185. Mira variables

As evolved stars cool and expand on the red giant or asymptotic giant branch (AGB), they become pulsationally unstable. Such stars are classified, according to the amplitude and regularity of their light curves, as Mira (M), semi-regular (SR), and irregular (L) variables.

Miras are AGB stars of initial mass $1.5 - 4 M_\odot$, with high mass-loss rates, and high luminosities ($\sim 10^3 L_\odot$) due to their large envelopes. They are characterised (and defined) by large variability (≥ 2.5 mag in V, 0.3–1.0 in K_S), and periods of 100–1000 d. They occupy a key stage of stellar evolution, contribute to the heavy-element enrichment of the interstellar medium and, being luminous, are important tracers of Galactic structure. One of the nearest is Mira itself, at ~90 pc.

I have mentioned them, in passing, in my essays on Galactic tracers (6), the Large Magellanic Cloud (38), discovering variability (61), the Andromeda survey (84), the distance to the Galactic centre (111), the distance scale (122), non-radial pulsators (148), and radial velocity time-series of long-period variables (158).

Here, I will look at some Gaia results regarding their use as distance indicators and probes of Galactic structure. Many other surveys (including ASAS, LAMOST, VISTA and ZTF) are also contributing to new advances.

The chemistry of Mira variables is dominated by either C-rich or O-rich species according to the strength of 'dredge-up' episodes during the asymptotic giant branch phase (essay 167), largely reflecting their initial mass and metallicity (Höfner & Olofsson, 2018).

Both types satisfy their own period–luminosity relations (e.g. Iwanek et al., 2021), with the O-rich relations typically being tighter in the near-infrared due to effects of significant circumstellar dust in the C-rich variables. This makes the O-rich Mira variables particularly useful distance indicators, both within our Galaxy and beyond.

They are contributing to the 'Hubble tension' debate (to reconcile the early Universe expansion rate based on the CMB with the local value derived from Type Ia supernovae in nearby galaxies) as an independent Population I calibrator of the supernova luminosities, currently best served by the classical Cepheids (essay 44).

With a limit of $V \sim 12.5$ mag, Hipparcos observed some 900 long-period variables, including Miras, semi-regular or irregular variables, O-rich, C-rich, and S stars. Hipparcos contributed, for example, to improvements in the period–luminosity relations and to suggestions that the semi-regular variables are Mira progenitors (Bedding & Zijlstra, 1998), to the physics of the dredge-up episodes (Barthès et al., 1999), and whether they are controlled by fundamental or first overtone pulsation modes (van Leeuwen et al., 1997).

The Gaia sample is, of course, vastly larger. In 2018, DR2 provided an all-sky catalogue of 550 737 variable stars (with G, G_{BP}, and G_{RP} photometric time-series), of which 151 761 are long-period variable candidates having $\Delta G > 0.2$ mag, with one-fifth of these considered to be Mira candidates (Mowlavi et al., 2018).

The 34-month DR3 (essay 76) contains 1.72 million long-period variable candidates, including 392 240 with derived periods ranging from 35–1000 d, of which more than 40 000 are identified as Mira variables confirmed by OGLE-IV (Lebzelter et al., 2023). Robin et al. (2012, Table 3.7) actually predicted some 40 000 with $G < 20$ mag, and around 18 000 with $G < 12$ mag.

Segregation into O-rich and C-rich Miras, using the Gaia BP/RP spectra to distinguish the different TiO bandheads, is discussed by Lebzelter et al. (2023, §2.4), Sanders (2023, §2.2), and Zhang & Sanders (2023, Fig. 3).

Let me turn to the use of Mira variables as distance indicators. The period–luminosity relation first established for Galactic Miras (Robertson & Feast, 1981) was soon shown to be much tighter for those in the LMC (Glass & Evans, 1981). Multiple sequences and other refinements were later revealed by the microlensing surveys MACHO and OGLE (Wood et al., 1999; Wood, 2000; Ita et al., 2004; Soszyński et al., 2013 and references).

Parallel work made use of the Hipparcos parallaxes (Whitelock & Feast, 2000). Whitelock et al. (2008) adopted a distance modulus of 18.39 ± 0.05 for the LMC to derive an infrared period–luminosity relation for O-rich Miras of the form $M_K = \rho(\log P - 2.38) + \delta$, with slope $\rho = -3.51 \pm 0.20$, and zero-point $\delta = -7.15 \pm 0.06$.

The Gaia data have been used in several studies to revisit the Mira period–luminosity relation (including dependencies on colour and metallicity), both in our own Galaxy (Sun et al., 2023[DR2]; Sanders, 2023[DR3]), and in the Magellanic Clouds (Bhardwaj et al., 2019[DR2]).

While a complete picture remains unclear, the general findings are that uncertainties in the Galactic period–luminosity relation (e.g. Sanders, 2023, Fig. 5) remain larger than those found in the LMC (Sun et al., 2023) and, using HST–WFC3 infrared data, in M101 (Huang et al., 2024). They may also be steeper at short periods than the LMC relations, perhaps suggesting the existence of population effects (Sanders, 2023).

Nonetheless, using these relations as anchors for Mira variables in other galaxies, Sanders (2023)[DR3] derived $H_0 = 73.7 \pm 4.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ for the Type Ia host galaxy NGC 1559, while Huang et al. (2024)[HST] found $H_0 = 72.37 \pm 2.97\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ for M101. As with recent Cepheid determinations, the Mira results suggest a discrepancy in H_0 between early and late Universe values.

A further, but exploitable, complication is that the pulsation period of Miras is correlated with their scale height and/or velocity dispersion (Feast, 1963). Interpreted as a period–age correlation, this allows them to be used as age indicators within the Galaxy and beyond (Grady et al., 2020). Mira variables in clusters, from Gaia-based membership determinations, confirm this connection (Grady et al., 2019; Marigo et al., 2022). Zhang & Sanders (2023) used 46 107 O-rich Mira candidates from Gaia DR3 to derive a period–age relation (with P in d) $\tau \approx (6.9 \pm 0.3)(1 + \tanh[(330 - P)/(400 \pm 90)])$ Gyr.

Combining these properties, Miras are being used as key probes of Galactic structure and evolution. As stated by Grady et al. (2020): *'Owing to their impressive brightness in the near infrared, we are able to trace the Miras right across the disk and through the bulge'.*

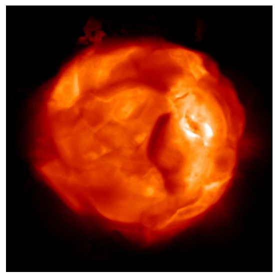
Using 21 149 O-rich Galactic Miras from Gaia DR2, they showed that the morphologies of both disk and bulge evolve as a function of age/chemistry. The disk is 'stubby' at the oldest ages (9–10 Gyr), but becomes thinner and radially extended ('peanut-like') at younger ages, consistent with the 'inside-out' and 'upside-down' formation of the Milky Way disk, and suggesting that the bar formation and buckling took place 8–9 Gyr ago. Similar results were found by Semczuk et al. (2022).

Such studies are starting to provide some profound insights into the formation of our Galaxy's central bar, and the nature of the associated nuclear stellar disk (Sormani et al., 2022) and nuclear star cluster (Neumayer et al., 2020). Sanders et al. (2024) used Miras from VVV, placed on the Gaia reference frame, to elucidate one possibility: that the bar formed ~8 Gyr ago, close to the time of the Gaia–Sausage–Enceladus infall merger, potentially implying that the bar was tidally-induced.

There are, I should stress, theoretical explanations for these correlations: a period–luminosity relation follows from the fact that stars of a given mass, excited by convection, only begin pulsating in the fundamental mode over a narrow range of radii (Trabucchi et al., 2019). That between period and age is traced to the dependency on mass (Trabucchi & Mowlavi, 2022).

But a recurrent topic in the consideration of Mira variables is the finding that the scatter in the Galactic period–luminosity relation is larger than for the Large Magellanic Cloud and, at the same time, that the Gaia parallax standard errors for Miras are often significantly underestimated, by some 30–80%. This has been attributed in part to (presently uncalibrated) time-dependent chromatic displacements. But it is probably compounded by their large physical sizes (e.g. Mira, with $R \sim 400 R_\odot$, subtends ~40 mas). This means that many are resolved by Gaia, resulting in significant photocentric motions due to their large convection cells (Andriantsaralaza et al., 2022; Maíz Apellániz, 2022).

This has been further demonstrated by El-Badry et al. (2021, §5) who invoked the presumably identical parallaxes of some binary companions, and by Andriantsaralaza et al. (2022) who compared Gaia and VLBI parallaxes for a sample with masing circumstellar envelopes, finding significant differences for many.


Chaivassa et al. (2018, Fig 1a)

Models by Chiavassa et al. (2011) already predicted this sort of effect. Chiavassa et al. (2018) used 3D hydrodynamic simulations of convection to construct intensity maps in the Gaia G band (325–1030 nm). Comparison with solar neighbourhood semi-regular variables from Gaia DR2 suggested time-dependent photocentric excursions of 5–10% of the stellar radius, with convection-related variability accounting for a substantial part of the Gaia DR2 parallax error.

This was further confirmed with Gaia EDR3 by Chiavassa et al. (2022) for a sample of red supergiants in the young cluster χ Per (at 2.260 ± 0.020 kpc). An implication, further discussed by Kochanek (2023), is that these inferred photocentric displacements might be used as a probe of the star's surface dynamics. Woodland & Montez (2022) showed that the same phenomenon also affects the interpretation of 'proper motion anomalies' (essay 174) when attempting to identify potential long-period binary companions.

Such considerations are clearly complicating the use of Galactic Mira variables in constructing a robust local distance ladder. The extent to which this continues to be the case with future Gaia releases remains to be seen.