Pulsation of EE Cam

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ABSTRACT

EE Cam is a previously little studied Delta Scuti pulsator with amplitudes between those of the HADS (High-Amplitude Delta Scuti stars) group and the average low-amplitude pulsators. Since the size of stellar rotation determines both which pulsation modes are selected by the star as well as their amplitudes, the star offers a great opportunity to examine the astrophysical connections. Extensive photometric measurements covering several months were carried out. 15 significant pulsation frequencies were extracted. The dominant mode at $4.934 \text{ cd}^{-1}$ was identified as a radial mode by examining the phase shifts at different wavelengths. Medium-dispersion spectra yielded a $v \sin i$ value of $40 \pm 3 \text{ km s}^{-1}$. This shows that EE Cam belongs to the important transition region between the HADS and normal Delta Scuti stars.

Subject headings: stars: variables: delta Scuti — stars: individual (EE Cam)
1. Introduction

The Delta Scuti stars are common pulsators on and near the main-sequence situated inside the classical instability strip. They generally pulsate with nonradial modes and small photometric amplitudes in the millimag range. These stars also essentially share the high rotational velocity of the average star of spectral type A. However, a number of Population I stars shows dominant radial modes, amplitudes in excess of 0.3 mag and rotates with a projected rotational velocity less than 30 km s$^{-1}$. The members of this subgroup are called HADS (High-Amplitude Delta Scuti stars).

For the Delta Scuti stars, there exists a strong connection between rotation and pulsation properties, such as amplitude. We are presently engaged in a program to examine the stars between the two extremes of amplitude (e.g., for 44 Tau, see Antoci et al. 2007; Zima et al. 2007). We note that with extensive data and nonradial mode identifications the aspect angle can be determined accurately, so that the true rotational velocity can be obtained from the spectroscopic $v \sin i$ measurements.

The list of pulsators in the HIPPARCOS catalogue (ESA 1997), as reanalyzed for multiperiodicity by Koen (2001), contains a number of stars belonging to this 'intermediate' group. EE Cam (HIP 27199, HD 37857) is a promising target with reported peak-to-peak amplitudes near 80 millimag. Its rotational velocity is presently unknown, but was suspected to be low because of the relatively large pulsational amplitude. In particular, we are interested in detecting another variable such as 44 Tau (Antoci et al. 2007) which has a $v \sin i$ value of only 2 km s$^{-1}$, in order to separate the effects of true low rotational velocity and geometric aspect. Olson (1980) classified EE Cam as an F3 giant (gF3). The catalog by Nordstrom et al. (2004) gives a temperature of 6530K and a $[\text{Fe/H}]$ abundance of 0.06 relative to the Sun. Koen (2001) analyzed the Hipparcos data and suggested two frequencies of 4.93 and 5.21 c/d, respectively.

2. New photometry

In 2006 and 2007, photometric observations were performed using the Vienna University Automatic Photoelectric Telescope (APT; Strassmeier et al. 1997; Granzer, Reegen & Strassmeier 2001) located at Washington Camp, Arizona, USA. The “Wolfgang” telescope acquired altogether 304 hours of Strömgren $vy$ data from 2006 February 14 to 2006 April 2 and from 2006 September 19 to 2007 April 5. The three-star technique was employed with HD 35606 (C1, $V = 8^{m}.15$, $B - V = 0.48$, F8) and HD 32745 (C2, $V = 8^{m}.21$, $B - V = 0.96$, G0) as comparison stars. Since for C2, long-term variability at time scales of days could not be excluded,
the data reduction was applied solely relying on C1. While the three-star technique was not applied in the final reductions, the importance of the technique in checking for possible small-amplitude variability in the chosen comparison stars was again demonstrated.

A complete list of the measurements used to extract the light curves is provided in Table 1. Typical examples of light curves of EE Cam are shown in Fig. 1 together with the multifrequency solution derived in the next section.

3. Multiple frequency analysis

The pulsation frequency analyses were performed with a package of computer programs with single-frequency and multiple-frequency techniques (PERIOD04\textsuperscript{1}, Lenz & Breger 2005), which utilize Fourier as well as multiple-least-squares algorithms. The latter technique fits up to several hundred simultaneous sinusoidal variations in the magnitude domain and does not rely on sequential prewhitening. The amplitudes and phases of all modes/frequencies are determined by minimizing the residuals between the measurements and the fit. The frequencies can also be improved at the same time.

To decrease the noise in the power spectra, we have combined the measurements obtained in the $y$ and $v$ passbands. The dependence of the pulsation amplitude on wavelength was compensated by multiplying the $v$ data set by an experimentally determined factor of 0.64 and increasing the weight of these data points correspondingly. This scaling creates similar amplitudes in both passbands but does not falsify the power spectra. Note that different colors and data sets were only combined to detect new frequency peaks in the Fourier power spectrum and to determine the significance of the detection. The effects of imperfect amplitude scaling and small phase shifts between colors can be shown to be negligible for period finding. For prewhitening, separate solutions were obtained for each color by multiple least-square fits. In the analysis of the Delta Scuti Network campaign data, we usually apply a specific statistical criterion for judging the reality of a newly discovered peak in the Fourier spectra, viz., a ratio of amplitude signal/noise = 4.0 (see Breger et al. 1993).

Our analysis consists of a number of different steps to be repeated. Each step involves the computation of a Fourier analysis (power spectrum) from the original data or a previously prewhitened fit. The dominant peaks in the power spectrum were then examined for statistical significance and possible effects of daily and annual aliasing. For computing

\textsuperscript{1}The computer package to determine periodicities can be obtained from http://www.univie.ac.at/tops/period04.
new multifrequency solutions, the amplitudes and phases were computed separately for each color, so that even these small errors associated with combining different colors were avoided. Note that the new multifrequency solutions were always computed from the observed (not the prewhitened) data. Because of the day-time and observing-season (annual) gaps, different alias possibilities were tried out and the fit with the lowest residuals selected. The resulting optimum multifrequency solutions were then prewhitened and the analysis repeated while adding more and more frequencies, until the new peaks were no longer statistically significant.

An independently performed SigSpec analysis (Reegen 2007), which employs a statistical treatment of Discrete Fourier Transform (DFT) amplitudes that would be produced by white noise, provided exact consistency with the results obtained from the above procedure. Fig. 2 shows the details of the search for the multiple frequencies, which are listed in Table 2.

The average residuals of the 15-frequency fit in the $y$ passband were $\pm 0.005$ mag per single measurement, which is higher than the 0.003 mag expected from typical APT campaigns. This is caused by the large number of presently unresolved additional pulsation frequencies with small amplitudes, as revealed by the power spectrum of the residuals.

We can now compare the new multifrequency results with a previous result based on much fewer data: the two frequencies of 4.93 and 5.21 cd$^{-1}$ found by Koen (2001) are in exact agreement with our two frequencies showing the highest amplitudes.

It is possible to estimate the nonradial degree, $\ell$, of the dominant pulsation mode from the available photometry (for a recent application see Lenz et al. 2007). From the $v$ and $y$ passbands we derive a value of $\phi(v) - \phi(y) = +3.3 \pm 0.4^\circ$. In this temperature domain, such positive values generally indicate radial pulsation. Indeed, preliminary pulsation model calculations for EE Cam identify a unique value of $\ell = 0$, i.e., radial pulsation.

The frequency ratio $f_1/f_2 = 0.946$. Such a frequency ratio cannot be identified with radial modes (e.g., see Suarez, Garrido & Goupil 2006), so that $f_2$ has to be nonradial. We also note that $f_1$ and $f_6$ form a close frequency pair. Such close frequencies are not unusual in Delta Scuti stars (e.g., see Breger & Pamyatnykh 2006). In the case of EE Cam, however, we cannot yet exclude the possibility that the close-frequency pair could be an artifact of strong amplitude variability of the dominant mode.
4. Spectroscopy

EE Cam certainly deserves a thorough spectroscopic study. Here we present new results which shed light on the subject of the rotation of the star. Two spectra of EE Cam and one spectrum of a standard star, HD 89449 (40 Leo, F6IV), were obtained with the David Dunlop Observatory 1.88m telescope on Feb. 14, 2006. For EE Cam, the UT start times were 05:15:19 (1220 s exposure time) and 06:14:02 (1803 s exposure time), while for HD 89449 the values were 06:52:16 and 200s.

The spectra were centred at the Mg I 5184 Å triplet and covered the range 5070 to 5306 Å with an effective spectral resolution of about 0.35 Å. A full technical description is given in Rucinski (2002). The spectra were rectified and then processed using the broadening function (BF) formalism (as described in the same paper) and subsequently improved during the DDO binary-star program (for the last paper of the series, see Pribulla et al. (2007)). The BF’s were determined over the span of 61 points at the 6.7 km s$^{-1}$ spacing thus covering ±150 km s$^{-1}$. With such processing, a BF of a very sharp-line spectrum has a half-width at the base of 19.5 km s$^{-1}$. The broken line in the figure (Figure 3) shows the rotational profile calculated for the limb darkening of $u = 0.7$ (this choice is not critical) in comparison with the BF for EE Cam. The BF differs from the simple rotational profile in having a well-defined, but unexplainable structure. The complex shape of the BF for EE Cam can be interpreted as: (1) a superposition of two sharp peaks, possibly from two different, unresolved stars with slightly different velocities or (2) one broad peak with some self-absorption, or (3) signatures of two shocks propagating through the atmosphere. The most likely is the last interpretation as the first two have no real support in what we know about the star. If the broadening of the BF at the base is interpreted by rotation of EE Cam, then the observed half-width at the base (45.4 and 44.8 km s$^{-1}$ respectively) can be used to estimate $v \sin i$. The two BF’s, when corrected for the intrinsic broadening introduced by the formalism and for $v \sin i \approx 17$ of the template itself, give $v \sin i = 40$ km s$^{-1}$. The real uncertainty is larger than one determined from the difference of the two spectra and is about 3 km s$^{-1}$ as based on results for similar stars observed in the DDO programme. Note that the depression of the baseline around the BF peak is of no importance; it is a characteristic feature for BF’s of stars with rotationally broadenened lines as this reflects the uncertainty of the pseudo-continuum placement in the spectrum rectification step. At the time of observations, the star appeared to have the mean heliocentric velocity of $+11 \pm 1$ km s$^{-1}$, on the assumption that the radial velocity of the template star HD 89449 is $+6$ km s$^{-1}$. This assumed the fit by the rotationally broadened profile, as shown in Figure 3 note that the standard/template star in the BF technique is used to determine the broadening profile for the program star as shown in this figure (and used for the $v \sin i$ determination) as well as the relative radial velocities. The mean radial velocity of EE Cam was estimated at $+14.9$ km s$^{-1}$ in Nordstrom et al. (2004).
The intensity of the BF can be used as an indication of the spectral match of the template; an integral of unity indicates a perfect match and an identical spectral type (or more exactly, an identically strong Mg I 5184 Å triplet). The two spectra gave the BF integrals of 0.91 and 0.90 which means that the lines are weaker than in the F6IV standard HD 89449 indicating a spectral type close to F5. This is confirmed by the data in the Tycho-2 Catalog ([Høg et al. 2000]) (star number GSC 4098-123) where the mean magnitudes give a well defined color index $B - V = 0.427$ which corresponds to the spectral type F5 on the Main Sequence.

5. Conclusion

Extensive photometric measurements at the millimag level covering several months were carried out. The frequency analysis has revealed 15 significant pulsation frequencies. The residuals show that many additional modes in the 0 to 15 cd$^{-1}$ are present with small amplitudes. The dominant pulsation at 4.934 cd$^{-1}$ was identified as a radial mode by examining the phase shifts of the light curves at different wavelengths. The second most dominant mode at 5.214 cd$^{-1}$ was found to be nonradial. This star, therefore, is an excellent example of a star showing both the properties of the HADS and the common small-amplitude pulsators, in which the radial modes are either absent or very weak.

This picture of a star in the astrophysical transition region is supported by new measurements of the projected rotational velocity: two medium-dispersion spectra yielded a $v \sin i$ value of $40 \pm 3$ km s$^{-1}$. This value is higher than the upper limit of 30 km s$^{-1}$ for the HADS, but lower than the rotational velocity of the typical low-amplitude Delta Scuti star.

Due to the relatively high amplitudes and the rich pulsation spectrum, EE Cam is ideal for further detailed studies of mode identification in order to compare to asteroseismic models.

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Fig. 1.— Sample light curves of EE Cam. The four successive nights (out of a total of 87 nights) have typical residuals between the observations and the 15-frequency fits. Both passbands $y$ and $v$ are shown.
Fig. 2.— Power spectra of EE Cam for the 2005 and 2006 photometry. The panels show the power spectra after the inclusion of additional frequencies into the multiple-frequency solution. Note the 1 cd$^{-1}$ alias patterns (spectral-window insert of the top panel). The lowest panel clearly shows the power spectrum of the residuals from the 15-frequency solution: the excess power in the 5 to 15 cd$^{-1}$ range shows additional pulsation frequencies and demonstrates the rich pulsation spectrum of EE Cam.
Fig. 3.— The Broadening Functions for two spectra of EE Cam, as explained in the text. The rotational profile with $v\sin i = 40$ km s$^{-1}$, centered at +11 km s$^{-1}$, is shown by a broken line.
Table 1. Journal of the photometric observations of EE Cam

| Start HJD | Length hours | Start HJD | Length hours |
|-----------|--------------|-----------|--------------|
| 245 0000+ |              | 245 0000+ |              |
| 3791.5925 | 3.30         | 4079.6626 | 1.78         |
| 3796.6821 | 0.80         | 4080.6584 | 2.28         |
| 3797.6170 | 1.18         | 4081.6584 | 7.60         |
| 3798.6337 | 1.82         | 4084.9154 | 0.48         |
| 3799.5965 | 2.78         | 4086.6439 | 6.64         |
| 3803.6372 | 1.51         | 4090.6314 | 6.14         |
| 3805.5997 | 1.28         | 4093.6188 | 5.04         |
| 3808.6153 | 1.60         | 4094.6146 | 6.86         |
| 3810.6021 | 1.82         | 4095.6139 | 3.13         |
| 3997.8792 | 3.14         | 4100.5988 | 6.88         |
| 4000.9181 | 2.24         | 4101.5946 | 5.05         |
| 4003.8632 | 3.61         | 4102.5953 | 6.81         |
| 4005.8595 | 3.77         | 4103.5930 | 6.81         |
| 4010.8476 | 3.61         | 4104.5869 | 6.96         |
| 4023.9142 | 2.54         | 4105.5876 | 6.87         |
| 4024.8081 | 5.19         | 4108.5755 | 6.95         |
| 4025.8054 | 5.21         | 4116.5703 | 6.48         |
| 4028.7963 | 5.51         | 4117.5707 | 6.48         |
| 4029.7944 | 5.51         | 4124.5788 | 5.75         |
| 4030.7936 | 5.52         | 4127.5763 | 5.58         |
| 4031.7896 | 5.67         | 4128.5810 | 5.39         |
| 4035.7800 | 6.00         | 4134.5845 | 4.94         |
| 4038.8807 | 3.66         | 4135.6248 | 3.96         |
| 4048.7434 | 2.33         | 4136.5857 | 4.84         |
| 4049.7408 | 2.33         | 4140.5878 | 4.55         |
| 4050.7387 | 2.33         | 4143.6649 | 2.39         |
| 4054.7279 | 2.33         | 4146.6432 | 2.82         |
| 4055.7273 | 2.17         | 4147.6938 | 1.44         |
| 4056.7237 | 2.33         | 4152.5903 | 3.67         |
Table 1—Continued

| HJD Start | Length (hours) | HJD Start | Length (hours) |
|-----------|----------------|-----------|----------------|
| 245 0000+ | 245 0000+      |           |                |
| 4057.7199 | 2.33           | 4153.5906 | 2.24           |
| 4058.7168 | 2.33           | 4154.5913 | 3.51           |
| 4059.7159 | 2.17           | 4156.5923 | 3.35           |
| 4060.7150 | 2.17           | 4157.5928 | 3.27           |
| 4061.7102 | 2.33           | 4158.5935 | 3.24           |
| 4062.7057 | 2.33           | 4160.5943 | 3.03           |
| 4064.7010 | 2.33           | 4161.6335 | 2.08           |
| 4067.6962 | 2.18           | 4169.6321 | 1.60           |
| 4069.6876 | 2.33           | 4170.5992 | 2.24           |
| 4070.6872 | 2.18           | 4171.6000 | 2.24           |
| 4071.6826 | 2.34           | 4172.6004 | 2.08           |
| 4072.6826 | 2.24           | 4173.6007 | 2.08           |
| 4074.6737 | 2.34           | 4174.6013 | 1.92           |
| 4077.6648 | 2.34           | 4175.6017 | 1.92           |
| 4178.6033 | 1.60           |           |                |
Table 2. Detected pulsation frequencies of EE Cam

| Frequency | Detection Significance (cd\(^{-1}\)) | Amplitude S/N | Amplitude y filter | Notes |
|-----------|--------------------------------------|----------------|-------------------|-------|
| f1        | 4.934                                | 97             | 0.0360            |       |
| f2        | 5.214                                | 51             | 0.0195            |       |
| f3        | 9.840                                | 16             | 0.0065            |       |
| f4        | 8.333                                | 15             | 0.0061            |       |
| f5        | 8.457                                | 13             | 0.0049            |       |
| f6        | 4.937                                | 9.8            | 0.0036            |       |
| f7        | 10.147                               | 8.7            | 0.0036            | \(=f_1+f_2\) |
| f8        | 7.905                                | 7.9            | 0.0032            |       |
| f9        | 4.765                                | 7.8            | 0.0029            |       |
| f10       | 10.869                               | 6.5            | 0.0027            |       |
| f11       | 6.205                                | 6.2            | 0.0024            |       |
| f12       | 7.263                                | 5.9            | 0.0024            |       |
| f13       | 9.548                                | 5.2            | 0.0021            |       |
| f14       | 7.665                                | 4.9            | 0.0019            |       |
| f15       | 10.319                               | 4.6            | 0.0019            |       |

Note. — A detection is considered significant if the amplitude signal/noise ratio \(\geq 4.00\) (Breger et al. 1993). This is similar to a power signal/noise ratio of \(~ 12.6\). The noise was calculated over 2 \(cd^{-1}\) ranges.