# 149. Gravito-inertial asteroseismology

In essay #51, I gave some background to asteroseismology (the science of stellar oscillations), concentrating on its importance in providing, through modelling, some of the most basic stellar properties, notably masses, radii, and luminosities. And I focussed on Gaia's pivotal role in assessing the fidelity of the underlying asteroseismic models, through a comparison of their inferred 'asteroseismic distances' (from their luminosities) with those derived from Gaia's high-accuracy astrometry. I also looked at the distribution of main-sequence non-radial pulsators in the HR diagram in essay #148.

With the purpose of these essays being to survey the many areas of astronomy that Gaia is contributing to, but also to serve as a didactic introduction to the many aspects of Gaia's broad scientific panorama, I will continue my consideration of various aspects of asteroseismology, and look at how Gaia is extending some of studies opened up by the space mission CoRoT, and dramatically advanced by NASA's Kepler and most recently TESS.

Specifically, I will look at some aspects of what is grandly termed 'gravito-inertial asteroseismology'.

I don't know when the term 'gravito-inertial' was first applied in this field (certainly in the 1990s if not before), but it simply refers the study of gravity modes (g-modes) in rotating (intermediate-mass) stars. Such modes are, in consequence, subject to both a Coriolis term, as well as the normal buoyancy, as restoring forces.

Stellar rotation brings further complexity in the underlying patterns of asteroseismic oscillations. These, in turn, provide deeper insight into internal stellar structure. Theoretical models have been confronted with the high-cadence Kepler space photometry. And the main point that I will underline here is the recent finding that Gaia's photometric time-series, while temporally rather sparse, and now validated by the Kepler results, are providing their own valuable contributions to this field.

Today, asteroseismology has a vast literature. ADS returns more than 2000 refereed papers, since 2000, which mention asteroseismology in the abstract. So my scope in this essay is, evidently, duly restricted.

Until the 1950s, periodic variability was attributed to *radial* pulsations, in which the plasma throughout the star oscillates with some specific 'fundamental' frequency, or in various overtones thereof, with all points at a given radius oscillating in phase. This accounted for the variability of several classes of stars, such as the RR Lyrae and the classical Cepheids.

But the discovery of higher frequency periods were difficult to reconcile with radial pulsations alone. Ledoux (1951) demonstrated that *non-radial* oscillations of a rotating star could explain the complex variability of the bright long-period (50-hr) variable $\beta$ CMa, and in particular the proximate oscillation periods, and the phase relations between the observed spectral line broadening and the measured radial velocity.

Subsequent studies showed that non-radial oscillations occur across the HR diagram, ranging from the Cepheid and $\delta$ Scuti stars, to the DA white dwarfs, and to the Sun itself (e.g. Unno et al., 1989). The discovery of the 'five-minute' solar oscillations (Leighton et al., 1962) led to the emergence of the field of helioseismology, in which non-radial pulsations have been used to infer physical properties throughout the Sun's interior.

Osaki (1971) demonstrated that non-radial pulsations will also introduce periodic changes in spectral line profiles: in equivalent widths, depths and asymmetries.

With that by way of a short historical background, I will not try to summarise the explosion of the field since, nor venture into the complex and imperfectly understood excitation mechanisms, some combination of the $\kappa$ mechanism, differential rotation, and convection.

Described by spherical harmonics, non-radial pulsations (and their velocities) are characterised by their frequency and three (quantum) numbers: the radial order $n$ (the number of nodes between the star's centre and surface), the azimuthal order $m$ (where $2m$ is the number of longitudinal nodes), and the non-radial degree $l$ (specifying the number of nodal lines in planes parallel to the equator). Illustrative animations are given, amongst others, by the Whole Earth Telescope.

The rest of this essay gives some highlights of a recent study by Aerts et al. (2023), who looked at the properties of the 15 062 gravity-mode pulsators classified in Gaia Data Release 3 (De Ridder et al., 2023).

Their study started by independently verifying the classification of the g-mode variables made as part of the DR3 data release, then comparing the observational properties from Gaia with those from Kepler for those stars observed by both, and finally using the resulting metrics to validate the much larger sample of g-mode pulsators, and their astrophysical properties, on the basis of the Gaia data alone.

More specifically, they started with the g-mode pulsators assigned to the classes of Slowly Pulsating B stars (SPB stars) and $\gamma$ Doradus stars (De Ridder et al., 2023). Let me recall here (see essay #148) that these are main-sequence dwarfs with masses in the range $1.3-9M_\odot$, with convective hydrogen-burning cores, and whose internal (differential) rotation properties can be determined from their complex g-mode oscillations.

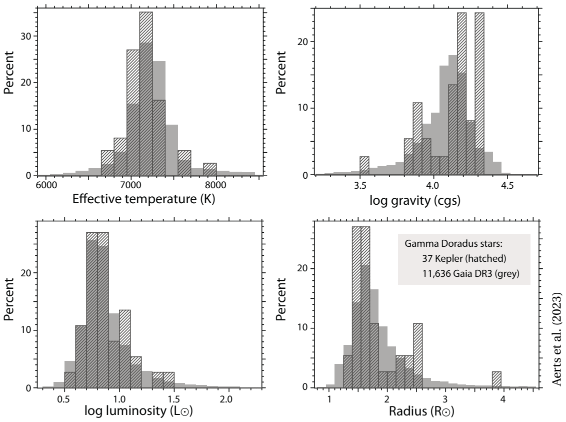
One important finding from that earlier study was that many of the Gaia g-mode pulsators occur *outside* the 'standard' borders of the instability strips for these two classes – a finding ascribed to some combination of inaccuracies in the Gaia effective temperatures, their rapid rotation, incomplete input physics (such as heavy element opacities), or binary-driven instabilities.

For those pulsators whose luminosity ($\log L$), effective temperature ($T_{\rm eff}$), and gravity ($\log g$) were determined (and given in the table `GSP-Phot`) by Coordination Unit 8 of the Gaia Data Processing Analysis Consortium (DPAC), their properties were compared with those of the 63 *bona fide* g-mode pulsators (37 $\gamma$ Dor and 26 SPB) observed with Kepler and follow-up spectroscopy (Mombarg et al. 2021; Pedersen et al. 2021).

In particular for the g-mode pulsators for which an estimate of the spectral line broadening is available from Gaia's Radial Velocity Spectrometer data (RVS, Creevey et al. 2023; Frémat et al. 2023), they could test for any connection between the properties of the dominant g-mode of the stars (the only mode available from Gaia at this stage of the data processing) and their rotation and/or spectral line broadening. Such studies have been previously hampered by the small sample sizes, or inhomogeneous photometric and spectroscopic data.

Following some re-classification of the Gaia DR3 SPB stars to the $\gamma$ Dor class (based on their $T_{\rm eff}$), resulted in a sample of 15 062 g-mode pulsators, of which 11 636 are $\gamma$ Dor, and 3426 are SPB. In other words, a major increase over the 37 $\gamma$ Dor and 26 SPB sample from Kepler.

The Gaia and Kepler distributions of effective temperature, luminosity, and radii agree extremely well for the 11 636 $\gamma$ Dor pulsators, although with gravities somewhat lower than the asteroseismic values (see figure).



The interpretation was a little more involved for the SPB pulsators, due to the fact that the Gaia sample covers mainly the cooler and less massive class members.

It is also worth emphasising that the accuracy of the *dominant* frequency determined from the Gaia data is presently limited by the current DR3 temporal coverage, but nonetheless it is broadly consistent with the much denser Kepler sampling, and with the detection of g-mode frequencies with an amplitude in the Gaia time series $\gtrsim 4$ mmag.

Line-profile variations caused by the g-modes of $\gamma$ Dor and SPB stars occur at the level of several to tens of km s$^{-1}$ (e.g. De Cat et al., 2006), with some of this knowledge actually gained from spectroscopic follow-up on the $\gamma$ Dor stars discovered with Hipparcos (Mathias et al., 2004). In practice, high-resolution multi-epoch spectroscopy is required to distinguish these variations from rotational broadening alone. But in principle this offers a powerful tool for identifying the spherical wavenumbers ($l$, $m$) of the dominant oscillations.

Aerts et al. (2023) found that the (DPAC DR3 RVS) quantity `vsini_esphs` provides a good estimate of the time-independent spectral line broadening, reflecting the fact that the surface rotation of the stars in their samples is the dominant broadening mechanism. At the same time, a regression analysis demonstrated that the dominant g-mode frequency is also a significant predictor of the Gaia DR3 `vbroad` parameter and its standard deviation (Frémat et al., 2023).

While Gaia was not optimised for asteroseismology, it is contributing substantially to the field: through its accurate trigonometric distances for comparison with asteroseismic models; through the provision of significant variability type classification and the object placement in the HR diagram; by discovering significant numbers of new pulsators along with their mode identification; and, from the RVS spectra, insights into the various line-broadening mechanisms.