SF2A 2011
G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)

ROTATION ON THE OSCILLATION SPECTRUM OF SOLAR-LIKE STARS

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Abstract. One of the main sources of uncertainty in the asteroseismic models of solar-like stars is the poor match between predicted oscillation frequencies and observed ones in the very high frequency domain. Today, such deviation is usually corrected by fitting the affected frequencies with polynomials which are then physically explained by possible effects of turbulence, diffusion, etc., i.e., the so-called “surface effects”. In this work, we show that the effect of the stellar deformation due to rotation is of the same order or even larger than the aforementioned surface effects. Moreover, we show that rotation effects, even for the low velocities generally observed in solar-like stars, becomes important for the asteroseismic analysis and cannot be neglected when modeling such stars.

Keywords: oscillations, rotation, pulsation, solar-like stars, stellar structure, stellar evolution

1 Introduction

Asteroseismology is nowadays the unique tool to probe the stellar interiors and hence provide information on both stellar structure and evolution. Today, stellar physics witnesses a significant boost (see Suárez 2010, for a short review), thanks to the space era, where satellites like *MOST* (Walker et al. 2003), *CoRoT*(Baglin 2003), and *Kepler*(Gilliland et al. 2010), are providing asteroseismic data with unprecedented accuracy (see eg. Poretti et al. 2011; Catanzaro et al. 2011; Balona et al. 2011; Breger et al. 2011; Chaplin et al. 2010a; García Hernández et al. 2009; Bruntt et al. 2007, to name a few).

One of the main source of uncertainty in asteroseismology comes from the effect of rotation, which not only interacts with other physical processes, but also affects the form of the resonant cavity (see eg. Goupil et al. 2005; Goupil 2009). For slow-to-moderately rotating stars, like solar-like stars, the oscillation computation is undertaken using the perturbation approach (see eg. Soufi et al. 1998; Suárez 2002). It has been shown that for such rotators, rotation effects cannot be neglected for asteroseismic studies (e.g. Suárez et al. 2009; Briquet et al. 2009; Casas et al. 2009, 2006; Suárez et al. 2006a, 2007; Rodríguez et al. 2006b,a; Poretti et al. 2005).

Analysis of low-mass models for different turbulent diffusion coefficients (Mathis et al. 2007) revealed that rotation may increase the horizontal transport and the rotational effects upon frequencies. Moreover, it has been found that the effects of rotationally-induced mixing in solar-type stars is not strong enough to impose a rigid rotation, as opposed to the solar case (see e.g. Eggenberger & Carrier 2006, who studied the solar-like star β Virginis).

Furthermore, excited modes in solar-like stars are high-order (therefore high-frequency) p modes with small inertia. Since they propagate mainly through the outer layers of the star, their frequencies are more sensitive to changes in the surface physical properties, where the centrifugal force becomes more efficient. The present work examines and evaluates the effects of rotation in this high-frequency domain, and its impact on the different seismic diagnostics techniques based on the asymptotic properties of the oscillations. The main results have been published in the paper Suárez et al. (2010) (hereafter S10).

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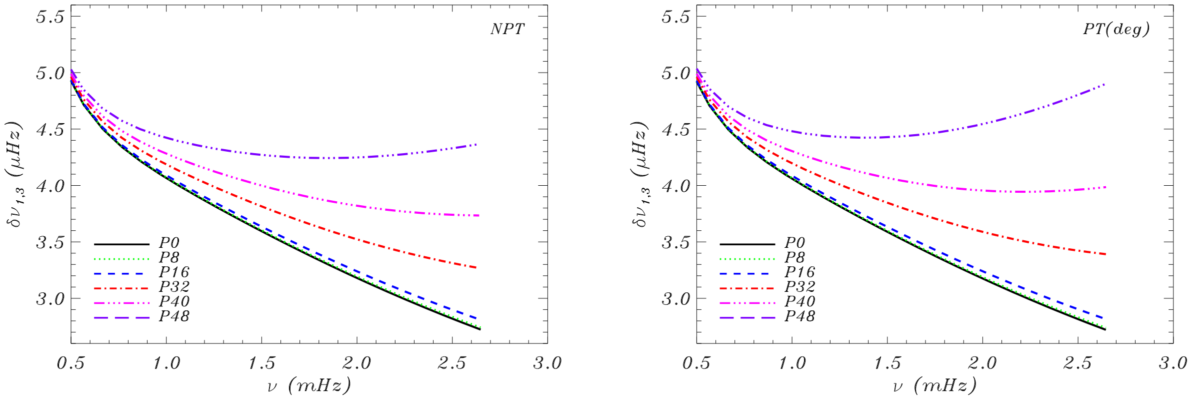

Fig. 1. Small spacings $\delta\nu_{1,3}$ as a function of the oscillation frequency, calculated using NP (left panel) and P (right panel, including near degeneracy effects) approaches. Different line types correspond to spacings computed for different rotational velocities. Figures taken from S10.

2 Peturbative vs. non-perturbative approaches

This work has been performed using 1D asteroseismic models, i.e. equilibrium models plus their corresponding oscillation models following the perturbative approach.These were computed using the evolutionary code CESAM (Morel 1997), and the adiabatic oscillation code FILOU (Suárez 2002; Suárez & Goupil 2008), following the prescriptions by the ESTA/CoRoT team (Moya et al. 2008). The equilibrium models take the rotation into account by including an effective gravity (due to the centrifugal force), but without modifying the spherical symmetry. Depart from spherical symmetry were considered in the oscillation computations, as well as the effect of near degeneracy (more details in Suárez et al. 2006b). The perturbative approach (from now on P approach) is only valid for a certain range of star distortion and frequency domain as explained in (Lignières et al. 2006; Reese et al. 2006) from which a complete calculation (non-perturbative approach, NP) is necessary. The first semi-empirical determination of such a limit was obtained for the well-known δ Scuti star Altair (Suárez et al. 2005), but no equivalent had been done so far for solar-type stars. In the present work we show that the P approach is valid up to $v_{\rm rot} = 40 - 50\,{\rm km\ s^{-1}}$, which can be illustrated in the comparison of small spacings shown in Fig. 1. This frequency spacing is expected to be small when the star does not rotate. However, the figure shows how such spacings are no longer small when increasing the rotational velocity. As can be seen, both P and NP predict almost identical results, except for higher velocities where slight differences come up. Both calculations are based on a polytropic model of index $n = 3$ with $M = 1.3\,{\rm M_\odot}$ and $R = 1.276\,{\rm R_\odot}$. The characteristics of all P and NP models are listed in Table 1 of S10.

3 Effect of rotation on diagnostics of echelle diagrams

One of the most frequently used techniques for seismic diagnostics of solar-like stars is the representation of the oscillation frequencies in the so-called echelle diagram which consists in depicting the oscillation frequencies as a function of the same frequencies modulo $\Delta\nu$.

Figure 2 shows such diagrams calculated for a realistic model of a solar-like star (see Table1 in S10), assuming a uniform rotation of $32\,{\rm km\ s^{-1}}$. It can be seen that ridges are altered significantly towards the highest frequency domain. In S10, it is shown that for rotational velocities of about $16\,{\rm km\ s^{-1}}$ and higher, diagnostics on large spacings and on modal identification through echelle diagrams can be altered by the presence of the $m \neq 0$ components of the rotationally split modes. These effects are detectable in the observed frequency range (from $\nu_{\rm max}$ to higher frequencies). More specifically we found that the larger the rotational velocity of the star is, the more chances the observed ridges in echelle diagrams correspond to $\ell = 0$ and/or $\ell = |m|$ modes. This is in agreement with the the empirical correlation found by Suárez et al. (2002) between the amplitudes of p modes with the angle of inclination i (details in S10).

The effect of rotation on the oscillations may go from a few μHz up to $20 - 30\,\mu{\rm Hz}$ for the largest rotational velocity considered (around $50\,{\rm km\ s^{-1}}$). This is of the same order or even larger than the so-called *surface*

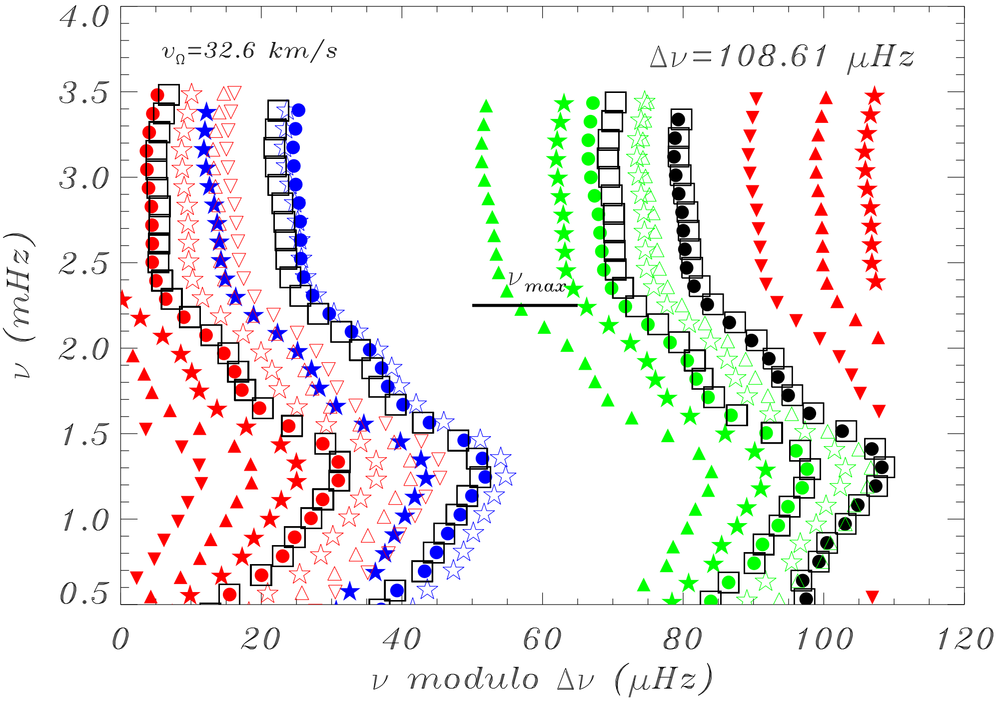

Fig. 2. Echelle diagrams for the uniformly-rotating models. Open squares correspond to ridges of the non-rotating stellar reference model. Black and green symbols represent $\ell = 0$ and $\ell = 2$ modes, respectively. Blue and red symbols represent $\ell = 1$ and $\ell = 3$ modes, respectively. Filled circles represent both $\ell = 0$ and $m = 0$ modes. For the rest of modes, filled and empty symbols represent the $-m$ and $+m$ frequencies, respectively. Stars, triangles, and inverted triangles represent modes with $|m| = 1$, 2, and 3, respectively. The small horizontal line shows the location of the $\nu_{\max}$ frequency. Figure taken from S10.

effects. These later are, for instance, the turbulence (Straka et al. 2006) (up to 5 μHz, from $\nu_{\max}$ to higher frequencies). Moreover microscopic diffusion might also contribute to such surface effects (Thoul & Montalbán 2007; Théado et al. 2005) which are of the order of a few μHz.

In addition, other wisely used diagnostic tools based on frequency combinations in asymptotic regime are also altered, so their use, and more importantly the physical conclusions obtained with them must be considered with care (see Sect. 2 of S10).

4 Conclusions

The main conclusion of the present work is that rotation should be considered as one of the so-called surface effects because their effects on the oscillation spectrum of solar-like stars are of the order or even larger than other physical effects considered to explain such discrepancies between predicted and observed frequencies in the high-order frequency domain. As a consequence, this also indicates that the Sun asteroseismic standard model should be revised. In general, rotation effects, particularly structure distortion due to the centrifugal force must be taken into account for a proper analysis and interpretation of the Sun and solar-like stars, even if their rotational velocity is small. This result might also be important for asteroseismic studies aiming at characterizing with high accuracy the exo-planetary systems around solar-like stars (see García et al. 2011; Chaplin et al. 2010b; Metcalfe et al. 2010; Stello et al. 2009, as examples of studies based on Kepler data).

JCS acknowledges support from the “Instituto de Astrofísica de Andalucía (CSIC)” by an “Excellence Project post-doctoral fellowship” financed by the Spanish “Conjerería de Innovación, Ciencia y Empresa de la Junta de Andalucía” under project “FQM4156-2008”. JCS also acknowledges support by the Spanish “Plan Nacional del Espacio” under project ESP2007-65480-C02-01, and financial support from CNES. DRR acknowledges support from the CNES through a post-doctoral fellowship.

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