Frequency analysis of *Kepler* data for a strikingly nonlinear delta Scuti star

S.J. Murphy*[1], D.W. Kurtz[1], L.A. Balona[2], KASC Working Group 4

Introduction

The δ Sct stars are found at the junction of the main-sequence and the classical Cepheid instability strip. They pulsate predominantly in low-order pressure modes (sound waves) with periods in the range 0.01 and 0.25 days. The pulsations are driven by the kappa (opacity) mechanism operating in the second partial ionisation zone of helium.

The pulsations cause changes in temperature and radius, which are seen as luminosity variations in stars' light curves. This star has particularly large changes in luminosity for a δ Sct star, and is therefore called a High Amplitude Delta Scuti star; only 0.24% of stars in the δ Sct region of the Hertzsprung-Russell diagram fall in this category (Lee et al. 2008).

The degree of nonlinearity featured in this star is beyond anything that ground based data can possibly detect. With the exciting, new, extremely high-precision data being obtained with *Kepler*, δ Sct and other types of stars are being seen in greater detail than ever.

The primary goal of the Kepler mission is to detect Earth-like planets in the habitable zone of solar-like stars (Koch et al. 2010). Kepler continuously monitors ~150,000 stars with micromagnitude precision for planetary transits, and as such, is perfectly poised for asteroseismic studies.

Asteroseismology is the study of the internal structure of the stars, using sound waves generated from their interiors. Since such studies benefit the primary mission, around 1% of *Kepler* observing time is made available to asteroseismology (Gilliland et al. 2010).

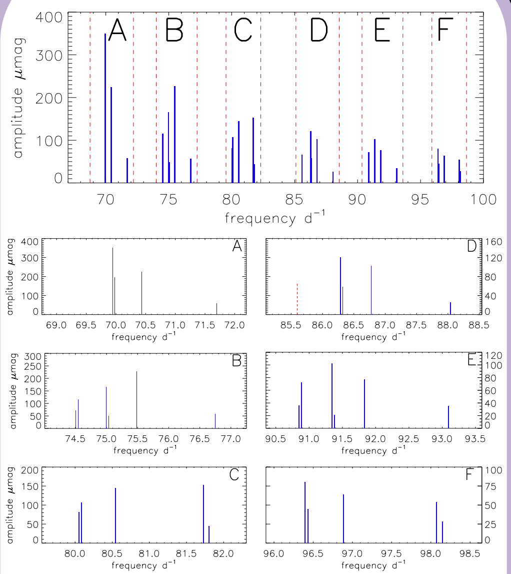

Figure 1. Repetitive patterns are caused by adding f_1 to other combinations of frequencies, hence panels A&D, B&E, and C&F are each separated in frequency by $f_1 = 16.345\ d^{-1}$. The frequency range displayed by each is shown in the top panel. The lowest frequency peak indicated in red in panel D is $4f_2$; $4f_2 - f_1$ is too low in amplitude to be distinguishable from noise, hence it is not seen in panel A. The cause of relative amplitude changes of neighbouring peaks following the addition of f_1 is unclear.

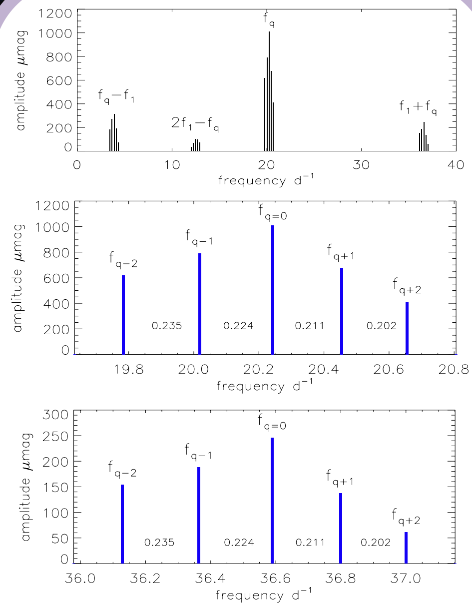

Figure 2. Upper Panel: The main quintuplet at 20.243 d^{-1} forms different quintuplets throughout the Fourier spectrum in combination with f_1. One can see the similar amplitude ratios of the quintuplets as the shape of the quintuplet is maintained in each combination. The middle panel shows the main quintuplet at 20.243 d^{-1}, and the bottom panel shows the quintuplet at 20.243 + f_1. The subscripted number following 'q' is the mode's quantum number, *m*.

The quintuplet

The Fourier transform of the light curve shows a quintuplet centred at 20.243 d^{-1}, with each component separated by an average of 0.218 d^{-1}. It is possible to infer the rotation period of the star by assuming that the quintuplet arises from rotational splitting of a quadrupole (l = 2) mode. As such, we have inferred a rotational period of 4.59 days for this star, which is very plausible for its type.

The quintuplet also forms combinations with the fundamental radial mode, in a way that can be seen in figure 2. Combinations with f_1 are found as f_q +/- f_1 and $2f_1 - f_q$, where f_q denotes the central frequency of the quintuplet. The amplitude ratios are approximately maintained in these combinations.

Combination frequencies

Resonances can occur between the radial and nonradial modes of a pulsating variable star (Buchler, Goupil & Hansen 1997). The huge number of combination frequencies observed in the Fourier transform make this star so unusual. Such is the high nonlinearity, that only 5 independent modes are found with amplitudes over 1 mmag, in addition to a quintuplet whose central component has an amplitude of 1.011 mmag.

A total of 157 frequencies were extracted down to an amplitude limit of 100 μmag; most independent frequencies occur in the range 16-25 d^{-1} – the remainder form as combinations of the main frequencies. Furthermore, these combinations occur predictably in patterns. Figure 1 shows how the same combinations of frequencies occur with different coefficients of f_1, the dominant fundamental radial mode frequency.

Conclusions

We extracted and prewhitened 157 pulsation frequencies from the Fourier transform of the light curve of this star, most of which were found to be combination frequencies. Such high nonlinearity is presently an extremely rare phenomenon.

Spectroscopy is required to determine if the quintuplet we found is indeed a quadrupole mode. This can be done with either time-series spectroscopy, or by determining the rotation rate and inferring the expected splitting of the quadrupole mode. At high resolution, spectroscopy will allow a full abundance analysis too, testing our suspicion of chemical peculiarity.

References

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Affiliations

* To whom correspondence should be addressed; smurphy6@uclan.ac.uk
1. Jeremiah Horrocks Institute of Astrophysics, University of Central Lancashire, Preston, PR1 2HE, UK
2. South African Astronomical Observatory, P.O. Box 9, Observatory 7935, Cape Town, South Africa

Future Work

In addition to the spectroscopy being obtained for this star, we plan to study changes in periods and amplitudes of the main pulsation modes as more *Kepler* data become available. We are also investigating the observed morphological similarity between this light curve and those of white dwarfs with convective layers.