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Kepler observations of rapidly oscillating Ap, δ Scuti and γ Doradus pulsations in Ap stars

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ABSTRACT

Observations of the A5p star KIC 8677585 obtained during the *Kepler* 10-d commissioning run with 1-min time resolution show that it is a rapidly oscillating Ap (roAp) star with several frequencies with periods near 10 min. In addition, a low frequency at 3.142 d^{-1} is also clearly present. Multiperiodic γ Doradus (γ Dor) and δ Scuti (δ Sct) pulsations, never before seen in any Ap star, are present in *Kepler* observations of at least three other Ap stars. Since γ Dor pulsations are seen in Ap stars, it is likely that the low frequency in KIC 8677585 is also a γ Dor pulsation. The simultaneous presence of both γ Dor and roAp pulsations and the unexpected detection of δ Sct and γ Dor pulsations in Ap stars present new opportunities and challenges for the interpretation of these stars. Since it is easy to confuse Am and Ap stars at classification dispersions, the nature of these Ap stars in the *Kepler* field needs to be confirmed.

Key words: asteroseismology – stars: chemically peculiar – stars: individual: BD+44 3063 – stars: oscillations – stars: variables: general.

1 INTRODUCTION

The *Kepler Mission* is designed to detect Earth-like planets around solar-type stars (Koch et al. 2010). To achieve that goal, *Kepler* will continuously monitor the brightness of over 150 000 stars for at least 3.5 yr in a 105-deg^2 fixed field of view. Photometric results from the 10-d commissioning run show that micromagnitude precision in amplitude can be attained for the brighter stars (8–10 mag) for long-cadence (29.4-min) exposures. With this level of precision, interesting pulsational behaviour never seen before is being found in many stars (Gilliland et al. 2010). In addition, *Kepler* has a small allocation for short-cadence (1-min) exposures. In this mode it is possible to detect and study the light variations of short-period pulsating stars such as solar-like pulsators, δ Sct stars and rapidly oscillating Ap (roAp) stars.

The roAp stars, discovered by Kurtz (1982), are found amongst the coolest subgroup of Ap stars, namely the SrCrEu group (6400–10 000 K). About 40 roAp stars are known at present, with temperatures in the range $6400 \lesssim T_{\rm eff} \lesssim 8400$ K, and exhibiting either single or multiperiodic pulsations with periods in the range of 5.6–21 min. These oscillations are interpreted as acoustic modes of low degree and high radial order (typically $n > 15$), which are modified at the surface layers by strong, large-scale magnetic fields. In that respect they are quite different from the δ Sct stars which, having similar mass and effective temperature, tend to have oscillations with radial order not exceeding 4 or 5. The difference in the radial orders of the oscillations found in these two classes of pulsators is thought to result from the difference in the regions where the modes are excited. While in roAp stars the oscillations are believed to be excited in the region of hydrogen ionization (Balmforth et al. 2001; Cunha 2002; Saio 2005; Théado et al. 2009), which is partially or fully stabilized against convection by the presence of strong magnetic fields, in δ Sct stars the excitation takes place in the region of second helium ionization (Dupret et al. 2005).

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Despite the general understanding of the driving of oscillations in roAp stars, there are still a number of puzzling questions to be answered. Whereas models of hot roAp stars show that driving of pulsations is possible when convection is suppressed, this is not the case for cooler roAp stars. For example, Saio, Ryabchikova & Sachkov (2010) find that all roAp-like pulsations are stable in magnetic models of HD 24712 (HR 1217; DO Eri) in which convection is suppressed. A second puzzling aspect is that apparently non-oscillating Ap stars called 'noAp stars' occupy a similar part of the Hertzsprung–Russell (HR) diagram as the roAp stars. At present it is not clear what determines which of these peculiar magnetic stars show high radial overtone p-mode pulsation, and which are apparently non-variable. This may either be the result of a selective driving mechanism or simply an observational bias. It is hoped that the *Kepler Mission*, with its ability to detect much lower amplitude roAp stars than has previously been possible, will illuminate these problems.

The global magnetic field which is present in all Ap stars plays an essential role in roAp oscillations, influencing their geometry, frequencies and energy balance. The presence in some roAp stars of frequency multiplets with spacings exactly equal to the angular frequency of rotation led Kurtz (1982) to introduce the oblique pulsator model, according to which the observed pulsations are axisymmetric about the magnetic axis, which is tilted with respect to the rotational axis. This simple picture is challenged by the fact that in some stars the peaks lying symmetrically about the central peak in the multiplet do not have identical amplitudes. This could potentially be explained by the combined effect of rotation and magnetic field on the pulsations, which may break the alignment between the pulsation and magnetic axis (Bigot & Dziembowski 2002; Gough 2005). However, that requires the magnetic and centrifugal effects on the oscillation frequencies to be comparable, something that is not expected except, possibly, for particular combinations of the magnetic field strength and oscillation frequencies (Cunha 2007).

Most roAp stars do not show the rotational multiplets predicted by the oblique pulsator model either because the rotational period is too long (and the multiplets unresolved) or because they have amplitudes below the threshold of detectability. Many do, however, show multiple frequencies which in some cases can be interpreted in terms of modes of alternating spherical harmonic degree, ℓ, and of consecutive radial orders, n.

In the case of linear, adiabatic oscillations, in a spherically symmetric star, at high radial order the frequencies of modes of the same degree are repeated at approximately regular intervals (Tassoul 1980). This interval, defined as the frequency difference between modes of the same ℓ but successive radial orders n, $\Delta\nu = \nu_{n\ell} - \nu_{n-1,\ell}$, is called the large separation, and is a measure of the mean density of the star. Moreover, in the same asymptotic limit of high radial orders, if modes of alternating even and odd ℓ are present, then the peaks in the frequency spectrum are separated by $\simeq\Delta\nu/2$, while if only modes of the same ℓ are present, the separation between consecutive peaks is $\simeq\Delta\nu$.

In some roAp stars a pattern of nearly equally spaced frequencies is indeed observed. If these are interpreted in accordance with the asymptotic relation derived by Tassoul (1980), the average large separation allows the stellar parameters to be constrained. In practice, the presence of a magnetic field breaks the spherical symmetry of the pulsating star, and perturbs the oscillation frequencies away from the values predicted by this asymptotic relation. This has been shown theoretically in a number of studies that considered oscillations in the presence of a large-scale magnetic field (Cunha & Gough 2000; Saio & Gautschy 2004; Saio 2005; Cunha 2006). According to these works, a pattern of nearly equally spaced peaks may still be found in particular sections of the frequency spectrum, but it is also clear that the magnetic field can distort the regular frequency pattern. This problem can be resolved by matching of observed frequencies with frequencies calculated from models which include the effect of a magnetic field (Saio 2005).

The use of the asymptotic relationship or direct frequency matching requires that we associate the observed frequencies with the correct value of ℓ. In roAp stars which show rotational modulation, the value of ℓ may be inferred from the number and relative amplitudes of the rotational multiplets. However, application of the method to HD 24712 gives conflicting results (Saio et al. 2010). On the other hand, an alternative mode identification cannot reproduce the observed rotational multiplet structure in this star.

It is quite clear that we are far from a complete understanding of pulsations in roAp stars, even though impressive advances have been made both observationally and theoretically over the last few years. The varied properties of roAp pulsations present a wide range of interesting challenges. Each roAp star seems to have its own peculiar characteristics. There were no previously known roAp stars in the *Kepler* field of view, though several Ap stars were known prior to the satellite's launch. It was therefore of great interest to discover that one of these stars pulsates in several frequencies in the roAp star range. This star, KIC 8677585 (BD+44 3063; ILF1+44 20; JD2000 position: 19:06:28, +44:50:33, $V = 10.3$), is classified as A5p (Macrae 1952).

We have mentioned that at the level of precision attained in *Kepler* observations, new and interesting behaviour is being found in many stars. As an additional example of this, we have noted that several stars in the *Kepler* field which have been classified as Ap stars pulsate with periods typical of γ Dor and δ Scuti stars. This result is a challenge to our current view which holds that the role of diffusion and the presence of a magnetic field will render these pulsations stable. This result is clearly relevant to the possible presence of γ Dor and/or δ Sct pulsations in roAp stars and we should perhaps not be surprised if pulsations at these longer periods are also visible in roAp stars observed at the micromagnitude level. Indeed, just such behaviour is seen in KIC 8677585 where a low-frequency variation typical of γ Dor pulsation is present.

In this paper we present an analysis of *Kepler* observations of several probable Ap stars in which γ Dor and δ Sct pulsations are visible. We then present a detailed analysis and discussion of the newly discovered roAp star KIC 8677585 and its relationship with other roAp stars and with the δ Sct and γ Dor variables.

2 PULSATIONS IN Ap STARS

In general, low-frequency pulsations in Ap stars are thought to be unlikely. The settling and diffusion which give rise to the chemical inhomogeneities in these stars drain out He from the He II driving zone, stabilizing low radial order acoustic modes. In addition, damping of these pulsations is expected in Ap stars due to magnetic slow wave leakage if the magnetic field strength is greater than about 1 kG. Indeed, the lack of detectable δ Sct or γ Dor pulsations in roAp stars (and Ap stars in general) in ground-based observations support these ideas.

Prior to the *Kepler* observations, the only Ap star known to pulsate in low frequencies is HD 21190 (F2III SrEuSi). In this star there is at least one mode with a frequency of $6.68\,\mathrm{d}^{-1}$ which is probably a radial mode (Koen et al. 2001). The star is multiperiodic, but other frequencies could not be extracted from the photometric data. High-time resolution spectroscopic observations of HD 21190 show

Table 1. Ap stars observed by *Kepler*. The last column is a classification based on the visibility of high (δ Sct) and low (γ Dor) frequencies.

KIC	Name	Sp type	Mag	Classification
8677585	ILF1+44 20	A5p	10.27	roAp/γ Dor
8750029	ILF1+44 257	A5p?	9.66	δ Sct/γ Dor
8881697	ILF1+44 259	A5p	10.57	δ Sct
9020199	HD 182895	F0p	8.86	δ Sct/γ Dor
9147002	HD 180239	A2p	9.94	Constant
9216367	ILF1+45 298	A2p:	12.12	γ Dor?
9640285	ILF1+46 40	F5p	11.77	Constant?

moving bumps in the cores of spectral lines, indicating the presence of high-degree non-radial pulsations (González et al. 2008). HD 21190 is the most evolved Ap star known; its unique stage of evolution may offer clues as to why it pulsates.

Kepler observations of stars in the δ Sct instability strip have shown that the distinction between the long-period γ Dor stars and the short-period δ Sct stars visible in ground-based observations is absent at amplitudes below the millimagnitude level (Grigahcène et al. 2010). This surprising, and as yet unexplained result, shows that at the precision level of *Kepler* one may expect challenges to our current understanding of pulsations in other types of stars. Indeed, *Kepler* observations of other Ap stars indicate that acoustic pulsations of low radial order may be more common than previously thought.Table 1 lists information for stars in the *Kepler* field of view which have been classified as Ap. However, these classifications have never been confirmed and they may turn out to be in error. Ap and Am classifications are easily confused at classification dispersions. In at least three of these stars δ Sct pulsations are clearly present. In two of the stars, multiperiodic γ Dor pulsations are also visible (Fig. 1).

The clear presence of γ Dor pulsations in two presumed Ap stars is most surprising. The multiperiodicity renders any explanation in terms of orbital or tidal interaction invalid. This has a bearing on pulsations in roAp stars. Clearly if the presumed Ap stars with low-frequency modes are indeed Ap stars, it may not be surprising to encounter low-frequency modes in roAp stars, contrary to our current views regarding damping of these oscillations. Confirmation of the classifications of the stars in Table 1 is, however, required.

3 OBSERVATIONS

The *Kepler* data for KIC 8677585 consist of 14 264 nearly continuous photometric data points taken during the time interval (truncated Barycentric Julian Date) BJD 54953.53–54963.25 (9.73 d). These are short-cadence exposures obtained in a 58.85-s cycle, of which the effective exposure time is 54.18 s, as described by Gilliland et al. (2010). The 'uncorrected' data used here consist of aperture photometry in which a few points have been flagged as bad for one reason or another and a few more deviate significantly from the mean. Removing these points leaves 14 222 data points that can be analysed. KIC 8677585 has a very small contamination factor of less than 3 per cent, so the probability of any of the pulsation signals measured coming from a nearby star is low.

The only ground-based photometric observations available prior to *Kepler* launch for KIC 8677585 were five-colour photometry using Sloan filters from the *Kepler* Input Catalogue (KIC). The KIC also contains a number of derived quantities including the stellar radius, $R/\mathrm{R}_\odot$, the effective temperature, T_{eff}, and the surface gravity $\log g$. There is no guarantee that these values are appropriate, especially for Ap stars. For KIC 8677585 these are $R = 1.6\,\mathrm{R}_\odot$, $T_{\mathrm{eff}} = 7400$ K and $\log g = 4.2$, values that are reasonable for a cool Ap star. From these values a luminosity of $\log L/\mathrm{L}_\odot = 0.8 \pm 0.2$ can be estimated (assuming a typical standard deviation of 0.5 mag in the absolute magnitude). Frequently, estimates of fundamental parameters for Ap stars from photometry are poor because of the strong line blanketing caused by overabundances of rare earth elements by orders of magnitude compared to normal stars. Nevertheless, for KIC 8677585 spectroscopic estimates of T_{eff} and $\log g$ are in good agreement with those of the KIC.

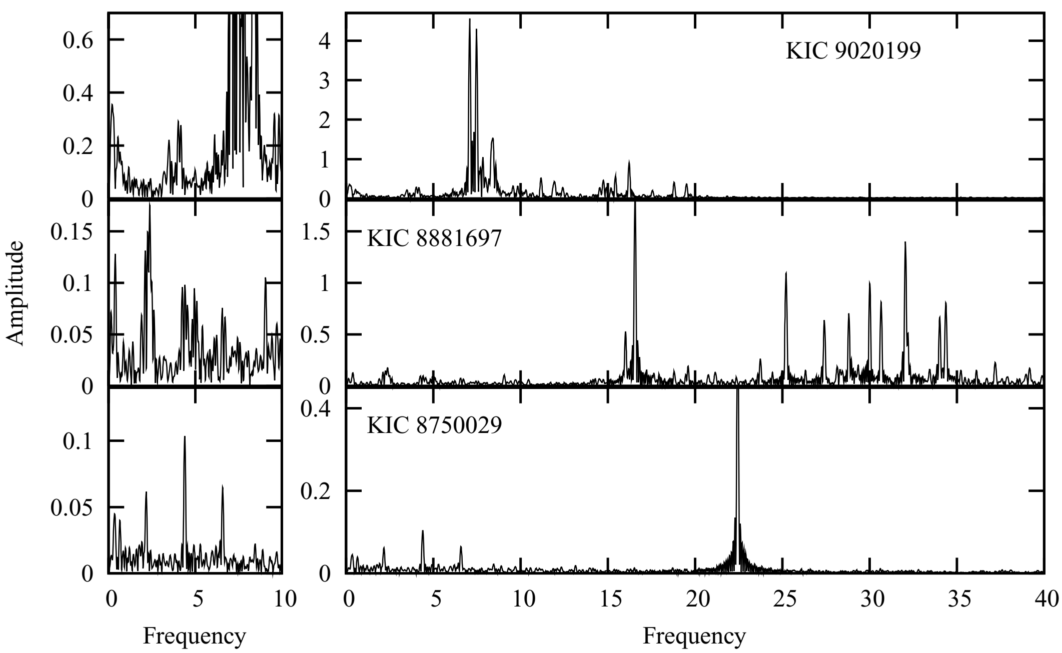

Figure 1. Periodograms of Ap stars observed with *Kepler* showing both δ Sct variations and multiperiodic γ Dor variations. The frequencies are in cycles d^{-1} and the amplitudes in millimagnitude. The left-hand panel shows the low-frequency region on an expanded amplitude scale.

3.1 Stellar parameters of KIC 8677585

One high-resolution spectrum of the star was obtained using High Efficiency and Resolution Mercator Echelle Spectrograph (HERMES; Raskin & Van Winckel 2008) installed at 1.2-m Mercator Telescope at the Roque de los Muchachos Observatory on La Palma, Canary Islands (http://www.mercator.iac.es). The resolving power of HERMES is about 85 000. The reduction was done with software developed for this instrument.

From the magnetically null Fe I line at 5434.523 Å we measured the projected rotational velocity to be $v \sin i = 4.2 \pm 0.5\,\mathrm{km\,s^{-1}}$. Lines of Nd III, Pr III and Eu II are very strong, as is typical for the roAp stars. The equivalent width of the interstellar Na I D1 line (39 mÅ) and an empirical calibration by Munari & Zwitter (1997) shows that the colour excess for the star is less than $E(B - V) = 0.05$.

The Balmer line profiles are good indicators of effective temperature for roAp stars. We have compared observed and synthetic profiles of the Hα and Hβ lines. The synthetic calculations of Balmer line profiles were done using the SYNTH code by Piskunov (1992) with model atmospheres from the NEMO grid (Heiter et al. 2002). By fitting the Balmer profiles we derived $T_{\mathrm{eff}} = 7600 \pm 200$ K. The Balmer line profiles are not very sensitive to $\log g$ at this temperature. We estimated $\log g = 4.0 \pm 0.3$ from the ionization equilibrium of Fe I and Fe II lines and Cr I and Cr II lines, taking into account the indication from photometry.

3.2 Magnetic field

The mean magnetic field modulus $\langle B\rangle$ can be detected in Ap stars from high-resolution spectra using spectral lines with resolved Zeeman components. The line of Fe II at 6149.24 Å is commonly used for this in cool Ap stars. In KIC 8677585 it shows partial Zeeman splitting. To obtain the mean magnetic field modulus we calculated synthetic spectra with the SYNTHMAG code of Piskunov (1999) for a range of abundances and magnetic field strengths. The spectral line list was taken from the Vienna Atomic Line Database (VALD; Kupka et al. 1999), which includes lines of rare earth elements from the DREAM data base (Biémont, Palmeri & Quinet 1999). The synthetic spectra were then compared with the observations for the best match which yields an estimate of the magnetic field modulus of $\langle B\rangle = 3.2 \pm 0.2$ kG from line of Fe II 6149.24 Å. We note that this line in KIC 8677585 is blended in the blue wing, probably with the line of Sm II 6149.063 Å.

4 POSITION IN THE HR DIAGRAM

In Fig. 2 we show the location of KIC 8677585 in the theoretical HR diagram and compare it with other roAp stars and with noAp stars for which temperatures and luminosities are available in the literature. We have used the spectroscopic temperature $\log T_{\mathrm{eff}} = 3.881 \pm 0.012$ and $\log L/\mathrm{L}_{\odot} = 0.8 \pm 0.2$ which is the luminosity from the KIC parameters, assuming a standard deviation of 0.5 mag for the absolute magnitude.

KIC 8677585 appears to be on the zero-age main sequence with an effective temperature close to the mean value for the roAp stars. Further observations are desirable to refine the effective temperature and luminosity.

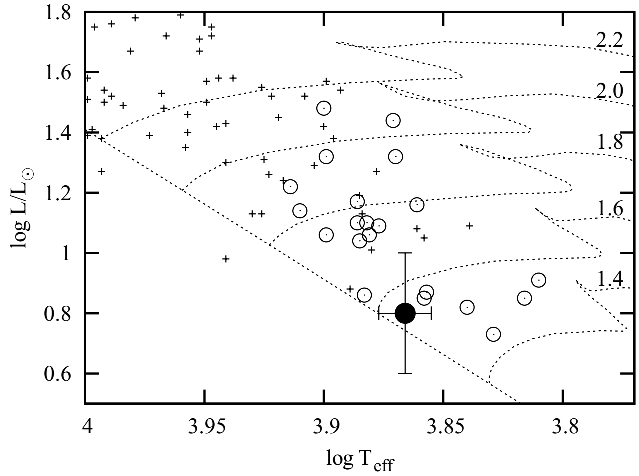

Figure 2. Location of the roAp stars (open circles) and noAp stars (crosses) in the theoretical HR diagram. Also shown is the zero-age main sequence and several evolutionary tracks labelled in solar masses. The location of KIC 8677585 is shown by the filled circle. The evolutionary tracks were calculated with the Warsaw–New Jersey code with no convective overshoot.

5 FREQUENCY ANALYSIS

A periodogram of the light curve shows that KIC 8677585 varies in two quite distinct frequency regions: a low-frequency and a high-frequency domain. In the low-frequency domain the only periodicity is $f_3 = 3.141 \pm 0.004\,\mathrm{d^{-1}}$ (36.359 ± 0.052 μHz) with an amplitude of $A = 23.1 \pm 1.7$ μmag. The high-frequency domain contains at least seven components in the range 1450–1680 μHz. Outside these two regions, the background noise level (average top of the peaks) in the periodogram is approximately 5 μmag. The significant frequencies are listed in Table 2. In the table we display the false alarm probability (FAP; Scargle 1982), showing that there is some doubt about the reality of f_8,f_9,f_{10} and especially f_{11}. It should be noted that the FAP is only to be taken as a guideline. Different approaches to calculate it yield different probabilities, which need to be interpreted in the context of their underlying definitions and assumptions. We consider f_9 to be almost certainly of instrumental origin since *Kepler* data have not yet been corrected for long-term drift.

Table 2. Frequencies, f (μHz), amplitudes, A (μmag) and phases (rad) extracted from *Kepler* data of KIC 8677585 for a model $V = V_0 + \sum_n A_n \sin(2\pi f_n(t - t_0) + \phi_n)$, where the epoch of phase zero is $t_0 =$ BJD 54950.000. The last column is the Scargle FAP as calculated by SIGSPEC (Reegen 2007).

N	f	A	ϕ	FAP
1	1659.919 ± 0.036	32.9 ± 1.7	0.29 ± 0.05	0
2	1621.856 ± 0.044	27.1 ± 1.7	0.01 ± 0.06	0
3	36.359 ± 0.052	23.1 ± 1.7	−1.50 ± 0.08	0
4	1587.709 ± 0.076	15.1 ± 1.8	0.76 ± 0.12	0
5	1676.042 ± 0.082	14.7 ± 1.7	1.07 ± 0.12	0
6	1586.062 ± 0.088	14.2 ± 1.8	0.38 ± 0.13	10^{-8}
7	1504.307 ± 0.101	11.9 ± 1.7	0.66 ± 0.15	10^{-5}
8	1674.749 ± 0.131	9.1 ± 1.7	1.97 ± 0.19	0.02
9	2.611 ± 0.116	10.0 ± 1.8	−0.93 ± 0.17	0.03
10	1458.451 ± 0.142	8.4 ± 1.7	−0.61 ± 0.21	0.04
11	1602.281 ± 0.137	8.7 ± 1.7	2.56 ± 0.20	0.19

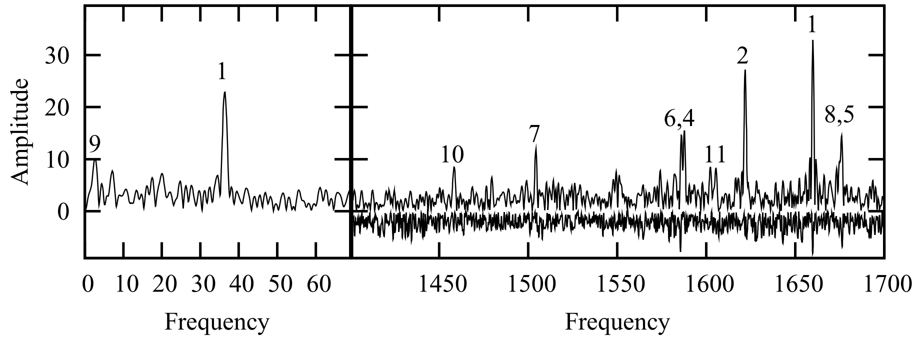

Figure 3. Periodograms of KIC 8677585. The left-hand panel shows the region around $f_3 = 36.7$ μHz and the right-hand panel shows the region showing roAp-type pulsation. In this region, a section of the periodogram with twice the frequency has been plotted upside down to show the probable existence of the second harmonic. The peak identifications of Table 2 are shown.

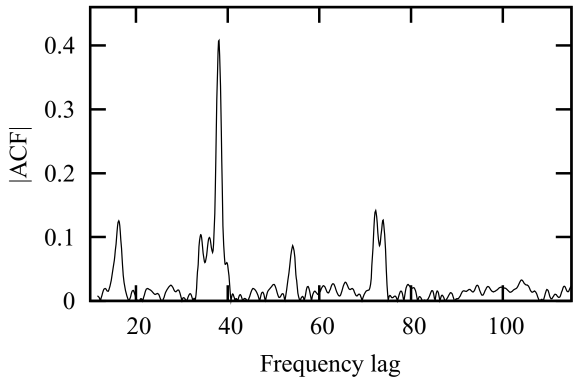

Figure 4. Absolute value of the autocorrelation as a function of frequency lag (in μHz) for the frequency range 1390–1850 μHz.

The periodograms in the two regions are shown in Fig. 3. In this figure the region around twice the frequency of the main peaks is plotted to show the probable detection of the second harmonic of f_1 and f_6. Harmonics are quite common in the light curves of roAp stars, but it seems extraordinary that they should be present in the extremely low amplitude variations seen here.

Inspection of Fig. 3. shows a certain regularity in the frequency spacing of the peaks. One can quantify this by calculating the autocorrelation function (ACF) of the spectral significance within a certain frequency range. Fig. 4 shows the absolute value of the ACF as a function of frequency spacing for the frequency range 1390–1850 μHz. There is no change when restricting the frequency range even further, but the ACF obviously gets worse as the range is expanded. From the figure, the highest peak occurs at a frequency lag of 38.1 μHz with smaller peaks at 72.3, 73.9, 16.2 and 54.2 μHz. From these values the large separation most likely is in the ranges 36–39 μHz or 72–76 μHz.

6 MODELLING OF KIC 8677585

Despite the limitations posed by the lack of reliable stellar parameters, the frequencies found in the high-frequency domain do provide sufficient information for a first modelling of this star.

As mentioned in Section 1, among other effects, the magnetic field modifies the oscillation frequencies. A typical oscillation spectrum of a multiperiodic roAp star may still show a pattern of frequencies that resembles the pattern found in a non-magnetic star, but often some of the frequencies are displaced in relation to the non-magnetic positions. Also, the large separations are usually slightly enlarged (by a few μHz) in relation to their non-magnetic counterparts.

When the effect of the magnetic field is not taken into account in the models, matching of observed and calculated frequency differences are certainly to be preferred to matching of individual frequencies themselves, particularly when a regular pattern is found. With this in mind, we will use the effective temperature and $\log g$ derived from the spectrum of the star, i.e. $T_{\rm eff} = 7600 \pm 200$ K and $\log g = 4.0 \pm 0.3$, and the two possible intervals for the observed large separation, namely 36–39 μHz and 72–76 μHz, to constrain the models.

We considered a grid of possible equilibrium models for the star, obtained using the ASTEC stellar evolution code (Christensen-Dalsgaard 2008b). We calculated evolutionary sequences of models for masses in the range 1.3–2.1 $M_\odot$, in steps of 0.2 $M_\odot$, setting the initial relative abundance of metals at the surface to $Z/X = 0.0229$ and the helium abundance to $Y = 0.26$. Moreover, we considered no core overshooting and a fixed value for the mixing-length parameter of $\alpha = 1.8$. The intention was not to do a detailed modelling of the star, varying all possible parameters in a fine grid. That we hope to perform later, when significantly longer time series of *Kepler* data for this star become available. For the moment we are mostly interested in finding how the choice of the interval for the large separation influences the basic properties of the star.

In Fig. 5 we show the evolutionary sequences considered here in the $\log g$–$\log T_{\rm eff}$ and $\log L/L_\odot$–$\log T_{\rm eff}$ diagrams. The position of KIC 8677585, along with the 1σ error box is also shown in the former. For models within the error box, we then computed the oscillation frequencies using the ADIPLS code (Christensen-Dalsgaard 2008a) and, from these, derived the corresponding large separations.

Fig. 6 shows the $T_{\rm eff}$–$\Delta\nu$ diagram along with the models whose large separations were found to be within either of the two intervals considered.

In Fig. 5 the position of these models in the HR diagram is shown, along with corresponding evolutionary tracks.

The oscillation frequencies of the two best models of our grid are shown in the upper and middle panels of Fig. 7. A schematic amplitude spectrum of KIC 8677585 in the high-frequency domain, with an indication of the frequency separations between different peaks, is shown for comparison in the lowest panel. The best models correspond to those that minimize a χ^2 function taking into account both the non-seismic data and the large separation. For the latter we considered the two intervals determined from the observations, hence the existence of two best models. The properties of these two models are presented in Table 3.

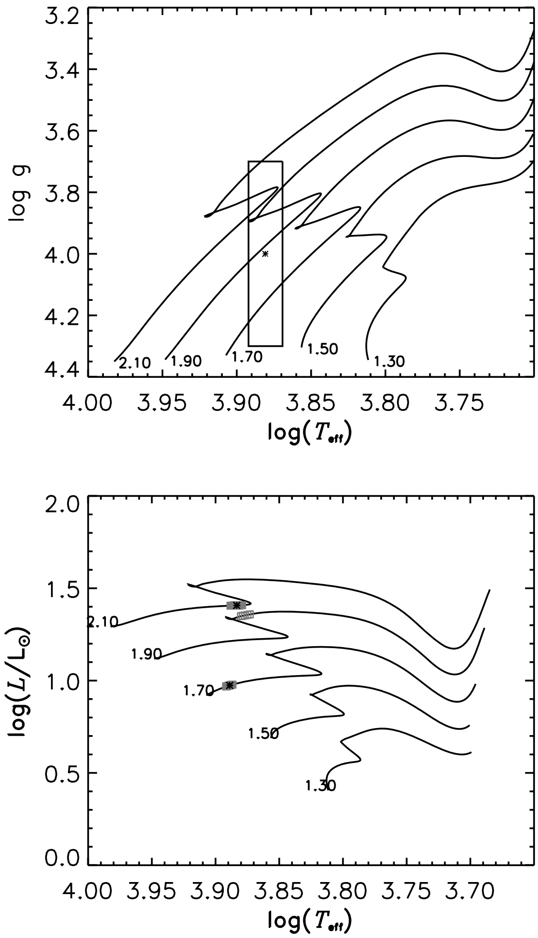

Figure 5. $\log g$–$\log T_{\rm eff}$ (upper panel) and $\log L/{\rm L}_\odot$–$\log T_{\rm eff}$ (lower panel) diagrams showing the evolution sequences considered in the modelling. The position of KIC 8677585 is shown in the upper panel by a star, along with the 1σ error box. In the lower panel, models with large separations within either of the two intervals allowed by the observations are shown by grey stars. The properties of the two models marked by black symbols are given in Table 3.

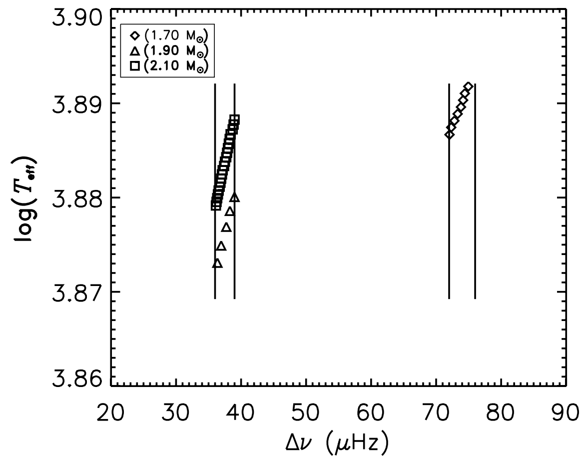

Figure 6. $T_{\rm eff} - \Delta\nu$ diagram: vertical lines show the limits of the possible intervals for the large separation, namely 36–39 μHz and 72–76 μHz. Different symbols show models of different mass whose large frequency separation was found to be within one of the above intervals.

From the figure one could naively say that models with the smaller option for the large separation reproduce best the seismic data. However, that is a dangerous statement to make for a number of reasons. First, the comparison of individual frequencies, between models and observations, is known to be risky due to possible systematic effects that may result from the incorrect modelling of the surface layers of stars; secondly, no detailed exploration of the parameter space was considered in the modelling, i.e. the step considered in stellar mass was large and no variation of chemical composition or convective overshoot was considered in the present grid; thirdly, the effect of the magnetic field on the oscillations was not taken into account.

An example of the importance of taking these effect into account is shown in the middle panel of Fig. 7 where the dashed lines show the model frequencies obtained including the effect of a dipole magnetic field with a polar strength of $B_{\rm p} = 4.2$ kG. Those frequencies have been obtained by the method of non-adiabatic analysis described in Saio (2005), where the oscillations are assumed to be axisymmetric to the magnetic axis. The latitudinal dependence of an axisymmetric oscillation mode is represented by a sum of components proportional to spherical harmonics $Y_\ell^{m=0}$. The latitudinal degree of each mode is identified by l_m which is the ℓ value for the component having the largest kinetic energy. The parameters of unperturbed model (shown in Fig. 8) are similar to those of model 2 in Table 3, but a slightly larger mass of 1.75 M$_\odot$ is adopted because a composition of $(X, Z) = (0.7, 0.02)$ is used.

Although the large separation for a given latitudinal degree hardly changes, the relative frequencies between different degrees are affected by the presence of a magnetic field. This comes from the fact that modes of different degree are affected differently by the magnetic field, as seen in Fig. 8 where oscillation frequencies are shown as a function of $B_{\rm p}$. In this model, calculated frequencies agree with observed ones at $B_{\rm p} \approx 4.2$ and 0.7 kG as indicated by vertical lines in Fig. 8. Model frequencies are similar at the two different values of $B_{\rm p}$ because the magnetic effect changes cyclically as first found by Cunha & Gough (2000). The former value of $B_{\rm p}$ is consistent with the mean modulus $\langle B \rangle = 3.2$ kG from the spectroscopic analysis (Section 3.2). We note that, in addition to the frequencies listed in Table 2, the periodogram (Fig. 3) shows minor peaks at ≈1.55 and 1.69 mHz (and possibly at ≈1.48 mHz) which correspond to frequencies of $l_m = 2$ modes. A future long-term observation will clarify the reality of these frequencies. Then, we will be able to better constrain the stellar parameters and examine the theory for the oscillations of magnetic stars.

Although all the frequencies shown in Fig. 8 are below the critical acoustic frequency, no high-frequency modes in this model are excited. [We note that for low-mass models ($M \lesssim 1.6\,{\rm M}_\odot$) high-frequency modes in the observed frequency range are excited by the kappa mechanism in the hydrogen ionization zone.] Since the stability of high-order p modes seems sensitive to the treatment of the optically thin layers, we need further investigation on the excitation of the high-order p modes.

7 DISCUSSION

The frequencies of the pulsations seen in KIC 8677585 are typical of roAp stars, but the amplitudes are an order of magnitude below any that have been detected from ground-based observations. The outstanding feature of this star, however, is the presence of the low frequency at $f_3 = 3.142\,{\rm d}^{-1}$ which has never been seen in roAp stars. A simple calculation shows that the critical rotational frequency for roAp stars is typically in the range 2–5 d^{-1}. If f_3 is due to rotation, the star must be rotating at close to the critical

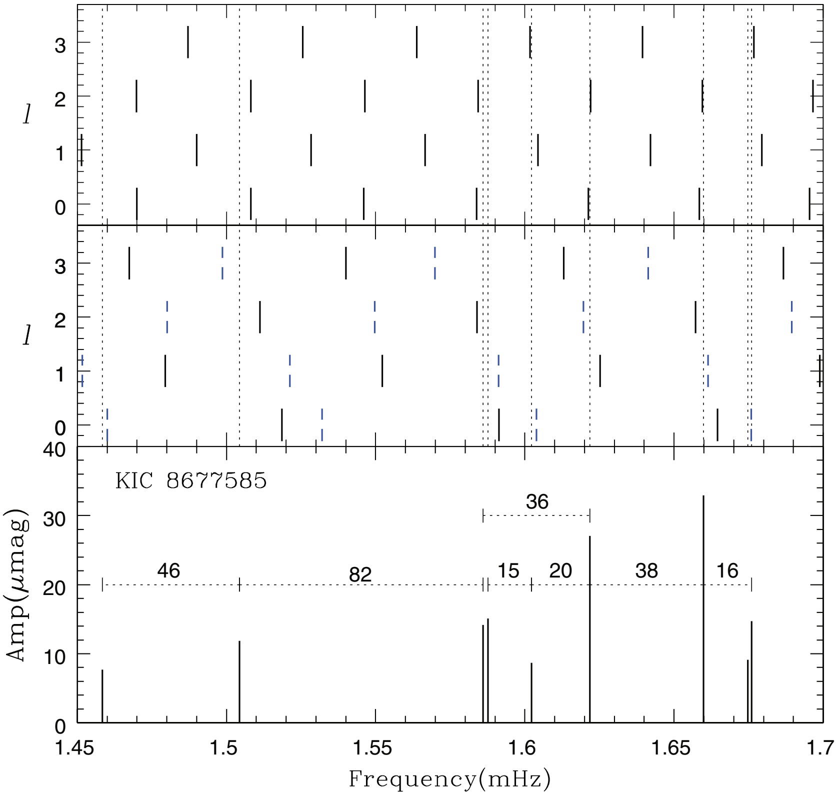

Figure 7. The bottom panel is a schematic depiction of the observed frequencies in KIC 8677585. The numbers along the dotted horizontal lines indicate frequency differences in μHz. Solid vertical lines in the other panels show the location of calculated frequencies for $\ell = 0$ to 3 modes in models 1 (top panel) and 2 (middle panel) (cf. Table 3). The dashed lines in the middle panel are frequencies calculated including the effect of a dipole magnetic field ($B_\mathrm{p} = 4.2$ kG) for a model similar to model 2.

Table 3. Data for the best models derived from the the non-magnetic grid.

	Model 1	Model 2
$M/\mathrm{M}_\odot$	2.1	1.7
$R/\mathrm{R}_\odot$	2.89	1.71
Age (Gyr)	0.746 28	0.591 79
T_eff (K)	7645	7742
$L/\mathrm{L}_\odot$	25.53	9.42
log g	3.839	4.203
$\Delta\nu$ (μHz)	37.39	73.31

rate. All known roAp stars rotate slowly, and the measured $v \sin i = 4.2 \pm 0.5\,\mathrm{km\,s^{-1}}$ for this star effectively rules out the possibility that f_3 could be the rotation frequency. Such a low projected rotational velocity cannot accommodate a rotational frequency of $3.142\,\mathrm{d^{-1}}$ unless the inclination is close to zero, in which case no modulation will be seen. A secondary body orbiting just above the photosphere could have an orbital frequency with this value. However, the light curve at f_3 is, within the observational errors, purely sinusoidal. An eclipse will give rise to a considerable number of harmonics with amplitudes which should have been observed if they are present. A tidal distortion may, however, possibly account for f_3. Precise radial velocity observations are required to resolve this issue.

The limiting factor for observations of faint sources is set by source confusion, rather than the photometric accuracy computed for isolated sources. An estimate of the crowding metric calculated from the point spread function of surrounding objects is provided for most sources in the KIC. For KIC 8677585 the contamination coefficient is 0.029. It is therefore not impossible that f_3 may be due to the small contribution from a (faint) neighbouring star. To check this possibility, we looked at the pixel-by-pixel power spectrum. There is nothing indicating that f_3 is due to a background star. There are no stars in the KIC near KIC 8677585 down to magnitude 19 or in the Two Micron All Sky Survey (2MASS) catalogue. This, of course, does not rule out a background star, but it does rule out a star well separated from KIC 8677585 yet still in the target aperture. Another target on the same channel does not show the f_3 frequency. This frequency does not correspond to any known instrumental systematic signal. For f_3 to arise in a much fainter contaminating star would require that this be the only frequency of variation of that star, which again is unlikely.

The presence of a low-frequency γ Dor pulsation in KIC 8677585 must be considered in the context of pulsations detected by *Kepler* in other Ap stars. We have seen that pulsations in the γ Dor and δ Sct frequency regimes in Ap stars may be more common than previously supposed from ground-based observations. Clearly if the presumed Ap stars with low-frequency modes are indeed Ap stars, it means that the low-frequency γ Dor f_3 mode in KIC 8677585 is not unique to the star and requires an explanation in the context of Ap stars as a whole rather than specific to this star. The pulsations in γ Dor stars are thought to be driven by the convective blocking mechanism (Guzik et al. 2000). The possible presence of oscillations of that nature in KIC 8677585 and other Ap stars suggests that the convective blocking mechanism may be active in cool Ap stars.

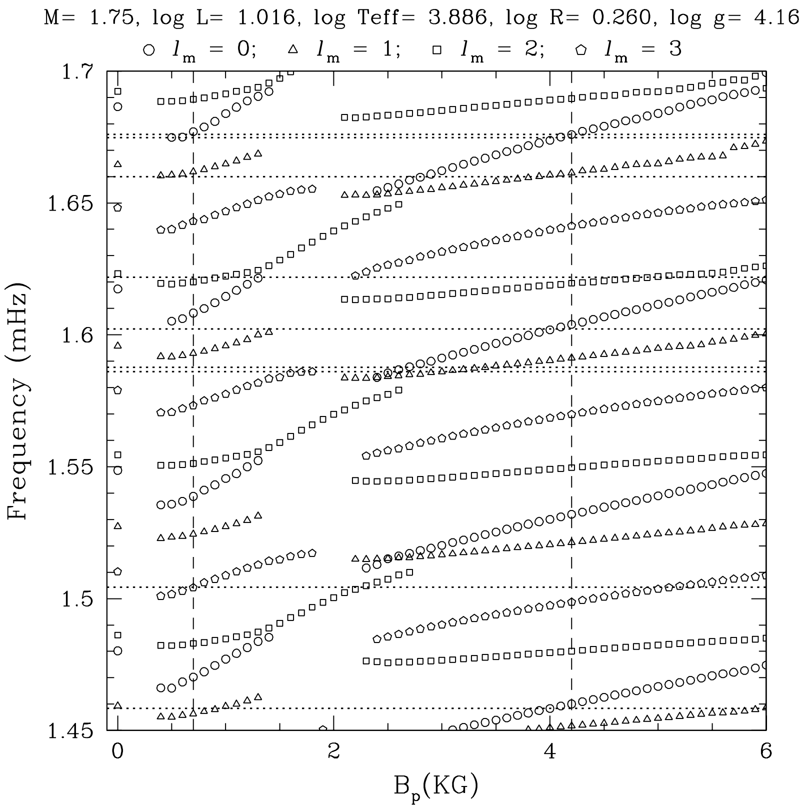

Figure 8. Oscillation frequency versus magnetic field strength at poles B_p. Horizontal dotted lines indicate observed frequencies of KIC 8677585, while vertical dashed lines indicate the magnetic field strengths which yield frequencies that roughly agree with the observed ones.

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