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Ultralong-period Cepheids: a possible primary distance indicator?

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Abstract. We present a project that aims to provide a complete theoretical and observational framework for an as yet unexplored class of variable stars, the ultralong-period Cepheids (P longer than 80–100 days). Given their very high luminosities (M_V up to −7 mag), with the *Hubble Space Telescope* we will be able to observe them easily in stellar systems located at large distances (∼100 Mpc). This limit will be further increased, out to the Hubble flow (∼350 Mpc), using future ground-based facilities such as the *European Extremely Large Telescope*. The nature of their pulsation is as yet unclear, as is their evolutionary status, which seems different from the central helium-burning phase generally associated with classical Cepheids. These objects have been found to cover a very large metallicity range, from [Fe/H] ∼ −2 dex to solar values, and they are located in heterogeneous stellar systems, from dwarf to spiral galaxies. Once completely characterized, they could provide a crucial test, since they have been found in all Type Ia supernova host spiral galaxies that have been monitored for variability over long periods and that currently offer sound constraints on the estimated value of the Hubble constant.

Keywords. stars: distances, stars: variables: other

1. Introduction

Here we present an ongoing project devoted to understanding the nature of ultralong-period (ULP) Cepheids and their utility as stellar candles. In the near future, this new class of possible distance indicators will allow us to directly reach distances of cosmological interest, representing both an important alternative to Type Ia supernovae (SNe Ia) and a better calibrator than classical Cepheids of this important secondary distance indicator (as well as of other indicators). The reason for our interest in these stars is their intrinsic luminosity, which is 2–4 magnitudes brighter than that of typical classical Cepheids used so far to establish the extragalactic distance ladder. They may allow us to extend the current observational limit up to 100 Mpc (NGC 1309 is the most distant galaxy containing identified classical Cepheids; it is located at 33 Mpc: see Riess *et al.* 2011). In addition, the ESA astrometric satellite *Gaia* will provide trigonometric parallaxes at micro-arcsec accuracy, and hence precise direct distances to Large and Small Magellanic Cloud (LMC, SMC) ULP Cepheids. And last but not least, the potential of ULPs will be further enhanced by the next generation of ground-based telescopes, such as the *European Extremely Large Telescope* (*E-ELT*; Deep *et al.* 2011; Fiorentino

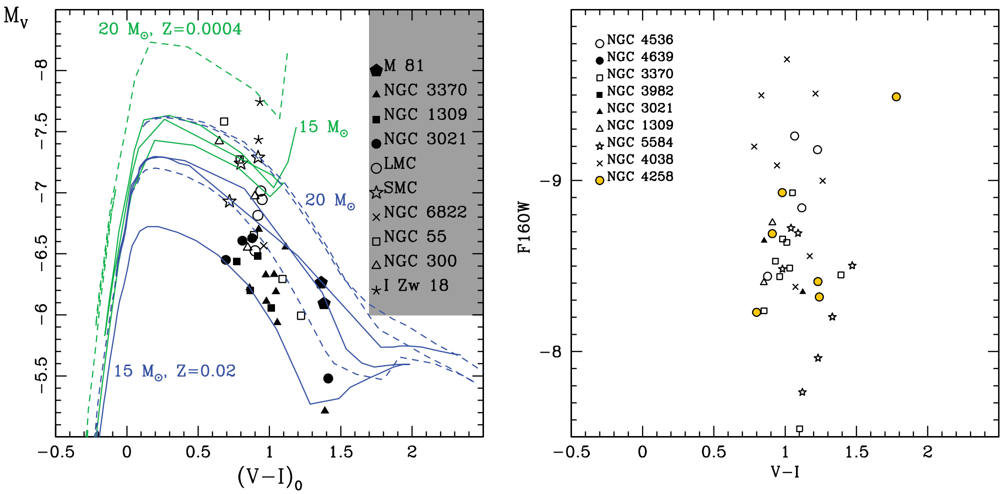

Figure 1. Colour–magnitude diagrams for the ULP Cepheids in (left) $V, (V-I)$ and (right) F160W, $(V-I)$. Distance moduli are taken from the literature and reddening values used to plot the ULP Cepheids in this plane are given by Schlafly & Finkbeiner (2011).

et al. 2011), which can make ULP Cepheids (observable up to 320 Mpc) the first primary distance indicator capable of directly measuring H_0 in a 'single step'.

ULP Cepheids in the Magellanic Clouds were certainly identified for the first time by H. Leavitt in 1908. In recent years, several new identifications of ULP Cepheids have been achieved using modern photometric data (CCD observations), leading to a sample of approximately 60 ULP Cepheids (Riess *et al.* 2011; Fiorentino *et al.* 2012; and references therein). The lack of past interest in these objects can be attributed to the fact that they are outliers in the classical Cepheid period–luminosity (PL) relation. Furthermore, their detection has been biased by two main observational properties that have long conspired to make them elusive: (i) very long time baselines (up to several years) are needed to characterize their periods adequately, and (ii) their very high intrinsic luminosities causes their saturation in photometric observations of nearby galaxies.

Recently, Fiorentino *et al.* (2012) compiled all ULPs for which V and I-band photometry is available and analysed the pulsation properties of 37 ULP Cepheids, with periods longer than 80 days, in 10 galaxies with metallicities ranging from metal-poor ($Z = 0.008$: the Magellanic Clouds, NGC 6822, NGC 55, NGC 300 and I Zw 18) to metal-rich ($Z \sim 0.02$: NGC 1309, NGC 3370, NGC 3021 and M81). This ULP sample has been further increased by the detection of 27 additional ULP Cepheids in the galaxy sample used by Riess *et al.* (2011; NGC 4536, NGC 5584, NGC 4038 and NGC 4258) to calibrate SN Ia host galaxies. On the basis of their observed properties, such as their loci in the colour–magnitude diagram (CMD) and the Wesenheit–period (WP) relation, Fiorentino *et al.* (2012) suggested that ULPs are the counterparts at high luminosity of the shorter-period ($P \lesssim 80$ days) classical Cepheids. They do not confirm the flattening in the Wesenheit index suggested by Bird *et al.* (2009). Instead, they found $\mathrm{Wes}(I, V-I) = -3.68 - 2.66 \log P$, with $\sigma = 0.34$ mag. They concluded that ULPs lie within a large range (~ 0.4 mag) around a WP relation consistent within the errors with that of the LMC's Cepheids. Finally, they qualitatively investigated the metallicity dependence of the Wesenheit index derived from the V and I bands. They do not find a significant metallicity dependence, in good agreement with the theoretical modelling

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of classical Cepheids. Thus, metallicity differences do not seem to be the cause of the spread around the WP relationship. The main cause might be the non-homogeneity and poor statistics of the sample, but also the use of mean magnitudes and colours that may not be well determined.

2. ULP CMDs and evolutionary state

In this section we show the loci of ULP Cepheids in the CMD. We still lack homogeneous photometry for the whole sample. Thus, in Fig. 1 we show separately the available $V, (V-I)$ (left) and F160W, $(V-I)$ photometry (right). In the optical CMD, we show the evolutionary tracks from Bertelli *et al.* (2009) for $M_* = 15$ (solid lines) and 20 $M_\odot$ (dashed lines) spanning the full metallicity range, i.e. for $Z = 0.0004$ (representative of I Zw 18; dark green lines) and $Z = 0.02$ (solar composition; blue lines). These masses bracket the luminosities observed for ULP Cepheids. In particular, the brightest ULPs have been observed in I Zw 18. It is clear that these very high luminosities are difficult to account for. In fact, the evolutionary track for 20 $M_\odot$ and $Z = 0.0004$ does not exhibit a 'classical' blue loop crossing the instability strip (IS). This has some effect on the evolutionary time spent in the IS and, in turn, on the probability to observe these objects. A metal-rich star ($Z = 0.02$) with a mass of approximately 20 $M_\odot$ spends some 2500 yr in the IS, whereas a very metal-poor star spends only 400 yr there. Note that the blue-loop phase has to be treated with caution, as discussed in Fiorentino *et al.* (2012). In addition, for modelling very massive stars, the effects of rotation are not negligible, although this is assumed in standard stellar evolutionary models. The global effect of more significant rotation is to increase the stellar luminosity—and thus the same luminosity could be associated with a lower mass—and to increase the evolutionary time required to move towards the red part of the CMD (Heger *et al.* 2000).

With only a few exceptions, and in spite of the large range in metallicity, most ULP Cepheids seem to occupy the same region in the CMD, i.e. their IS ranges from $(V-I) \sim 0.7$ to approximately 1.5 mag. In addition, the main difference between ULP Cepheids in different galaxies seems to be their intrinsic luminosity, with metal-rich ULP Cepheids being fainter. These metal-rich ULP Cepheids also exhibit shorter periods ($P \lesssim 100$ days) than their metal-poor counterparts. To properly describe this behaviour, we are developing a full pulsation and theoretical evolutionary scenario for these very bright pulsators with metallicities ranging from $Z = 0.0004$ to $Z = 0.02$, taking advantage of our experience in modelling classical Cepheids (Bono *et al.* 1997; Fiorentino *et al.* 2002; Marconi *et al.* 2005). These models will also be transformed to the *Hubble Space Telescope (HST)*/Wide-Field Camera 3 photometric system to give us the opportunity to interpret the full sample of ULP Cepheids available.

I Zw 18: The discovery of two *bona fide* ULP Cepheids with periods of 125 and 130.3 days in I Zw 18 poses some problems for the theoretical interpretation of these objects. The ULP Cepheids lie in a region of the CMD where current stellar evolution models do not predict the existence of core-helium-burning blue loops, the evolutionary phase thought to produce Cepheids. To understand the real nature of these intriguing objects and to constrain their regular periodicity, we decided to follow them up using the ground-based Telescopio Nazionale Galileo (*TNG*). Unfortunately, the severe crowding in the star-forming region of I Zw 18 allowed us to observe only one of the ULPs, V15 (Fiorentino *et al.* 2010). The preliminary V-band light curve is shown in Fig. 2 (left-hand panel). We have used both space- and ground-based data to refine this light curve. We have derived a shorter period compared with the previous period we found using only *HST* data, as well as a shorter temporal baseline (Fiorentino *et al.* 2010).

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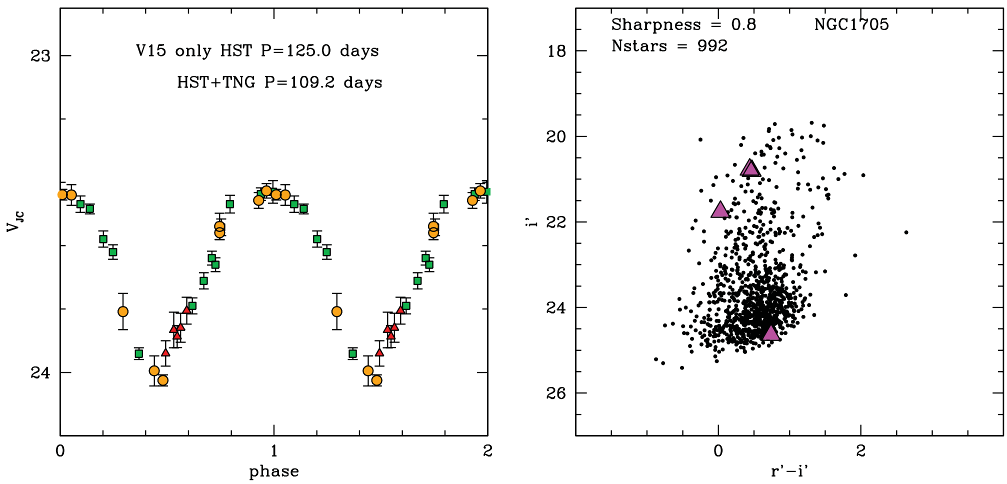

Figure 2. (left) New light curve for the brightest Cepheid in I Zw 18, V15. The light curve has been obtained by combining both *TNG* (orange circles) and *HST* (red triangles and green squares) data. (right) Preliminary CMD of NGC 1705 with data taken at the *Gemini-South* telescope, with a few *good* variable-star candidates (magenta triangles).

NGC 1705: In this context, observations of pulsating objects in the low-metallicity regime can provide sound constraints on the physical mechanisms involved, in particular when linked to the star-formation history of the host galaxy. In fact, star counts are directly correlated with the evolutionary time spent in the different phases. With this in mind, we obtained observation time on the *Gemini-South* telescope to look for long-period variables in the blue compact galaxy NGC 1705. Its detailed star-formation history is known through careful analysis of $UBVIJH$ data taken with *HST*/WFPC2, ACS and NICMOS (Annibali *et al.* 2009). By analogy to I Zw 18, we expect to observe ULP Cepheids in NGC 1705 (in addition to classical Cepheids), given the occurrence of several stars with masses around and greater than 15 $M_{\odot}$, and thus to have the opportunity to constrain the ULP Cepheids' evolutionary state. A very preliminary CMD obtained with *Gemini* in *un*calibrated r' and i' is shown in Fig. 2 (right-hand panel). Using magenta triangles, we have highlighted four good variable-star candidates from a list of more than 20. In particular, two very luminous candidates seem to show very long periodicity ($P \gtrsim 100$ days). However, these are only preliminary results and a proper calibration of the final photometry and a more detailed period determination have to be done.

3. Conclusions

In conclusion, we are following up galaxies in which ULP Cepheids have been observed and we are performing new variability studies, in particular in the metal-poor range ($Z \lesssim 0.008$). A new homogeneous and larger sample will help us to understand the nature of these objects. In fact, observations of such massive objects (from 15 to 20 $M_{\odot}$) in the low-metallicity regime poses some problems for their interpretation as blue-loop stars crossing the classical IS and their existence also offers some constraints on the internal structure of these objects. On the other hand construction of new, accurate evolutionary and pulsation models for ranges of masses corresponding to very metal-poor ULP Cepheids will allow us to understand the true status of these pulsators and confirm their nature as cosmological standard candles.

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