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CCD Studies of δ Scuti Stars in Open Clusters

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Abstract. Asteroseismology on δ Scuti stars has until now produced very few convincing results – if we aim at doing strong tests of details of stellar modelling. The main reason for the lack of success is probably that these stars often rotate, which split nonradial oscillation frequencies into many more frequencies. These many frequencies and the fact that the more evolved δ Scuti stars contain a strong chemical composition gradient at the edge of the convective core, produce a very complicated eigenfrequency spectrum. In contrast to this, we expect, in principle, seismological studies of δ Scuti stars to be a very simple task: One has to compare theoretical oscillations in model stars with the observed oscillations. However, in order to produce convincing asteroseismological results, we need to do three things: (1) Detect as many eigenfrequencies as possible at high precision, (2) identify the eigenmodes and (3) improve the theoretical models. By observing δ Scuti stars in open clusters using CCDs, we have a possibility to improve on (1) and (2) as well as providing an opening for an improvement in the theoretical models by doing accurate calibrations of the basic cluster properties. In this paper I shall describe some of the results from CCD studies of δ Scuti stars in open clusters and identify some future prospects for this technique.

1. Asteroseismology on δ Scuti Stars

Asteroseismology on A and F main sequence stars (e.g. δ Scuti stars) has until now produced very few convincing results. The main reason for the lack of success is that these stars are rotating quickly which splits nonradial ($\ell >= 1$) oscillations into many more frequencies. These many modes, and the fact that the more evolved δ Scuti stars contain a strong chemical composition gradient at the edge of the convective core, produce a complicated eigenfrequency spectrum. Since only a small fraction of the possible eigenmodes oscillate with high enough amplitudes to be detected in a classical ground-based multi-site campaign, we have in most cases only been able to detect frequencies, but not been able to use those for improving on stellar modelling, which is the goal.

1.1. Seismological Studies of Stars

Seismological studies of stars (asteroseismology) is in principle a very simple task: One has to compare observed oscillations with theoretical oscillations in a model star. A stellar oscillation can be described in two terms: the eigenfrequency of the oscillation and the eigenmode, which is a classification of the oscillation in terms of quantum numbers, n, ℓ and m. In order to do a proper asteroseismological test one needs information on both these terms.

1.2. Modelling Stars

One of the major problems in modelling stars is the difficulty of treating the mixing in stellar interiors due to gravitational settling and fluid motions. In the sun some progress has been made, indicating settling of helium, but it is difficult to separate the different types of mixing. δ Scuti stars offer a different setting: convection is almost absent at the surface, but present in the core. Rotation is fast, which amplifies the fluid motions. Processes like convective overshoot might be important in δ Scuti stars, and we expect therefore – by studying multi-mode δ Scuti stars – to learn much more about stellar evolution in general, especially concerning the effects which cannot be studied in helioseismology.

1.3. Asteroseismology on δ Scuti Stars

Asteroseismology of δ Scuti stars therefore needs three things:

- We need to detect as many modes as possible – as many eigenfrequencies as possible.
- We need to identify the eigenmode.
- We need to improve our theoretical models on δ Scuti stars.

2. Model Frequencies

The modelling of stellar evolution and adiabatic oscillation frequencies has been done by many groups (e.g. Christensen-Dalsgaard 1982; Christensen-Dalsgaard & Berthomieu 1991). An example of such model calculations by J. Christensen-Dalsgaard is shown in Fig. 1.

2.1. Avoided Crossings and Rotation

In Fig. 1 one can follow the evolution of oscillation frequencies with age for a non-rotating star. The diagram shows that the structure of the oscillation pattern is a function of frequency. High-order modes (with high n) show a nice comb-like structure (approximately satisfying the asymptotic relation), while the lower orders (and lower frequencies) turn out to show a quite crowded structure. Since only a small fraction (seemingly random subset) of the possible modes are observed to oscillate at a detectable level, one may have troubles in comparing the observed and the calculated modes. The identification is further complicated by rapid rotation, which results in a splitting of frequencies (with different m). The rotational effects on oscillation frequencies have been estimated by several authors, e.g. Kjeldsen et al. (1998).

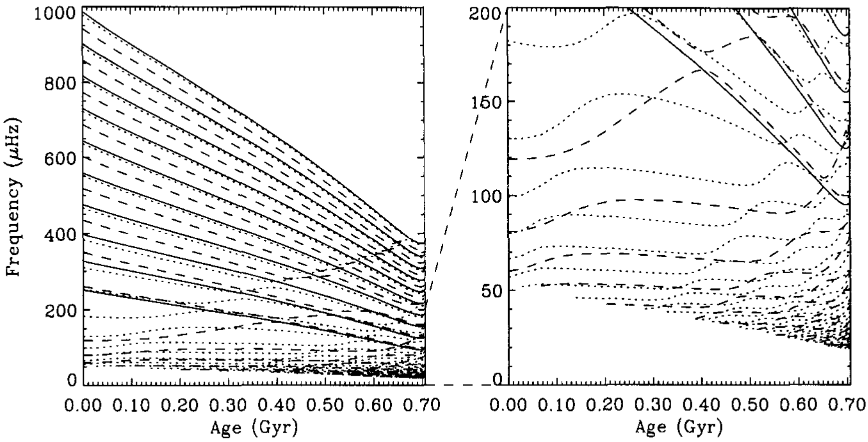

Figure 1. Evolution of oscillation frequencies with age, for a 2.2 $M_\odot$ star which is representative for δ Scuti stars. Only modes with $n < 10$ are included, for $\ell = 0$ (solid lines), $\ell = 1$ (dashed) and $\ell = 2$ (dotted). The right-hand panel shows a blow-up of the low-frequency (g mode) region. Note in particular the *avoided crossings* between modes of the same ℓ. Model calculations by J. Christensen-Dalsgaard.

2.2. Stellar Properties

One major problem in calculating a good model is the limited knowledge of the basic stellar properties, such as mass, temperature and luminosity. For non-rotating stars the basic properties can be estimated to within a few per cent. However, this is not the case for rotating stars. In a rotating star one will not be able to use the magnitude and colour index directly, since the flux will depend on the angle between the rotation axis and the line-of-sight. A detailed study of photometric parameters for rotating models of A- and F-type stars have been carried out by Pérez Hernández et al. (1999). It is shown that the effect of rotation on those parameters should not be ignored.

2.3. Mode Identification

An accurate oscillation frequency is only useful if one is able to calculate an equally accurate model frequency. This can, of course, only be done if the mode has been identified. There are several techniques to identify modes, e.g. the amplitude-ratio technique by Viskum et al. (1998) which is based on Bedding et al. (1996) and a different technique used by Breger et al. (1999).

3. CCD Studies of δ Scuti Stars in Open Clusters

CCDs (Charge Coupled Devices) are widely used in astronomy because they have very high quantum efficiency. Reading out a CCD results in a digital

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image which can be reduced and processed in a semi- or fully-automatic way by use of standard reduction packages. This means that we may detect oscillations in a large number of stars if we do time-series photometry in open star clusters. Differential CCD-photometry can at the same time be done to very high precision (see Kjeldsen & Frandsen 1992). Since a colour–magnitude diagram for an open cluster allows one to measure the distance, reddening, chemical composition and age for the cluster as well as for individual stars, one will be in a much better position when trying to calculate models for cluster stars compared to normal (and often brighter) stars.

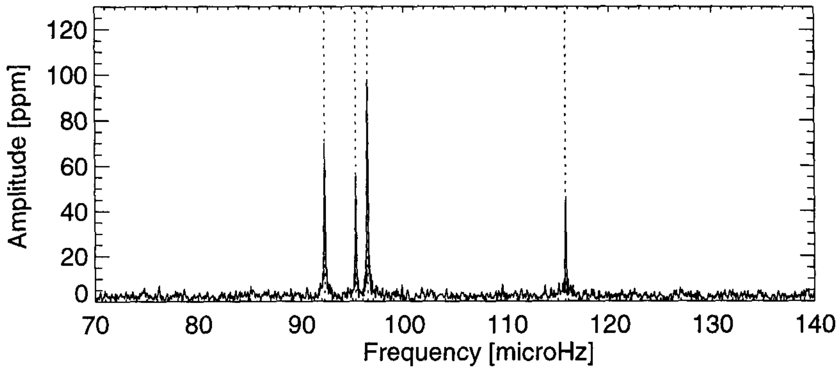

Figure 2. A dedicated δ Scuti network – 90 d and 6 telescopes. See text for details.

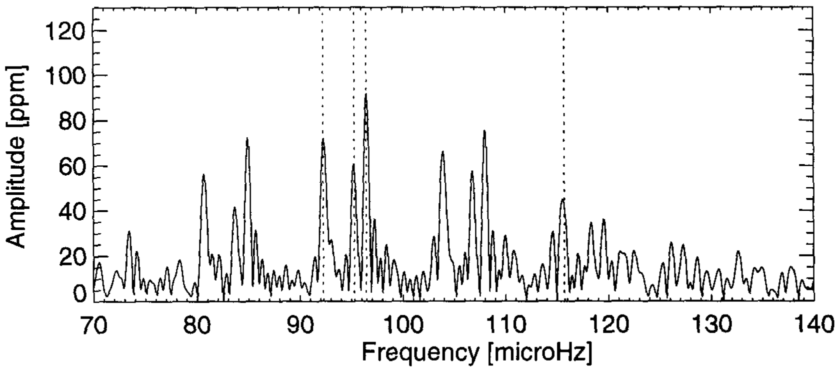

Figure 3. A classical single site campaign – 3 weeks with 9 hr per night. See text for details.

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3.1. Examples of CCD Studies of δ Scuti Stars

Despite the great possibilities of combining δ Scuti stars, CCDs and open clusters, most campaigns on open cluster variables are done by use of more classical instrumentation, such as photoelectric photometers (this is true for STEPHI, WET and DSN). CCD work has been done by Jahn, Kaluzny, & Rucinski (1995) on, e.g., the cluster NGC 7789. Fifteen variable stars were discovered during four nights of monitoring of NGC 7789. One δ Scuti star which is a blue straggler in the cluster was discovered during those observations. Other examples are Choi et al. (1998, 1999). The best example of a CCD campaign on cluster δ Scuti star is the STACC campaign on NGC 6134 (Frandsen et al. 1996). The observations consisted of time series differential CCD photometry from two sites over a period of 10 d. The precision was for the best stars below 300 ppm in the final amplitude spectrum, allowing detection of mmag oscillations. The main problem in the Frandsen et al. (1996) campaign turned out to be the frequency resolution. After 10 nights one is still not able to resolve some of the close modes.

4. A Dedicated δ Scuti Network

A dedicated network of telescopes could be the solution to improving the quality of the observations significantly. In order to study how such a network would improve the quality of the data, I have simulated data for a network of 6 small telescopes. The network in the simulation contains:

- 6 sites – e.g. placed like the GONG network;
- Telescope diameters of 40-50 cm;
- Wide field (differential photometry) – FOV: several degrees;
- Two colour (red and blue) and Hβ.

The spectral resolution would be about 0.13 μHz and the noise level would allow detection of modes with amplitudes of 30–40 ppm.

4.1. The Amplitude Spectrum of a Network

In order to evaluate the improvement of the data in a dedicated δ Scuti network, I present two figures showing the amplitude spectrum for the network data (Fig. 2) as well as the amplitude spectrum for a simulated classical single site campaign over 3 weeks with 100% duty cycle (optimistic!). I assume that scintillation noise dominates at all frequencies (which may not be completely true – see Kjeldsen & Frandsen 1992). The input frequencies are at 92.27 μHz, 95.29 μHz, 96.45 μHz and 115.74 μHz and the amplitudes are 71 ppm, 56 ppm, 95 ppm and 45 ppm. In Fig. 2 one can clearly see that the dedicated network allows the determination of frequencies as well as amplitudes. For the classical single site (Fig. 3) the situation is clearly more difficult.

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Discussion

Luis Balona: I would like to appeal to observers to obtain as large a wavelength coverage as possible in photometry. For me, I would choose BVI or vyI, as this will give a large baseline for mode identification.

Hans Kjeldsen: I agree; the effect is strongly dependent on wavelength. So B and I would be a good idea!

Yanqin Wu: If the combination frequencies can be used to constrain the inclination angle between the rotational axis and line-of-sight (as we may have shown in white dwarfs), combined with $v \sin i$ measurements this should provide values of $\Omega_{\rm rot}$ for asteroseismology study.

Hans Kjeldsen: Great!

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