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GRAVITO-INERTIAL MODES AT THE SURFACE OF RASALHAGUE

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Abstract. With the spectro-polarimeter Neo-Narval of the Bernard Lyot Telescope at the Pic-du-Midi observatory we observed two rapidly rotating stars: the A7V star Altair (α Aql) and the A5IV star Rasalhague (α Oph) in September 2020 and May 2024 respectively. Both of these stars have high Vsini (respectively 230 km/s and 240 km/s) which broadens their lines significantly. This large rotational broadening allowed us to monitor waves travelling at the surface of the stars and identify them as gravito-inertial ones. Here we discuss Rasalhague data and present our preliminary analysis, which shows that high azimuthal order waves travel across the surface of that star.

Keywords: stars: asteroseismology – stars: fast rotation

1 Introduction

Rotation has many consequences on the life of stars, essentially through the fluid motions it induces like large-scale baroclinic flows, differential rotation in convective regions or small-scale-turbulence in radiative zones. All these effects deserve attention in the models. Moreover, rotation is also important when interpreting observations since it modifies the surface flux distribution through so-called gravity darkening or when it perturbs the eigenmode spectrum. In any case, rotation breaks spherical symmetry, and if fast enough, requires two-dimensional stellar models (Espinosa Lara & Rieutord 2013).

Two-dimensional modelling of stars is still a young domain of astrophysics and observational test cases are very welcome. Fortunately, a few stars in the solar neighbourhood are very good test cases of these new 2D models. These are rapidly rotating early type stars like Vega (α Lyr), Altair (α Aql), Rasalhague (α Oph), etc. Because of their proximity they can be imaged by optical interferometers (Monnier et al. 2007; Monnier et al. 2012; Zhao et al. 2009; Aufdenberg et al. 2006; van Belle 2012), which bring interesting constraints on their fundamental parameters. In addition if they oscillate, they offer a large set of observables that are prized data to guide their modelling.

The first star of this kind to be studied in detail was Altair. In addition to interferometric data (Monnier et al. 2007), it shows a rich spectrum of oscillation frequencies (Buzasi et al. 2005; Le Dizès et al. 2021; Rieutord et al. 2024) that allowed Rieutord et al. (2024) to give a rather precise estimate of its age at 90 ± 10 Myrs following Bouchaud et al. (2020)'s work. Moreover, gravito-inertial waves have also been observed on the surface of Altair thanks to high resolution spectroscopy with the spectropolarimeter Neo-Narval at the Pic-du-Midi (Rieutord et al. 2023). Such data open a window on the near-surface layers of Altair, which are a possible place of its magnetic activity.

To go further we obviously need other examples with such many observational constraints. Rasalhague (α Oph) is the next candidate since it is also close to the Sun at 14.68 pc (Altair is at 5.14 pc) and has been imaged by interferometry (Zhao et al. 2009), while it is also a rapidly rotating star ($V\sin i \sim 240$km/s) with a rich oscillation spectrum (Monnier et al. 2010). Moreover, it is a priori slightly more massive than Altair, $2.2\mathrm{M}_\odot$

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versus 1.86 $M_\odot$, and probably more evolved. Interferometry says that its inclination is $\sim 88°$ therefore viewed almost equator on (Fig. 1).

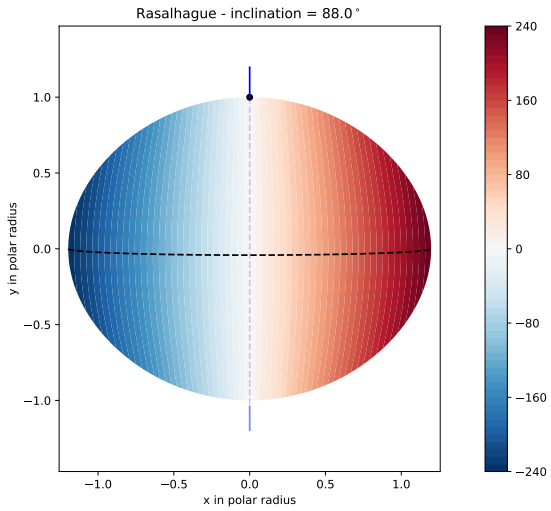

Fig. 1: Rotational velocity field of Rasalhague projected along the line of sight according to our best model. Velocities are in km/s.

	Rasalhague (α Oph)	
	Observation	Model
Parallaxe (mas)	67.13±1.06	
Mass ($M_\odot$)	$2.4^{+0.23}_{-0.37}$	2.22
R_{eq} ($R_\odot$)	2.858±0.015	2.865
R_{pol} ($R_\odot$)	2.388±0.013	2.385
ε		0.168
ω_k		0.63
i	88°	
T_{eq} (K)	7570±124	7674
T_{pol}(K)	9384±154	9236
L ($L_\odot$)	31.3±1	31.1
V_{eq} (km/s)	240±12	242
P_{eq} (hrs)	14.5	14.35
$X_{env.}$		0.70
$X_{core}/X_{env.}$		0.37
Z		0.02

Table 1: Comparison between observationally derived parameters of the star α Oph, and the concordance 2D-ESTER model. Data are from Zhao et al. (2009) and Monnier et al. (2010). Parallax is from Hipparcos.

2 Rasalhague's modelling

Using the constraints given by the first interferometric investigations of α Ophiuchi (Zhao et al. 2009), we derived a two-dimensional ESTER model (Espinosa Lara & Rieutord 2013; Rieutord et al. 2016) that matches these constraints. This model is summarized in table 1.

The model gives an equatorial rotation period of 14.35h quite close to the 14.5h derived by Monnier et al. (2010) from the light curve of Rasalhague, collected in 2009 by the *Microvariability and Oscillations of Stars* (MOST) satellite (Walker et al. 2003).

3 Observations

To reveal surface waves associated with the variability of Rasalhague we performed a spectroscopic monitoring of that star with the high-resolution spectrometer Neo-Narval fed by the 2-meter Bernard Lyot Telescope at Pic-du-Midi (e.g. Thomson-Paressant et al. 2023). We could observe Rasalhague during 13 hours spread over 4 nights in between June 2nd, 2024 and June 11th, 2024. Each spectrum was reduced to deliver the mean absorption line profile, from which we extracted the signal that modifies the profile in each spectrum. These perturbations of the line profile are shown in a sort of space-time diagram (Fig. 2) where we can easily see their propagation from the red side to the blue side of the line.

Making a Lomb-Scargle analysis of this signal both in time and in longitude, one may observe that the frequencies range is in the interval $[10, 50]$ c/d like Altair. However, the azimuthal wavenumbers of the excited waves are much larger than in the case of Altair.

4 Preliminary analysis

Following Rieutord et al. (2024), we construct an $m-\omega$ diagram where we plot the power spectral density as a function of time-frequency and the azimuthal wavenumber m. This diagram is shown in Fig. 3. It shows that most of the visible waves belong to the set of gravito-inertial waves as they are all at a slightly higher frequency than the Coriolis frequency when viewed in an inertial frame, as is the observer. Waves that are situated in

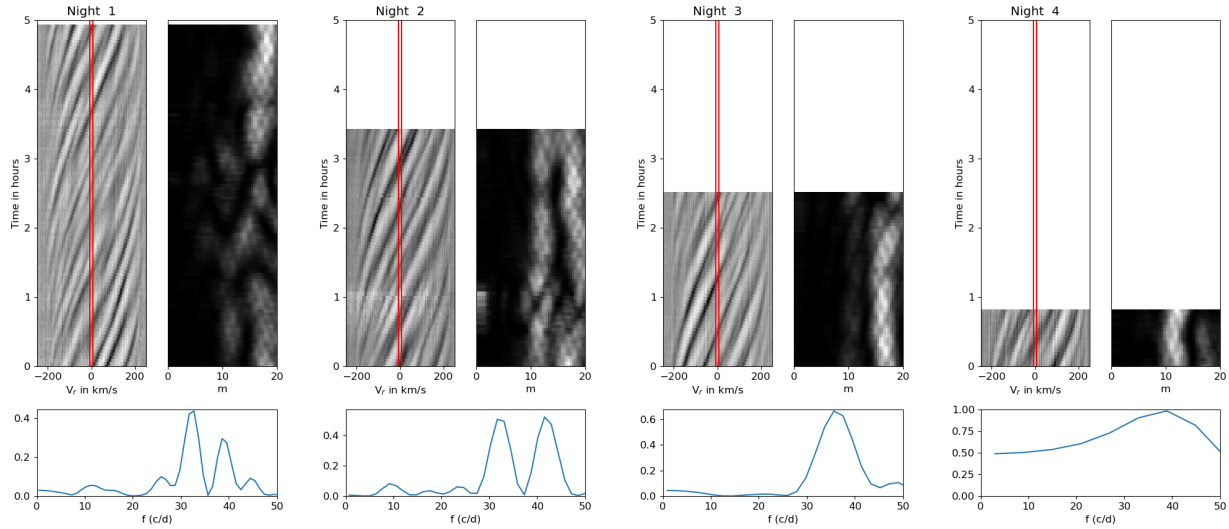

Fig. 2: From Left to Right: for each night we show on left the signal in a radial velocity-time diagram. On its right, we show the azimuthal power spectrum as a function of time, while the bottom plot shows the power spectrum formed from the data in between the two red lines of the radial velocity-time diagram and using the Lomb-Scargle algorithm.

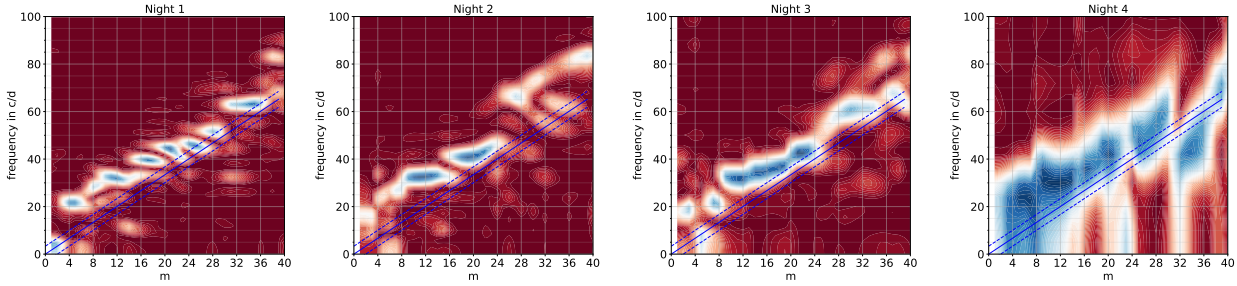

Fig. 3: For each night we show an m-ω diagram. The solid blue line shows the frequency of a steady perturbation in the co-rotating frame. The two blue dashed lines represent the inertial band $[-2\Omega, 2\Omega]$ in the co-rotating frame.

between the two dashed lines are quasi inertial waves since their frequency in the corotating frame belong to the $[-2\Omega, 2\Omega]$ sub-inertial band. We note that one mode at $m = 1$ or $m = 2$ visible on the first night is possibly a sub-inertial wave. The higher frequency of most of the waves, compared to Ω, shows that all these waves are prograde. This prograde nature suggests they may be equatorial Kelvin waves. Such waves have indeed been already invoked to explained some frequencies of the photometric spectrum of Rasalhague (Monnier et al. 2010). A more detailed investigation is now needed.

5 Conclusions

The detection of gravito-inertial waves at the surface of Rasalhague through high-resolution spectroscopic monitoring is very interesting as it opens a new window on the physical properties of that star, helping us in the modelling of fast-rotating stars with 2D-models. As the case of Altair has shown us (Rieutord et al. 2023), the waves detected on Rasalhague's surface, exhibiting especially high azimuthal wavenumbers, should be good probes of layers close to the surface of that star. Typically, these waves allow us to investigate the nature of layers at depths less than 5% of the radius, namely places where hydrogen and helium are ionized. These are

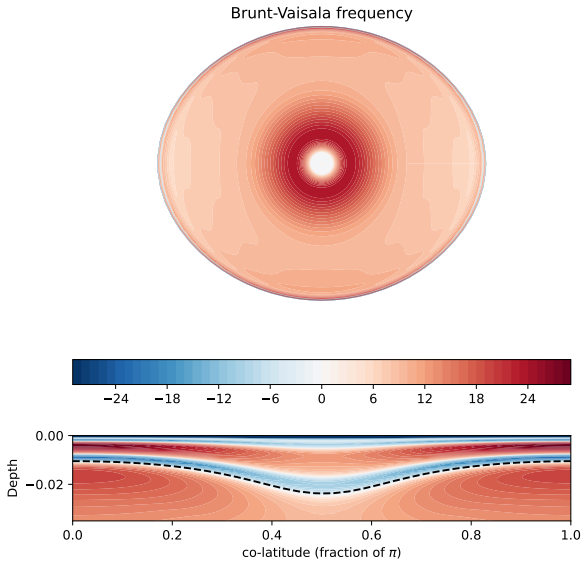

Fig. 4: Meridional view of the Brunt-Väisälä frequency variations in the model of Rasalhague of Tab. 1.

also places where thin convective layers develop (see Fig. 4), which may lead to some weak magnetic activity. The foregoing results are obviously preliminary and require now specific modelling (e.g. Mirouh 2022). This is the next step, which will be presented in a forthcoming work.

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