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The search for δ Scuti stars in open clusters*

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Abstract. In order to improve the tests of models of stellar evolution, observations giving tighter constraints on the models were initiated by the formation of an informal group STACC (Frandsen, 1992). The purpose of the group is to search for and make observations of δ Scuti stars in open clusters.

This paper presents some of the results of the search, mainly for distant open clusters with a rich population of variables. Included is an announcement of a target list (Frandsen & Arentoft 1998, *The Book*) and four examples of new Colour-Magnitude (CM) diagrams of open clusters considered to be interesting targets. Finally, we present the fruits of extensive searching: an open cluster that contains many δ Scuti stars.

Key words: δ Scu – stars: evolution – stars: oscillations – open clusters and associations: individual

1. Introduction

The modelling of the interior of stars has made a lot of progress due to helioseismology. The unusually rich set of data available for the Sun has enabled extensive testing of physical models. For other stars the situation is less favorable. Even with the best solar models, the effect of rotation and the physics of a convective core are still poorly understood. The Sun is a slow rotator and has no convective core. Both type of physics have important effects on the mixing in the stellar interior. In order to derive the age of stars we must understand the physics of stellar interiors better than we do at present.

Normally the observables, of interest for the interior of a star, constitute a very small set and do not provide strong constraints on the physics, nor on the model parameters like mass and radius. Moreover, stellar oscillations in solar type stars are difficult to observe due to their low amplitudes (Frandsen 1997, Kjeldsen & Bedding 1997). To extend the range of observables we consider δ Scuti stars, which also exhibit a rich oscillation spectrum. For example, recent results for FG Vir (Breger et al. 1997, 1998) show the presence of 24 modes. Unfortunately, the modes in this class of pulsators are low order modes that are more difficult to analyse than the high order overtones observed in the Sun, so that it will be necessary to have a large data base spanning a long time scale and a large number of stars. This requirement can only be met by observing many pulsators simultaneously. It should also be emphasized, that additional high quality observations, photometric as well as spectroscopic, are needed to determine abundances (Z), rough initial stellar parameters and rotational velocities. Without these parameters it is impossible to use the observed frequencies to test the models.

The magnitude of the work to be carried out is clearly too large for a single institute. This led to the formation of STACC (Small Telescope Array with CCD Cameras) to search for suitable targets and subsequently to make multi-site observations (Frandsen, 1992).

This article begins with a section on the status of the search. New CM diagrams are needed for most clusters, and several such diagrams, obtained using CCD photometry, are presented. A first example of a good northern target for time series CCD photometry is presented: the open cluster NGC 1817. A revised strategy for the search for targets preceeds the conclusion.

2. Status of search

Observations of δ Scuti stars in the southern cluster NGC 6134 have been published by Frandsen et al. (1996). Further work is in progress on this cluster based on Strömgren photometry from May 1996. Spectroscopic data are still needed before a full model analysis can be carried out (e.g. no $V \sin i$ exists for the pulsating stars).

Another southern cluster, NGC 2660, contains a number of δ Scuti stars, but is quite distant, $d = 2.5$Kpc. At such a distance supplementary spectral observations can only be done using very large telescopes and long exposures.

After the two-site observations of NGC 6134, STACC activities have been devoted to the search for a similar northern cluster, for which results are presented by Viskum et al. (1997a). In the present paper we present the discovery of a second open cluster, NGC 1817, with a nice population of δ Scuti stars in a field of view small enough to observe all pulsators simultaneously.

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* Based on observations made at the European Southern Observatory, La Silla, the Nordic Optical Telescope, ORM, La Palma and the IAC80, OT, Tenerife

Aware of the difficulty of locating clusters like NGC 6134, we have also worked on the nearby cluster Praesepe, which is known to have the largest number of pulsators of any open cluster. This cluster does not offer the opportunity to observe many pulsators simultaneously, which is a major disadvantage. Observations of individual stars in Praesepe are described by Breger et al. (1993; 1994) and Belmonte et al. (1994). There happens to be a pair of δ Scuti stars, BN Cnc and BV Cnc, which *can* be observed simultaneously. Observations by STACC members recently led to the discovery of 4 new frequencies in BV Cnc (Arentoft et al. 1997).

In view of recent developments in the field, our strategy has been modified somewhat. Our goal is now to obtain more extensive and complete data sets (Sect. 5).

In order to support groups that want to participate in the search for clusters with a large population of variables, we have compiled a document (‘*The Book*’): The STACC Open Cluster Target List (Frandsen & Arentoft, 1998).

2.1. *Content and purpose of The Book*

The idea of STACC is that the programs can be carried out with CCD cameras on small ($0.5 < D < 1.5$m) telescopes. The observations are simple. They offer students or advanced amateurs an opportunity to learn how to do high precision CCD photometry. The observations have to be done carefully along lines that have been described by Gilliland & Brown (1988) and Kieldsen & Frandsen (1992).

We have collected all the relevant information we could find on each cluster. The document contains an introduction to the subject with some guidelines for making the observations. Then follows the main section on a number of target clusters (mostly northern).

3. New Colour-Magnitude diagrams for four target clusters

CM diagram of clusters often do not permit a reliable estimate of the distance and age of a cluster. If the age is wrong, the chances of discovering δ Scuti stars could be much smaller, than what one estimates based on the assumed age. If the distance (or reddening) is wrong, the magnitude of the δ Scuti stars will not be as assumed and the exposure time not optimally chosen.

To illustrate what can be achieved by CCD colour photometry, we present the results for four clusters (also included in *The book*); see Viskum et al. (1997a) for more examples. The previous CM diagrams were not adequate (Fig. 1), mostly because the photoelectric photometry did not go faint enough. Photographic data generally is of low precision and not very useful, when it exists. In many other cases it is necessary to extend the dynamic range and the accuracy by new, modern observations.

3.1. *Two northern clusters*

The observations were made in 1991 by Hans Kjeldsen at the Nordic Optical Telescope (ORM, La Palma). The Tek512 chip on the Aarhus-Tromsø Low Dispersion Spectrograph (LDS) was used to take CCD frames in Strömgren b and y. Using Johnsson B and V data (Mermilliod, 1994) we have transformed the $b-y$ index to the Johnsson $B-V$ index, using a linear fit for stars that are present in both datasets.

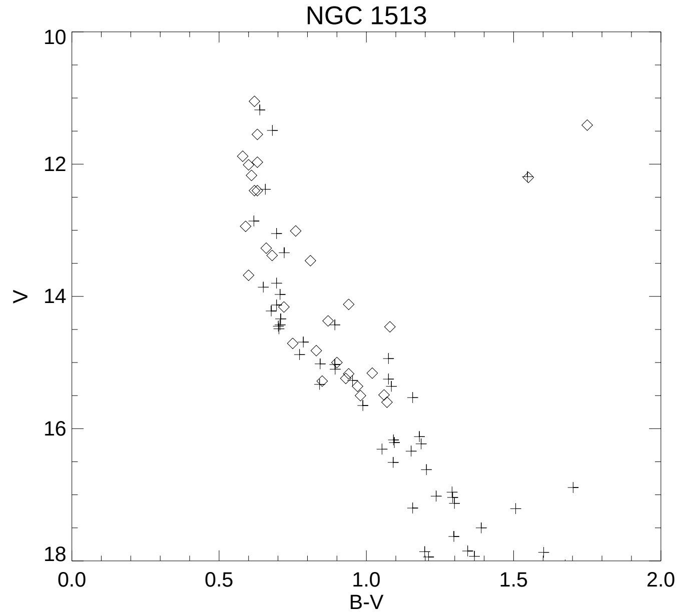

Fig. 1. Colour-Magnitude diagram for NGC 1513, diamonds are data from the Open Cluster Database and crosses are CCD data from this investigation. Some stars are present in both sets and occur twice in the diagram

3.1.1. NGC 1513

New data on this cluster (Fig. 1) extend the main sequence by two magnitudes. An impression of a fairly narrow main sequence is reinforced by the new data with some outliers (binaries, non-members). One of two observed giants are common to the two datasets. The age is given by Lyngå (1987) as $\log t(years) = 8.63$, but the CM diagram indicates that we are seeing a younger cluster, just beyond $\log t = 8.0$. The main sequence covers a range of seven magnitudes and there are only two giants. This is confirmed by the age $\log t = 8.2$ determined by del Rio & Huestamendia (1988). δ Scuti stars might be present, but amplitudes are expected to be small as these stars will be unevolved.

3.1.2. NGC 2324

This cluster is situated in a crowded region and consequently the CM diagram (Fig. 2) is more perturbed by field stars than in the case of NGC 1513. The cluster contains a number of giants, and it is probably a cluster with an age close to $\log t = 9.0$ in agreement with the published value $\log t = 8.8$ (Lyngå, 1987). With the reddening of $E(B-V) = 0.11$, we get a turnoff colour of $(B-V)_{turnoff} = 0.1$ consistent with this age. The CCD observations again extend the CM diagram to fainter stars,

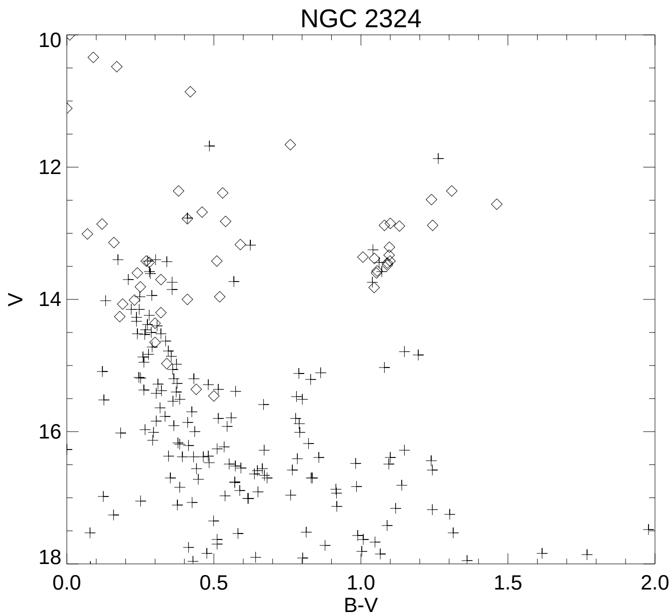

Fig. 2. Colour-Magnitude diagram for NGC 2324, diamonds and crosses as in the previous figure

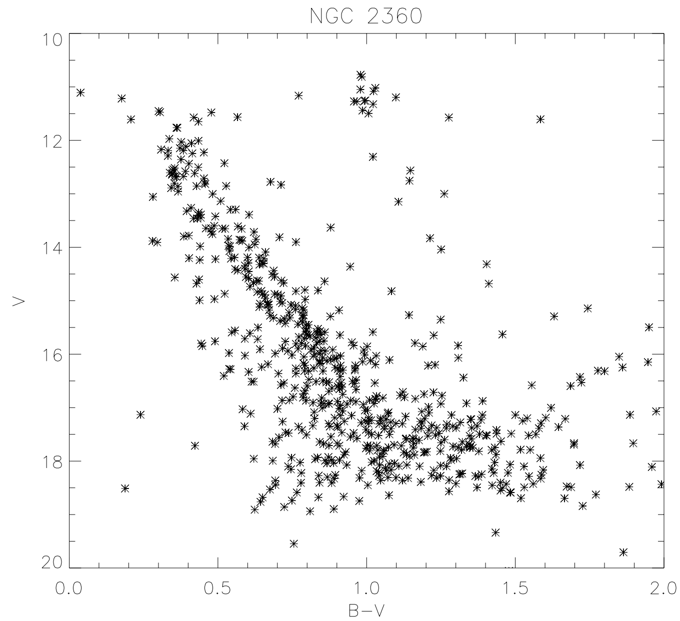

Fig. 3. Colour-Magnitude diagram for NGC 2360, CCD data.

although the position of the main sequence is hard to trace at faint magnitudes due to the presence of many field stars. There is a well developed population of giant stars and a group of stars between the giants and the turnoff point. Stars in this latter group are in the instability region and have magnitudes around $V = 13-14$. The cluster should be a good target to search for δ Scuti stars, even though they are somewhat faint for performing time series photometry.

We have short time series data for both clusters. However, due to problems with the field rotator on the telescope, which at the time was not fully operational, the guiding was poor. This introduced flat field problems that increase the low frequency noise. In NGC 2324 the exposures were not deep enough to give a precision at $V = 13$ adequate to detect small amplitude δ Scuti stars, since the exposure time was limited by the bright stars. Nevertheless there are indications of variability for some stars.

3.2. Two southern clusters

The observations of the two southern clusters were made at La Silla by M. Gelbmann and U. Heiter, University of Vienna, using the Danish 1.54m telescope and the DFOSC instrument with a Loral $2\text{k} \times 2\text{k}$ chip. The field of view of this combination is quite large ($15' \times 15'$).

3.2.1. NGC 2360

The data cover a range of 7 magnitudes, which means that the main sequence is well defined in the CM diagram (Fig. 3). The main sequence is rather broad and somewhat fuzzy due to the presence of field stars. The field is mildly crowded and in the outskirts of the cluster, field stars represent a fair fraction of the stars. The number of subgiants is small. Still, we expect that variables should be present in a cluster of this type with an age given by $\log\, t = 9.00$ (Lyngå, 1987). This value is based on a small reddening $E(B-V) = 0.07$ giving a fairly red $(B-V)_{turnoff}$. The reddening should be checked, as the morphology (only a small group of red giants) suggests it could be slightly younger.

3.2.2. NGC 2489

The CM diagram (Fig. 4) is not very different from the previous one except for the lower content of field stars, So one might expect the parameters for this cluster to be similar to those of NGC 2360. In fact, the age is given as $\log t = 8.5$, a factor 3 smaller than for NGC 2360. This mainly reflects the difference in reddening: $E(B-V) = 0.07$ for NGC 2360, $E(B-V) = 0.34$ for NGC 2489 as given by Lyngå (1987). The reddening for NGC 2489 is even larger in Ramsay & Pollaco (1992), which give $E(B-V) = 0.45$. The distance is almost the same to NGC 2360 and NGC 2489. If we assume, that the red giants have the same absolute magnitudes, then the apparent magnitude difference between red giants of 1 magnitude is consistent with a difference in reddening of 0.3–0.4.

Both clusters look like good targets: they have the right age and distance and some evolved stars above the hot end of the main sequence. The magnitude of δ Scuti stars would be bright enough that spectroscopy can be carried out to check membership, rotation etc.

4. A successful search

We have observed two clusters, NGC 1817 and NGC 2215, at the IAC80 at Observatorio del Teide, Tenerife, 1996, using a Thomson CCD. The field of view is appr. $8' \times 8'$. The CM diagrams

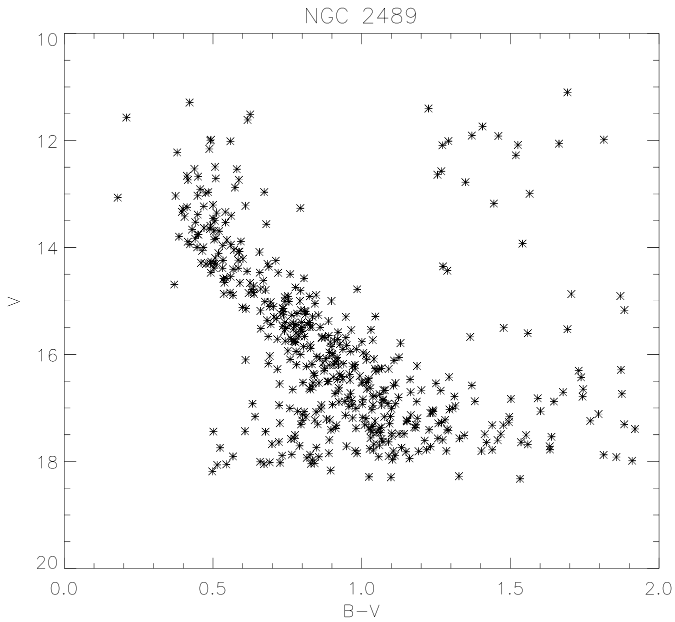

Fig. 4. Colour-Magnitude diagram for NGC 2489, CCD data.

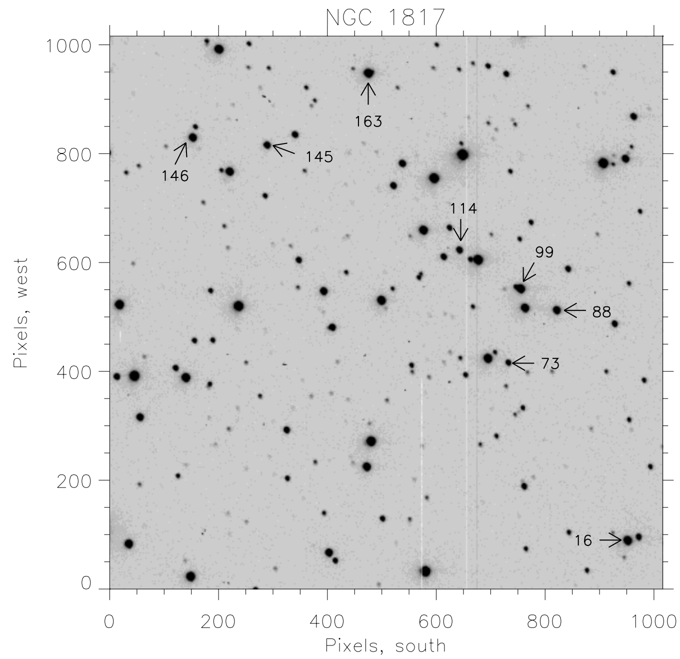

Fig. 5. One CCD frame for the open cluster NGC 1817. The variable stars are labeled with a running number.

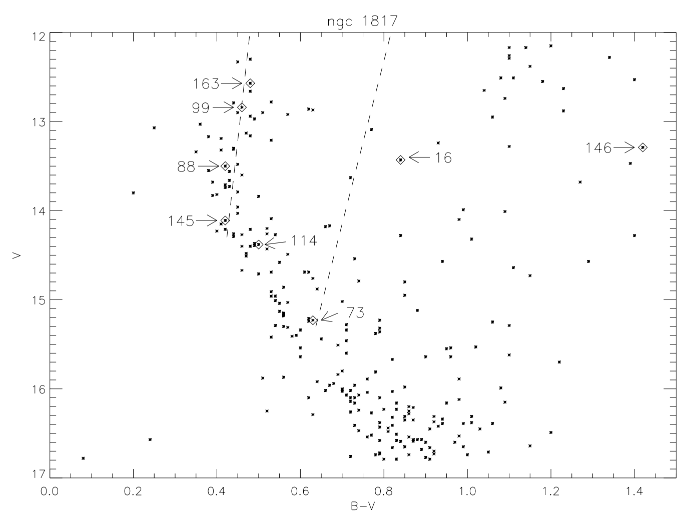

Fig. 6. Colour-Magnitude diagram for NGC 1817 (Mermilliod, 1994). Variables are plotted as diamonds. The position of the instability is plotted as well.

can be found in *The Book*. After detecting only a few pulsating stars in most other cases (including NGC 2215), NGC 1817 turned out to be of special interest. This is the first northern open cluster suitable for relative CCD photometry, in the sense that it contains a nice set of δ Scuti stars within a small field of view. Time series were obtained for this cluster on two nights, 5 hours each night. The guiding was good. Only a part of the cluster could be covered by the FOV of the CCD. A region was chosen avoiding the brightest stars (Fig. 5). Light curves were obtained for 176 stars in the field. Among the light curves several showed periodicities in the range typical for δ Scuti stars. These stars are labeled with their sequence number in the finding chart.

In the CM diagram (Fig. 6) the position of the variables has also been plotted. Most of them are located at the estimated position of the instability strip. The CM diagram is typical for a middle age cluster, $\log t = 8.90$, and the distance is given as 1.8 Kpc (*Astronomical Almanac 1996*).

The light curves have been analysed and dominant frequencies determined for the variables. Table 1 summarises the information for all stars. The classification is preliminary, is based on the shape of the lightcurve only, and is not necessarily consistent with the location in the CM diagram.

To document the detection of the variables, we present three figures with lightcurves for the two nights observed. In the case of the star 163 we are looking at the light curve of a δ Scuti star with more than one period (Fig. 7). Subsequent Fourier analysis (Fig. 10) confirmed that there are two periods (see Table 1). Two additional examples are shown in Fig. 8 and Fig. 9, where the variation is less conspicuous, but still unambiguous. Again the periods are typical for δ Scuti stars, and the position in the CM diagram is consistent with this interpretation. One variable is definitely not a δ Scuti star, as the colour is much too red. It appears not to be member of the cluster.

More observations are needed, before a multisite campaign can be initiated. The procedures to be followed in the future are described in the next section, where we discuss the revised strategy for STACC after the observations done the last few years.

For the cluster NGC 2215 the search was less successful. Only 5 hours on one night were obtained, and no variable stars were identified. This could be a result of the small size of the

Table 1. Detected frequencies in the proposed variables in the field of NGC 1817. The phase is relative to Feb. 13, 1996 at 0h UT. The classification comes from the light curve only.

ID	V	B-V	ν [μHZ]	A [mmag.]	ϕ [rad]	S/N	Type
16	13.4	0.84	207	6.4	0.24	3.8	δ Sct
73	15.23	0.63	168	4.41	2.64	3.5	δ Sct
	-	-	285	4.45	2.02	3.5	
88	13.50	0.42	208	2.76	1.77	3.1	δ Sct
	-	-	269	4.31	-2.78	4.8	
99	12.84	0.46	143	2.74	1.99	3.4	δ Sct
	-	-	210	5.04	-0.18	6.9	
114	14.38	0.50	205	3.07	2.06	4.0	δ Sct
	-	-	284	4.27	-0.86	5.6	
145	14.11	0.42	384	2.52	0.93	3.7	δ Sct
146	13.29	1.42	158	2.39	-1.9	3.0	
	-	-	260	2.65	-1.50	3.4	
163	12.57	0.48	152	5.62	3.02	5.6	δ Sct
	-	-	222	3.01	-1.79	4.3	

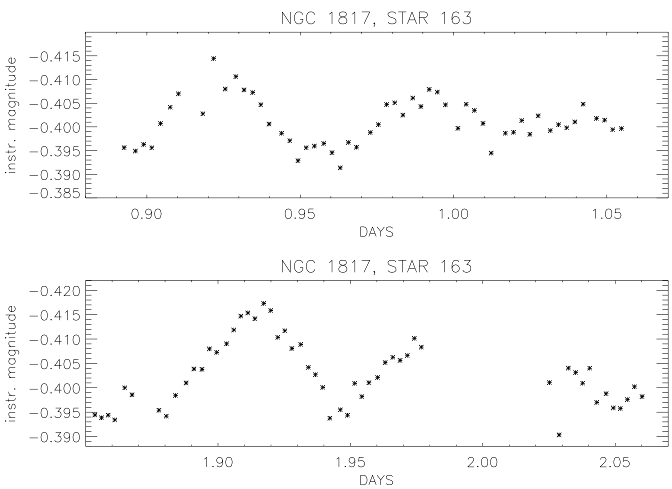

Fig. 7. Light curve for a δ Scuti star (# 163). This is a case easily recognized as a δ Scuti. It is evident that more than one mode is present.

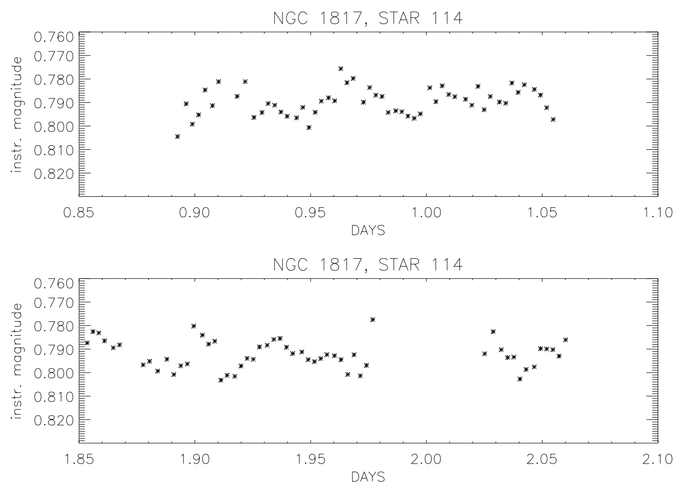

Fig. 8. Light curve for # 114.

data set, and the lack of δ Scuti stars with large (above a few mmag) amplitudes.

5. Strategy for the future

Important progress is being made in the study of stars with masses around 2 $M_\odot$, typical for δ Scuti stars. If by asteroseismology one understands the ability to derive firm results about the physics of the stellar interior using observed pulsation frequencies, then we are starting to see results on δ stars applying seismic techniques. Still, even for δ Scuti stars with more than 10 frequencies detected, mode identification is often ambiguous and therefore little information about the interior can be derived.

For single, isolated stars a breakthrough took place recently, when mode identification was announced for 8 out of 24 frequencies in FG Vir. Different methods gave the same result for 8 modes (Viskum et al. 1997b; Breger 1997). The observational efforts involved were large, and are not easily repeated for another star.

For open clusters, one cannot use quite the same techniques as for a bright star. But, analysing a group of stars simultaneously, and therefore knowing temperature and magnitude differences accurately, information about the modes can be derived. But, this only works, when the age, distance and metallicity of the cluster is well determined. Also, rotational velocities are needed and make it necessary to measure high quality spectra. The lack of good quality 'classical' data has so far prevented a completion of the analysis of the pulsators in NGC 6134.

With this in mind we have modified our strategy to reach our goal: *a new, improved test of stellar evolution*. The new scheme can be split into three parts.

5.1. Locating a target

From the experience gained so far, a sufficient number of variables in a cluster will only be detected either by sheer luck

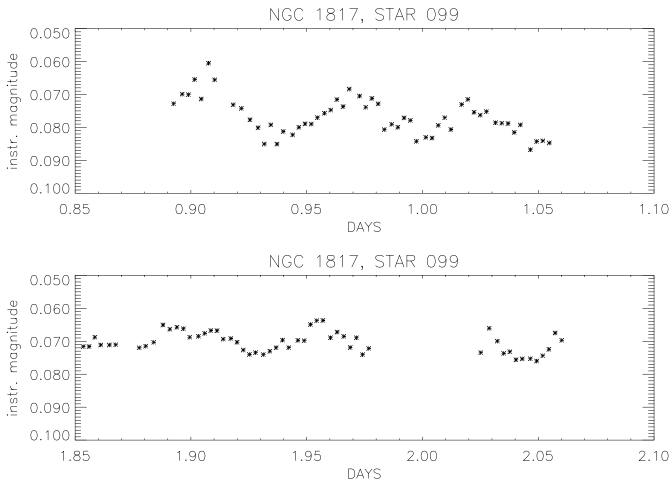

Fig. 9. Light curve for # 99.

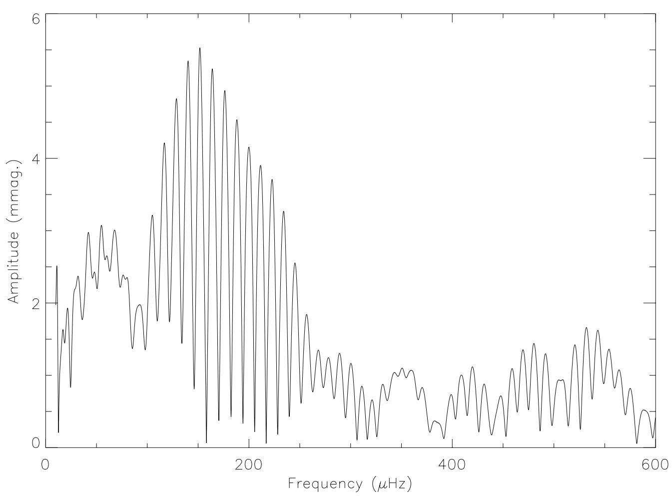

Fig. 10. Amplitude spectrum of the light curve of # 163. This is the most prominent variable.

(NGC 6134 to some extent was such a case) or by a systematic approach (NGC 1817). One has to optimize the choice of targets, in which a search for variables is carried out, and to optimize the techniques applied.

The parameters from the literature are in many cases unreliable, and the photometry of bad quality or only done for the brightest stars. New CCD observations, covering a large dynamic range, are needed, since they will lead to more accurate values for the reddening, distance and age of the clusters. This enables us to find the apparent magnitudes of possible δ Scuti stars.

CCD Photometry, as practised generally, suffers from flat field errors (Viskum et al. 1997a). Techniques as discussed by Kuhn et al. (1991) and later Wild (1997) should be implemented.

Open clusters, in which the isochrone turns upwards and almost follows the instability strip, seem to have the largest number of pulsators. Typically, this corresponds to an age of just below 1 Gy.

A section appears in *The Book* on techniques and methods with a few diagrams to help decide on the instrumental parameters and limitations. The reduction of series of CCD frames can be done efficiently using the software package MOMF (Kjeldsen & Frandsen, 1992).

5.2. Classifying the target

When a good target has been located (NGC 6134, NGC 1817), the theoretical interpretation is difficult or even impossible, if detailed information is missing for the variable stars. A complete set of data must be obtained.

A lot of nights are needed to obtain data of comparable quality to the data we have seen for FG Vir (Breger et al. 997, 1998). This represents the largest investment in terms of observing hours and manpower.

The second step therefore consists of a determination of further parameters and more information about the target:

- Variables should be confirmed
- Membership in the cluster by the pulsating stars assured by measurements of radial velocities
- Rotational velocities measured from high resolution, high S/N spectra, to know what rotational splittings are to be expected.
- A study of elemental abundances. Chemically peculiar stars might show up.

This second step can be quite a problem to carry out. The pulsating stars in most clusters are faint ($V > 12$). Some of the observations are not easily done unless one has access to a large telescope ($D > 2$m).

5.3. The campaign

With all the basic data in store, the time is ripe for a large, multisite campaign of relative CCD photometry. If we take FG Vir as a typical example of a δ Scuti star, detection levels around 0.3 mmag should be aimed at, and time coverage to give a frequency resolution better than 0.2 μHz in order to separate multiple, close frequencies.

As mode identification is so important for the analysis of the pulsation spectra, a time series of short exposure ($t \sim 5$ min) spectra for at least *one* pulsating star in the cluster would be of great value.

6. Conclusion

A document/manual *The Book* is available for observers interested in δ Scuti stars (and other variables) in open clusters.

The type of clusters of interest for the STACC project is illustrated by new CM diagrams for four clusters based on two colour CCD photometry.

The highlight presented here is the discovery of a population of δ Scuti stars in NGC 1817. This makes the cluster a very attractive target for a future multisite CCD photometry campaigns.

Even with one northern cluster that matches what we are looking for, the search for open clusters with a rich population of δ Scuti stars has been more difficult than expected. A more systematic approach is suggested here.

When a useful cluster has been located, extensive observations of individual stars, both photometrically and spectroscopically, are necessary. Proper modeling can not be done before high quality data exists.

The Book is available on request from the authors.

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