Royer 2019B_PNPS009

Asteroseismic and spectroscopic analysis of rapidly-rotating delta Scuti stars

Semester : 2019B **Science Cat. : Stars and stellar population**

Abstract

This project aims at combining ultra-precise photometry (being obtained by the BRITE satellites and ground telescopes) with high-resolution spectroscopy to derive seismic constraints on the interior of rapidly rotating intermediate-mass stars. By modelling the effects of gravity darkening on line profiles, high-resolution spectroscopy will provide us with an estimate of both the inclination angle and the equatorial velocity for rapid rotators with low-to-moderate v sin i. Determining the actual equatorial velocity v and inclination angle i is crucial to properly understand oscillation power-spectra.

We propose to collect spectra with high signal-to-noise ratio (SNR ~ 600) for seven bright targets, selected as delta Scuti stars. It requires 1.1 night of SOPHIE in service mode.

Telescopes

Telescope	Observing mode	Instruments
OHP193	service	SOPHIE

Applicants

Name	Affiliation	Email	Country		Potential observer
Frederic Royer	Observatoire de Paris (GEPI)	frederic.royer@obspm.fr	France	Pi	
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Astronome-adjointe Rhita-Maria Ouazzani	Observatoire de Paris (LESIA)	rhita-maria.ouazzani@obspm.fr	France		

Applicants are continued on the last page

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Is this a long term proposal: Yes

Several semesters are required to complete the programme in terms of target number and SNR.

Overall scheduling requirements

The appropriate observation time of each target in service mode is listed below:

* 29 Cyg: early September
* UV Ari: mid October - mid November
* V483, V696, V775 Tau: mid November - mid December
* LM Hya: January - mid February
* DP UMa: February

Observing runs

run	telescope	instrument	time request (minimal)	moon	weather	mode	seeing	configuration	comments / constraints
A	OHP193	SOPHIE	1n (1n)	Bright	Clr	service	any	Observing mode: High-Resolution mode (R=75000) Read-out mode : Fast	None

Targets

Field	RA	Dec	Epoch	Exposure (sec.)	Runs	S/N	Red Magn.	Infrared Magn.	Diameter (arcsec)	ToO	Comments
DP UMa	12:02:06.78	+43:02:44.2	J2000	2400	A	600	5.22				
V775 Tau	04:22:03.52	+14:04:37.9	J2000	3840	A	600	5.72				
LM Hya	08:26:27.21	-03:59:14.9	J2000	3360	A	600	5.6				
V696 Tau	04:20:36.31	+15:05:43.6	J2000	2640	A	600	5.26				
UV Ari	02:44:57.58	+12:26:44.5	J2000	2400	A	600	5.17				
29 Cyg	20:14:32.03	+36:48:22.7	J2000	1920	A	600	4.93				
V483 Tau	04:19:57.70	+14:02:06.6	J2000	3360	A	600	5.58				

Scientific Rationale

Introduction

The asteroseismic analysis of δ Scuti stars revealed the presence of periodic patterns in their p-mode frequency spectra (García Hernández et al. 2009, 2013; Mantegazza et al. 2012; Paparó et al. 2013; Michel et al. 2017). These patterns were found to be compatible with the expected large separation ($\Delta\nu$) for these stars. A solid confirmation came from the scaling relation found between the observed spacing and the mean density computed for a sample of well-known stars (including binary stars) at different rotation rates (García Hernández et al. 2015). As predicted by oscillation models (Suárez et al. 2014; Reese et al. 2008; Ouazzani et al. 2015) these results demonstrate that $\Delta\nu$ can be detected in δ Scuti stars and that it scales with the star's mean density independently of its rotation rate. Being able to detect $\Delta\nu$ is crucial: first it provides an accurate constraint on the position of the star in the HR diagram, second it is a fundamental characteristic of the p-mode spectrum. A systematic search for this new observable among δ Scuti stars will be a key part of our strategy. The next fundamental characteristics of the p-mode spectrum are the rotation rate and the inclination angle (Reese et al. 2017). By modelling the effects of gravity darkening on line profiles (Frémat et al. 2005), high-resolution spectroscopy will provide us with an estimate of both the inclination angle and the equatorial velocity for rapid rotators with low-to-moderate $v \sin i$. Our project is therefore to combine ultra-precise photometry with high-resolution spectroscopy to derive seismic constraints on the interior of rapidly rotating intermediate-mass stars.

Rapid rotators are distorted by centrifugal acceleration and this deviation from spherical symmetry creates a gradient of gravity and temperature from the poles to the equator: the equator becomes fainter and cooler than the poles. The observed line profiles, integrated over the full apparent disk of the star, show specific shapes depending on the variation of the equivalent width with $T_{\rm eff}$ and $\log g$, and the inclination angle i of the rotational axis on the line-of-sight. These profiles can be modelled and offer a way to disentangle i and v. The best-known case for which this was done is Vega (see Takeda et al. 2008), which was observed at very high signal-to-noise ratio (SNR) and very high spectral resolution. We will apply the same methodology, by combining line profiles with similar signatures (Royer et al. 2014) and using the FASTROT (Frémat et al. 2005) computer code to compare the computed (best fitting) profiles with the observations. The effect is illustrated in Fig. 1. It shows an average line profile of HD 223855 (a B9.5V target from the previous programme, dedicated to late-B and early-A type stars seen pole-on), shaped by gravity darkening, superimposed with the best fitting FASTROT model ($v \sin i$ = 64.5 km s^{-1}, v = 357.5 km s^{-1}, i = 10°.4), and the corresponding view of the apparent disk with the temperature gradient from the pole to the equator. The current analysis of the B–A pole-on sample (Royer et al. in preparation) allows us to quantify the technical needs for applying the methodology to cooler spectral types, such as δ Scuti stars.

Determining the actual equatorial velocity v and i is crucial to properly understand oscillation power-spectra (Reese et al. 2013, 2017).

Sample and objectives

The proposed targets (Table 1) have been selected from the complete list of targets to be observed with the BRITE Constellation satellite, which was defined as bright δ Scuti stars with $V \lesssim 6$ mag (observable with the satellites), and with low-to-moderate $v \sin i$. These criteria were imposed in order to be able to search for, detect and model the gravity darkening signatures in high signal-to-noise spectroscopic data. The present sample is composed of stars classified as δ Scuti pulsators (Rodríguez et al. 2000), from which V483 Tau, V775 Tau, LM Hya, and DP UMa have been classified as belonging to binary systems with a δ Scuti component (Liakos & Niarchos 2017). The star 29 Cyg is a well-known λ Bootis star, whose photometric data are currently being analysed by the team. This characteristic makes the star even more interesting because the outcome of the present project may shed some light on the role of rotation in the λ Bootis phenomenon.

The objectives of the project are:

1. Determine accurate fundamental parameters for the sample of stars, in order to test new seismic diagnostics from photometric data obtained with the BRITE satellite. This will enable us to establish a guideline for properly analysing and interpreting rotating stars. This will be particularly important for preparing and maximising the scientific return of the PLATO 2.0 mission (Rauer et al. 2014), for which accurate stellar densities (obtained from large separations) and ages are of key importance for the characterisation of planetary systems;

2. Develop seismic diagnostics. We will use the observed data to test seismic diagnostics that we develop from theoretical pulsation spectra of rapidly rotating stars. In particular, we will search for patterns related to the rotational splittings of p-modes (predicted but not detected yet, Reese et al. 2017). Line profile variations and multi-colour photometry diagnostics have also been developed and will be tested on the stellar sample. Constraints on mode energy are now

becoming available thanks to new non-adiabatic calculations of the mode-excitation mechanisms. This is a first step required to study the mode amplitudes, for which a non-linear code is necessary. Our theoretical models are produced by current 1D and 2D stellar evolution codes: CESTAM (Marques et al. 2012) and MESA (Paxton et al. 2011) for 1D stellar models; STAROX (Roxburgh 2006) and ESTER (Espinosa Lara & Rieutord 2007) for 2D stellar models, respectively[1], as well as perturbative and non-perturbative oscillation codes: GraCo (Moya & Garrido 2008), FILOU (Suárez & Goupil 2008), ACOR (Ouazzani et al. 2012) and TOP (Reese et al. 2006);

3. Derive constraints on internal transport processes in massive and intermediate-mass stars. Detections of rotational splittings or oscillatory components in the large frequency separation will provide us with constraints on angular momentum and chemical element transport processes. Identification of individual modes (for example from the analysis of line profile variations) would also constrain these processes especially if some mixed modes can be identified.

Technical Justification

Complementary photometric time series

The list of proposed targets is included in a scientific observation proposal that was submitted to the BRITE-Constellation Executive Science Team (BEST) and which has been accepted in February 2017. Targets are not scheduled a priori, since BRITE's time allocation policy is based on observation fields. The full list of BRITE targets includes some 27 objects, among which 12 are observable from OHP, and 7 can be scheduled in semester B. The remaining targets will be part of subsequent proposals.

All the proposed targets were approved to be observed with the BRITE satellites. Four of them have already been observed (see Table 1). In particular 29 Cyg was observed in two BRITE campaigns (2017, 2015). It was also observed in 2018, but the new data have not been released (data is being processed before release to PIs). Then V483 Tau, V696 Tau, and V775 Tau were also observed in 2018 campaign, but as for 29 Cyg, data are still being processed. The rest of the objects are in the list of approved targets, and awaiting to be scheduled in BRITE's observations.

Two of the proposed objects (DP UMa, 29 Cyg) are currently being observed in a multi-site observation campaign to obtain multi-colour photometric light curves, which will be used for mode identification (Reese et al. 2017). In this campaign, the light curves are observed in four colours (Strömgren filters) simultaneously with twin photometers installed at Observatorio de Sierra Nevada (OSN, 90 cm) and San Pedro Mártir Observatory (85 cm). These observations will be combined with the BRITE data in order to minimise the effects of BRITE's spectral window, which has a very high frequency resolution but contains periodic gaps in their time series. That is, we will observe very precise low-frequencies from BRITE (thanks to its 20 second sampling), and reasonably precise medium-to-high frequencies from OSN, including multi-colour information.

Table 1: Details of the target parameters. ST is the spectral type. t_{exp} gives the individual exposure time (in s) to get SNR = 300 at 5500 Å in average conditions. The last column is the status of BRITE observations.

Star	ST	$v \sin i$ (km s^{-1})	RA (h m s)	Dec (° ′ ″)	V (mag)	t_{exp} (s)	BRITE status
29 Cyg	A2	86	20:14:32.03	36:48:22.70	4.93	480	processed
UV Ari	A7	86	02:44:57.58	12:26:44.70	5.17	600	approved
V483 Tau	F0	110	04:19:57.70	14:02:06.70	5.58	840	in process
V696 Tau	F0	79	04:20:36.31	15:05:43.60	5.26	660	in process
V775 Tau	A3	33	04:22:03.52	14:04:37.90	5.72	960	in process
LM Hya	F0	11	08:26:27.21	−03:59:14.90	5.60	840	approved
DP UMa	F0	89	12:02:06.78	43:02:44.20	5.22	600	approved

Spectroscopic analysis

The signature of gravity darkening is very small and it mainly affects faint spectral lines, thus a very high signal-to-noise ratio (SNR) is required to detect it. Figure 3 shows examples of line profiles in a FASTROT model with atmospheric parameters in the range covered by our targets: T_{eff} = 7500 K, $\log g$ = 4 and $v \sin i$ = 75 km s^{-1}. It corresponds to a rapidly rotating model (rotation rate of $\Omega/\Omega_{\mathrm{c}}$ = 0.9, Ω_{c} being the critical angular velocity) seen at a low inclination angle: i = 15°. At SNR = 600 (turquoise bands in Fig. 3), the difference between flat-bottomed profiles and classical profiles is not highly significant for

[1] Currently, neither the STAROX code nor the ESTER code can fully carry out 2D stellar evolution. STAROX introduces the effects or rotation subsequently to a 1D evolution calculation whereas ESTER approximates the effects of evolution by changing the composition in the stellar core.

individual lines. A carefully selected list of lines sensitive to gravity darkening (up to ~ 30 lines depending on rotational broadening) will be used to create co-added profiles, with enhanced SNR, thus allowing us to compare the observations with our grid of FASTROT models.

Therefore, we aim at reaching SNR ~ 600 and analysing the co-added line profiles. The individual exposure times for the targets (Table 1) were estimated in order to reach SNR = 300 around 5500 Å. Four such exposures per object are then necessary to obtain the required total SNR. Combining all single exposures will provide for each target a spectrum with a high enough SNR to search for the spectroscopic signatures of gravity darkening in the spectral line profiles.

None of the targets are present in the SOPHIE archive database with the required SNR, in high resolution mode. As our targets are few and scattered in right ascension, we ask for service mode observations to optimise their scheduling.

We seek to constrain the inclination angle of the proposed objects with a precision that allows us to determine the actual stellar surface rotational velocity to within 30-40%. Likewise, an inclination angle with precision better than 50-60% is required to properly estimate the oscillation mode visibilities. The error estimate of the derived inclination angle, performed in the current analysis of the late-B early-A pole-on star sample, is shown in Fig. 2 and gives the relative error on i as a function of the rotation rate Ω/Ω_c. At high SNR and for strong gravity darkening signatures ($\Omega/\Omega_c \gtrsim 0.6$) the inclination angle can be determined with a precision of ±10%.

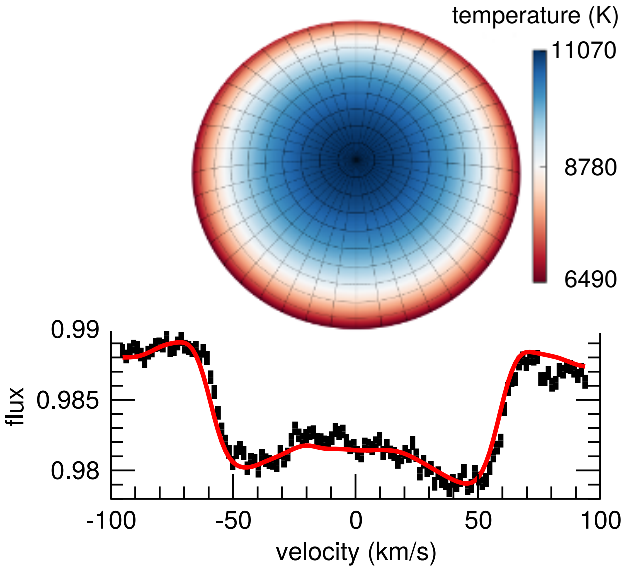

Figure 1: Gravity darkening signature in an average line profile of HD 223855 (B9.5V) in black, with its error bar, and the best fitting FASTROT model in red. On top, a modelled view of the apparent disk, colour coded by temperature.

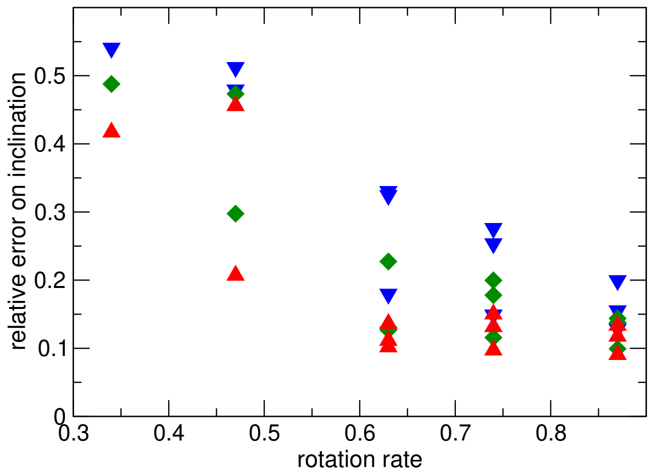

Figure 2: Results from simulations (for an A0 star) showing the relative error on derived inclination angle i, for different i and $v \sin i$, versus the rotation rate Ω/Ω_c. The symbols stand for the different SNR used in the simulated spectra: ▼ 400, ◆ 600, ▲ 800.

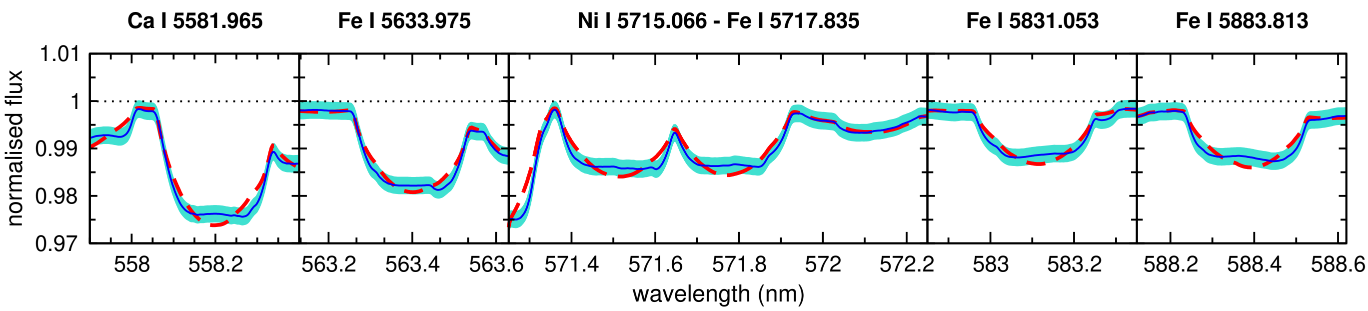

Figure 3: Examples of line profiles distorted by gravity darkening for a late A-type star. Blue profiles are taken from a FASTROT model at $T_{\rm eff}$ = 7500 K, $\log g$ = 4 and Ω/Ω_c = 0.9, observed at $v \sin i$ = 75 km s^{-1}. Turquoise bands represent the ±1σ noise level at SNR = 600 and the red dashed lines are the non distorted profiles, with a classical rotational broadening. The dotted line gives the continuum level.

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Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Kevin Bouchaud	Doctor	Yes	Dr. Daniel Reese	Yes	2019/12	No

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Justify the nights

The total integration time needed to reach the required SNR (600) for each of the 7 targets is indicated in the target list. This total is to be divided in 4 exposures (not necessarily consecutive). The required overhead time, assumed to be 5 minutes per exposure, is then equal to 7×4×5 = 140 min = 2h20.
In total, the exposure time is 5h30, together with an overhead of 2h20:
5h30 + 2h20 = 7h50 ~ 1.1n for 7h winter nights.
The total amount needed to achieve the observations is equivalent to 1.1 night.

Relevant previous Allocations: Yes

A previous programme, dedicated to the search of gravity darkening signatures in early-A and late-B-type stars seen pole-on, has benefited from several time allocations: 2014B_PNPS008 (2n), 2015B_PNPS008 (5n), 2016B_PNPS004 (3n). A paper is in preparation on the results from the detection and analysis of the signatures. The current proposal takes advantage of the experience gained from this analysis.

Additional remarks

FTE of Applicants:
Royer (3 man×month); Suárez (2 man×month); Frémat (2 man×month); Reese (2 man×month); Monier (1 man×month); Michel (1 man×month); Lignières (1 man×month); García Hernández (1 man×month)

Related Publications

* Monier R., Gebran M., Royer F., Kilicoglu T., Frémat Y., 2018, "HR 8844: A New Transition Object between the Am Stars and the HgMn Stars?", ApJ 854, 50
* Reese D. R., 2018, "Seismology of rapidly rotating and solar-like stars", Habilitation thesis, Observatoire de Paris (https://tel.archives-ouvertes.fr/tel-01810853)
* Reese D. R., Lignières F., Ballot J., et al. 2017, "Frequency regularities of acoustic modes and multi-colour mode identification in rapidly rotating stars", A&A, 601, A130
* Zorec J., Frémat Y., Domiciano de Souza A., Royer F., et al. 2016, "Critical study of the distribution of rotational velocities of Be stars. I. Deconvolution methods, effects due to gravity darkening, macroturbulence, and binarity", A&A 595, 132

Observing run info :

Applicants

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