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Space observations of B stars with CoRoT

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Abstract

We present the preliminary results of the exploration of pulsating B stars observed with the CoRoT[1] space mission. The previously known group of Slowly Pulsating B stars gains a substantial amount of new candidates, offering the opportunity to test stellar models beyond individual cases. Besides these well-defined stars, the analysis of other B star candidate pulsators hints towards the presence of different variability behaviour, co-existing in the same space in terms of the timescale of the variations and location in the ($T_{\rm eff}$,$\log g$) diagram.

Introduction

The CoRoT space mission (see "The CoRoT Book", Fridlund et al. 2006) is a great opportunity for main sequence B-star asteroseismology. Two different kinds of datasets are available, each measured with an unprecedented duty cycle and precision. One type of dataset, the EXO field, contains tens of thousands of stars, and will continue to grow in the following months and years. Its main goal is to detect planetary transits, but this data also results in the discovery of new pulsators, where the B-star candidates can be selected from. The main advantage of this dataset is the wealth of stars, which will be used to constrain statistical properties of the target classes as a whole. The other dataset from CoRoT (SISMO field)

[1]The CoRoT space mission, launched on 27 December 2006, has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil , ESA, Germany and Spain.

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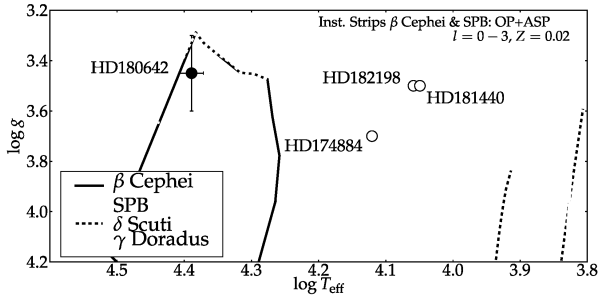

Figure 1: ($T_{\rm eff}$,log g) diagram, showing the position of the B stars in the initial run's SISMO channel. HD180642 is a known, bright β Cephei star. The CoRoT photometry clearly showed the binary nature of the former SPB candidate HD174884. HD181440 and HD182198 are two cool SPB star candidates. The instability strips are taken from Miglio et al. (2007).

is specifically aimed at asteroseismology, and focuses on few stars, but with an even higher precision and better sampling of 32 sec. The goal of this dataset is to do in-depth case studies of individual stars.

Non-emission main sequence B-star asteroseismology is restricted to two classes of stars so far: the Slowly Pulsating B stars (SPB stars hereafter; Waelkens 1991) are stars with masses between 3 and 8 $M_{\odot}$, showing high-order g modes with periods roughly between 1 and 3 days. The second class is that of the hotter β Cephei stars, with a mass range between 7 and 20 $M_{\odot}$. These stars usually have no surface convection zone, or at most a thin convective layer near the surface. The mechanism that drives these pulsations is the κ mechanism (e.g. Dziembowski & Pamyatnykh 1993).

SISMO field

In the CoRoT field dedicated to asteroseismology of the initial, first short and long runs, four non-emission B stars have been targeted (Fig. 1). The optical spectra obtained for these stars (Solano et al. 2005) have been used to derive the abundances and fundamental parameters (in preparation by Niemczura and collaborators). The main B target HD180642 is a known β Cephei star target, its dominant mode was already identified as radial by Aerts (2000). Because of the huge amplitude of this mode, non-linear effects have to be taken into account to model this star (Briquet et al., 2009). The three other secondary targets are candidate SPB stars. The achieved precision of the light curves showed that one of these candidates is actually a binary, and will be subject to a separate analysis. The two other targets are cool SPB candidates or cool B stars, which could hopefully help to determine the red boundaries of the SPB instability strip.

EXO field

The CoRoT satellite continues to transmit light curves of thousands of stars, of which most have never been observed outside the CoRoT program. Because so little is known about these stars, there is no other choice than to rely on automated classification methods based on CoRoT's white light photometry to unravel their nature (Debosscher et al. 2007, Sarro et al. 2008). Our main interest is to extract the B-type pulsators from the sample (β Cephei

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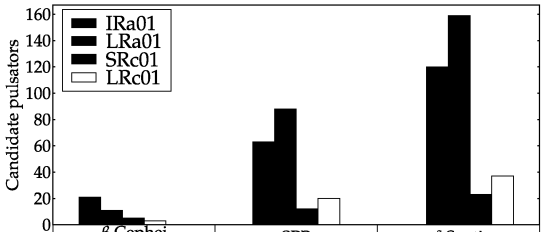
and SPB), while the cooler δ Scuti stars are in our case only used as a reference to limit the red edge of the SPB instability strip. We used the CoRoT Variability Classifier (in preparation by Debosscher and collaborators), which uses 2 independent supervised classification methods. In essence, the code compares the observed light curves from CoRoT with other targets that are independently observed and whose pulsational properties are determined with high reliability. Next, the code labels the CoRoT light curves with its 'best match'.



	β Cephei	SPB	δ Scuti
IRa01	21	63	120
LRa01	11	88	159
SRc01	5	12	23
LRc01	3	20	37

Figure 2: Results from the CoRoT Variability Classifier on all available runs, showing only the most probable candidates. There are significantly more β Cephei, SPB and δ Scuti star candidates detected in the fields directed at the galactic anticentre (IRa01,LRa01) than the fields towards the galactic centre (SRc01,LRc01).

Initially, we restricted the selection to those stars assigned to the same class with both methods. The results from this extraction can be seen in Fig.2. For all these stars, an automated complete frequency analysis was performed on which we will report in a forthcoming paper (in preparation by Degroote and collaborators), after some basic piecewise detrending to correct for the largest (instrumental) jumps still occurring in the light curves. A model of the form $F(t) = C + \sum_{i=1}^{n_f} A_i \sin[2\pi(f_i t + \phi_i)]$ with A_i and ϕ_i free parameters for each $i = 1, \ldots, n_f$, is fitted to each light curve, with frequency values f_i determined by the highest peak in the Scargle periodogram (Scargle 1982) of each prewhitening stage.

Some post-processing has been done to build a reliable frequency list: identification of candidate harmonics and combination frequencies and rare window frequencies. Frequency regions with known instrumental effects are also avoided.

In a next step, Strömgren photometry was obtained with INT-WFC for the stars in the initial run and used to determine the effective temperature $T_{\rm eff}$ and gravity $\log g$ of each star, in order to be able to roughly compare the stars with the predicted instability strips. This was done following the method of Balona (1994) and allowed us to place the new suspected B-type pulsators in a ($T_{\rm eff}$,$\log g$) diagram, and compare their position with theoretical predictions (Fig. 3).

It is immediately clear that almost all SPBs are situated well within the predicted area, as well as most of the δ Scuti stars. However, the picture is entirely different for the β Cephei candidates. Although these stars are supposed to be the hottest in the sample, several appear to exist with much lower effective temperature than the SPBs, in some cases even comparable to the $T_{\rm eff}$ typical of δ Scuti stars. Because of this discrepancy, the classification of the subsample was redone using a simple, but also more flexible cluster algorithm. Instead of comparing each light curve with light curves from already known class members, we compare

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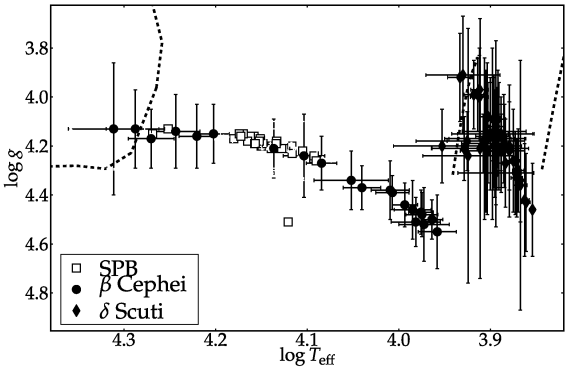

Figure 3: Position of the most probable β Cephei, δ Scuti and SPB stars in the ($T_{\rm eff}$,log g) diagram. The SPB and δ Scuti candidates are located well within their instability strips (dashed lines), while the β Cephei stars are spread out over the diagram.

the light curves to each other, taking also the temperature and gravity information into account in the process. The most important choice we have to make here is the number of groups we are willing to divide the subsample into. This arbitrariness is resolved by the observation that the clusters are stable with respect to these changes; introducing more groups tends to divide existing groups instead of mixing them. Raising the number of groups therefore means resolving more differences between observations. The result is a confirmation of the tight clustering of SPB and δ Scuti stars, and the breaking up of the β Cephei candidates in a hot and cool part.

To obtain a global picture of every group of stars in the ($T_{\rm eff}$,log g) diagram, we graphically depict the distribution of the highest-amplitude frequency and average frequency, and the main amplitude of pulsation modes of the stars in the four groups we found (Fig. 4). In terms of frequencies, both the δ Scuti candidates and SPB candidates confirm their expected position in the ($T_{\rm eff}$,log g) diagram. The stars on the hot side of the SPB candidates, (formerly β Cephei candidates and indicated as group U1 in Fig. 4), appear to have frequencies between these two classes. For this subgroup, two possible explanations come to mind when investigating the light curves and their frequencies (some examples can be found in Fig. 5): either they are candidate Be stars, which would explain some of the more erratic behaviour in the light curves (e.g. Neiner et al 2005), or they are in fact true candidate SPB-stars, but are rapid rotators, shifting their frequencies to higher values. The second unidentified group of stars (indicated as U2) lies in between the δ Scuti and SPB group, both in temperature and frequency value. They are difficult to separate from the β Cephei stars without any additional colour information. This group's main amplitudes are low, thus more difficult to detect from ground-based observations than the main amplitudes of the other three groups. This collection of U2 stars seems rather heterogeneous in nature.

An example of one of these stars, is CoRoT 102771057 (Fig. 5). We see from the fit and the power spectrum that this star pulsates with many frequencies. A few frequencies clearly stand out, and are spread out over a wide range: the first frequency is in the β Cephei p-mode range; $f_1 = 6.0872 \pm 0.0002\,{\rm d}^{-1}$, the second frequency equals $f_2 = 3.2834 \pm 0.0002\,{\rm d}^{-1}$, in between the p- and g mode range, while the third frequency, $f_3 = 0.5141 \pm 0.0003\,{\rm d}^{-1}$, enters the g mode range. On top of that, some power excess is detected around $\approx$ 7.9 d^{-1} and

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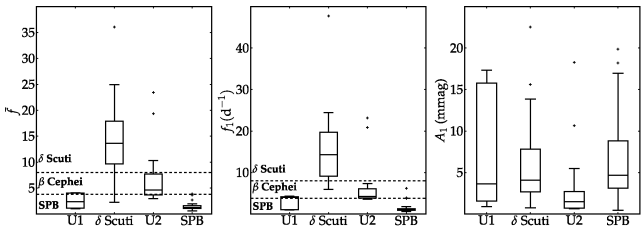

Figure 4: Properties of reclustered groups (box and whiskers denote the 50% and 75% interval, the horizontal line is the median value). Reclustering divided the β Cephei candidates in two groups of undetermined type (U1 and U2). Dotted lines show the frequency regions where SPB, β Cephei and δ Scuti pulsations are to be expected. The distribution of average (*left*) and first (*middle*) frequencies are shown. The amplitudes of U2 stars are clearly smaller than the amplitudes of the other groups. (*right*).

$\approx 9.3\,\mathrm{d}^{-1}$, which could very well be multiplets with $\Delta f \approx 0.16\,\mathrm{d}^{-1}$. This wealth and broad range of frequencies for U2 stars is striking, because, at present, no star has been predicted to pulsate in this region of the HR diagram. Theory, however, does predict the existence of some type of B star pulsations in the hot part of this region (Townsend 2005, Savonije 2005).

If we focus on the unidentified group of stars on the hot side of the SPB group (U1), we see that, in contrast to the previous group, these stars form a fairly homogeneous group. Their dominant mode amplitude is on the low side of the β Cephei range, while their frequencies are on the high side of the SPB frequency range. They show small groups of peaks, around $2\,\mathrm{d}^{-1}$, $4\,\mathrm{d}^{-1}$, $6\,\mathrm{d}^{-1}$ and even $8\,\mathrm{d}^{-1}$. The collection of peaks is a signature of slightly variable frequencies or amplitudes, making them good pulsating Be star candidates.

One of the stars that is behaving as a classical SPB star, is shown in Fig. 6. Around 60 frequencies are identified between $0\,\mathrm{d}^{-1}$ and $3\,\mathrm{d}^{-1}$. There are a few peaks above $3\,\mathrm{d}^{-1}$, but they can all be reasonably well explained by combination frequencies. A candidate period spacing of $\Delta P \approx 0.08$d is also detected.

Finally, although no typical β Cephei stars are confidently identified in the Initial Run's subsample of stars with available ground-based photometry, there are certainly good candidates available. An example is shown in Fig. 6: a star with frequencies between 3 and $10\,\mathrm{d}^{-1}$.

Conclusion

From the exploration of pulsating B stars in the SISMO field, we can conclude that they are compatible with current theoretical models. Rotational velocities and different evolutionary stages will be further exploited in upcoming runs.

In the initial run's EXO field, we have encountered a large number of new pulsating B stars. For the SPB candidates, the T_{eff} is as expected, but for the candidate β Cephei stars, there are two groups, one of which the T_{eff} is not compatible with theory. There are several likely scenarios to explain the behaviour of these two groups; they could be binary pulsators, fast rotating SPBs or δ Scuti with retrograde modes. For the hottest stars (U1), it is also possible that they are pulsating Be-stars. A thorough frequency analysis and theoretical interpretation of the results is ongoing and will be presented in a forthcoming paper. To further discriminate between the different types, spectroscopic observations from the VLT will be used in the future.

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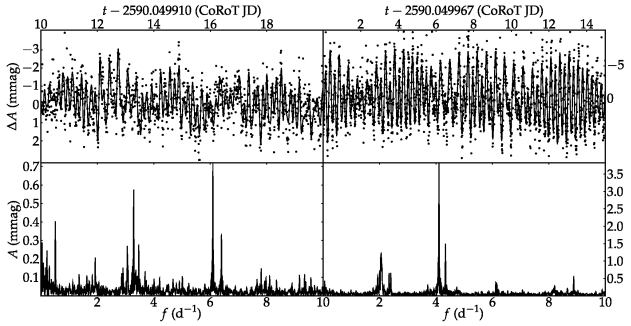

Figure 5: Example light curves and frequency spectra of a star of unknown type U1 having a rich spectrum similar to the one of a β Cephei star but a lower temperature (*left*) and U2 showing both frequencies too high for an SPB star and too low to be a β Cephei or δ Scuti star (*right*).

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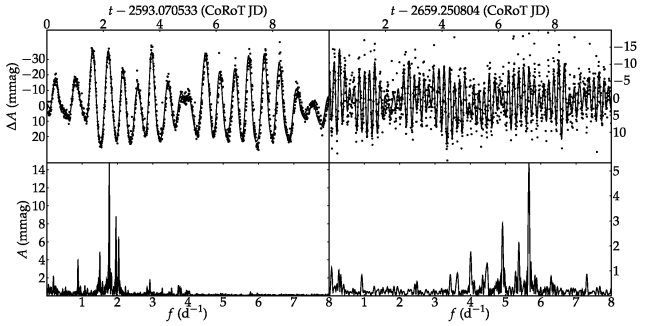

Figure 6: An SPB candidate (*left*) and a β Cephei candidate (*right*). Plotted are a zoom on the light curve (*top*) and part of the frequency spectrum (*bottom*). The SPB candidate shows strong pulsations around $f \approx 2\mathrm{d}^{-1}$, while the β Cephei candidate shows clear variations with frequencies above $f > 4\mathrm{d}^{-1}$

DISCUSSION

Chiosi: Studying the evolution of Pop III low mass stars, Marigo et al. (2001) suggested that old stars of about 0.9 $M_{\odot}$ with age of about 12 Gyr could intersect the instability strip in the region of δ Scuti while burning hydrogen in the core (turn-off). Therefore if Pop III stars of low mass could form, we expect a new class of δ Scuti-like pulsators with roughly the same colors and luminosity but longer periods ($P \sim M^{-0.5}$) because of the lower masses involved. In there any way to check whether the new class of pulsators you have presented might correspond to this prediction? It would be nice because it would prove the existence of Pop III.

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