Session 1B: DATA
Space missions

Asteroseismology of sun-like stars with MOST

D. B. Guenther[1], T. Kallinger[2], D. Huber[2], M. Gruberbauer[2], W. W. Weiss[2],
R. Kuschnig[2], J. M. Matthews[3], A. F. J. Moffat[4], S. M. Rucinski[5],
D. Sasselov[6], G. A. H. Walker[3]

[1] Saint Marys University, Halifax, Canada
[2] Universität Wien, Wien, Austria
[3] University of British Columbia, Vancouver, Canada
[4] Université de Montral, Montral, Canada
[5] University of Toronto, Toronto, Canada
[6] Harvard-Smithsonian Center for Astrophysics, Cambridge, USA

Abstract

The first sun-like star targeted by MOST was Procyon. This bright star with well-determined parameters and convincing evidence for the existence of p-modes from groundbased observations was expected to be an easy object for us. To our surprise (and to the surprise of many experts) we were unable to identify any p-modes. We returned to Procyon twice. Based on the results from the latest run, with noise levels reduced by a factor of two over previous runs, we are now ready to comment on the nature of Proycon and its oscillation spectrum.

Individual Objects: Procyon

MOST Instrument

MOST is a space telescope in a sun-synchronous polar orbit. It is capable of obtaining precise uninterrupted photometry of bright stars for up to 2 months. The satellite is equipped with a 15-cm Maksutov telescope feeding a CCD (350 - 700 nm). The primary observing mode uses a Fabry microlens that projects an image of the telescope pupil onto the CCD. Because the pupil image remains stable despite small pointing errors of up to 10 arcsec, this observing mode provides the most precise photometry obtainable.

During the first two years of the MOST mission, an additional CCD detector was used for star-tracking. This detector stopped working in early 2006. Star-tracking was relocated to the open field section of the CCD but this forced us to read the CCD every couple of seconds to maintain the satellite's orientation. Consequently, the science field exposures now have to be stacked onboard to achieve the desired signal-to-noise (S/N) for each measurement. This adapted observing mode actually provides higher total count rates per exposure and therefore better S/N than the original observing mode.

Since its launch MOST has carried out numerous asteroseismic observations of Wolfe-Rayet stars (e.g., Lefvre et al. 2005), planet transits (e.g., Miller-Ricci et al. 2007), star spots (e.g., Walker et al. 2007), roAp Stars (e.g., Huber et al. 2007), and red giants (e.g., Kallinger et al. 2008). In addition, it has motivated the development of SigSpec (Reegen 2007), an algorithm that provides a correct statistical measure of the probability that an amplitude peak in an oscillation spectrum is not due to white noise.

It is MOST's observations of sun-like stars, though, that have proven to be the most challenging. This is exemplified by the case of Procyon, the topic of this talk.
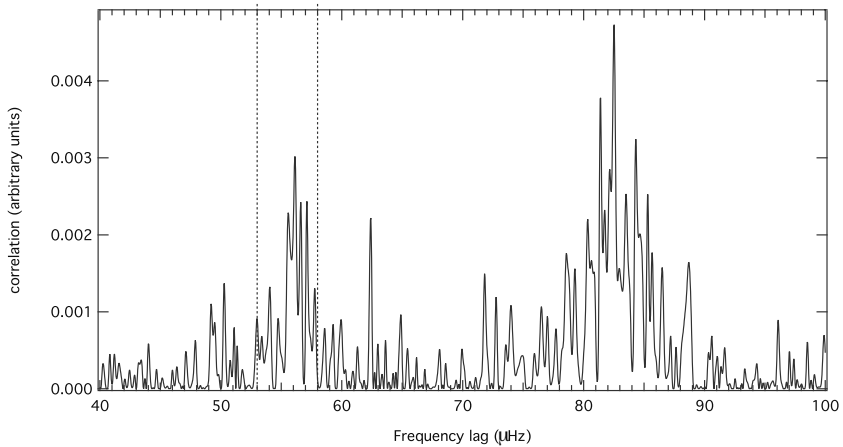
Figure 1: Autocorrelation in frequency of MOST 2007 observations of Proycon.

Procyon

In the context of asteroseismology, Procyon is classified as a sun-like star. It is near the main sequence. Its composition is close to solar. It has a convective envelope, albeit a very thin one, that is believed to drive nonradial oscillations. And in aid of modeling, its mass, luminosity and effective temperature are well-known.

It was an obvious first target for MOST because it is well located within the continuous viewing zone of MOST, it is bright, and it has already been the subject of ground-based radial velocity (RV) measurements (e.g., Martic et al. 2004; Eggenberger et al. 2004). Furthermore, based on scaling arguments derived from theoretical models (Kjeldsen & Bedding 1995) we expected the amplitude of the nonradial oscillations to be well above the few parts-per-million threshold of the MOST instrument.

We were, therefore, surprised when we were unable to unambiguously see p-modes in our first observations of Procyon (Matthews et al. 2004). Specifically, we could not see a regularly spaced sequence of p-modes in amplitude versus frequency plots. At the time we concluded that if there are p-modes on Procyon, the peak amplitudes have to be less than 15 ppm in luminosity and/or the modes themselves have to have lifetimes shorter than 2 to 3 days.

The result was unpopular and several critical papers appeared shortly thereafter, including Bedding et al. (2005). They suggested that: 1. the capabilities of the MOST telescope, which were unproven at that time, were exaggerated and that it did not have the claimed sensitivity; 2. the data reduction strategy was inadequate or flawed; and 3. the stray light contamination was not dealt with properly. Since then the MOST telescope has shown with other targets that its sensitivity is well within the claimed limits, the data reduction strategy, which includes the new tool SigSpec, is reliable, and that the stray light contamination, which is a serious issue, is well-modeled (Guenther et al. 2007) and filtered out of the data.

We re-observed Procyon one year later in 2005. The results were similar, that is, we could not see regularly spaced p-modes in the data. Finally, following the improved S/N performance of the MOST telescope, noted above, and to coincide with networked ground-based RV observations of Procyon, we re-observed Procyon for a third time in 2007. We were able to improve the point to point scatter, and as a consequence, the S/N ratio by a factor of two in amplitude over our previous runs.

We believe we can see evidence for p-mode signal in the data but are still unable to identify p-modes. For example, the autocorrelation between 500 and 1500 μHz, see figure 1, shows two broad peaks, one at 83 μHz corresponding to the orbit frequency, and the other at 55 μHz, corresponding to the expected value for the large spacing. Regardless, when we plot the most significant peaks in an echelle diagram we do not see any well-defined sequences of common l-values. Indeed, the identified frequencies in the RV observations of Martic et al. (2004) and those of Eggenberger et al. (2004) show little agreement with each other or with our modes.

Short Model Lifetimes

Short mode lifetimes smear out the frequency peaks and, depending on the resolution of the spectrum, introduce multiple peaks around the true mode frequency. In figure 2 we show the discrete Fourier transform of a single mode with a damping and stochastic excitation time of 2 d. The peak amplitude is diminished to 60% its original amplitude and multiple peaks surround the true mode frequency.

When we simulate an entire spectrum of modes, the multiple peaks interfere with each other making it difficult to identify the true mode frequency. In figure 3, left panel, we show the echelle diagram obtained from a simulated spectrum of modes with 2 d lifetimes. The open circles are the mode frequencies and the filled circles are the extracted frequencies. The extraction fails for a significant number of modes.

In Guenther et al. (2008) we describe several techniques to extract the true frequencies. The most straightforward method we tried is to extract peaks from a spectrum smoothed by a running Lorentzian with half-width corresponding to the expected mode lifetime. In the case of the simulated spectrum whose echelle diagram is shown in the left panel of figure 3, this
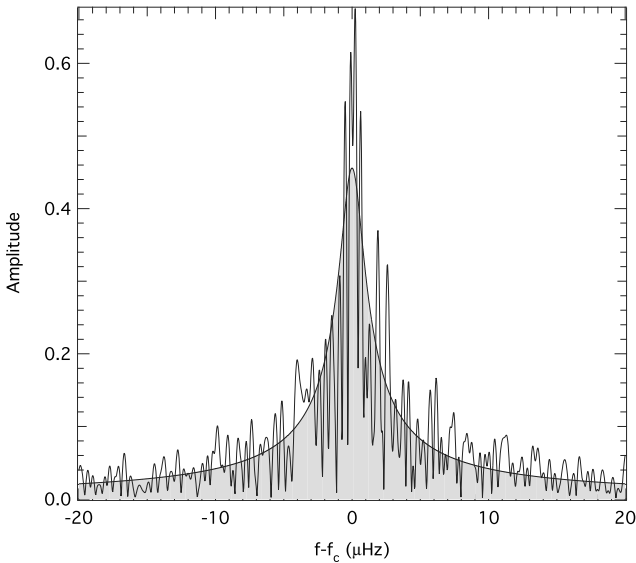

Figure 2: Simulation of how a damped and stochastically re-excited oscillation signal with a lifetime of 2 days would appear in the MOST 2007 Procyon data.
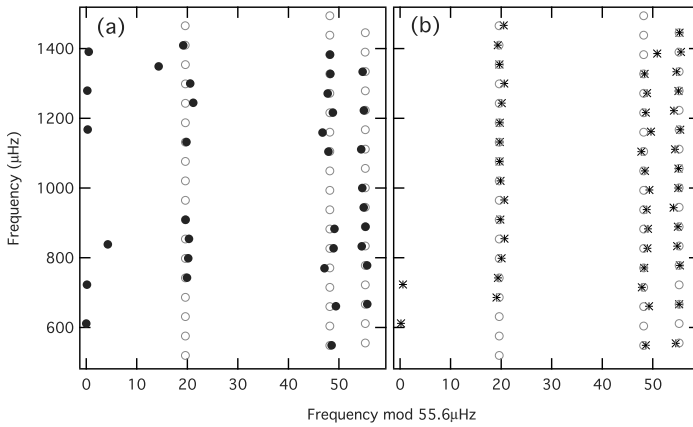
Figure 3: (a) Frequencies for a simulated oscillation spectrum of Procyon (open circles) are plotted with the peak frequencies which are recovered from that simulated oscillation spectrum (filled circles). (b) Same as (a) but the peak frequencies are selected from the Lorentzian-smoothed oscillation spectrum.
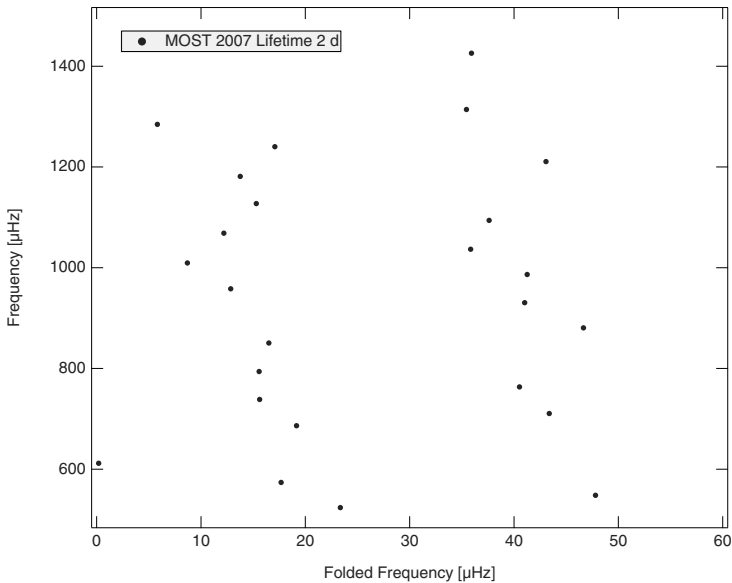

Figure 4: Echelle diagram of the MOST 2007 Procyon data, where frequencies have been extracted assuming that the modes have short 2 d lifetimes

technique yields nearly all the original modes as shown in the right panel of figure 3. After applying a 2d running Lorenztian to our 2007 Procyon data and extracting the peaks from the smoothed data we get the echelle diagram shown in figure 4. This is a cleaner looking echelle, although, there is still some scatter visible.

Despite improving the echelle diagram for our Procyon 2007 observations under the assumption of 2 d lifetimes we recognize that there are other possible explanations for our inability to unambiguously identify p-modes in Procyon. For example, the oscillation amplitudes in luminosity could be below that predicted by models. This could be due to Procyon's thin convective envelope. Because the driving region (the superadiabatic layer) is very near the surface, the region is less optically thick than in stars like the sun. We speculate that this could lead to greater radiative damping of the luminosity variations than predicted.

On a cautionary note, we find that for the purposes of establishing and identifying intrinsic modes in a star, it is best that as few physical assumptions about the star are included in the extraction as possible. As we have discussed, our initial echelle diagram was significantly improved by including the assumption that the modes have 2 d lifetimes. We could further improve the look of the diagrams by assuming that the peaks are regularly spaced according to the asymptotic relations. The procedure, called comb filtering, specifically selects the optimum set of peaks that fit the expectation of regular spacing. If physical processes within the star, such as short mode lifetimes, are responsible for the ragged looking echelle diagrams for Procyon then a neatly combed echelle diagram will do nothing but lead us astray.

Convection

Recent models of Procyon's thin convective envelope computed by the Yale convection group (Guenther et al. 2008) show that the frequency location of the peak power in the convective eddies as they manifest themselves at the surface coincides with the expected frequency range of the peak in power for the p-modes. In the case of the sun, for example, the two power peaks are separated in frequency. The coincidence of the power peaks for Procyon, if true, further complicates the process of extracting p-modes from the observations since the granulation noise has to be isolated from the overlapping p-mode signal.

References

Bedding, T. R., Kjeldsen, H., Bouchy, F., et al. 2005, A&A, 432, 43
Eggenberger, P., Carrier, F., Bouchy, F., & Blecha, A. 2004, A&A, 422, 247
Guenther, D. B., Kallinger, T., Reegen, P., et al. 2007, CoAst, 151, 5
Guenther, D. B., Kallinger, T., Gruberbauer, M., et al. 2008, ApJ, in press
Huber, D., Saio, H., Gruberbauer, M., et al. 2008, A&A, 483, 239
Kallinger, T., Guenther, D. B., Matthews, J. M., et al. 2008, A&A, 478, 497
Kjeldsen, H., & Bedding, T. R. 1995, A&A, 293, 87
Lefevre, L., Marchenko, S. V., Moffat, A. F. J., et al. 2005, ApJL, 634, 109
Martic, M., Lebrun, J.-C., Appourchaux, T., & Korzennik, S. G. 2004, A&A, 418, 295
Matthews, J. M., Kuschnig, R., Guenther, D. B., et al. 2004, Nature, 430, 51
Miller-Ricci, E., Rowe, J. F., Sasselov, D., et al. 2007, ApJ, 366, 164
Reegen, P. 2007, A&A, 467, 1353
Walker, G. A. H., Croll, B., Kuschnig, R., et al. 2007, ApJ, 659, 1611

First asteroseismic results from CoRoT

E. Michel[1], A. Baglin[1], W. W. Weiss[2], M. Auvergne[1], C. Catala[1], C. Aerts[3], T. Appourchaux[4],
C. Barban[1], F. Baudin[4], M.-L. Briquet[3], F. Carrier[3],
J. Debosher[3], J. de Ridder[3], R.A. Garcia[5], R. Garrido[6], J. Gutierrez[7], T. Kallinger[2],
L. Lefevre[1], C. Neiner[7], E. Poretti[8], R. Samadi[1], L. Sarro[9], and the CoRoT Team

[1] LESIA-Observatoire de Paris - CNRS (UMR 8109) - Univ. Paris 6 -
Univ. Paris 7, pl. J. Janssen, F-92195 Meudon, France
[2] Institut fur Astronomie, Wien Univ., Tuerkenschanzstrasse 17, A-1180 Wien, Austria
[3] Instituut voor Sterrenkunde, Katholieke Univ. Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
[4] IAS, Univ. Paris 11 - CNRS (UMR 8617), F-91405 Orsay, France
[5] Labo. AIM, CEA/DSM-CNRS-Univ. Paris 7, SAp, F-91191 Gif-sur-Yvette, France
[6] IAA-CSIC, Camino Bajo de Huetor, 50 E-18008 Granada, Spain
Univ. Paris 7, pl. J. Janssen, F-92195 Meudon, France
[7] GEPI-Observatoire de Paris - CNRS UMR 8111, pl. J. Janssen, F-92195 Meudon, France
[8] INAF-Osservatorio Astron. di Brera, Via E. Bianchi 46, I-23807 Merate (LC) Italy
[9] LAEFF, Apt. 78, E-28691 Villanueva de la Cañada Madrid, Spain

Abstract

About one year after the end of the first observational run and six months after the first
CoRoT data delivery, we comment the data exploitation progress for different types of stars.
We consider first results to illustrate how these data of unprecedented quality shed a new
light on the field of stellar seismology.

Conclusions

The CoRoT data fulfil expectations in terms of noise level, duration of the runs and continuity
of the observations. The analysis of the light-curves allows to explore stellar variability at
an unprecedented level of precision and for an unprecedented range of time scales. The first
interpretation studies confirm the great help we can expect from these data to improve our
understanding of stars structure and evolution. These results also confirm space photometry
as an efficient component of the strategy to develop stellar seismology.

The complete paper with additional details is published in CoAst, 156, page 73 (2008).

First results on the Be stars observed with the CoRoT satellite

J. Gutiérrez-Soto[1,2,3], C. Neiner[2], A.-M. Hubert[2], M. Floquet[2], A.-L. Huat[2], P.D. Diago[3], J. Fabregat[2,3], B. Leroy[1], B. de Batz[2], L. Andrade[4], M. Emilio[5], W. Facanha[4], Y. Fremat[6], E. Janot-Pacheco[4] , C. Martayan[2,6], J. Suso[3]

[1] LESIA, Observatoire de Paris, CNRS, Université Paris Diderot
place Jules Janssen 92195 Meudon Cedex, France
[2] GEPI, Observatoire de Paris, CNRS, Université Paris Diderot
place Jules Janssen 92195 Meudon Cedex, France
[3] Observatori Astronòmic de la Universitat de València,
Ed. Instituts d'Investigació, Polígon La Coma, 46980 Paterna, València, Spain
[4] University of Sao Paulo, Brazil
[5] Universidade Estadual de Ponta Grossa, Brazil
[6] Royal Observatory of Belgium, 3 Avenue Circulaire, B-1180 Brussels, Belgium

Abstract

In this paper we present an overview of the analysis of some of the Be stars observed with the CoRoT satellite up to this date. Be stars are very fast-rotating B-type stars which may pulsate as β Cephei or SPB stars. CoRoT has already observed 5 bright Be stars in the seismology fields and several tens of fainter ones in the exoplanet fields with an unprecedented quality and with a time duration from 20 to 150 days. Multiple frequencies are detected in the majority of the stars. Pulsations, outbursts, beating phenomenon, possible transient modes, rotation, amplitude variability, etc. have been found in their light curves. In order to complement this study, ground-based spectroscopic data have also been analysed for the stars located in the seismology fields.

Individual Objects: HD 181231, HD 175869

Introduction

Be stars are non-supergiant B stars that show or have shown at one or another moment emission in Balmer lines. It is generally agreed that the origin of this emission is the presence of an equatorial circumstellar disk, fed by discrete mass loss events. For a complete review of the Be phenomenon and its properties, see Porter & Rivinius (2003).

Be stars are very fast rotators ($\Omega/\Omega_{Crit} \sim 90\%$). Short-term variations are present in these stars due to the nonradial pulsations or/and rotational modulation. The spectroscopic analysis led by Rivinius et al. (2001) of μ Cen suggested that nonradial pulsations combined to the near break-up rotational velocity are probably the mechanism responsible for the mass ejection. However, μ Cen is, up to now, the only known Be star for which this behaviour could be shown.

Recently, the Canadian mission MOST observed during several weeks 5 Be stars with spectral types ranging from 09.5V to B8V. Modes typical of β Cep and/or SPB stars have been identified, suggesting that pulsations are present in all rapidly rotating Be stars (see eg. Saio et al. 2007).

The observation of Be stars with the CoRoT satellite (Baglin et al. 2002) is providing photometric time series with an unprecedented quality that will allow us to perform a deep

study of the role of nonradial pulsations and their relation with the Be star outbursts. The CoRoT mission is providing 5 months of continuous observations of 1 or 2 bright Be stars per long run. In addition, CoRoT is observing simultaneously many faint Be stars per long run. Moreover, some bright and faint stars are being observed during shorter periods of observations (short runs). Here we present the first results obtained from the analysis of the light curves of the Be stars observed with CoRoT.

Observations and frequency analysis

Observations were obtained with the CoRoT satellite during the Initial Run (IR) in the anticenter direction and in the Short Run (SRC1) and first Long Run (LRC1) in the center direction. The time duration of the three runs are 54.7, 27.2 and 156.6 days respectively. The period analysis was performed by means of standard Fourier analysis and least-square fitting.

Results and discussion

SEISMO fields

The analysis of two Be stars observed in the seismology field of CoRoT, namely HD 181231 and HD 175869, are presented in this section.

HD 181231 is a B5IVe star which showed low-amplitude variability with a frequency at 0.67 c/d from ground-based observations (Gutiérrez-Soto et al. 2007). The CoRoT light curve of 156.6 days (see Fig. 1 of poster by C. Neiner) shows a beating due to the presence of multiple frequencies. More than 30 significant frequencies have been detected. The three largest-amplitude frequencies are around 1.24, 0.62 and 0.69 c/d, with amplitudes of 1.6, 1.2 and 1.1 mmag respectively. The phase diagram with the frequency 0.62 c/d (upper panel of Fig. 1), shows a double wave, while the frequency 0.69 c/d shows a single-wave diagram (lower panel of Fig. 1).

Ground-based spectroscopic data of this star were also obtained with FEROS at the 2.2m telescope in la Silla as a part of a large program (PI Ennio Poretti) and at the Pic du Midi with the NARVAL spectropolarimeter (PI Coralie Neiner). The line-profile of the Mg II 4481 shows variations with the frequency 0.69 c/d. From Telting & Schrijvers (1997) we estimate a ℓ-value of $3-4$. See poster by Neiner et al. (2008) in these proceedings.

HD 175869 is a B8IIIVe star which was found to be nonvariable from Hipparcos data. The CoRoT light curve of 27.2 days shows low-amplitude variations of the order of 0.2 mmag. A frequency compatible with the rotational frequency and its 5 harmonics are detected. Other significant low-amplitude frequencies with amplitudes of few ppm are also found.

EXO fields

To date, 7 confirmed Be stars have been observed in the exoplanet fields of CoRoT during the IR. All of them showed emission in the Hα line in the spectroscopic observations taken with CAFOS at the 2.2m telescope in Calar Alto (PI Juan Fagregat). All the 7 stars have spectral types earlier than B5 and high-resolution spectra are needed to have a better classification. All these stars are highly variable when analysing their CoRoT light curves. Most of them present the beating phenomenon and therefore we find signal in many frequencies. As is often observed in Be stars, the detected frequencies range from 0.4 to 4 c/d. The amplitudes determined with the least-square fitting range from 40 to a few 0.01 mmag. Note that we have considerably improved our detection level and 3 of the 7 stars would never have shown variability from ground-based observations, since the largest amplitude for these stars is around $0.3-0.2$ mmag.
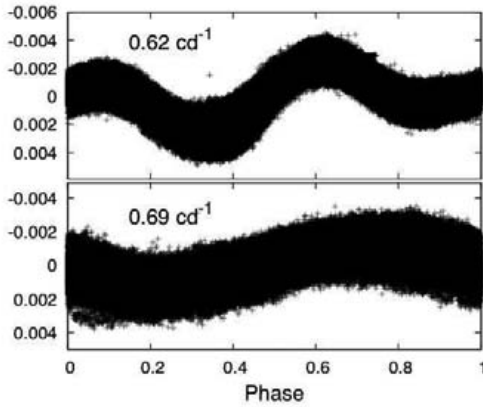
Figure 1: Phase diagram of the star HD 181231 with the frequency 0.62 c/d (upper panel), and with 0.69 c/d (lower panel)

Here we present a brief discussion of each observed star: The CoRoT light curve of the star 0102904910 shows beating of several frequencies. Many peaks around the frequencies 3.97, 3.84 and 1.92 c/d are clearly detected in the periodogram. We also found changes in the amplitude of the detected frequencies during the observations.

The light curve of the star 0102791482 shows variations with very high-amplitude of the order of 0.04 mag. The frequency analysis results on multiple frequencies (some tens) and many combinations, due to the high amplitude.

The star 0102766835 shows a long-term trend larger than the 57.7-d duration of the run in its CoRoT light curve, which would be produced by changes in the circumstellar disk. After prewhitening from this long-term trend, we found many frequencies around 0.93 and 0.88 c/d and combinations. We noticed that after adjusting a large number of frequencies (~ 50) to the light curve, some signal that appears to be non-sinusoidal is still present suggesting that some of the amplitudes or/and frequencies are changing during observations.

The analysis of the light curves of the stars 0102761769, 0102725623 and 0102964342 yields several frequencies with amplitudes of the order of 0.2 to 0.6 mmag.

The star 0102719279 shows several fadings in its CoRoT light curve (see Fig. 2). A fading is an ejection of matter or outburst, but due to the inclination angle ($i \sim 90$), the material in the envelope is hiding the star (see Hubert & Floquet 1998 for some examples with Hipparcos data). An outburst seems to occur around the Julian day 2454141, a second around 2454148 and a third much stronger one around the days 2454151-2454152. Note that the outbursts produce a fading of ~ 100 mmag in the light curve. The amplitude of the oscillations increases until the moment when the strongest outbursts occurs, and then suddenly the amplitude decreases while the average magnitude increases slowly to approximately reach the same level as before the outbursts. The outburst occurs when the amplitude of the variations is the largest.

From the Fourier analysis of the whole light curve, we detected several close frequencies around 1.16 c/d and the double 2.32 c/d, and around 0.98 c/d. As we noticed that the amplitudes change very much for the datapoints before and after the outbursts, we performed
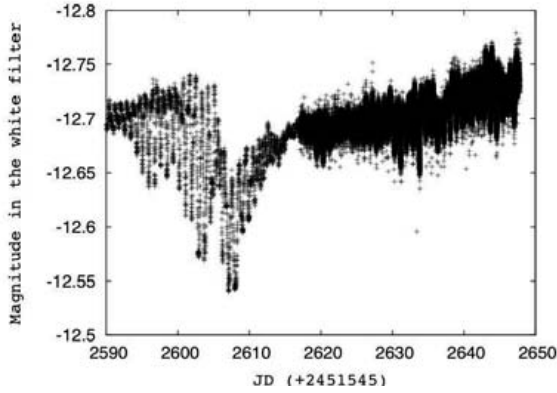
Figure 2: Light curve of the star 0102719279, observed in the exoplanet fields.
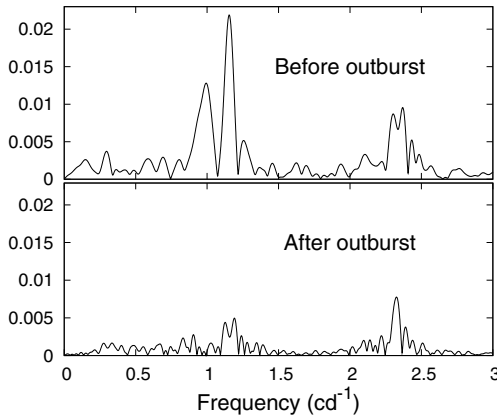

Figure 3: Periodogram of the light curve of the star 0102719279 before and after the outburst.

a Fourier analysis for both datasets. We clearly see in Fig. 3 that the amplitudes change dramatically for the frequencies close to 1 (the peaks disappear) and to 1.16 c/d (the amplitude decreases from 20 to 5 mmag). Therefore, there is a link between the outbursts and the change in amplitude.

Conclusion

The high precision, the high duty-cycle and the long-duration of the CoRoT observations presented in this paper have allowed us to detect many low-amplitude frequencies which would have never been detected from ground-based observations.

This is a summary of the results:

- Be stars are highly variable

- Most of the stars show a beating produced by multiple frequencies.

- A change of amplitude of the oscillations is observed along the light curve in some stars.

- A link between amplitude variations and outbursts have been found in one Be star.

Finally, we need models taking into account effects of fast rotation on oscillation frequencies to classify the modes and to discriminate between rotation and pulsations.

References

Baglin, A., Auvergne, M., Catala, C., et al. 2002, in Radial and Nonradial Pulsations as Probes of Stellar Physics, ed. C. Aerts, T. R. Bedding, & J. Christensen-Dalsgaard, IAU Colloq., 185, ASPC, 259, 626

Gutiérrez-Soto, J., Fabregat, J., Suso, J., et al. 2007, A&A, 476, 927

Hubert, A.-M., & Floquet, M. 1998, A&A, 335, 565

Neiner, C., Gutiérrez-Soto, J., Frémat, Y. et al. 2008, CoAst, 157, 349

Porter, J. M., & Rivinius, Th. 2003, PASP, 115, 1153

Rivinius, Th., Baade, D., Štefl, S., et al. 2001, A&A, 369, 1058

Saio, H., Cameron, C., Kuschnig, R., et al. 2007, ApJ, 654, 544

Telting, J., & Schrijvers, C. 1997, A&A, 317, 723

Coralie Neiner, Juan Gutiérrez-Soto, and Maja Vučković