Asteroseismology of Fast Rotating Stars (FRStars)

P.I.	Juan Carlos Suárez[1]
C.I.	Frédéric Royer[2], Antonio García Hernández[1], Eloy Rodríguez[1,3], Javier Pascual-Granado[3], Andrés Moya[1], Rafael Garrido[3], Richard Monier[2], Daniel R. Reese[2], François Lignières[4], Jerôme Ballot[4], Rhita-Maria Ouazzani[5], Yves Frémat[6]
Aff.	1. Universidad de Granada. Campus de Fuentenueva s/n. 18081 Granada, Spain. 2. Observatoire de Paris. 92195 Meudon. France 3. Instituto de Astrofísica de Andalucía (CSIC). Glorieta de la Astronomía s/n. 18008. Granada, Spain 4. Université de Toulouse, UPS-OMP, IRAP, F-31400 Toulouse, France 5. Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Denmark 6. Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium

Note for evaluator: *Citations are denoted by superscript (numbers). The complete bibliography list is given in Appendix 1. The list of proposed targets and bright stars in the fields are given in Appendix 2.*

Scientific justification

Context. The analysis of δ Scuti stars revealed the presence of periodic patterns in their p-mode frequency spectra [1–4]. 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 $\Delta\nu$ and the mean density computed for a sample of well-known stars (including binary stars) at different rotation rates[5]. As predicted by oscillation models [6–8] 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 parameter of the p-mode spectrum. A systematic search for this new observable among δ Scuti stars will be a key part of our strategy.

For hybrid δ Scuti - γ Doradus pulsators, we will be able to probe the deep interior (g-modes), in addition to the envelope. The pulsation modes of γ Dor stars are in the asymptotic regime, which means that, for slow rotation rates, their pulsation modes are evenly spaced in period. However, A and early F type stars can be moderate to fast rotators: $V \sin i$ values range from 40 to 130 km/s depending on the spectral type[9]. In that case, the period spacing is no longer constant, but varies linearly with the pulsation period[10]. Such a feature has been found in dozens of *Kepler*[11] stars, thereby paving the way for γ Dor seismology[12,13] , and enabling us to establish a new seismic diagnostic of rotation for these stars[14]. Combining seismic diagnostics based on both g- and p-modes will bring valuable constraints on the whole interior of our hybrid target stars.

Only ultraprecise photometry combined with high-resolution spectroscopy is able to give us a complete picture of stellar interiors, including rotation. In moderate and fast rotators, spectral resolution translates into spatial resolution by enabling us to disentangle different longitudes of the stellar surface. As a result, non-radial modes will perturb line profiles by introducing "moving bumps". A detailed analysis of these line-profile variations allows us to identify corresponding modes, because the shape and the behaviour of the variations depend on the properties of the modes.

In addition, high-resolution spectroscopy may also provide an estimate of the inclination of fast rotators with low-to-moderate $V\sin i$. Indeed, determining the actual V and i is crucial to properly understand oscillation power-spectra[15,16]. These are determined by analysing the spectral lines affected by gravity darkening and observed with a very high S/N ratio, i.e. for very bright stars[17]. Although the *CoRoT* [18] and *Kepler* missions have provided us with ultra-high precision photometric data, most of their targets are too faint to have their inclination determined through the aforementioned spectral analysis. Currently, only the BRITE constellation covers such a gap, as will the forthcoming *CHEOPS* mission[19].

Objective 1. Provide observed oscillation spectra for a sample of stars with accurate global stellar parameters: mass, evolutionary stage, rotation. Such a sample will be constructed from space photometric data (BRITE), seismic indices (at least the large separation) and complementary constraints (from spectroscopy/binarity). This sample of stars with accurate fundamental parameters will also be crucial for testing new seismic diagnostics and conducting a more detailed analysis of internal transport processes. This sample 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[20], for which accurate stellar density (obtained from large separations) and ages is of key importance for the characterisation of planetary systems.

Objective 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) and the period spacings of gravito-inertial modes. Line profile variation[21] and multicolour photometry diagnostics have been also developed and will be tested on the stellar sample. Constraints on mode amplitudes are now becoming available thanks to new non-adiabatic calculations of the mode-excitation mechanisms. Our theoretical models are produced by current 1D and 2D stellar evolution codes[a] (e.g. CESTAM[22], MESA[23] for 1D, STAROX[24] and ESTER[25] for 2D, respectively) and the oscillation codes like GraCo[26], FILOU[27], ACOR[28] and TOP[29,30].

Objective 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 and the period spacing 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 mode can be identified.

Procedure and data analysis

Step 1. **Analysis of lightcurves**. Firstly, we will search for gaps in the lightcurve, which will be filled using the autoregressive-moving average method MIARMA[31]. Then, in order to find the oscillation spectrum, we will apply a classical pre-whitening and cleaning algorithm, using the SigSpec[32] code. Particular care will be taken to properly remove harmonics and high-order combinations. Amplitude ratios and phase differences will be obtained for the modes with the highest S/N ratio in both the red and blue bands.

Step 2. **Fundamental parameters.** For those stars with high-resolution and high SNR spectroscopy we will determine the effective temperature, surface gravity, luminosity, and metallicity. We will use the Balmer lines to derive T_{eff} / log g and atomic lines to derive abundances: the Fe II lines will yield [Fe/H] through a model atmosphere and spectrum synthesis approach. The Vsin$i$ will be derived by analyzing the Mg II triplet at 4480 Å, as well as all those metal lines that will be visible even at larger Vsin$i$ values. A detailed abundance analysis will be performed. The modelling of the complete spectrum as well as of the existing (spectro)photometry by taking into account the effects due to stellar flattening and gravity darkening[33,34] will provide us with an estimate of the angular speed and of the inclination angle. When accurate HIPPARCOS or Gaia[35] data are available, we will make use of the parallax to improve our determinations. For those targets with no hi-res spectroscopy available, dedicated spectroscopic campaigns on those objects will be undertaken to gather HR and high SNR echelle spectra (e.g. on HERMES@Mercator, Sophie@OHP, ...).

Step 3. Asteroseismic modelling. First, we will design and develop model grids that allow us to make a first comparison, for slow rotators, between 1D+Perturbative oscillations and 2D+Non-Perturbative oscillations. Once the BRITE lightcurves are analysed, we will refine (eventually extend or improve) the model grids in order cover all the science cases described above. Finally, we will combine all the information to fully characterise the objects (objective 1). This will be the basis for the 2nd and 3rd objectives.

Technical justification

The list of proposed targets to be observed by the BRITE constellation (see Table 1 in Appendix 2) has been selected as appropriate for the scientific objectives described above. As requested, we provide a list of bright objects for guiding close to the proposed targets (Table 2 in Annexe 2). The selection of targets has been done using the R00 catalogue of δ Scuti stars[36]. Magnitudes and spectral types were cross-checked with recent catalogues. In order to be selected, objects had to be brighter than V~6.5-6.6, not of Am-type, and not too evolved (preferably in the main sequence). For these objects, we have checked for available high-resolution spectra. Targets in Table 1 have been arranged in order of priority. Those with high-resolution spectra have the highest priority, followed by fainter targets which do not have spectra yet. Considering the typical periods found for these stars, and the experience gained with the CoRoT satellite, we consider that to resolve all the modes (within a Rayleigh frequency of about 0.04 d^{-1}) we would need at least 30 days of continuous observations. Furthermore, we request to observe targets using both the red and blue colour bands, in order to identify the modes thanks to multi-colour mode identification techniques based on the latest predictions by non-adiabatic studies. In case not all of the stars can be observed in both colours, priority goes to the longest observation of the largest possible number of proposed targets with the best precision.

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[a] 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.

Appendix 1. Bibliography

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Appendix 2. Targets

Table 1. List of proposed objects. No indicates the number of priority; P, the main oscillation period in days; V, the visual magnitude; b-y_0, the colour index between the Strömgren b and y_0 bands; $V\sin i$, the projected surface rotational velocity; HRS, the number of available high-resolution spectra (E and S stand for Elodie and Sophie spectrographs, respectively); GCVS, the generic name of the star within the constellation field; HD, the identification number in the HD catalogue, and the coordinates (AR, DEC) in epoch 2000.

N	P	V	b-y_0	$V\sin i$	HRS	GCVS	HD	Coord
1	0.0490	6.23	0.195	15	1E	-	64491	07 55 40.82741 +35 24 45.6670
2	0.0630	5.72	0.189	32	4E, 4S	V775Ta	27628	04 22 03.51779 +14 04 37.9098
3	0.0440	6.08	0.138	37	1E	IKPeg	204188	21 26 26.66200 +19 22 32.2985
4	0.0267	4.93	0.099	80	11E, 2S	V1644C	192640	20 14 32.03331 +36 48 22.6921
5	0.0366	5.26	0.125	82	1E, 1S	V696Ta	27459	04 20 36.31046 +15 05 43.6250
6	0.0438	5.98	0.162	85	1S	CNBoo	124953	14 16 04.1396 +18 54 42.457
7	0.0412	4.18	0.171	97	114E, 1S	EpsCep	211386	22 13 58.40842 +69 53 51.1615
8	0.0549	5.58	0.171	102	10S	V483Ta	27397	04 19 57.70354 +14 02 06.7197
9	0.0230	4.18	0.044	110	5E, 1S	lamBoo	125162	14 16 23.01880 +46 05 17.9005
10	0.0265	4.75	0.124	130	11E, 1S	iotaBoo	125161	14 16 09.92995 +51 22 02.0267
11	0.0763	4.96	0.175	150	11S	CLDra	143466	15 57 47.44007 +54 44 59.1440
12	0.0210	5.79	0.047	90	-	V1431A	183324	19 29 00.98795 +01 57 01.6159
13	0.1250	4.80	0.105	145	-	DDUMa	74439	08 37 08.83418 -76 09 50.4367
14	0.0470	5.70	0.209	100	-	RCMa	57167	07 19 28.18202 -16 23 42.877
15	0.0380	5.60	0.112	13	-	LMHay	71297	08 26 27.20825 -03 59 14.9199
16	0.0550	6.54	0.128	129	-	V386Pe	24809	03 58 03.14347 +34 48 50.2853
17	0.0396	6.38	0.166	16	-	V526Ca	4818	00 50 57.39556 +51 30 28.9185
18	0.0156	6.26	0.061	60	-	RZCas	17138	02 48 55.51097 +69 38 03.4417
19	0.0500	6.22	0.120	180	-	GGVir	110377	12 41 34.39202 +10 25 34.5711
20	0.0400	5.22	0.170	78	-	DPUMa	104513	12 02 06.78485 +43 02 44.1692
21	0.0685	6.21	0.134	141	-	AVCet	8511	01 24 02.53973 -08 00 26.6947
22	0.0210	6.18	0.101	130	-	EXEri	30422	04 46 25.74999 -28 05 14.8038
23	0.0355	5.17	0.135	68	-	UVAri	17093	02 44 57.57945 +12 26 44.7297
24	0.0322	6.14	0.159	138	-	MOHya	111786	12 51 57.89547 -26 44 17.7838
25	0.0600	6.11	0.182	83	-	HRLib	142703	15 56 33.37364 -14 49 45.9760
26	0.0299	6.06	0.166	98	-	BGCet	3326	00 36 06.85711 -22 50 32.4079
27	0.0800	6.04	0.185	-	-	NZPav	186786	19 51 01.23646 -65 36 18.3146

Table 2. List of bright stars. RA and DEC the targets' coordinates (AR, DEC) in epoch 2000; HIP, the stars' ID in the Hipparcos catalogue; *V*, the visual magnitude (Hypparcos), and GCVS, the generic name of the star within the constellation field.

RA	DEC	HIP	V	GCVS
10.897379	-17.986606	3419	2.2061	betCet
2.294522	59.149781	746	2.3579	betCas
10.126838	56.537331	3179	2.4107	alfCas
14.177213	60.71674	4427	2.1379	gamCas
21.453964	60.235284	6686	2.7146	delCas
45.569888	4.089739	14135	2.6196	alfCet
47.042219	40.955647	14576	2.0969	betPer
56.871152	24.105136	17702	2.848	etaTau
58.53301	31.883634	18246	2.898	zetPer
59.463467	40.010215	18532	2.8348	epsPer
68.980163	16.509302	21421	1.0024	alfTau
101.287155	-16.716116	32349	-1.0876	alfCMa
107.09785	-26.3932	34444	1.9628	delCMa
113.649472	31.888282	36850	1.5811	alfGem
116.328958	28.026199	37826	1.2947	betGem
138.299906	-69.717208	45238	1.6625	betCar
178.457697	53.69476	58001	2.4286	gamUMa
194.006943	38.318376	63125	2.8471	alf02CVn
190.415181	-1.449373	61941	2.8213	gamVir
195.544158	10.95915	63608	2.998	epsVir
187.466063	-16.515431	60965	2.9449	delCrv
188.596812	-23.39676	61359	2.8099	betCrv
200.149239	-36.71229	65109	2.7717	iotCen
208.671162	18.397721	67927	2.7957	etaBoo
213.9153	19.182409	69673	0.1114	alfBoo
221.246739	27.074225	72105	2.5167	epsBoo
200.981419	54.925352	65378	2.254	zetUMa
206.885157	49.313267	67301	1.7994	etaUMa
229.251724	-9.382914	74785	2.5739	betLib
239.712972	-26.114108	78265	2.8274	pi.Sco
240.083355	-22.621706	78401	2.2617	delSco
241.3593	-19.805453	78820	2.594	bet01Sco
243.586411	-3.694323	79593	2.8283	delOph
249.289746	-10.567092	81377	2.5708	zetOph
245.997858	61.514214	80331	2.8717	etaDra
296.564918	10.613261	97278	2.8695	gamAql
297.695827	8.868321	97649	0.8273	alfAql
306.411904	-56.73509	100751	1.8583	alfPav
296.243661	45.13081	97165	2.8683	delCyg
305.557091	40.256679	100453	2.3548	gamCyg
310.35798	45.280339	102098	1.2966	alfCyg
311.552843	33.970257	102488	2.6429	epsCyg
326.046484	9.875009	107315	2.546	epsPeg
319.644885	62.585574	105199	2.5141	alfCep