158. Radial velocity time-series of LPVs

GAIA DATA RELEASE 3 was issued in June 2022, and the next major release, DR4, is not scheduled until 2025. But on 10 October 2023, the Gaia Data Processing and Analysis Consortium (DPAC) published five papers forming part of a special 'Focused Product Release'. The first, which I looked at in essay 157, relates to many new Gaia sources in the globular cluster ω Cen.

The second, considered here, involves the application of Gaia's own radial velocity *time-series* measurements to the class of long-period variables (LPVs). The associated study, by Trabucchi et al. (2023), gives some first insights into how the full radial velocity time-series (in contrast with a single mean value) complements the availability of Gaia's time-series *photometry* in characterising this broad and important class of variable star.

AS USUAL, some context. Gaia's epoch *photometry* is in three broad wavelength bands (G, BP and RP). It yields some 70 high-accuracy photometric data points (focal-plane passages) over 5 years, albeit at (non-uniform) epochs dictated by the deterministic scanning law; with more at intermediate ecliptic latitudes, but fewer at higher and lower latitudes. These data have proven immensely powerful in confirming and/or discovering, and characterising, huge numbers of variable stars of all types, both intrinsic and extrinsic.

Specifically Gaia DR3, based on the first 34 months of data, includes nearly 10 million variables (essay 76). Supervised machine learning has classified the photometric time-series into 24 variability classes, amongst them 15 000 Cepheids, 270 000 RR Lyrae, nearly 500 000 rotational variables, more than 2 million eclipsing binaries, and more than 1.7 million long-period variables.

LPVs are intrinsic variables with periods range from days to 1000 days or more, embracing pulsating red giants and supergiants, including Mira variables, as well as semi-regular variables generally pulsating in an overtone. Also included by virtue of their similar light curves are some binary systems, including the 'ellipsoidal variables' (ELL) in which the variability originates from the body's gravitationally distorted shape (essays 79, 133).

WHILE MULTI-EPOCH radial velocity observations are acquired by Gaia's radial velocity spectrometer (RVS) for all sufficiently bright sources, $G_{\rm RVS} \lesssim 16$ (essay 86), and quasi-simultaneously with the epoch photometry, only *mean* values have generally been made available so far in DR3. An exception is for the Cepheids (Ripepi et al., 2023) and RR Lyrae (Clementini et al., 2023) variables, for which the radial velocity time series were included as part of the Gaia DR3 release.

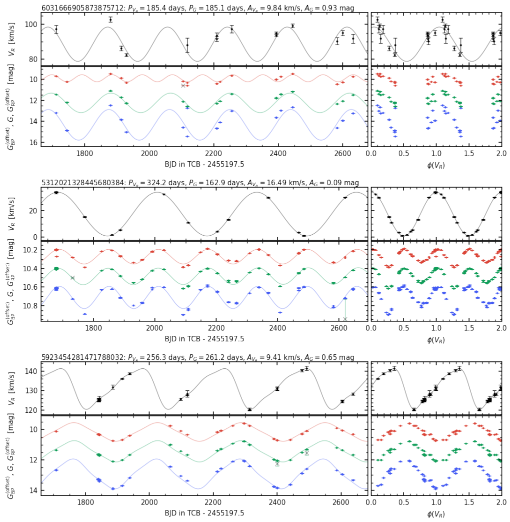
Anticipating the publication of full multi-epoch radial-velocity data with Data Release 4 in 2025, the 'Focused Product Release' described by Trabucchi et al. (2023) provides the radial-velocity time series (and derived variability parameters) for 9614 long-period variables with high-quality observations in the range $G = 6 - 14$ mag, critically selected from the 1.7 million LPV candidates identified in Gaia DR3 (Lebzelter et al., 2023).

Amongst these are their 'top-quality subsample' of 6093 stars whose radial-velocity periods are fully consistent with the values derived from the G, BP, and RP photometric time series. The radial-velocity time series have an average of 24 measurements per source (but ranging between 12–90), non-uniformally over the 34-month span of the DR3 catalogue observations.

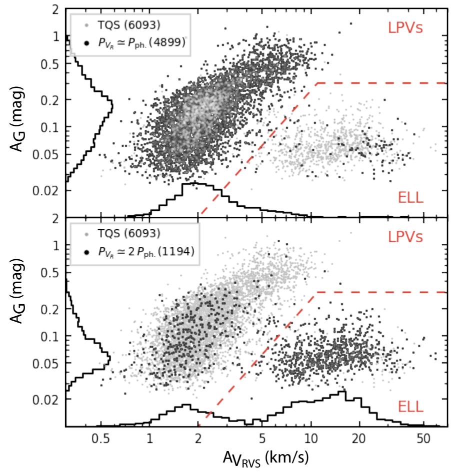
Three examples are shown in the following figure: in each, the radial velocity time-series (in black) is acquired simultaneously with the photometric time series in BP (blue), G (green), and RP (red), each suitably offset, and shown phase-folded in the right panels. The three examples show, top to bottom: a source showing a 'mixed consistency' between the radial velocity and photometric time series (see below); a (binary) ellipsoidal variable; and a more classical pulsating long-period variable.

The detailed analysis of Trabucchi et al. (2023) shows that the majority, 88%, are genuine long-period variables. The other 12% are mainly ellipsoidal binaries.

Quality checks against radial velocities available in the literature show excellent agreement, based on 89 matches with sources from APOGEE, 167 from GALAH, and 1226 from RAVE (of which 60, 119, and 784, respectively, are in their 'top-quality sample').



Trabucchi et al. (2023)



Trabucchi et al. (2023)

THE SIMULTANEITY of Gaia's radial velocity and photometric time series assists with various challenges associated with the identification, classification, and physical interpretation of long-period variables.

As one example, since the periods of long-period variables extend to several hundred days, obtaining velocity curves at high resolution with a good phase coverage has been an observational challenge, and the total sample of well-observed Mira variables still numbers only a few tens of objects. Over wide ranges of period and metallicity, these suggest a consistent pattern in the velocity variations, with s-shaped velocity curves in the near-infrared, and velocity amplitudes of 20–30 km s^{-1}.

Radial velocities are particularly important for ellipsoidal variables, viz. close binaries typically comprising a red giant and a main sequence star. Despite the absence of eclipses, the gravitationally induced elongation of the red giant leads to rotational brightness variations (essay 133). In turn, this generally results in a different period for the system's photometric variability compared with the orbital period from the radial velocities. The pre-Gaia compilation of radial velocities accompanying the detailed photometric monitoring of objects by the MACHO and OGLE projects counts just 81 objects in the Large Magellanic Cloud (Nie & Wood, 2014).

AS Trabucchi et al. (2023) demonstrate, the distinction between the ellipsoidal and long-period variables can be made more robustly than by simply comparing the ratio between the radial velocity and photometric periods. As shown in the figure below (their Figure 10), the diagram of photometric amplitude, $A_{\rm G}$, versus radial velocity amplitude, $A_{\rm RVS}$, delineates one region populated by smaller $A_{\rm G}$ and larger $A_{\rm RVS}$ which characterises the ellipsoidal variables (ELL), and a distinct region defined by larger $A_{\rm G}$ and smaller $A_{\rm RVS}$ which characterises the pulsating long-period variables (LPV).

For the pulsating long-period variables, the photometric variability amplitude increases with pulsation period. But a second grouping is characterised by long periods and comparatively small *G*-band amplitudes. The current consensus seems to be that these sources are also pulsating long-period variables, but where the dominant period identified by the variability processing pipeline is probably a long *secondary* period (LSP).

Nevertheless, their adopted classification is broadly consistent with the ratios of radial velocity to photometric periods. Among sources in their 'top-quality sample' (TQS), 89% of those identified as ellipsoidal variables show the expected 2:1 ratio between their radial velocity and photometric periods, while around 86% and 96% of the long-period variable candidates showing respectively pulsation or 'long secondary period' variability are more consistent with a 1:1 ratio.

THE PUBLICATION OF the radial-velocity time series for almost 10 000 long-period variables constitutes by far the largest such database now available. And many more will follow with Gaia DR4! As Trabucchi et al. (2023) stress, the high-quality time-series data of this 'Focused Product Release' will also serve a valuable role in providing the community with a means of preparing for the far more extensive time series content of DR4.

In the early days of the technical studies for Gaia, one of my tasks was to underline to ESA's advisory committees and decision-making bodies the importance of contempraneous multi-epoch multi-colour photometry, and the even greater challenge of making simultaneous multi-epoch radial velocity measurements.

The scientific case for doing so was strong (see essay 86), as was the resistance to making observations from space that could, even if only in principle, be made from the ground. It is thus gratifying to read in Trabucchi et al. (2023), the statement that *'The availability of simultaneous photometric measurements gives a unique added value to the Gaia catalogue'.*