230. The Oosterhoff dichotomy

THE OOSTERHOFF dichotomy is a long-standing problem in the understanding of Galactic globular clusters. It refers to the observational fact that they divide into two distinct groups according to the average period of their RR Lyrae stars pulsating in the fundamental mode (RR ab), $<P_{ab}>$. There is a gap between the two mean periods, of about 0.55 days and 0.65 days, referred to as the Oosterhoff gap, which divides systems into the classes Oosterhoff I and II (Oo I and Oo II) respectively.

Oosterhoff (1939) offered no explanation, although he concluded that *'Globular clusters seem to hide many secrets, which probably may be at least partly uncovered when more accurate data about the variable stars will be obtained.'* More than a century later, this particular secret has at last been 'partly uncovered' by Gaia.

IT IS USEFUL to start this story a decade or two before Oosterhoff's work, with Solon Bailey of the Harvard College Observatory. His extensive studies of variable stars in globular clusters are at the origin of the nomenclature used to classify RR Lyrae variables (Bailey, 1902; Bailey et al., 1919). He divided these so-called 'cluster variables' into four classes (a–d), of which classes a and b are usually grouped together as RR Lyrae ab. These are the most common, comprising 90% of all RR Lyrae, pulsating in the fundamental mode, and displaying the characteristic steeply rising asymmetric light curve.

And, today, his widely-used period–amplitude diagrams are referred to as 'Bailey diagrams'. Two examples, from Smith et al. (2011), are shown over: the first illustrates the separation between the RR Lyrae ab and RR Lyrae c variables in M15 (this is *not* the Oosterhoff gap!). The second shows the Oosterhoff gap, evident in the plot of the mean period of RR ab stars versus [Fe/H] for Galactic globular clusters (two unusual clusters, NGC 6388 and NGC 6441, are labeled as Oo III).

Numerous studies since have tried to explain the Oosterhoff gap. While there is now a consensus that it is correlated with the cluster's metallicity, with the more metal-poor (Oo II) having larger mean periods (Castellani et al., 2003), an explanation remains elusive.

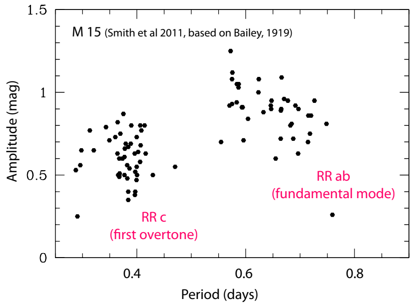
WITH REFERENCE to some recent overviews of its historical development (e.g., Fabrizio et al., 2021; Luongo et al., 2024), I will pick out just a few milestones.

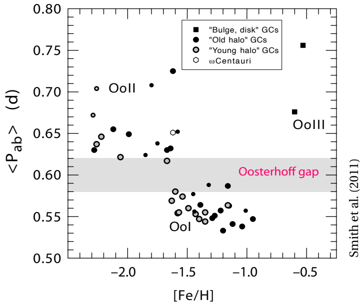
In an early study, van Albada & Baker (1973) suggested that the dichotomy was related to the transition between pulsation modes: between the blue edge of the fundamental mode and the red edge of the first overtone mode, RR Lyrae stars can pulsate in both modes, sometimes simultaneously as double pulsators (and confirmed theoretically by Bono et al., 1997). In this case, the Oo I pulsators would extend to higher temperature, and hence with a shorter average pulsation period.

Sandage (1981) proposed that it stemmed from a higher luminosity of Oo II RR Lyrae ab stars at a fixed temperature (and assuming similar mass), resulting in longer pulsation periods. Since a significant He enrichment is needed to justify the assumed Oo II overluminosity, this explanation would imply an anticorrelation between metallicity and helium, since Oo II clusters are generally more metal-poor. Later evidence has argued against a strong dependence of the RR Lyrae luminosity on metal content (Castellani et al., 2003).

Pre-Gaia studies of the Oosterhoff dichotomy have also been focussed on specific populations, for example in the Large Magellanic Cloud (Bono et al., 1994), in the Boötes dwarf spheroidal galaxy (Siegel, 2006), in Andromeda (Contreras Ramos et al., 2013), in the Galaxy halo (Carney et al., 1991; Abbas, 2014), and most recently in the central bulge region using data from OGLE and Vista (Prudil et al., 2019a; Prudil et al., 2019b).

AROUND 20 YEARS AGO came prescient hints that the dichotomy may hold a key to understanding the formation history of the halo (Catelan, 2004). The argument runs as follows (Catelan, 2009): while the Galactic halo shows a sharp division between Oo I and Oo II types (with very few clusters with mean RR Lyrae ab pulsation periods in the range 0.58–0.62 days), the dwarf spheroidal satellite galaxies of the Milky Way, as well as their respective globular clusters, actually fall preferentially within the Oosterhoff gap (e.g. Siegel, 2006).





With growing evidence that the Galactic halo has been built up from the accretion of smaller protogalactic fragments, not unlike the present-day Milky Way dSph satellite galaxies, then the present-day halo should not, Catelan argued, display the Oosterhoff dichotomy. Therefore, he concluded, the Galactic halo cannot have been assembled by the accretion of dwarf galaxies resembling the present-day Milky Way satellites.

SUMMARISING THE status of the Oosterhoff dichotomy at the start of the Gaia era, Fabrizio et al. (2019) argued that further progress required accurate and homogeneous metal abundances across the full range of known RR Lyrae variables. Accordingly, they derived iron abundances for 2382 fundamental-mode pulsators from SDSS–SEGUE, and distances from Gaia DR2. Their resulting Bailey diagram shows a steady variation from the metal-poor, [Fe/H] = –3.0/–2.5, to the metal-rich, [Fe/H] = –0.5/0.0, regime. They argued that the smooth transition as a function of metallicity indicates that the Oosterhoff dichotomy among Galactic globular clusters is the consequence of the lack of intermediate metallicity clusters hosting RR Lyrae variables.

Further insights came from a study of 3653 RR Lyrae stars (2661 RRab, 992 RRc) by Zhang et al. (2023), based on metallicities from SDSS and LAMOST, and full positions and space velocities from Gaia EDR3. From their locations in the Bailey diagram, they found that the Oo I RR Lyrae stars are more metal-rich, with radially dominated orbits and large eccentricities, while Oo II RRLs are more metal-poor, and have only mildly radially dominated orbits. They found that the Oosterhoff dichotomy of the Milky Way's halo is more apparent for the inner-halo region than for the outer parts.

Including the halos of the Milky Way's two largest satellites, the LMC/SMC, they found that the Oosterhoff dichotomy varies with Galactic location, and from galaxy to galaxy. They concluded that it results from a combination of stellar *and* Galactic evolution.

THE PICTURE was consolidated by Prudil & Arellano Ferro (2024), in work also based on Gaia EDR3. They found that the Oosterhoff gap, in the $< P_{ab} >$ versus [Fe/H] plane, is mostly populated by globular clusters associated with Milky Way dwarf galaxies, and those with only a small number of fundamental mode RR Lyrae pulsators. Indeed, their only globular clusters lying within the Oosterhoff gap are NGC 6402 (M14) associated with the Kraken/Heracles mergers (Kruijssen et al., 2020; Horta et al., 2021), and NGC 6715 (M54) associated with the Sagittarius merger.

From a catalogue of 2824 RR Lyrae stars in 115 Galactic globular clusters (including 1594 fundamental-mode, 824 first-overtone, and 28 double-mode pulsators), Cruz Reyes et al. (2024) also drew attention to the fact that their sample does not exhibit the Oosterhoff dichotomy.

CURRENT understanding is nicely brought together in the Gaia DR3 study by Luongo et al. (2024). They calculated orbits and integrals of motion for the Galactic globular clusters and field RR Lyrae stars previously attributed to halo streams. The likely origin of the field RR Lyrae (shown below) was matched to their globular cluster $E - L_z$ counterparts. The resulting Bailey diagrams for the inferred *in situ* stars show a wide and continuous range of metallicities, with no sign of the Oosterhoff dichotomy. The accreted halo RR Lyrae stars, in contrast, clearly show a much smaller metallicity dispersion, and a clear Oosterhoff gap.

Although they did not isolate the cause of the Oosterhoff dichotomy, they conclude that it was 'imported' into the Milky Way by these ancient mergers. It represents an important advance in our understanding of its origin. It is, I think, difficult to imagine this progress in the absence of Gaia's astrometry, and its deep insights into the phase-space structure of our Galaxy's halo.