148. Non-radial pulsators

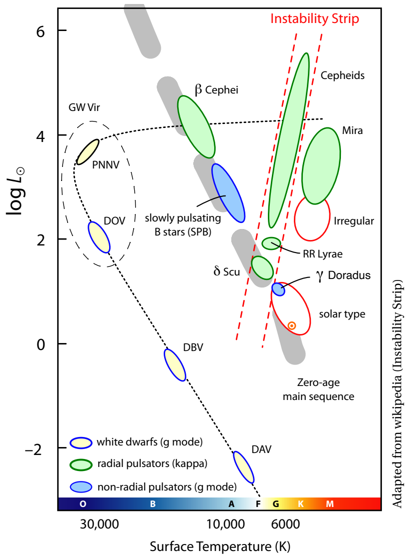
I have discussed the variability of Gaia stars in several essays, focusing on Cepheids (#43), on RR Lyrae (#45), their detection and classification (#61), their distribution across the Hertzsprung–Russell diagram (#62), and in the context of citizen science (#132). Here I want to look another specific aspect (amongst many possible topics!): non-radial pulsators on the main sequence.

Firstly, for some context. Variable stars cover a large range of phenomena. At the top level, we must distinguish between intrinsic variables (where the luminosity of the star itself changes with time), and extrinsic variables (in which *apparent* variability occurs for example due to eclipsing binary companions or rotating structural features such as sunspots).

Intrinsic variables include eruptive variables and flare stars, as well as explosive variables including novae, dwarf novae, and the most explosive supernovae. There are also numerous pulsating types, some of which are especially important because of their application to distance measurements. Pulsating as the result of the so-called 'κ mechanism', they change in brightness as they cyclically expand, and then contract, on periods ranging from days to weeks or months. The expansion phase is due to the blocking of the outflow of energy by gas with a high opacity, with expansion eventually halting as the density decreases, then reversing due to gravity.

In this class (coloured green in the figure opposite) are the Cepheids, RR Lyrae, and δ Scuti (and the related SX Phoenicis and rapidly oscillating Ap, or RoAp, stars), along with the Mira and β Cephei variables.

The opacity source driving the amplitude variations differs amongst these pulsating sources. Falling in the so-called 'instability strip' are the δ Scuti (and SX Phoe and RoAp) on the main sequence, the RR Lyrae at the intersection with the horizontal branch, and the highest luminosity Cepheids at the intersection with the supergiants. All these are driven by the changing opacity of He III. Mira variables are controlled by ionised hydrogen (H II), and the more massive β Cep (unrelated to Cepheids) driven by changing iron opacity.



Adapted from wikipedia (Instability Strip)

As a result, these pulsating stars vary over very different timescales, with very different amplitudes (extending up to many magnitudes), and sometimes along with multiple frequency (harmonic) components.

Also on the main sequence are the γ Dor variables, and the slowly-pulsating B (SPB) stars, both of which are driven by non-radial gravity-mode (g-mode) pulsations, for which the shape rather than the radius changes.

White dwarfs are also found to be pulsating over a range of temperature and luminosity, grouped into three regions, and also mainly driven by low-degree ($l \leq 2$) non-radial g-modes. They are excited by opacity variations in the relevant dominant species, viz. the DAV (or ZZ Cet) stars dominated by hydrogen, the DBV dominated by helium, and the DOV and PNNV (together known as GW Vir variables) dominated by He/C/O (e.g. Córsico et al., 2022).

There are a number of very interesting results coming from Gaia on the δ Scuti and β Cephei variables, but I will concentrate in the following on some new insights being gathered on the (non-radial g-mode) pulsators in the SPB and γ Dor classes.

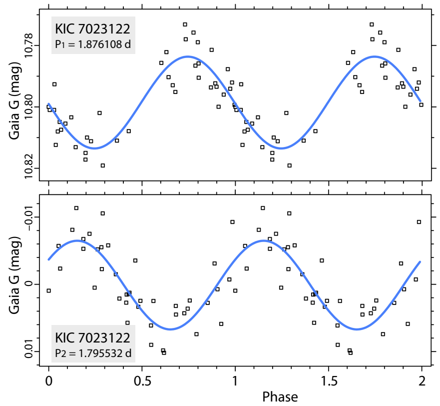
On the main sequence, the intermediate- and high-mass ($M \gtrsim 1.3 M_\odot$, spectral types O, B, A, and F) β Cep, SPB, δ Scuti and γ Dor variables, all possess convective cores, whose physical conditions cannot be extrapolated from those of dwarf stars like the Sun.

And while stellar structure theory broadly predicts the occurrence of pulsation modes in these stars (e.g. Dupret et al., 2005; Burssens et al., 2020), a better understanding of their interiors has been limited by their small numbers, the even smaller number for which asteroseismology, the most important tool for investigating their internal physics (e.g. Aerts, 2021), has been obtained, and the complexity of the theoretical models required for their more complete understanding.

To give a flavour for the theoretical complexity, the short-period δ Scuti stars (0.5–6 hr) are more precisely described by low-order p- and g-modes (pressure/gravity), with the former being mainly driven by the κ mechanism in the He II partial ionisation zone, but supplemented by the so-called γ mechanism, related to the details of heat flow during the compression phase.

While the longer period γ Dor stars (0.4–3 d) correspond to pulsations in non-radial (and often high-order) g-modes, their driving mechanism is less well understood, and has been partly explained by a convective 'flux blocking' mechanism at the base of their convective envelope. To make matters more complex, such theoretical models predict the possible occurrence of simultaneous δ Scuti p-modes and γ Dor g-mode oscillations for the same stellar model (Dupret et al., 2005).

Given the importance of asteroseismology for their modelling, the fact that these objects are often multi-periodic, with low amplitudes, makes them generally difficult to analyse with sparse time series. However, Gaia's accurate multi-epoch photometry, along with the global astrophysical parameters (notably from the Gaia DR3 GSP–Phot tables) allows them to be detected in large numbers, and accurately located in the Hertzsprung–Russell diagram. One such Gaia observation series, from De Ridder et al., 2023, is shown here.

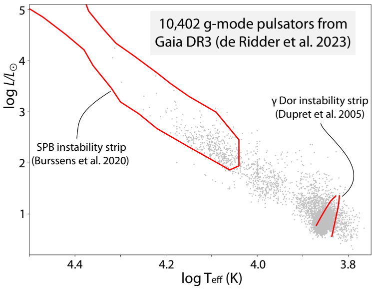


A γ Dor pulsator and its two g-mode frequencies from Gaia

de Ridder et al. (2023)

Starting with the 450 605 variable sources in DR3 classified by Rimoldini et al. (2023), De Ridder et al., 2023 identified the dominant oscillation mode in 100 000 intermediate- and high-mass dwarfs, including 10 402 non-radial pulsators of the SPB and γ Dor classes.

Their precise location in the Hertzsprung–Russell diagram, enabled by the accurate Gaia distances, shows that they occupy a much more extended region of the main sequence as compared with the suggested boundaries of the SPB instability strip by Burssens et al. (2020), and of the γ Dor instability strip by Dupret et al. (2005).



de Ridder et al. (2023)

To be clear, the precise borders depend on the physics of internal rotation, gravitational settling, radiative levitation, shear mixing, and others. Nonetheless their study shows that the instability strips cover broader regions of the HR diagram than has been predicted theoretically, in particular between the SPB and δ Scuti groups, and beyond the γ Dor. These pulsators typically have a dominant frequency corresponding to those for fast rotators pulsating in 'gravito-inertial' modes (Salmon et al. 2014; Saio et al. 2017; Saio et al. 2017; Aerts et al. 2023).

They also quantified the effect of increased stellar rotation on the oscillation amplitudes. The $v \sin i$ data (from the Gaia DR3 ESP–HS spectroscopic tables) resulted in a dependency of 46 μmag per km s^{-1}.

The Gaia time-series photometry is still subject to instrumental variations not yet fully calibrated. Improvements, and longer time series, will allow more rigorous object classification, better placement in the HR diagram, and more robust identification of frequencies and amplitudes of secondary pulsation modes, all leading to improved ingredients for theoretical modelling.

Gravito-inertial asteroseismology has the capability of providing high-precision masses, radii, and ages, although with only a couple of dozen objects modelled in this way to date. Subsequent investigation of these g-mode pulsators has confirmed that Gaia has a role in asteroseismology (Aerts et al., 2023). And as they conclude: *'While the Gaia mission was not designed to detect non-radial oscillation modes, its multitude of data and homogeneous data treatment allow us to identify a vast number of new gravity-mode pulsators that have fundamental parameters and dominant mode properties in agreement with those of such Kepler bona fide pulsators'.*