POSTERS

3D simulations of internal gravity waves in solar-like stars

Lucie Alvan, Allan Sacha Brun and Stéphane Mathis

Laboratoire AIM Paris-Saclay, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp,
F-91191 Gif-sur-Yvette Cedex, France
email: lucie.alvan@cea.fr, allan-sacha.brun@cea.fr, stephane.mathis@cea.fr

Abstract. We perform numerical simulations of the whole Sun using the 3D anelastic spherical harmonic (ASH) code. In such models, the radiative and convective zones are non-linearly coupled and in the radiative interior a wave-like pattern is observed. For the first time, we are thus able to model in 3D the excitation and propagation of internal gravity waves (IGWs) in a solar-like star's radiative zone. We compare the properties of our waves to theoretical predictions and results of oscillation calculations. The obtained good agreement allows us to validate the consistency of our approach and to study the characteristics of IGWs. We find that a wave's spectrum is excited up to radial order $n = 58$. This spectrum evolves with depth and time; we show that the lifetime of the highest-frequency modes must be greater than 550 days. We also test the sensitivity of waves to rotation and are able to retrieve the rotation rate to within 5% error by measuring the frequency splitting.

Keywords. hydrodynamics, waves, stellar dynamics, methods: numerical

1. Spectrum of gravity waves

Because they can propagate deeply in radiation zones of stars, internal gravity waves (IGWs) are essential to probe stellar interiors (García *et al.* 2007). The spectrum presented in Fig. 1 (left) has been obtained with the ASH code (Brun *et al.* 2004). Our model nonlinearly couples the convective envelope to the stable radiative core of the Sun (Brun *et al.* 2011), assuming a realistic solar stratification from $r = 0$ up to $0.97\,R_\odot$, and gravity waves are excited by convective penetration.

The richness of this spectrum allows us to analyse quantitatively the properties of the waves and to compare them with linear or asymptotic predictions (e.g. Christensen-Dalsgaard 2003 and Kosovichev 2011). We retrieve for example the constant spacing in period between two modes of consecutive radial orders. The spectrum evolves depending on the depth from where it is extracted, showing the effect of radiative damping. And it evolves also with time, since g modes have a finite lifetime. We observe that high-frequency modes have a nearly constant amplitude over more than 550 days so their lifetime must be much longer.

2. Effect of rotation

One of the interests for our 3D simulations resides in our ability to distinguish between several values of the azimuthal order m. The model studied is rotating at the solar rotation rate ($\Omega_\odot = 2.6\ 10^{-6}\ \mathrm{rad\,s^{-1}}$). We show in the right panel of Fig. 1 the rotational splitting affecting a g mode of degree $l = 2$. We expect this frequency shift to follow the asymptotic formula available in the frame rotating with the star, for $n \gg l$,

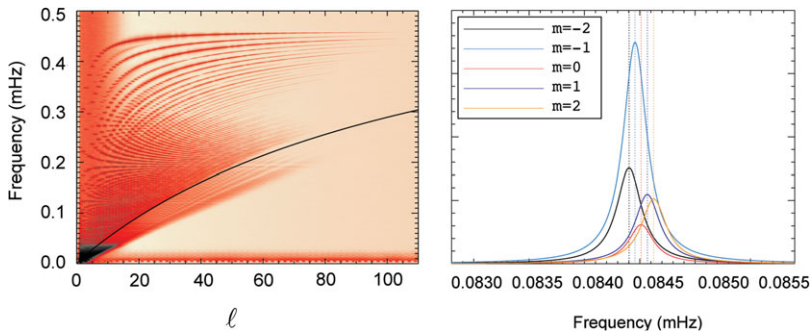$$\omega_{lm} = \omega_{l0} + \frac{m}{l(l+1)}\Omega'_\odot. \qquad (2.1)$$

Figure 1. *Left*: Spectrum of IGWs for $r_0 = 0.33\,R_\odot$. The black line highlights radial order $n = 58$. *Right*: Rotationnal splitting for $l = 2$, $-2 < m < 2$ and $n = 8$. The peaks have been fitted with a Lorentzian to determine precisely the position of their maximum.

By repeating our measurements over several modes of different radial orders n, we show that the relative error between the real rotation rate $\Omega_\odot$ and $\Omega'_\odot$ is about 35% for $n = 5$, but is less than 5% for $n \geqslant 30$. This measure gives us a quantitative information about the validity of the asymptotic approximation. We also note the asymmetry observed between prograde and retrograde modes which is in agreement with the one predicted by Belkacem *et al.* (2009).

3. Conclusion

Thanks to these new results, a detailed analysis of IGWs in 3D non-linear dynamical simulations is possible. For the first time, we are able to model the behaviour of both propagative and standing waves in a realistic 3D cavity (Alvan *et al.* 2012, Brun *et al.* 2013). The complementarity between our simulations and asymptotic analysis leads to interesting predictions about the lifetime of the modes and the accuracy of the rotation-rate measurement. We are currently developing new models taking into account a velocity gradient deep in the radiative zone (instead of a flat profile) and we will be able to study both the effect of this differential rotation on waves and the angular momentum transport induced by IGWs.

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