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Ultra-long period cepheids: observations, theory, and use as standard candles

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This paper presents a review of the main properties of ultra-long-period Cepheids (ULPs). The analysis is based on the largest sample of known ULPs, comprising 73 pulsators, including the first ULP discovered in the Milky Way. These intrinsically highly luminous variables can be observed at distances greater than 100 Mpc. They have been hypothesized as the extension of classical Cepheids at higher periods, masses, and luminosities. However, whether this is the case or they constitute a distinct class of pulsators remains to be verified, as well as their suitability as standard candles. If confirmed as reliable distance indicators, they would enable direct measurements of cosmological distances without relying on secondary distance indicators, reducing potential systematic errors in the calibration of the cosmic distance scale. In addition, the potential of the upcoming Rubin LSST survey to enhance the sample with high-quality data is investigated.

KEYWORDS

stars, variable stars, classical cepheids, extragalactic distance scale, survey

1 Introduction

Musella et al. (2021), Musella (2022), and Musella et al. (2024) (hereafter referred to as M21, M22, and M24) investigated ultra-long-period Cepheids (ULPs), first classified by Bird et al. (2009), and then analyzed by Fiorentino et al. (2010) and Fiorentino et al. (2012), to evaluate their potential as stellar standard candles. With light-curve shapes resembling classical Cepheids (CCs), mean luminosities in the range $-9 < M_I < -7$ mag, masses ranging between 13 and 20 $M_{\odot}$, and periods larger than ~80 days, ULPs could represent their high-mass, high-luminosity counterpart. Their brightness makes them ideal for probing cosmological distances directly, especially with next-generation telescopes, thereby minimizing reliance on secondary distance indicators and reducing systematic uncertainties in calibrating the extragalactic distance scale and determining the local H_0. In this context, ULPs could contribute to understanding the well-known Hubble tension (a 5σ discrepancy) existing between the value of the Hubble constant derived from cosmic microwave background investigations (coupled with Λ cold dark matter theory), $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} (Planck Collaboration et al., 2020), and that obtained from the cosmic distance ladder in the local Universe, $H_0 = 74.03 \pm 1.04$ km s^{-1} Mpc^{-1}, mainly based on the geometrical calibration of CC period–luminosity (PL) relation and the subsequent calibration of Type Ia supernovae using CCs (Riess et al., 2022).

This paper reviews the properties of ULPs to assess their reliability as stellar standard candles and understand whether they represent the high-mass, high-luminosity extension of CCs or a different class of pulsators.

2 ULP sample

The sample, which includes all known ULPs collected from the literature, is described in detail in M22 and M24, with reported distances, reddening, and metallicity. It contains the 18 ULPs observed in the galaxies LMC, SMC, NGC 55, NGC 300, NGC 6822, and IZw18 and analyzed by Bird et al. (2009); 7 ULPs in M31 (Ngeow et al., 2015; Kodric et al., 2018; Taneva et al., 2020); 2 in M33 (Pellerin and Macri, 2011); 2 in M81 (Gerke et al., 2011); 1 in NGC 4151 (Yuan et al., 2020); 2 in NGC 6814 (Bentz et al., 2019); and 40 (photometrically homogeneous ULPs) observed in the framework of the SH0ES project (Riess et al., 2011) in the galaxies M101, NGC 1015, NGC 1309, NGC 1448, NGC 2442, NGC 3370, NGC 3972, NGC 3982, NGC 4038, NGC 4258, NGC 4536, NGC 4639, NGC 5584, NGC 7250, and UGC9391 (Riess et al., 2016; Hoffmann et al., 2016), along with the first ULP found in the Milky Way (MW, Soszyński et al., 2024). For all known ULPs in the Magellanic Clouds and M33 and five of the seven pulsators in M31, M24 adopted the new periods and homogeneous photometry published in the Gaia DR3 catalog (Gaia Collaboration and et al., 2023; Ripepi et al., 2023). For one of the two remaining M31 ULPs and the new MW ULP, new periods and Gaia magnitudes were determined based on the light curves from the Gaia Pencil Beam Survey (Evans et al., 2023) and the Gaia DR3 database, respectively. The Gaia magnitudes were transformed into the Johnson V and I magnitudes using the transformations by Pancino et al. (2022).

3 ULPs as distance indicators

To analyze the ULPs as distance indicators and compare their properties to those of CCs, the most useful tool is the period–Wesenheit (PW) relation in the V and I bands ($W(VI) = I - 1.55(V - I)$, Madore, 1982). This relation is a reddening-free formulation of the PL relation that, by adopting an extinction law, combines magnitudes and colors to correct for reddening effects.

In the first paper on the ULPs, Bird et al. (2009) compared their PW with that of LMC CCs from OGLE, finding a flat PW relation, markedly different from that of the CCs. Subsequently, Fiorentino et al. (2012) and Fiorentino et al. (2013), by extending the Bird sample with two ULPs from M81 and 17 ULPs observed by the SH0ES project, did not confirm the previously suggested flat relation. Instead, they found a PW relation in good agreement with that of LMC CCs, though with a larger scatter. Before the publication of the Gaia DR3 catalog, M22 (see their Figures 1, 2) analyzed the Wesenheit magnitudes of the ULP sample described in Section 2 (without the MW ULP) using photometry from the literature. This ULP sample was compared with CCs in the LMC from OGLE (Soszyński et al., 2015) and in NGC 4258 (Riess et al., 2016; Hoffmann et al., 2016). They found that the ULPs exhibit a much larger scatter than the LMC CC sample but a dispersion comparable to that observed in NGC 4258.

Subsequently, M24, using the new and more accurate Gaia photometry (see details in Section 2) and also including the new MW ULP, observed a significantly reduced scatter—particularly at the longest periods—and a better agreement with the PW relation defined by shorter-period CCs (see figure 3 in M24).

Figure 1 presents an updated version of figure 1 in M22, including new data from M24, showing a comparison between the M24 ULP sample and the CCs in the LMC and NGC 4258.

The PW relation computed by M24, including all the ULPs, is $W(VI) = -2.11(\pm 0.49)\log P - 4.98(\pm 0.96)$, with a $\sigma = 0.36$ smaller than that obtained by M22 ($\sigma = 0.42$).

As previously noted in M22, the period range $\log P > 2.15$ is poorly sampled, which can significantly impact the reliability of the slope determination. A more robust result is, therefore, obtained by considering only ULPs with $\log P < 2.15$, for which M24 found $W(VI) = -2.77(\pm 0.76)\log P - 3.69(\pm 1.49)$, with $\sigma = 0.36$, in better agreement with the CC relation (characterized by a slope of -3.314 ± 0.008 and $\sigma = 0.077$, based on 2455 LMC CCs, Soszyński et al., 2015) than the result obtained in M22.

This result also highlights that the improved photometric precision obtained using Gaia photometry reduces the uncertainties in the ULP $W(VI)$ relation, increasing its agreement with that of CCs, and further supports the hypothesis that ULPs are the same type of pulsating variables but in a higher mass and period range.

The larger dispersion still present in the ULP sample, compared to shorter-period CCs, is probably due to residual inhomogeneity in the photometry, blending effects, and limited statistics, particularly at the longest periods. The limited statistics are partly caused by intrinsic factors, such as the significantly shorter crossing time of the instability strip than that of classical Cepheids (the expected crossing times are approximately 2 and 1.2 Myr for a 14 and 20 $M_\odot$ stars, and approximately 10^5 and 10^4 years for 6 and 11 $M_\odot$ stars, respectively). However, the scarcity is also influenced by observational challenges, such as the long time baselines required to detect and characterize long-period variables.

4 ULP evolutionary phase

To investigate the evolutionary phase of ULPs, M22 (see their figure 4) analyzed their distribution in the V_0 *versus* $(V-I)_0$ color–magnitude diagram (CMD), always comparing their positions with those of LMC and NGC 4258 CCs. An updated plot using the new and more accurate Gaia photometry and the new MW ULP from M24 (see details in Section 2) is presented in Figure 2.

In this CMD, the ULPs appear to represent the high mass, high-luminosity extension of CCs, consistently with what is observed in the PW plane. The color distribution is broader than that of the LMC CCs, with the most luminous ULPs exhibiting unexpectedly blue colors. This behavior is significantly less evident when compared to the CCs in NGC 4258. The anomalous position of the M31 ULP H42 (Taneva et al., 2020), previously pointed out by M22, is resolved when adopting Gaia photometry (see M24).

Several potential causes of the ULP larger dispersion compared to CCs were already suggested in the previous section. However, given that the sample includes pulsators from different galaxies, M22 also investigated a potential dependence on metallicity by plotting $\log P$, V_0, and $(V-I)_0$ *versus* the ULP metallicity ($12 + \log(O/H)$); they found that the more metal-poor ULPs tend to have longer periods and appear slightly bluer and brighter than their metal-rich counterparts. This behavior may partly explain the CMD positions of ULPs hosted in galaxies such as SMC, NGC 55, NGC 300, and IZw18. This result is also confirmed when using the new Gaia

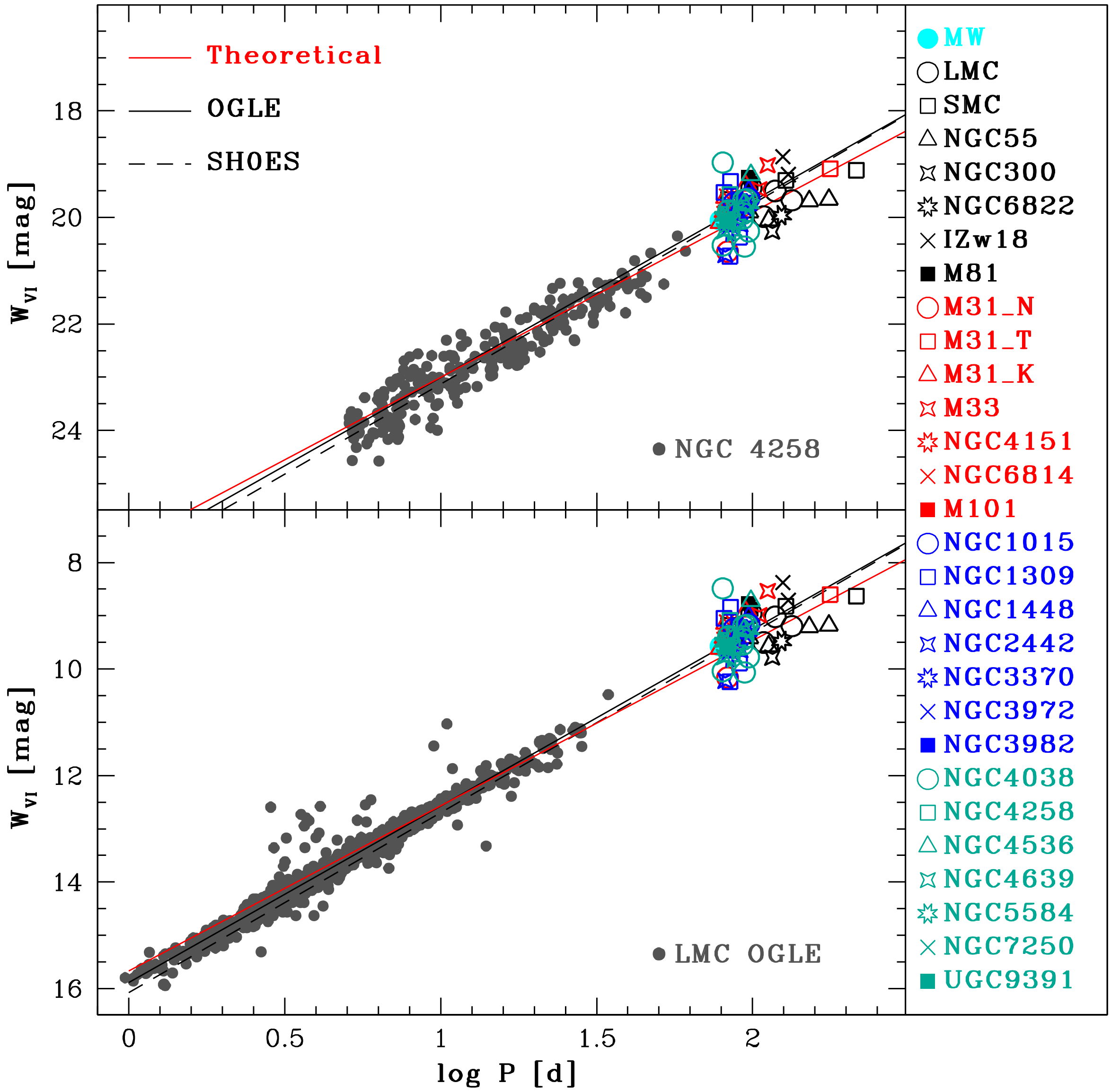

FIGURE 1
W(*VI*) for the M24 ULP sample (see Section 2), compared with CC samples from NGC 4258 (gray dots in the upper panel; Riess et al., 2016; Hoffmann et al., 2016) and LMC OGLE (gray dots in the bottom panel; Soszyński et al., 2015). The black dashed line and the black solid line in the bottom panel represent the *VI* Wesenheit relations obtained by the SH0ES project (Riess et al., 2016) and by Soszyński et al. (2015) for the LMC OGLE CC sample, respectively. The red line represents the theoretical, metallicity-dependent Wesenheit relation for the CCs (W^T_{VI}) obtained by Fiorentino et al. (2007), adopting $Z = 0.01$ (see Section 5 for details). The symbols used for the ULPs are labeled in the figure. This figure is an updated version of figure 1 in M22, including new data from M24.

DR3 magnitudes. No particular trend emerges when considering the SH0ES ULPs or variables with Gaia magnitudes, and both photometrically homogeneous samples span a wide range of colors. Moreover, although the SH0ES sample includes a large number of ULPs, it covers a limited range in period and metallicity, preventing firm conclusions.

It is also worth noting that NGC 4038, a galaxy observed as part of the SH0ES project, hosts nine ULPs, five of which are among the brightest in the CMD. The metallicity of this galaxy has been confirmed to be solar by Lardo et al. (2015). Although these nine ULPs share the same distance and reddening, they nonetheless exhibit a spread of approximately one magnitude in $(V-I)$, with the brightest ones appearing unexpectedly blue.

5 Comparison with theoretical models

Comparisons with theoretical evolutionary and pulsation models may offer deeper insights and potentially explain some of the observed behaviors.

M22, in their figure 6, compared the position of ULPs in the CMD with evolutionary tracks from Bressan et al. (2012), converted to Johnson filters using the bolometric correction by

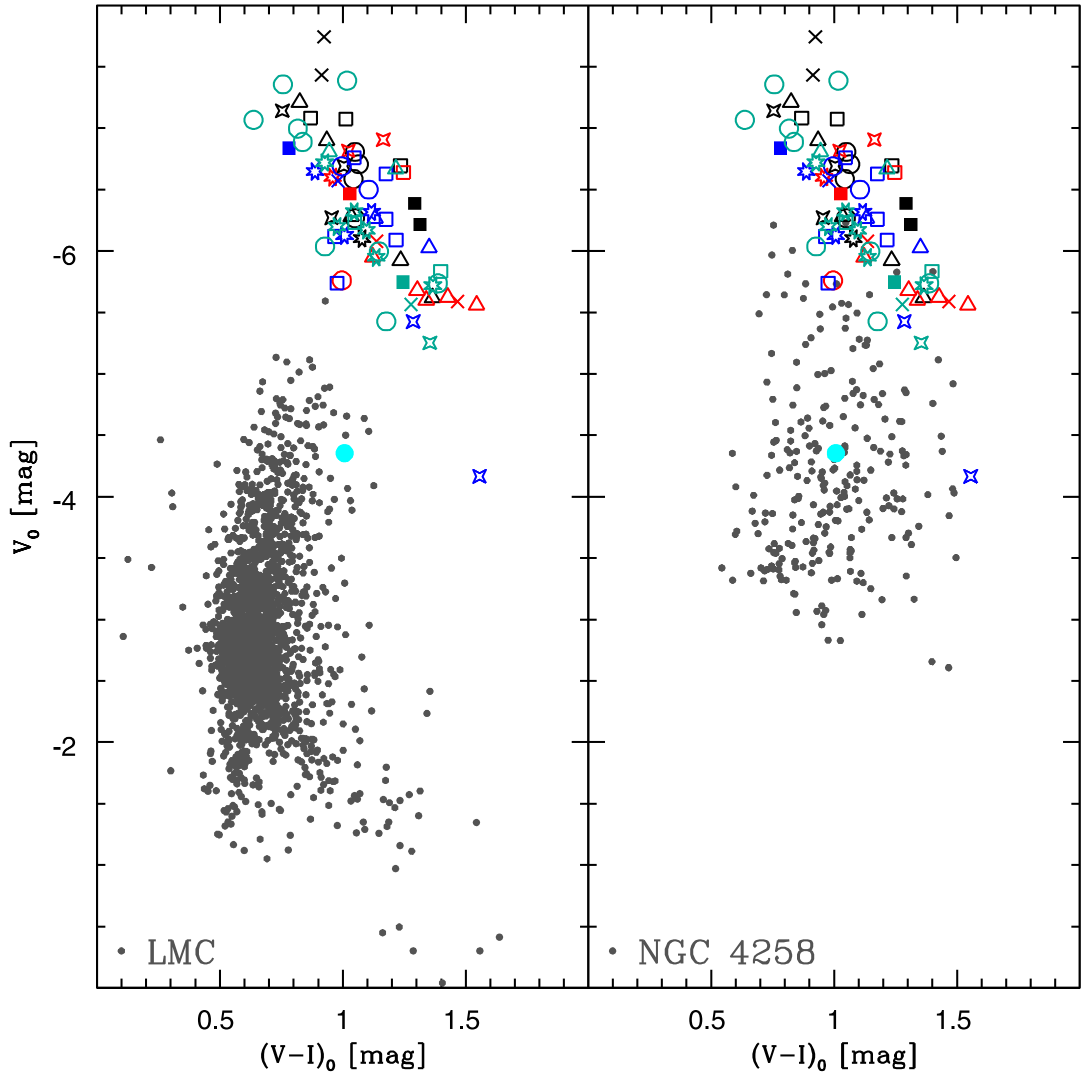

FIGURE 2
V_0 *versus* $(V-I)_0$ CMD for the M24 ULP sample (see Section 2); the left panel compares the ULPs with LMC OGLE CCs (gray dots), while the right panel compares them with CCs in NGC 4258 (gray dots). The symbols for the ULPs are the same as those used in Figure 1. This plot is an updated version of figure 4 from M22, including new data from M24.

Chen et al. (2019). In particular, they considered the tracks for 14 $M_\odot$ and 20 $M_\odot$, which represent the expected mass range for ULPs (Bird et al., 2009; Fiorentino et al., 2012), and four metallicity values ($Z = 0.005$, 0.01, 0.02, 0.03) consistent with those of the known ULPs. At these higher masses, evolutionary models do not predict a blue loop crossing the instability strip, a feature typically observed in CCs. For instance, Bird et al. (2009) suggested that the SMC ULP HV829 ($P = 84.4$ d) could be a second-crossing Cepheid. In addition, based on these tracks, when applying a period–luminosity–color–mass relation (a physical relation), several ULPs yield inconsistent results, such as the M31 ULP 8-1498 (Ngeow et al., 2015), as discussed in M21.

On the other hand, in Figure 1, the red solid line, as in M21 and M22, represents the theoretical, metal-dependent *PW* relation $W^T_{VI} = -2.67 - 3.1\log P + 0.08\log(Z)$ with a $\sigma = 0.11$ mag, derived by Fiorentino et al. (2007) for $Z = 0.01$[1]. This relation shows very good agreement with the observational one obtained for the ULPS (see Section 2 for details) and can also be adopted for these variables. The theoretical relation by Fiorentino et al. (2007) was developed within a framework of nonlinear convective pulsation models, spanning a broad range of stellar masses ($3 \le M \le 13\ M_\odot$) and chemical compositions ($0.0004 \le Z \le 0.04$ and $0.25 \le Y \le 0.33$ (see Fiorentino et al., 2002; Marconi et al., 2005; Marconi et al. 2010, and references therein). A key strength of these models is their ability to predict all pulsational observables (period, amplitude, and light-curve morphology) as functions of the input stellar parameters. On

1 This theoretical metal-dependent Wesenheit relation show a very small variation not larger of 0.04 mag in the metallicity range between 0.01 and 0.03.

this basis, modeling the observed light curves with pulsation models enables the simultaneous determination of individual distances and reddenings and the intrinsic stellar parameters of the pulsating stars (refer to Natale et al., 2008; Marconi et al., 2013; Ragosta et al., 2019).

Unfortunately, current models do not predict the existence of extremely metal-poor pulsators with such long periods, as observed for the two ULPs in IZw18. Moreover, the inconsistencies found for several ULPs among their mass, luminosity, and period prevent the reliable application of this method.

On this basis, the overall agreement between pulsation models and observations appears satisfactory when considering the mean statistical properties of CCs extrapolated to higher luminosities and periods; however, significant issues remain in accurately modeling individual ULPs.

In conclusion, these pulsators currently represent a challenge for both evolutionary and pulsation models, and additional data are needed to increase the number of known ULPs and improve the coverage of the light curves of the already known pulsators and the accuracy and precision of their periods and mean magnitudes.

On this basis, M24 investigated the expected outcomes from the Rubin LSST survey (Ivezić et al., 2019) for ULPs to analyze the possibility of obtaining, in a few years, a statistically significant and photometrically homogeneous sample while also improving the accuracy and precision of periods and mean magnitudes for the already known ULPs in Local Group galaxies.

6 Light curve's recovery of Local Group ULPs with Rubin LSST

In the framework of a project aimed at analyzing the capability of Rubin LSST for the study of various types of pulsating stars in different environments (Di Criscienzo et al., 2023; Di Criscienzo et al., 2024), M24 focused on the possibility of improving and/or increasing the sample of known ULPs through this survey by using the `PulsationStarRecovery` tool (Di Criscienzo et al., 2023). This tool simulates Rubin LSST time series based on a given variable star template, estimating the accuracy of recovering the light curve's period, morphology, mean magnitude, and amplitude as a function of various simulated observing strategies and survey duration. Additional details on how the tool `PulsationStarRecovery` works can be found in Di Criscienzo et al. (2023), Di Criscienzo et al. (2024), and M24.

M24 adopted four theoretical light curves, each defined by distinct stellar parameters (mass, effective temperature, and luminosity) consistent with expectations for ULPs (Fiorentino et al., 2012; Fiorentino et al., 2013, M21, and M22), with pulsation periods ranging from 80 to 120 days. These light curves were generated using the mentioned non-linear convective pulsation models and transformed into the Rubin LSST filters (*ugrizy*) using stellar bolometric corrections provided by Chen et al. (2019).

We have seen that Gaia provides more precise and accurate data for ULPs in the LMC, SMC, M31, and M33. To evaluate the potential of the Rubin LSST survey to extend these results to more distant galaxies within the Local Group, M24 analyzed the recovery of ULP light curves from LSST-simulated time series in the only three galaxies hosting known ULPs and observable from the Vera C. Rubin Observatory: NGC 6822, NGC 300, and NGC 55. The analysis also considered the impact of crowding and blending, considering that CCs and ULPs may be located in densely populated regions.

The main results obtained by M24 are as follows:

- A highly accurate recovery of the input period (errors below 1%–2%) is achievable from the second year of the survey, with negligible dependence on period, sky position, or distance.
- The *u* band is unreliable for accurately determining mean magnitudes and amplitudes.
- Disregarding the effects of crowding, mean magnitudes in the *grizy* bands can be recovered with an error ≤0.1 mag from the second survey year. However, crowding/blending introduces an additional source of uncertainty.
- Amplitude recovery in all bands presents greater uncertainties, especially in the *u* and *g* bands and during the early survey years. These uncertainties are worsened in the presence of blending.
- Preliminary estimates of crowding effects suggest that, despite amplitude reductions due to blending, Rubin LSST will still be capable of detecting new ULPs in the Local Group, particularly in the *gri* bands.
- Blending and crowding cause a shift in the mean magnitudes toward brighter values, with the effect becoming more significant as crowding increases. Therefore, it will be essential to estimate crowding on the real data and conduct artificial star tests, at least in the regions surrounding the ULPs.

The most crucial result is that it will not be necessary to wait for the survey's completion; even the early data releases will provide reliable data that will significantly enhance our theoretical and observational understanding of the use of ULPs as standard candles.

7 Conclusion

This work presents a review of the properties of ULPs to discuss their reliability as standard candles and determine whether they constitute the high-mass, high-luminosity extension of CCs or a different class of pulsators. Given their high intrinsic luminosities, ULPs offer the potential to directly reach the Hubble flow, eliminating the need for intermediate distance calibrators.

The analysis focuses on a comparative study of ULPs and CCs in the *PW* plane and the CMD, alongside a critical comparison with predictions from both stellar evolutionary and nonlinear convective pulsation models. Furthermore, it investigate the capability of the forthcoming Rubin LSST survey (Ivezić et al., 2019) to both increase the number of known ULPs and improve the precision and accuracy of the period and mean magnitude measurement for those already identified in Local Group galaxies.

The analyzed sample is that presented by M24, which includes all known ULPs—among them the newly classified MW ULP by Soszyński et al. (2024)—and adopts the accurate and precise Gaia DR3 photometry for 15 already known ULPs in Magellanic Clouds, M31, and M33.

Our results suggest that improving the precision and accuracy of ULP photometry decreases the uncertainties in their *PW* relation and increasing its agreement with that of CCs, thereby further supporting the hypothesis that ULPs represent the same class of pulsating variables but at higher masses and longer periods.

The wide color range observed in the CMD, along with comparisons to evolutionary and pulsation models, raises several questions and presents a significant challenge to current theoretical frameworks, which must reconcile the observed properties with the physical constraints derived from these pulsators.

In any case, obtaining a larger, photometrically homogeneous sample of ULPs spanning a broad range of metallicities is essential. In this context, the expected results from the Rubin LSST survey are promising. This study demonstrates that it will not be necessary to wait until the survey's completion to achieve reliable photometry for known ULPs and identify new candidates. Already from the initial data releases, we expect to obtain valuable information to better assess the reliability of ULPs as standard candles, from both theoretical and observational perspectives.

Author contributions

IM: writing – review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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