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At the crossroads of astrophysics and cosmology: Period–luminosity relations in the 2020s

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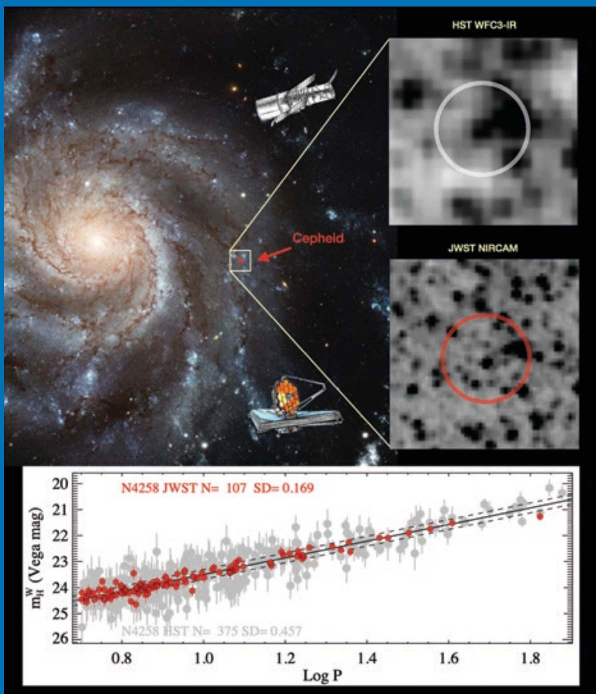

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AT THE CROSSROADS OF ASTROPHYSICS AND COSMOLOGY: PERIOD–LUMINOSITY RELATIONS IN THE 2020S

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Uncrowded Cepheids observed with the *James Webb Space Telescope (JWST)* in the near-infrared. High-resolution *JWST* observations can test confusion-limited *Hubble Space telescope (HST)* observations that are used to measure the Hubble constant. *JWST* provides superior source separation to negate crowding noise resulting in a factor of > 2.5 reduction in the dispersion of the Cepheid period–luminosity relation in galaxies that host Type Ia supernovae (image shown for NGC 5584) and the geometric distance reference, NGC 4258, with the period–luminosity relation shown here. The agreement between Cepheid distance measures between *HST* and *JWST* is excellent and provides the strongest evidence to date that systematic errors in *HST* Cepheid measurements do not play a significant role in the present 'Hubble tension,' now at 5σ confidence. The source of the Hubble tension remains an outstanding mystery of potentially cosmological origin and warrants further study. (Credit: Adam Riess, Johns Hopkins University, USA)

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AT THE CROSSROADS OF ASTROPHYSICS AND COSMOLOGY: PERIOD–LUMINOSITY RELATIONS IN THE 2020S

PROCEEDINGS OF THE 376th SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION BUDAPEST, HUNGARY 17–21 April, 2023

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Preface

This volume includes contributions from IAU Symposium 376, *At the crossroads of astrophysics and cosmology: Period–luminosity relations in the 2020s.*

In the early 1900s, Henrietta Leavitt, in 1908—and later Adams & Joy and Shapley & Walton, both in 1927—showed that bright Cepheid variables were characterised by a narrow range in spectral type or, equivalently, temperature at a given period. This, in turn, led to the establishment of a tight period–luminosity relation (PLR): more luminous stars are expected to have longer pulsation periods. The spectral-type/temperature restriction of Cepheids naturally led to the realisation that pulsating variables only occur in a narrow "instability strip" in the Hertzsprung–Russell diagram.

This classical instability strip is host to a range of periodic variable stars, including classical Cepheids (δ Cephei stars), Mira variables at the top of the asymptotic giant branch (AGB), Type II Cepheids, and RR Lyrae stars. SX Phoenicis and δ Scuti variables (jointly known as dwarf Cepheids or ultrashort-period variables) as well as anomalous Cepheids, and ZZ Ceti, V777 Herculis and GW Virginis pulsating white dwarfs are also found in specific instability strips. Many of these stellar types obey specific period–mean density relations. Curiously, not only pulsating stars exhibit PLRs: well-defined and long-established relationships between orbital periods and luminosities also exist for contact binaries of W Ursae Majoris (EW) type. Crucial remaining open issues in this broad field include the metallicity dependence of the zero point of the Cepheid PLR, the possible presence of a break at a pulsation period around 10 days, and the effects of binarity and circumstellar envelopes. Intrinsic PLR widths may offer unique insights into the physical processes shaping these relations and the underlying physical properties of the contributing stars (stellar structure, atmospheric parameters, and pulsation properties).

A promising approach to reducing the current systematic uncertainties associated with the present-day expansion rate of the Universe—the well-known tension in the Hubble parameter—is by trying to achieve improved local calibrations of primary distance indicators and their derivatives, including calibration of the photometric zero point of the Cepheid PLR, at both optical and—potentially with much reduced scatter—infrared wavelengths (e.g., starting from existing *Spitzer Space Telescope* data), for instance through trigonometric-parallax measurements of carefully selected Cepheid samples by the European Space Agency's *Gaia* satellite. Improvements in the Cepheid and Mira distance scales will be achievable to a level of 3–4% or better, based on forthcoming mid-infrared observations with the *James Webb Space Telescope* (*JWST*). Perhaps the most powerful use of the variety of PLRs present for variable stars is the ability to cross-check results from any individual technique. The diverse stellar types exhibiting PLRs are drawn from distinct stellar populations, with their own age and metallicity distributions. Working together, these techniques can explore population-based systematics in distance determination to provide insights into potential calibration biases in the current Type Ia supernovae calibration.

After much discussion, we decided to frame IAU Symposium 376 by initially focusing on the discrepancy in the Hubble constant based on different approaches, including the "standard" Cepheid PLR. This choice led to many productive and engaging discussions, triggered by numerous inspiring talks that highlighted the latest developments. In essence, this theme followed on from the Spring school on the distance ladder that had been organised at Konkoly Observatory during the week prior to the conference week.

From the outset, it became clear that the *JWST* will soon become a game changer given the amazing data already generated by this new observatory. Thanks to its flawless launch and smooth initial operations, the community is now looking at an observatory

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that may last much longer than its nominal five-year operational lifetime. In turn, this offers an enormously expanded scope for studies of the distance ladder. Even at this early time, we are seeing significant improvements in spatial resolution with respect to that offered by the *Hubble Space Telescope* at similar (near-)infrared wavelengths. In fact, preliminary results imply that the scatter in the Cepheid PLR at 1.5 μm may be reduced by a factor of 2–3. Multiple participants presented very exciting results based on early *JWST* data.

Another eye-catching aspect brought up in many inspirational contributions is the phenomenal distance accuracy currently achievable from Cepheid PLRs. *Gaia* cluster Cepheids now show Large Magellanic Cloud-like scatter in their period–Wesenheit relations, while the distance to Messier 33 has now been established to better than 1.3%. This finally allows us to understand secondary effects, such as the impact of period fluctuations (e.g., in Messier 51) on distance estimates.

Similarly, tip of the red giant branch (TRGB) distance determination has come a long way over the past three or more decades and promises to deliver a powerful alternative approach to the standard PLR technique for Cepheids, pushing to ever greater distances. In addition, newly developed stellar population methods now allow us to apply the "J-AGB" method, exploiting the characteristics of carbon-rich stars.

Meanwhile, comparisons of distance estimates using different, independent methods are finally coming together. By pursuing minimisation of systematics and secondary variability effects, over the past decade the distance ladder has narrowed from a consideration of many complementary, independent techniques to a streamlined ladder with well-defined rungs, from Geometry to Cepheids, from Cepheids to SNe Ia, and from SNe Ia to redshifts. However, the field is now returning to the broader implications resulting from this much-improved ladder, with a greater focus on cross-checks with other methods. *Gaia*, *JWST*, and soon the Vera C. Rubin Observatory's Legacy Survey of Space and Time will be game changers out to nearby galaxies at distances as far as tens of megaparsecs.

Despite an early focus on the challenges posed by the extragalactic distance scale, a significant fraction of the conference was dedicated to the underlying physics governing stellar pulsation and variability, for different types of tracers. Among the classical Cepheids, renewed interest focuses on multimode variability and period fluctuations, from short-period overtones to ultralong-period variability. Current developments promise exciting opportunities to much better determine the stellar mass–luminosity relation, often based on painstaking, detailed work where every object counts. Perhaps even more importantly, we are now reaching observational regimes where we can finally get a good handle on metallicity effects in the context of Cepheid variability.

AGB stars are coming back into fashion, particularly because of improved calibration methods and new theoretical developments. Parallaxes from masers obtained with very long baseline interferometry (VLBI), at nearby distances anchored by *Gaia* parallaxes, are providing very useful constraints. These are important developments in the era of the new extremely large telescopes which are more infrared-sensitive than their smaller counterparts. Moreover, the Square Kilometre Array, the next-generation Very Large Array (ngVLA), the Event Horizon Telescope, and other major radio initiatives open up new areas of research involving AGB and semi-regular variables as useful tracers of the physical processes taking place in and distances to numerous nearby galaxies.

RR Lyrae stars remain the workhorse PLR tracers for older stellar populations given their pre-eminent importance for near-field cosmology and for understanding the formation history of the Galaxy, particularly when combined with dynamical data. *Gaia* has also triggered a revival in this field, complemented by many cutting-edge ground-based projects. A major focus at the present time is on the metallicity dependence of the RR Lyrae PLRs, so that their empirical basis now supports theoretical arguments.

The wealth of data available at the present time and their high quality now allow us to consider secondary effects that may play a role in this field, such as the light-curve shape, multi-mode pulsation properties, period changes, binarity, circumstellar envelopes, etc.

This conference has clearly shown that stellar pulsation physics has reached a high level of maturity, so that our attention is increasingly focused on more diverse pulsator types other than classical Cepheids and RR Lyrae, including anomalous and Type II Cepheids, δ Scuti stars, magnetically and chemically peculiar stars, scaling relations and PLRs pertaining to supergiant pulsators, contact binary systems, and many others.

It has become clear that the importance of *Gaia* for studies of variable stars cannot be overstated. It has already collected more than a trillion CCD measurements down to $G{\sim}21$ mag with uncertainties as small as 1 mmag. At the same time, the mission provides colours, astrometry, and spectroscopic time-series observations (for future release), thus making it the perfect tool for variability studies. At the present time, we already have access to *Gaia* observations of 271,000 RR Lyrae stars among some 10 million variables in Data Release 3 (DR3), with DR4 potentially reaching up to 100 million variable stars.

The key outstanding issue in this field, pertaining to PLRs in general, relates to the systematics affecting the current crop of *Gaia* parallaxes. We still need better ways to mitigate those effects, particularly as regards those objects that exhibit 'astrophysical confusion' in the sense of outflows, disks, etc. At present, it appears that the 'counter-corrections' required to derive accurate distances are often similar to the intrinsic, recommended corrections, so that more work is required to overcome those limitations. Many methods have been proposed (cluster membership, asteroseismology, binary systems with interferometric orbits, Miras with VLBI parallaxes, etc.), so it appears that the field is slowly moving to an acceptable solution in this area as well. The picture that is emerging is that there is not a single 'best' parallax correction that may or may not be magnitude-dependent, but we will have to resolve this issue using a sample-based approach.

Numerous contributions discussed the structure of the Milky Way, showing the significant synergies among different variability tracers, although one should keep in mind that different ages may trace different spatial components. Combined with dynamical measures, we now have a pretty good handle on the orbits of the Magellanic Clouds and their wake, on the warped and flaring young disk structure of the Milky Way, and even on the structure of our Galaxy on the other side of the Galactic Centre.

Theoretical advances are, of course, equally important as all those beautiful observational results. At this time, it seems that we are overwhelmed with high-quality data sets and theory is taking a bit of a back seat. Nevertheless, numerous teams are working on improving our theoretical understanding of the underlying pulsation physics, offering ever more detailed tests of models aided by the unmatched quality of observational data, including such models that focus on the boundaries of the classical instability strip. Major advances are seen in the context of understanding and modelling the effects of rotation and convection, where we are slowly moving from 1D to more realistic 3D models.

In view of all of these exciting developments, the future of this field looks extremely promising. Increasing data volumes are fundamentally changing our approaches, as we have already seen in the *Gaia* context, and this will only be accelerated when facilities such as the Rubin Observatory and its Legacy Survey of Space and Time come online. Likewise, the Roman Space Telescope/*WFIRST* will also contribute to more and larger data sets, while smaller, ground-based facilities will still be required to provide reference data, follow-up opportunities, and complementary temporal sampling.

Beyond photometry and light-curve analyses, spectroscopy represents the next frontier, and also here the future looks bright. Leading on from APOGEE and GALAH, the field is looking forward to exploiting such facilities as 4MOST, WEAVE, DESI, SDSS-V, MOONS, and others, allowing us to start sampling the variable sky spectroscopically. In particular, radial velocity variability will be tackled with facilities like VELOCE (Cepheids) and, increasingly, *Gaia* (everything else?). It would be very helpful for the field as a whole to share analysis codes and improve accessibility to such tools so as to benefit a greater cross-section of the community.

Spectroscopic time-series observations clearly are the future of this field. Beyond the optical and near-infrared domains, X-ray variability, ultraviolet data, and radio approaches are increasingly hitting the forefront of the field, so we are warned to keep an eye out for new developments in those areas and an open mind as regards one's favourite wavelength range (even including gravitational waves?). Standardisation and cross-calibration remain a concern, but major efforts are undertaken to get this under control. We are eagerly looking forward to the era of the extremely large telescopes. And will artificial intelligence start to play an increasingly important role in our improved understanding? By the time that these developments have matured, a follow-up IAU Symposium will probably be warranted.

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