical exposure times were 1200 and 1800 s. The average signal-to-noise ratio S/N is ≈ 30. The spectra were reduced with standard IRAF procedures. The corresponding radial velocities were measured with the cross-correlation technique using synthetic spectra obtained with the programme SPECTRUM (Gray & Corbally 2004), and a grid of LTE-atmosphere models of solar-type chemical composition (Castelli & Kurucz 2003) (Table 9). Combined spectra having S/N > 100 were used to estimate the effective temperature of CT Her A: the best fit for two regions ($H_3$, MgII) was obtained with $T_{\text{eff}} = 8250$ K, $\log g = 3.7$ and $v \sin i = 60$ km/s (Fig. 9).

Eight spectra were also collected with the FOCES spectrograph attached to the DSAZ 2.2-m telescope of the Calar Alto Observatory (CLA) in 2009. The resolution is 40600. The spectral region covers 5000-6000 Å. The average S/N is ≈ 25. The radial velocities of both components were measured with the cross-correlation technique using synthetic spectra generated for temperatures of 8200 K with $\log g = 4.0$ and 4500 K with $\log g = 3.5$, and for $v \sin i = 50$ km/s. In this case, the 2-D cross-correlation programme TODCOR was used (Mazeh & Zucker 1994). All radial velocity measurements are presented in Table 9 available in electronic form only. We first checked that the radial velocities obtained for component A were compatible with the NAO radial velocities. In a plot versus time (cf. top panel of Fig. 10), we detected a long-term variation which had to be removed before fitting.

Table 9. Radial velocities of CT Her A (first three lines, table available in electronic form)

| HJD   | RV     | Error |
|-------|--------|-------|
| 2454247.47535 | -4.21  | 3.20  |
| 2454247.49155 | -52.88 | 2.21  |
| 2454248.37028 | -1.60  | 2.63  |

A Fourier analysis of the residuals obtained from the raw velocities performed with PERIOD04, and a preliminary fit with velocity semi-amplitude $K_A = 23.4$ km/s and systemic velocity $\gamma = -15.8$ km/s indicated a periodicity of $\approx 125.3 \pm 2.2$ days with semi-amplitude $K_C = 11.4$ km/s. The corresponding ephemeris can be described by: $HJD_{\text{max}} = 2454157.6 + 125.3 \times E$. Fig. 10 shows the model (solid line in top panel) and the raw and corrected radial velocity curves (bottom panels). The standard deviations of the radial velocity residuals amount to 11.69 km/s and 7.63 km/s, respectively for the raw data and for the data after subtraction of the model.

The corrected radial velocity curves were next used in combination with the $B$ and $V$ light curves to enable fitting of the following parameters with PHOEBE: the semi-axis major expressed in solar radii, $A$, and the systemic velocity, $\gamma$. The new parameter values and their formal uncertainties are listed in Table 11. This value of the semi-axis major, $A$, lies close to its approximate value $1127 \times E$. The values of the $\chi^2$ function are slightly worse than before. This new solution fits both light curves a little worse, particularly the primary eclipse in the $V$-filter, but accommodates the radial velocities reasonably: the means with their standard deviation of the residual radial velocities equals $1.7 \pm 5.8$ km/s and $1.4 \pm 12.3$ km/s, for component A and B respectively (Fig. 11). The main differences with the former solutions are the smaller value of the mass ratio ($q = 0.127$) and the higher value of the inclination ($i = 82.8^\circ$). Table 11 summarizes the physical properties of both components resulting from the combined data fitting. These properties appear to be compatible with the status of component A as a pulsator of type $\delta$ Scuti. The computed masses are
Table 10. Parameters of the combined light and radial velocity solution for CT Her.

| Parameter      | Filter B       | Filter V       |
|----------------|----------------|----------------|
| $i$ (°)        | 82.75 ± 0.04   |                |
| q              | 0.1267 ± 0.0006|                |
| A              | 8.48 ± 0.03    |                |
| $\gamma$ (km/s)| -16.2 ± 0.2    |                |
| $T_1$ (K)      | 8200           |                |
| $T_2$ (K)      | 4468 ± 7       |                |
| $\Omega_1$    | 4.269 ± 0.008  |                |
| $\Omega_2$    | 2.038          |                |
| $[L_1/(L_1 + L_2)]$ | 0.969      | 0.932          |
| $[L_2/(L_1 + L_2)]$ | 0.031      | 0.068          |
| $g_1$          | 1.0           |                |
| $g_2$          | 0.32          |                |
| $A_1$          | 1.0           |                |
| $A_2$          | 0.5           |                |
| $x_1$          | 0.585         |                |
| $x_2$          | 0.962         |                |

No. data 7960 2180
$\chi^2$ 0.0162 0.0055
No. RV data 55 (comp A) 7 (comp B)
$\chi^2$ 0.0038 0.0151

Table 11. Tentative absolute parameters of CT Her

| Parameter      | Comp A       | Comp B       |
|----------------|--------------|--------------|
| Mass (M$_\odot$) | 2.28 ± 0.01  | 0.29 ± 0.04  |
| Radius (R$_\odot$) | 2.06 ± 0.06  | 1.87 ± 0.08  |
| $T_{\text{eff}}$ (K) | 8200        | 4468 ± 80    |
| log g           | 4.17 ± 0.02  | 3.36 ± 0.02  |
| Luminosity (L$_\odot$) | 17.4 ± 2.4  | 1.2 ± 0.2    |
| $M_{\text{bol}}$ (mag) | 1.65 ± 0.15  | 4.50 ± 0.21  |

Furthermore consistent with those preliminarily derived by Hoffman & Harrison (2009) from spectroscopy only (they obtained $M_1 = 2.31 ± 0.11$ M$_\odot$ and $M_2 = 0.31 ± 0.09$ M$_\odot$ with $q = 0.13$ (in agreement with the q-values of Tables 5 and 10)). We propose that this new solution illustrates the uncertainty still remaining in the characterization of the physical parameters of CT Her: more realistic errors would thus correspond to the formal errors of Table 5 (Table 10) multiplied with a factor of 25-50 while an uncertainty of about 80 K would be closer to the truth in the case of $T_2$. The data collected at the phase of primary minimum are probably affected by the pulsations (this is indeed the case for other oEA stars), which may introduce some indetermination in the light curve modelling. However, our radial velocity data, in particular of component B, are too scarce to enable an accurate determination of the mass ratio. Accurate component radial velocities obtained from high-resolution échelle spectra would be necessary to obtain a more consistent determination of the absolute parameters of CT Her. Meanwhile, the solution(s) derived in Sect. 4 are currently the most adequate one(s).

7. Possible effect on the pulsation analysis

The presence of a third body can cause a cyclic variation of the systemic velocity. In that case, the resulting light travel time (LTT) effect will introduce periodical time delays in the pulsational analysis. We examined if any phase shifts could be detected by subdividing the $B$-filter data into 10 subsets arranged according to the orbital phase bin associated with the long-term ephemeris discussed in Sect. 6. We used the multivariate analysis method implemented in PERIOD04 (Breger 2005) to recompute the best-fitting phases for each subset with respect to the proposed multi-frequency solution. The outcome of these computations is that we find no obvious shift with respect to the initially adopted phases. Fig. 12 represents the computed phase shifts, and illustrates that there is no detection of a sys-
circles show the O-C values with the known orbital period or a parabolic model. Fig. 13 illustrates both cases: the own observed minima (one minimum was not useful for the O-C diagram of CT Her. For evident reasons, we prefer to discuss only the well-observed part of this diagram.

Table 12 lists the cycle numbers and the associated residual values for both models. However, the first reported times do not fit these models at all as is also obvious from the O-C diagram in the Atlas of O-C diagrams of Eclipsing Binary Stars [Kreiner et al. 2001]. Moreover, the scatter remains large in both cases. Interestingly, if we restrict the observations only to the 24 most recent times observed using the CCD technique, we obtain a tight-fitting linear model with a high correlation coefficient (0.9) indicating an increased orbital period of 1.7863789 days with respect to the known period (cf. the speckled circles in Fig. 13). The rms in this case is only 0.00135 days (117 s).

Using the information about a probable variation in systemic velocity with a period of 125.3 days and a semi-amplitude of 11.4 km/s (Sect. 6), we estimate a mass function equal to

\[ f(M) = 1.0385 \times 10^{-7} \times (1 - e^2)^{3/2} \times K_p^2 P = 0.019 M_\odot \]

and a corresponding O-C amplitude of 131 s. Because this is of the same order as the computed rms (117 s), we conclude that the LTT effect is barely observable from the currently available data and that the O-C diagram of CT Her does not contradict the proposed model of a variable systemic velocity due to the presence of a third body. Remark that the first two epochs of light minimum observed with a CCD show a flat trend, in full agreement with the period mentioned in the literature.

9. Summary and conclusions

CT Her is yet another oEA star, after Y Cam, in which a large set of pulsation frequencies has been identified thanks to a long-term photometric monitoring performed in two filters. We confirm the presence of rapid pulsations with a dominant frequency of 52.93664 Hz and a corresponding O-C amplitude of 131 s. As many as eight significant frequencies, all of which are located in the range 43.5-53.5 μHz, appear to reproduce the observed, complex behaviour reasonably well throughout the years 2004-2008.

\[ HJD_{\text{min}} = 2442522.92914 + E \times 157863799 \]

\[ E^2 \times 72394 \times 10^{-10} \]

Such a model implies a larger orbital period with a decrease dP/dt of 8.28 × 10^{-10} days d^{-1} (i.e. a secular period decrease dP/(Pdt) of 169 × 10^{-9} yr^{-1}). The rms is 0.01049 days (906 s). To check its significance with respect to the linear model, we used an upper one-tailed F-test to verify whether the null hypothesis that the sums of squared residuals of both models are equal holds. The test statistic equals

\[ (\chi^2_{\text{lin}} - \chi^2_{\text{par}}) \times (n - 3)/(\chi^2_{\text{par}} \times (3 - 2)) = 23.44. \]

The same LTT effect also implies a cyclic variation of the orbital period. Therefore, we investigated the O-C diagram in the LTT phase bin (orb. period ~ 125 days) and the results confirm that no significant differences on the (pulsation) frequencies are detected even though a 129.6 days LTT (solution with \( P_\text{orb} \) = 7863748 days (Sanzoglio 2011), we reject the null hypothesis that the sums of squared residuals of both models are equal holds. The test statistic equals

\[ (\chi^2_{\text{lin}} - \chi^2_{\text{par}}) \times (n - 3)/(\chi^2_{\text{par}} \times (3 - 2)) = 23.44. \]

Since this value is much larger than the tabulated value \( F_{0.01(1,145)} = 6.81 \) (Pozzallo 2011), we reject the null hypothesis at the 1% significance level (type I error), meaning that the parabolic model is statistically significant. We remark that Soydugan et al. (2008) used all previous O-C data (including the 26 first measurements) to derive an overall increase with a cyclic variation for the orbital period of CT Her. For evident reasons, we prefer to discuss only the well-observed part of this diagram.

Table 12. O-C values for two models representing the evolution of \( P_\text{orb} \) (first three used lines, table available in electronic form)

| HJD   | E    | O-Cₘ | O-Cₜ | p/s | Tech. |
|-------|------|------|------|-----|-------|
| 2438894.7540 | -2031 | -0.0508 | -0.0337 | p    | vis   |
| 2438953.7280 | -1998 | -0.0271 | -0.0103 | p    | vis   |
| 2439248.5090 | -1833 | 0.0020  | 0.0175  | p    | vis   |

...
and V offer the opportunity to study in detail the connection between pulsation and mass transfer in close binary systems, including the effects of tidal interaction.

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O-C 

0.04

0.06

Fig. 13. Evolution of the orbital period: O-C diagrams of CT Her using a constant and a variable model.

Furthermore, except for the dominant frequency, we showed that the amplitudes of these pulsation frequencies are variable on time scales of 1-2 years, perhaps even less than one year, assuming that the frequency content is stable (the fact that several frequencies are commonly found in different data sets suggests this). Considering the absolute parameters of the (actual) primary component of CT Her (Table 11), we conclude that the dominant frequency cannot correspond to the fundamental radial mode: rather, such a short period of pulsation for a 2 M⊙ star is typical of a high overtone radial mode or a non-radial pulsation mode of high order "p" (similar to RZ Cas, AS Eri or TW Dra). Using the improved ephemeris, we derived an accurate value of 94.56 for the ratio \( P_{\text{orb}} / P_{\text{puls}} \).

The analysis of recent spectra providing complementary radial velocities suggests that the light and radial velocity curves can be modelled simultaneously, provided that the radial velocity measurements are corrected for a long periodicity of \( \approx 125 \) days with a semi-amplitude \( K_C = 11.4 \) km/s. The presence of a third body in the system could explain such a light travel time effect. However, we were not able to confirm this suggestion from an investigation of the O-C diagram of CT Her as the expected O-C amplitude is of the same order as that of the noise. Neither did we detect an obvious orbital modulation in the phases of the multi-frequency solution.

Although the match between the model and the B- and V-light curves is excellent, we cannot yet claim to know the system parameters of CT Her uniquely, especially because accurate component radial velocities are lacking. Such component radial velocities are much needed in order to obtain a consistent determination of the absolute parameters of this Algol-type binary. Meanwhile, we acquired a new series of high-resolution spectra of CT Her with the Hermes spectrograph attached to the Mercator telescope (Raskin et al. 2011). High signal-to-noise spectra should also be very useful for application of the technique of spectra disentangling (e.g. TW Dra, Lehmann et al. 2009), allowing to recover the component spectra from the composite ones and to study the residual line profile variations for a spectroscopic identification of the excited modes. The results obtained from this study show that CT Her is a particularly interesting binary system. eEA stars indeed provide extremely useful asteroseismic targets since they offer the opportunity to study in detail the connection between pulsation and mass transfer in close binary systems, including the effects of tidal interaction.
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