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CoRoT Observations of O Stars: Diverse Origins of Variability

R. Blomme,[1] M. Briquet,[2] P. Degroote,[2] L. Mahy,[3] C. Aerts,[2,4] J. Cuypers,[1] M. Godart,[3] E. Gosset,[3] M. Hareter,[5] J. Montalban,[3] T. Morel,[3] M.F. Nieva,[6,7] A. Noels,[3] R. Oreiro,[2] E. Poretti,[8] N. Przybilla,[7] M. Rainer,[8] G. Rauw,[3] F. Schiller,[7] S. Simon-Diaz,[9,10] K. Smolders,[2] P. Ventura,[11] M. Vučković,[2] M. Auvergne,[12] A. Baglin,[12] F. Baudin,[13] C. Catala,[12] E. Michel,[12] and R. Samadi[12]

[1]*Royal Observatory of Belgium, Ringlaan 3, 1180 Brussels, Belgium*

[2]*Instituut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium*

[3]*Institut d'Astrophysique et de Géophysique, University of Liège, Bât. B5C, Allée du 6 Août 17, 4000 Liège, Belgium*

[4]*Department of Astrophysics, IMAPP, University of Nijmegen, PO Box 9010, 6500 GL Nijmegen, The Netherlands*

[5]*Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, 1180 Vienna, Austria*

[6]*Max Planck Institute for Astrophysics, Karl Schwarzschild Str. 1, Garching bei München 85741, Germany*

[7]*Dr. Karl Remeis Observatory & ECAP, University of Erlangen-Nuremberg, Sternwartstrasse 7, 96049 Bamberg, Germany*

[8]*INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, 23807 Merate (LC), Italy*

[9]*Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain*

[10]*Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain*

[11]*INAF, Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone (Roma), Italy*

[12]*LESIA, UMR 8109, Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon Cedex, France*

[13]*Institut d'Astrophysique Spatiale (IAS), Bâtiment 121, Université Paris-Sud, 91405 Orsay Cedex, France*

Abstract. Six O-type stars were observed continuously by the CoRoT satellite during a 34.3-day run. The unprecedented quality of the data allows us to detect even low-amplitude stellar pulsations in some of these stars (HD 46202 and the binaries HD 46149 and Plaskett's star). These cover both opacity-driven modes and solar-like stochastic oscillations, both of importance to the asteroseismological modeling of O stars. Additional effects can be seen in the CoRoT light curves, such as binarity and rotational modulation. Some of the hottest O-type stars (HD 46223, HD 46150 and HD 46966) are dominated by the presence of red-noise: we speculate that this is related to a sub-surface convection zone.

1. Introduction

The CoRoT satellite (Baglin et al. 2006) observed the NGC 2244 cluster and the Mon OB2 association from 08 Oct to 12 Nov 2008. As part of this 34.3-day run, high-precision photometric data were collected every 32 sec on six O-type stars (see Table 1). Below we discuss the light curve analysis of each of the stars in turn, going from the latest spectral type to the earliest one.

Table 1. O-type stars observed by CoRoT during run SRa02

star	spectral type	binary period
HD 46202	O9 V	
HD 46149	O8.5 V + OB-type	$P \approx 2.27$ yr
HD 46966	O8 V	
HD 47129	O7.5 I + O6 I	$P = 14.39625$ d
HD 46150	O5.5 V ((f))	
HD 46223	O4 V ((f$^+$))	

2. Analysis

2.1. HD 46202 (O9 V)

This star was studied by Briquet et al. (2011). In the periodogram they found a number of β-Cep like pulsation frequencies. The time-frequency diagram (see Fig. 1, left) shows that these frequencies are stable, at least during our campaign, confirming that they are indeed caused by pulsations driven by the opacity mechanism.

Asteroseismic modeling of HD 46202 was done using the Code Liégeois d'Évolution Stellaire (CLÉS, Scuflaire et al. 2008). The best agreement with the observed frequencies was found for models in the 23.3-24.9 $M_\odot$ range, with a core overshooting of 0.05-0.15 times the pressure scale height. The modeling showed that the observed modes are not excited in these models, thereby presenting a considerable challenge to the theoretical interpretation of the observations.

2.2. HD 46149 (O8.5 V + OB-type)

Degroote et al. (2010) found a rotation period of about 11.8 days in the light curve of HD 46149, which they attribute to the primary. They also found a number of frequencies with a constant spacing of $0.48 \pm 0.02\ \mathrm{d}^{-1}$. This is similar to stochastically excited p-modes. The time-frequency diagram indicates that these frequencies are not present during the whole duration of the observing run. A more detailed analysis shows that they have a lifetime of 3-4 days.

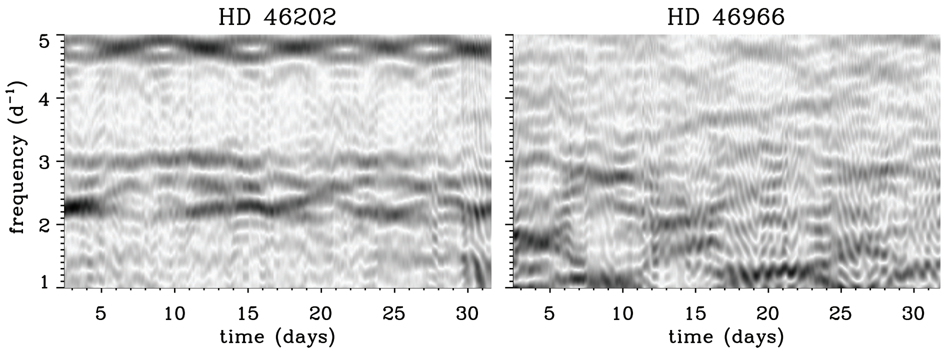

Figure 1. Time-frequency diagram of HD 46202 (left) and HD 46966 (right). The grey scale is proportional to the semi-amplitude, which was calculated from a Lomb-Scargle analysis on a sliding 5-day window of the observations (centered on the time given on the x-axis). The time is relative to the start of the observations.

2.3. HD 46966 (O8 V)

Blomme et al. (2011) applied classical pre-whitening to the periodogram of HD 46966. About 300 frequencies are required before the noise level is reached. Significance tests show that all 300 frequencies are significant. It is, however, highly suspicious that so many pulsation frequencies would be present in a single star. The time-frequency diagram (Fig. 1, right) clearly shows that none of these frequencies are stable. They are therefore not pulsational frequencies. A search for harmonics, linear combinations or frequency spacings did not turn up any significant results. Modeling with the ATON evolution code and the MAD pulsation code predicts pulsations in the 2-4 d^{-1} range, but no clear equivalent is seen in the observations.

All the above points to variations of a more chaotic or stochastic nature. A good description of this is given by a red-noise spectrum: red noise power increases as a power law toward lower frequencies. In Fig. 2, we fit the HD 46966 periodogram with a function that differs slightly from a power law at lower frequencies. It is important to stress that this red noise is not an instrumental effect, because its behaviour is different from star to star in the simultaneous CoRoT observations discussed here. Instead, it is caused by the star itself and it indicates stochastic, chaotic or quasiperiodic effects. It is seen in a number of other astrophysical situations, such as the optical light curves of Mira variables and red supergiants as well as in the X-ray light curves of active galaxies, dwarf novae and high-mass X-ray binaries (see references in Blomme et al. 2011).

At the moment we can only speculate about the possible causes of this red noise in O-type stars. One possibility is that it is caused by the sub-surface convection zone found in theoretical modeling (Cantiello et al. 2009). This zone is assumed to be responsible for a number of surface effects, such as microturbulence. Other possibilities include some type of granulation, or the onset of clumping in the wind.

2.4. HD 47129 (O7.5 I + O6 I)

This is the well-known binary Plaskett's star. Mahy et al. (2011) found the orbital period ($P = 14.39625$ d) in the observed light curve. They also found another significant

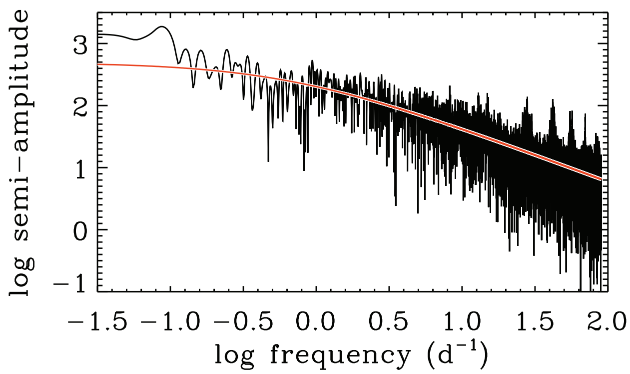

Figure 2. Fit to the red-noise component in the periodogram of HD 46966.

frequency ($0.823\,\mathrm{d}^{-1}$) with many harmonics. They tentatively ascribe this frequency to non-radial pulsations (NRPs), possibly generated by the tidal interaction from both components. The primary and secondary are known not to be tidally locked, because they have very different rotational velocities. Modeling with the ATON code shows that $l = 2, 3, 4$ NRPs with $0.8\,\mathrm{d}^{-1}$ are indeed possible.

2.5. HD 46150 (O5.5 V((f))) and HD 46223 (O4 V((f$^+$)))

These two stars behave in very similar ways, and are therefore discussed together. Blomme et al. (2011) found 500 significant frequencies in their analysis, but a time-frequency diagram shows that none of these are stable during the observing run. The ATON evolution code and MAD pulsation code were used to predict theoretical frequencies, but none of these were detected in the observations. Similarly to HD 46966, a description of the periodogram in terms of red noise is more appropriate.

3. Hertzsprung-Russell Diagram

Fig. 3 shows the position of the stars discussed here in the Hertzsprung-Russell (HR) diagram. We also added ζ Oph which shows β-Cep pulsations in the MOST photometry (Walker et al. 2005). We use squares to indicate those stars that show pulsations, and diamonds for red noise. This figure describes the extension of the β-Cep strip to the hottest stars. The three stars HD 46966, HD 46202 and ζ Oph are especially constraining in defining the extension of the β-Cep strip because HD 46202 and ζ Oph show β-Cep pulsations, but HD 46966 does not.

4. Conclusions

The CoRoT data of six O-type stars show diverse origins for their variability. They show β-Cep pulsations (HD 46202), solar-like oscillations (HD 46149), the effect of rotation (HD 46149), the binary period and tidally induced NRPs (HD 47129), as well as red

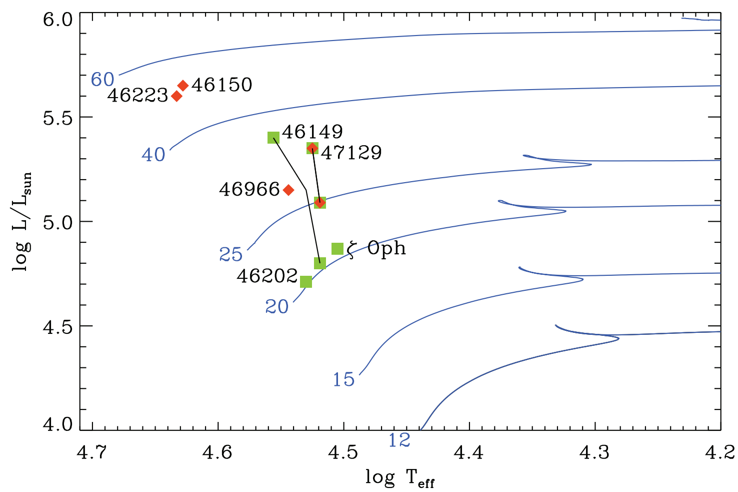

Figure 3. HR diagram indicating the position of the stars discussed here, as well as ζ Oph. $T_{\rm eff}$ and log L are from the papers cited in the text. Squares indicate pulsations, diamonds indicate the presence of red noise. Solid lines connect the binary components for HD 46149 and HD 47129. The stellar tracks are from Brott et al. (2011), with a Zero-Age Main Sequence rotational velocity of 220 km s^{-1}.

noise (HD 46966, 46150, 46223). Modeling the pulsations is possible for HD 46149 and HD 47129, but the other stars present problems. Although only six stars were studied, they can help in mapping out the extension of the β-Cep strip to the hottest part of HR diagram. The red noise we find in a number of these stars is intriguing. We cannot confidently identify its cause, but we speculate that it may be related to the sub-surface convection zone expected in these stars, or could be caused by granulation, or might indicate the onset of clumping in the wind. Quantitative modeling of these phenomena is urgently required to see which explanation best fits the data.

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Discussion

Simón-Díaz: For those stars in which you haven't detected clear frequency peaks but a type of red noise from the analysis of the photometry, would it be possible to obtain signatures of g-mode pulsations from spectroscopy, or can this already be excluded from your data? I mention this because these stars present an important "macroturbulent" broadening contribution to the line profiles. If high-order g-mode pulsations can be excluded for these stars, it would imply important consequences for the pulsational hypothesis used to interpret this broadening.

Blomme: This is somewhat difficult to answer. As we lack models for this red noise, we cannot really predict what its signature in velocity and in the spectrum would be. The absence of spectral variability in older data suggests these signatures will be difficult to detect.

Fullerton: Comment to Simón-Díaz: In a fragmentary spectroscopic time series, Fullerton et al. (1996) did not detect any statistically significant line-profile variations in HD 46150, which is broadly consistent with the expectation Ronny mentioned for "red-noise" variable.

Kubát: Is the "red-noise variability" detected also in stars of other spectral types?

Blomme: It is indeed seen in a number of astrophysical situations, such as optical light curves of Miras and red supergiants, as well as X-ray light curves of active galaxies, dwarf novae and high-mass X-ray binaries. It is not very frequent that a quantitative model is presented for such red noise, however. Usually only a qualitative explanation in terms of something stochastic or quasi-periodic is given.

Sana: One of the aims of asteroseismology is to get the fundamental stellar parameters. For one of the stars in your sample, HD 46202, an O9V star, you obtain a mass of $24\,M_\odot$, which is quite a bit larger than typical values for O9V stars (see e.g. Martins et al. 2005). Can you comment on this?

Blomme: The stellar evolution models indeed indicate a mass of $24\,M_\odot$. But the more sophisticated MAD code shows that the eigenfrequencies are not excited. This indicates a clear problem with the asteroseismic modeling. It would therefore be dangerous to take the numbers from this modeling as absolute truths.