IAU Symposium 376 | 17-21 April 2023

At the cross-roads of astrophysics and cosmology:
Period–luminosity relations in the 2020s

Scientific Programme and Book of Abstracts

CSFK KONKOLY ELKH Eötvös Loránd Research Network

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IAU Symposium No. 376

At the Crossroads of Astrophysics and Cosmology: Period-Luminosity Relations in the 2020s

Budapest, Hungary – 17-21 April 2023

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Scientific programme

Sunday, 16 April 2023

15:00–19:00	**Registration**		
19:00–21:00			
		Welcome cocktail Hotel Danubius Helia conference venue	

Monday, 17 April 2023

09:00–12:20	**Chair: Róbert Szabó**		
09:00–09:30		*Opening ceremony*	Addresses by the SOC and LOC
09:30–10:00	R	**Wendy Freedman** (remote)	The Extragalactic Cepheid Distance Scale
		Session I: Setting the Scene – The Extragalactic 'Problem'	
10:00–10:30	R	**Adam Riess**	Local Value of the Hubble Constant from SH0ES
10:30–11:00		*Coffee/tea break*	
11:00–11:30	I	**Rachael Beaton**	H0 at its Foundation: The Limitations of Anchors of the Distance Scale
11:30–11:50	C	**Louise Breuval**	The Cepheid Distance Scale and its Metallicity Dependence
11:50–12:20	I	**Myung Gyoon Lee**	The Tip of the Red Giant Branch as a Cosmological Probe
12:20–13:30		*Lunch*	

13:30–15:30	**Chair: Richard de Grijs**		
13:30–13:50	C	**Gergely Dálya**	Tackling the Hubble Tension with Gravitational Waves
13:50–14:10	C	**Richard I. Anderson**	A 1% Calibration of Long-period Variable Stars for the Extragalactic Distance Scale
14:10–14:30	C	**Pierre Kervella**	Inspecting the Ladder: the Cepheid Distance to the SN Ia Host Galaxy NGC 5584
14:30–15:00	R	**Igor Soszyński**	Period–Luminosity Relations in the Local Group of Galaxies
15:00–15:30	P	*Poster sparkler pitches [schedule TBD; chaired by session chair]*	
15:30–16:00		*Coffee/tea break*	
16:00–18:00	**Chair: László Kiss** *Session II: Stellar Pulsation Physics*		
16:00–16:20	C	**Arief Ahmad**	Self-excited Pulsations in Global 3D Simulations of Cool, Luminous and Evolved Stars
16:20–16:40	C	**Giulia De Somma**	New Theoretical Period–Luminosity–Colour and Period–Wesenheit Relations for Anomalous Cepheids
16:40–17:00	C	**Richard de Grijs**	New Double Mode Cepheids from the Zwicky Transient Facility Survey
17:00–17:20	C	**Saniya Khan**	Investigating *Gaia* (E)DR3 Parallax Systematics Using Asteroseismology of Cool Giant Stars Observed by *Kepler*, *K2*, and *TESS*
17:20–17:40	C	**Gergely Hajdu**	Circumstellar Matter Around RR Lyrae Variables
17:40–18:00	C	**Ernst Paunzen** (remote)	Pulsation of Chemically Peculiar Stars

Tuesday, 18 April 2023

09:00–10:30	**Chair: Nancy Evans**		
09:00–09:20	C	**Mami Deka**	A Study of Stellar Photosphere – Hydrogen Ionization Front Interaction in δ Scuti Stars
09:20–09:40	C	**Susmita Das**	A Multiwavelength Analysis of BL Her Stars: Models versus Observations
09:40–10:00	C	**Géza Csörnyei**	How 'Accurate' is 'Precise'? The Effect of Period Fluctuations on PL Relations
	Session III: Primary Period–Luminosity Relation Calibrators in the Milky Way		
10:00–10:30	R	**Gisella Clementini**	Impact of the ESA *Gaia* Mission on the Primary Period – Luminosity Relation Calibrators in the Milky Way: Cepheids and RR Lyrae
10:30–11:00		*Coffee/tea break*	
11:00–12:30	**Chair: Tatiana Muraveva**		
11:00–11:30	R	**Martin Groenewegen**	Primary Period–Luminosity Relation Calibrators in the Milky Way: Cepheids and RR Lyrae – Physical Basis, Calibration, and Applications
11:30–11:50	C	**Bogumił Pilecki**	Cepheids with Giant Companions – A New Abundant Source of Cepheid Astrophysics
11:50–12:10	C	**Mauricio Cruz Reyes**	A Calibration of the Galactic Cepheid Luminosity Scale based on *Gaia* DR3 Open Cluster Astrometry
12:10–12:30	C	**Erasmo Trentin**	Cepheid Metallicity in the Leavitt Law (C-MetaLL) Survey. The Metallicity Dependence of Cepheid Period–Luminosity Relations
12:30–13:40		*Lunch*	

13:40–15:30	**Chair: Caroline Huang**		
13:40–14:10	I	**Tatiana Muraveva**	RR Lyrae Stars as Distance Indicators in the *Gaia* Era
14:10–14:30	C	**Laurent Eyer**	Exploring the Complexities of Determining Mean Luminosity in Variable Stars: The Impact of Biased Means in Weighted Procedures
14:30–14:50	C	**Giuliana Fiorentino**	RRLs to Trace Early Galaxy Formation
14:50–15:10	C	**Bartłomiej Zgirski**	Near-Infrared Period–Luminosity Relations for Galactic RR Lyrae based on Photometry from OCA and *Gaia* DR3 Parallaxes
15:10–15:30	C	**Ilaria Musella**	The Cepheid Based Cosmic Distance Scale: New Constraints from Updated Synthetic Multi-filter Cepheid PL Relations
15:30–16:00		*Coffee/tea break*	
16:00–18:00	**Chair: Martin Groenewegen**		
16:00–16:30	I	**Abdelmajid Benhida**	Photometric and Spectroscopic Measurement Campaign on the RR Lyr (RR Lyrae) and R Scuti (RV Tauri), at the Oukaimeden Observatory in Morocco
16:30–16:50	C	**Weronika Narloch**	Period–Luminosity Relations for Galactic Classical Cepheids in the Sloan bands
16:50–17:10	C	**Vincenzo Ripepi**	On the Origin of Galactic Anomalous Cepheids
17:10–18:00		*Panel discussion* ***Chair: László Kiss*** *- New stellar observations and tools*	

Wednesday, 19 April 2023

09:00–12:30	**Chair: Gisella Clementini**		
	Session IV: Disentangling the Structural Components of the Milky Way		
09:00–09:30	R	**Vasiliy Belokurov** (remote)	Milky Way components with RR Lyrae
09:30–10:00	I	**Akiharu Nakagawa**	Stars and their Astronomical Applications
10:00–10:30	I	**Dorota Skowron**	The Structure of the Milky Way from Period–Luminosity Relations
10:30–11:00		*Coffee/tea break*	
11:00–11:20	C	**Fran Jiménez-Esteban**	Variability Properties of the *Gaia* DR3 Catalogue of Galactic AGB stars
11:20–11:40	C	**Yi Ren** (remote)	Granulation in Red Supergiants: The Scaling Relations
11:40–12:20	P	*Poster sparkler pitches [schedule TBD; chaired by session chair]*	
12:20–13:40		*Lunch*	
14:00–17:30		*Budapest sightseeing*	
18:30–20:30	R	**Adam Riess**	*Public talk at the Hungarian Academy of Sciences* *The Surprising Expansion History of the Universe*

Thursday, 20 April 2023

09:00–10:40	**Chair: Vincenzo Ripepi**		
09:00–09:20	C	**Matteo Monelli**	Towards Homogeneous Distances in the Local Group
09:20–09:40	C	**Teresa Sicignano**	The Distance Scales of Anomalous and Type 2 Cepheids from Near Infrared Observations in the Magellanic Clouds
09:40–10:00	C	**Mónica Taormina**	Early-type Eclipsing Binaries as Distance Indicators
10:00–10:20	C	**Alexandre Gallenne**	Sub-percent Binary Star Masses and Distances from Interferometric Observations
10:20–10:40	C	**Maria Tantalo**	On the Use of the Mean *J*-band Magnitude of Carbon Stars as a Distance Indicator
10:40–11:10		*Coffee/tea break*	
11:10–12:20	**Chair: Dorota Skowron**		
11:10–11:40	I	**Armando Arellano Ferro** (remote)	RR Lyrae Light Curves and their Role in the Globular Cluster Metallicity and Distance Determination
11:40–12:00	C	**Javier Minniti**	Using Classical Cepheids to Study the Far Side of the Milky Way Disk
12:00–12:20	C	**Antonio Garcia Hernandez**	The PL Diagram for dSct: Back in Business as Distance Estimators
12:20–13:30		*Lunch*	

13:30–15:30	**Chair: Biwei Jiang**		
13:30–14:00	R	**Marcella Marconi** (remote)	Theoretical Stellar Pulsation Physics
	Session V: Period–Luminosity Relations in the Nearby Universe		
14:00–14:30	I	**Anupam Bhardwaj**	Period–Luminosity–Metallicity Relations for Classical Pulsators at Near-Infrared Wavelengths
14:30–14:50	C	**Zoi Spetisieri**	First Direct Measurement of the Stellar Association Bias in the SN Host Galaxy M101
14:50–15:10	C	**Kayla Owens**	An Independent Analysis of the Multi-Wavelength Cepheid PL Relations in NGC 7250
15:10–15:30	C	**Kerdaris Kurbah**	A Multi-phase Study of Theoretical and Observed Light Curves of Classical Cepheids in the Magellanic Clouds
15:30–16:00		*Coffee/tea break*	
16:00–18:00	**Chair: Rachael Beaton**		
16:00–16:20	C	**Vincent Hocdé**	Metallicity Estimations of MW, SMC, and LMC Classical Cepheids from the Shape of the *V*- and *I*-band Light Curves
16:20–16:40	C	**Shu Wang**	Double-Mode RR Lyrae Stars – A Robust Distance and Metallicity Indicator
16:40–17:00	C	**Felipe Espinoza-Arancibia**	Empirical Constraints for the Instability Strip from the Analysis of LMC Cepheids
17:00–18:00		*Panel discussion* ***Chair: Patricia Whitelock****: The Role of Machine Learning and its Applications*	

Friday, 21 April 2023

09:00–10:40	**Chair: Patricia Whitelock**		
	Session VI: Non-Traditional Period–Luminosity Relations		
09:00–09:30	I	**Biwei Jiang**	The Period–Luminosity Relation of Red Supergiants
09:30–10:00	I	**Michał Pawlak** (remote)	Period–Luminosity Relations Formed by Contact and Close Binary Systems
10:00–10:20	C	**Patryk Iwanek** (remote)	Comprehensive Analysis of Mira-type Stars Variability and the Structure of the Milky Way
10:20–10:40	C	**Miora Andriantsaralaza**	Distance Estimates for AGB Stars – *Gaia* DR3 Parallax and PL Relation
10:40–11:10		*Coffee break*	
11:10–12:40	**Chair: Anupam Bhardwaj**		
11:10–11:30	C	**Clara Martinez-Vazquez**	Breaking the Law: A Segmented Period - Luminosity Relation in delta Scuti Stars
11:30–12:00	I	**Michele Trabucchi** (remote)	Long-Period Variables as Distance and Age Indicators in the Era of *Gaia* and LSST
12:00–12:20	C	**Caroline Huang**	The Mira Distance to M101
12:20–12:40	C	**Piotr Wielgórski**	Near-Infrared Period–Luminosity Relations for Type II and Anomalous Cepheids in the Solar Neighbourhood
12:40–14:00		*Lunch*	
14:00–15:30	**Chair: Shu Wang**		
14:00–14:30	I	**Xiaodian Chen**	Possible Studies on Variable Stars based on *CSST*
14:30–14:50	C	**Dieter Engels**	OH/IR Stars and the Period–Luminosity–Relation of Mira Variables
14:50–15:10	C	**Fangzhou Ren**	An Uncharted but Valuable Distance Indicator: Period–Luminosity Relation of W UrsaeMajoris-type Contact Binaries
15:10–15:30	C	**Megan Lewis**	Galactic Center Miras: Period–luminosity Relations and Circumstellar Effects
15:30–		*Summary and closing ceremony*	

Poster Session 1: Monday, 17 April 2023, 15:00–15:30

P01 **Christine Clement**
Helen Sawyer Hogg and the Globular Cluster Period–Luminosity Relation

P02 **Zsófia Bora**
Distance Measurements of Type Ia Supernovae from Light Curve Fitting

P03 **Anton Afanasiev**
Decreasing the Scatter of SN Ia Host Cepheid PL relations

P04 **Chul Chung**
Population Age Origin of the Host Mass Step in Type Ia Supernovae

P05 **Seunghyun Park**
Evidence for Strong Progenitor Age Bias in Type Ia Supernova Distance Scale: Lessons from Cepheids

P07 **Steve Ardern**
First Detection of CO Emission from Cepheid Variables: a Step to Reducing the H0 Error Budget

P08 **John Baruch**
A Proposal for the Absorption of Light by Dark Matter to Explain the Hubble Tension

P09 **John Baruch**
Is the Period–Luminosity Relation for Cepheids Upset by a Small Threshold for the Absorption of Light by Dark Matter?

P10 **Géza Csörnyei**
Cepheids in M51: Cross-checking the PLR Distance with Independent Estimates

P11 **Maria Tantalo**
Variable Stars in NGC 6822

P12 **Mahtab Gholami**
Variable Stars in an Irregular Dwarf Galaxy, IC10

P13 **Hedieh Abdollahi**
Detection of Long-Period Variable Stars in And IX to Study Star Formation History and Dust Production Rate

P15 **Jesper Storm**
The Effect of Metallicity on the PL Relation from a Baade–Wesselink Type Analysis of a Cepheids in the Milky Way and the Magellanic Clouds

P16 **Tahere Parto**
The Star Formation History and Chemical Enrichment of Sagittarius Dwarf Irregular Galaxy Derived from Long-period Variable Stars

P18 **Gustavo Medina Toledo**
RR Lyrae Stars as Standard Candles and Tools to Disentangle the Milky Way's History

P19 **Bastian Lengen**
On the Consistency of the Cepheid and TRGB Distance Scales

P20 **Zehao Zhang**
Dependence of Pulsation Mode of Cepheids on Metallicity

P21 **Henryka Netzel**
Non-Radial Modes in Classical Pulsators — Perspectives for Asteroseismology

P22 **Emese Plachy**
Classifying Milky Way Cepheids with *TESS*

P23 **Dóra Tarczay-Nehéz**
Testing Ultra-low Amplitude Cepheid Candidates in the Galactic Disk by *TESS* and *Gaia*

P24 **Gábor Kovács**
Thousand Faces of Convection

Poster Session 2: Wednesday, 19 April 2023, 11:40–12:20

P26 **József M. Benkő**
How Accurate Are those Periods?

P27 **Giordano Viviani**
VELOcities of Cepheids (VELOCE) DR1: An Unprecedented View of Cepheid RV Variability and Spectroscopic Binarity

P28 **Young-Beom Jeon**
Review of BOAO Short Period Variable Star Surveys to Calibrate Period–Luminosity Relations

P29 **Giovanni Catanzaro**
Metallicity Determination from IGRINS Spectra for a Sample of Galactic Cepheids

P30 **Nancy Evans**
The Mass of the Cepheid S Mus

P31 **Javier Minniti**
Spectral Energy Distribution Fitting to Find and Characterize Cepheids in Binary Systems

P32 **Garance Bras**
Observational Calibration of the Projection Factor of RR Lyrae Stars Using the SPIPS Pulsation Modeling

P33 **Manuel Sánchez-Benavente**
Multiband Photometry and Spectroscopy of RR Lyrae Field Stars

P34 **Vázsony Varga**
Improving the *Gaia* RR Lyrae Photometric Metallicities

P35 **Cecilia Mateu**
Calibrating RR Lyrae Absolute Magnitudes as a Function of Period Shift to Correct Post-ZAHB Evolution Systematics

P36 **Olivera Latković**
WUMaCat — The Largest Catalog of Individually Studied W UMa Stars

P38 **Eric Hintz**
IR Spectroscopy of Stars in Various Instability Strips

P39 **Adrienn Forró**
Validation of the RR Lyrae Identifications in the PanSTARRS PS1 3π Survey with K2 and *Gaia*

P40 **Csilla Kalup**
Combined *Gaia* and K2 Studies of Globular Cluster Variables

P41 **Ernst Paunzen**
Catalogue of Variable Stars in Open Cluster Fields

P42 **Monika I. Jurkovic**
The Classification Intricacy of Different Types of Cepheid Variable Stars and the Case of RU Camelopardalis

P43 **Mahdi Abdollahi**
Hierarchical Classification of Variable Stars Using Deep Convolutional Neural Networks

P45 **Marcella Di Criscienzo**
Light Curve Recovery with the Rubin Observatory's LSST

P46 **Vittorio Francesco Braga**
Light Curve Templates of RR Lyrae in the LSST Photometric System

P47 **Jae Woo Lee**
The Post-Mass Transfer Eclipsing Binary WASP 1814+48: Absolute Properties and Multiperiodic Pulsations

P48 **Justyna Olszewska**
Spectroscopic Analysis of the Variable Star CO Aurigae with the GATS Telescope

P49 **Tahereh Ramezani**
Non-Variable Stars

Abstracts of oral presentations

The Extragalactic Cepheid Distance Scale

Wendy Freedman[1], Barry Madore, Kayla Owens, In Sung Jang, Taylor Hoyt, Abigail Lee

[1]*University of Chicago, USA*

I will present a review of the Cepheid extragalactic distance scale. In addition, I will present preliminary new results on Cepheids from the James Webb Space Telescope.

The Local Value of the Hubble Constant from SH0ES

Adam Riess[1,2]

[1]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*
[2]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

The Hubble constant remains one of the most important parameters in the cosmological model, setting the size and age scales of the Universe. Present uncertainties in the cosmological model including the nature of dark energy, the properties of neutrinos and the scale of departures from flat geometry can be constrained by measurements of the Hubble constant made to higher precision than was possible with the first generations of Hubble Telescope instruments. A streamlined distance ladder constructed from infrared observations of Cepheids and type Ia supernovae with ruthless attention paid to systematics now provide 1.4% precision and offer the means to do much better. By steadily improving the precision and accuracy of the Hubble constant, we now see evidence for 5 sigma deviations from the standard model, referred to as LambdaCDM, and thus the exciting chance, if true, of discovering new fundamental physics such as exotic dark energy, a new relativistic particle, or a small curvature to name a few possibilities. I will review recent and expected progress, most recently based on measurements by the SH0ES Team from the Hubble Space Telescope, *Gaia* EDR3 and JWST.

H0 at its Foundation: The Limitations of Anchors of the Distance Scale

Rachael Beaton

Space Telescope Science Institute, Baltimore, United States

Over the last decade multiple distance measurement techniques have become capable of producing an estimate of the Hubble constant to better than10% precision, with many at the 5% level or better. Subsets of these distance techniques are fully independent, which presents a unique opportunity to reveal heretofore unrecognized systematics in the distances. In context of the on-going Hubble tension, this presents as an opportunity to remove uncertainty in interpreting the differences between H0 measurements in the early and late Universe. Comparisons of H0 measurements, however, are comparing complex systems and may not be insightful for revealing systematics in the distance techniques themselves. I will show that diversity in how the different techniques are anchored and the overall lack of overlap in anchoring techniques. I will discuss how observatories coming online in the 2020's can help resolve these issues in the 2030's.

The Cepheid Distance Scale and its Metallicity Dependence

Louise Breuval[1], Adam G. Riess[1,2], Pierre Kervella[3], Richard I. Anderson[4], Martino Romaniello[5]

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[2]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[3]*LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, 5 place Jules Janssen, F-92195 Meudon, France*
[4]*Institute of Physics, Laboratory of Astrophysics, École Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland*
[5]*European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85478 Garching bei München, Germany*

Cepheid variables are the best-calibrated primary distance indicators and are used as the first rung of the SH0ES distance ladder: their Period-Luminosity (PL) relation is calibrated geometrically in the Milky Way (MW) from *Gaia* DR3 parallaxes, in the LMC from eclipsing binaries, and in NGC 4258 with water masers. This relation is used, in turn, to calibrate the second rung of the distance ladder: type Ia supernovae (SNe Ia).

One of the remaining systematic uncertainties of the distance scale is due to differences in chemical abundances between Cepheids on the first rung and on the second rung. While Galactic Cepheids and the ones in host galaxies have a similar metallicity, Cepheids located in the Magellanic Clouds are more metal poor. It has been shown by several empirical studies that metallicity affects Cepheids brightness by about -0.25 mag/dex, meaning that metal-rich Cepheids are brighter than metal-poor ones.

In this talk, I will describe how we refined the calibration of this metallicity correction using the most precise distances to date and a large metallicity range of about 1 dex, covering the MW and the Magellanic Clouds. In particular, we found this effect to be independent of wavelength between the optical and the mid-infrared. Finally, I will identify factors which sharpen this term over past studies, including corrections for the depth of the Magellanic Clouds, better photometry, improved extinction estimates and revised metallicity measurements. I will conclude by showing the correlation between the metallicity term and the Hubble constant, and how it is used to make the first rung anchors consistent.

The Tip of the Red Giant Branch as a Cosmological Probe

Myung Gyoon Lee

Seoul National University, Seoul, Republic of Korea

The luminosity of the brightest stars (tip) of the red giant branch (TRGB) in the color-magnitude diagrams was used early for the introduction of the multiple stellar population concept by Baade. In the modern era equipped with high spatial resolution imaging telescopes the TRGB is considered to be an excellent standard candle for any types of resolved galaxies, playing as a powerful probe for cosmology. The TRGB has several advantages over Cepheids. I will review what we can do with the TRGB in cosmology, including how the TRGB can supplement Cepheids.

Tackling the Hubble Tension with Gravitational Waves

Gergely Dálya[1], LVK Collaboration

[1]*Department of Physics and Astronomy, Universiteit Gent, Ghent, Belgium*

The Hubble tension, which is the statistically significant discrepancy between the Hubble constant values measured using various techniques, is one of the most urgent issues in contemporary cosmology. The most promising way to solve this is to use a new, model-independent method to measure the value of the Hubble constant. Such a measurement can be accomplished in a number of ways using gravitational waves (GWs). As the distance of a compact binary coalescence event can be inferred directly from the GW data, these events serve as "standard sirens", and hence provide a Hubble constant value via the redshift of their host galaxy. Furthermore, even if the host galaxy of the GW signal cannot be identified, and so the exact recession velocity of the source cannot be measured, a statistical analysis using galaxy data from the localization region can be a viable alternative, given a sufficient event rate. In this talk, I will present the increasingly precise results from the global gravitational-wave detector network, our preparation for the upcoming fourth observing run, and some other lesser-known methods of GW cosmological inference, as well as the latest predictions for the future of gravitational-wave cosmology.

A 1% Calibration of Long-period Variable Stars for the Extragalactic Distance Scale

Richard I. Anderson[1], Nolan Koblischke[2], Laurent Eyer[3]

[1]*EPFL, Lausanne, Switzerland*
[2]*University of British Columbia, Kelowna, ON, Canada*
[3]*University of Geneva, Geneva, Switzerland*

Long-period variable stars (LPVs) are well known to obey Period-luminosity (P-L) relations that enable distance measurements. Several P-L sequences of long-period variable stars exist, with Cepheids and Mira stars being the most well-known types. Here, we present a novel method for exploiting the variability of a specific set of long-period variable stars for distance determination. Using observations from the Optical Gravitational Lensing Experiment (OGLE) and the ESA mission *Gaia*, we calibrate said group of LPVs for distance determination to an accuracy of approximately 1%. Our calibration sheds new light on reported disagreements among distance measurements based on other stellar standard candles, such as classical Cepheids and the Tip of the Red Giant Branch. We outline the path to using these LPVs for extragalactic distance measurements and their role in determining the Hubble constant.

Inspecting the Ladder: The Cepheid Distance to the SN Ia Host Galaxy NGC 5584

Pierre Kervella[1], Behnam Javanmardi[1,2], Antoine Mérand[3], Louise Breuval[1,4], Alexandre Gallenne[5,6], Nicolas Nardetto[7], Anton Afanasyev[1], Wolfgang Gieren[5], Grzegorz Pietrzyński[5,8], Vincent Hocdé[8], Simon Borgniet[1]

[1]*LESIA, Observatoire de Paris, France*
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[5] *Universidad de Concepción, Chile*
[6] *CNRS UMI 3386, Santiago de Chile*
[7]*Observatoire de la Côte d'Azur, France*
[8]*CAMK, Warsaw, Poland*

The tension on the Hubble constant H_0 as determined from the Planck+ΛCDM model (H_0=67.4 km/s/Mpc) and from the empirical Cepheids+SN Ia ladder (H_0=73.0 km/s/Mpc) has recently been reported to reach a 5-sigma level (Riess et al. 2022). The latter empirical value relies almost exclusively on the SH0ES research project. In Javanmardi et al. (2021), we present an independent analysis of the original HST images of the SN Ia host galaxy NGC 5584. With the goal to test and validate the 'resistance' of the Cepheid rung of the ladder, we intentionally used methods and tools different from those used by the SH0ES collaboration. This allowed us to investigate the possible influence of the adopted methodology on the determined distance. We will present an overview of our approach on NGC 5584, how it differs from the SH0ES analysis, and the development perspectives of this project in the coming years.

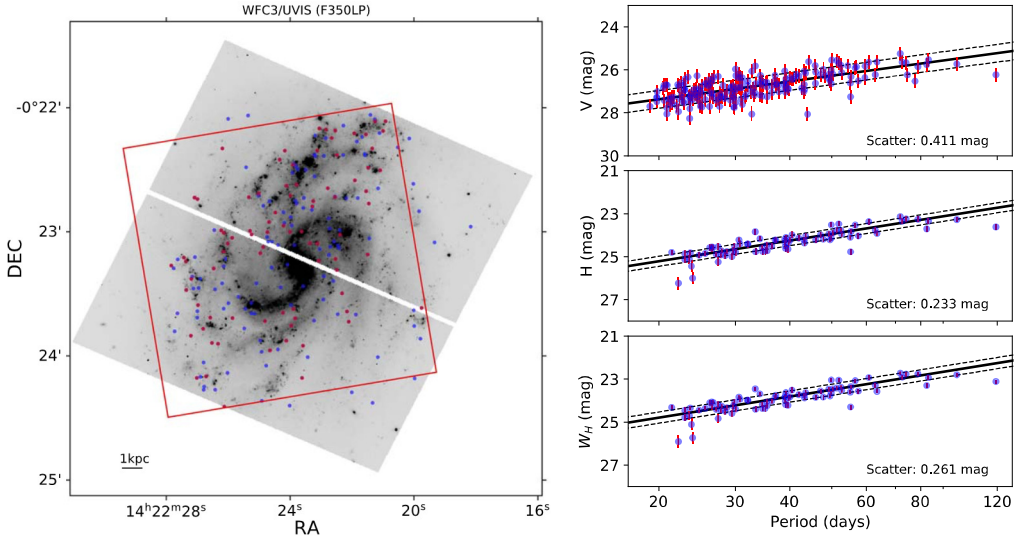

Figure 1. *Left panel: Map of the Cepheid stars in NGC 5584. Right panel: Period-luminosity relations (from Javanmardi et al. 2021, ApJ, 911, 12).*

Period-Luminosity Relations in the Local Group Galaxies

Igor Soszyński

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The Local Group galaxies, particularly the Large and Small Magellanic Clouds, have historically played and continue to play a unique role in the studies of the period–luminosity (PL) and period–Wesenheit (PW) relations, not just for pulsating stars. Calibrations of the PL and PW relationships at different wavelengths, measurements of their linearity, the influence of metallicity on the zero points and slopes of the PL relations, the distinction between various stellar populations in the PL plane, mapping the distribution of interstellar matter, and analyzing the three-dimensional structure of galaxies – these are some of the most common studies related to the PL and PW relations conducted in recent years. I will present the latest results on the PL relations obeyed by different types of variable stars in nearby galaxies – from delta Scuti stars to Miras and from contact binaries to mysterious long secondary periods exhibited by red giant stars.

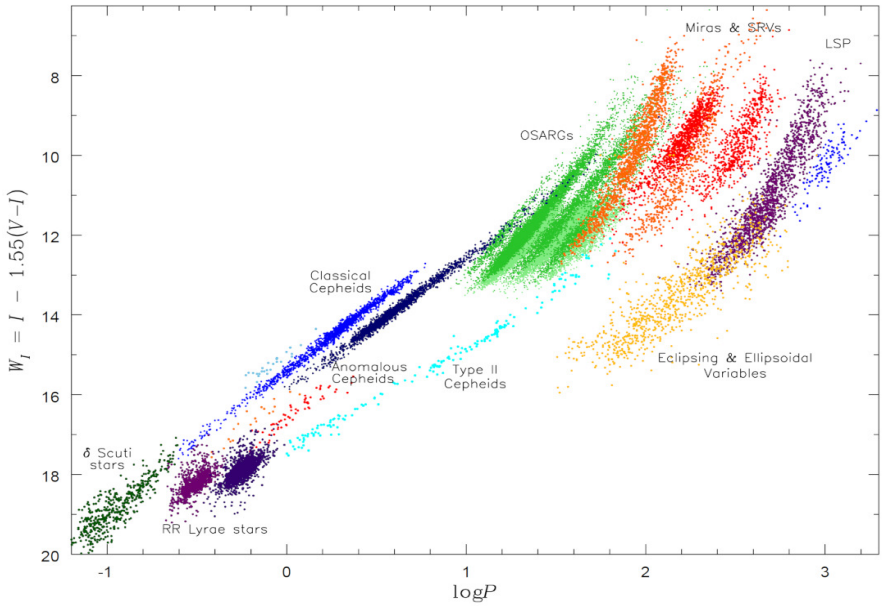

Figure 1: *Period–Wesenheit diagram for variable stars in the Large Magellanic Cloud.*

Self-excited Pulsations in Global 3D Simulations of Cool, Luminous and Evolved Stars

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The intrinsic variability of cool, luminous and evolved red giants, such as asymptotic giant branch (AGB) and red supergiant (RSG) stars, is caused by a combination of pulsations and convection. The interaction between convection and pulsations is complex, but large and deep convection cells are significant in the process that causes the pulsations. To gain a better understanding of the pulsations and the formation of significant outflows from AGB and RSG stars, it is essential to use advanced 3D models that take into account radiation and hydrodynamics. Latest simulations of evolved cool red giants cover a wider range of stellar characteristics than before. These simulations are able to demonstrate how the pulsations are self-excited and, due to the 3D nature of the simulations, we are able to study the pulsations throughout the entire stellar atmosphere. These simulations allow for the determination of important properties of the pulsations, including the fundamental pulsation period. In this talk, I will explain how the fundamental pulsation period can be extracted from the simulations and some of the challenges that come with doing so due to the interaction between convection and pulsations. Additionally, I will present recent findings on the relationship between the extracted pulsation properties and the characteristics of the simulated stars. The results of these analyses align well with both observational data and current theoretical understandings.

(Link to paper: https://doi.org/10.1051/0004-6361/202244555)

New Theoretical Period-Luminosity-Colour and Period-Wesenheit Relations for Anomalous Cepheids

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Anomalous Cepheids are interesting pulsating stars currently associated with intermediate-age stellar populations but without a completely clear formation scenario.

By relying on our nonlinear convective hydrodynamical code (see e.g., De Somma et al. 2022 and references therein) we present an updated theoretical framework for Anomalous Cepheids using updated predictions for the central Helium burning phase of the corresponding mass range and chemical compositions. The full amplitude pulsation properties are derived for both the Fundamental and the First Overtone mode, varying both the metal abundance and the helium content. In addition, the effect of variations in the superadiabatic convection efficiency is taken into account.

The resulting pulsation observables, namely the instability strip, the light and radial velocity curves, and the period-amplitude diagrams are discussed and compared with the literature. The predicted mean magnitudes and colors are used to derive the first theoretical Period-Luminosity-Colour and Period-Wesenheit relations in the *Gaia* bands. Finally, some applications to observational samples are presented.

New Double Mode Cepheids from the Zwicky Transient Facility Survey

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Multimode Cepheids pulsate simultaneously in more than one mode of oscillation. They provide an independent means to test stellar models and pulsation theories. They can also be used to derive metallicities. In recent years, the number of known multimode Cepheids has increased dramatically with the discovery of a large number of Galactic double-mode Cepheids. To date, 209 double-mode Cepheids have been detected in the Galactic bulge and disk, mostly based on the Optical Gravitational Lensing Experiment's (OGLE) catalogue. We recently conducted a comprehensive search for double-mode Cepheids in the northern sky based on Zwicky Transient Facility Data Release 5. We found 72 such objects in the Milky Way. The periods of the 30 sample objects already included in the OGLE catalogue show excellent agreement with the OGLE periods. The period ratios of our new Cepheids are consistent with those of known double-mode Cepheids, as evidenced by their loci in the so-called "Petersen diagram." Compared with OGLE, the completeness of our double-mode Cepheid sample is around 71%. The much improved temporal sampling of the Zwicky Transient Facility offers significant scope to find more double-mode Cepheids, especially at the distribution's short-period end.

Investigating *Gaia* (E)DR3 Parallax Systematics Using Asteroseismology of Cool Giant Stars Observed by *Kepler*, K2, and *TESS*

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Many efforts have been dedicated by the astrophysical community to better understand and describe *Gaia* parallax systematics, complementing the correction model provided with the EDR3 release papers (Lindegren et al. 2021, hereafter L21). Combining asteroseismology and spectroscopy, we now have access to distances to nearly 13,000 red-giant stars thanks to surveys observing in different locations of the sky: *Kepler*, K2, and *TESS*-SCVZ. In this context, we have identified the type of objects most suitable for investigating *Gaia* parallax systematics, namely red clump stars with low extinction. Using this "best" dataset, we present detailed results for parallax offsets as a function of magnitude, colour, and ecliptic latitude, both before and after applying L21 corrections.

Trigonometric parallaxes are essential for the calibration of period-luminosity relations (PLRs), whether it be for RR Lyrae, Cepheids or any other kind of stars. Our work helps informing the *Gaia* parallax systematics as well as probing the adequacy of L21 corrections, and thus finds a general applicability to all existing PL relations. Is there a residual zero-point trend with magnitude? How do the systematics operate? These are questions that we can address, with a dataset that is significantly larger than that of any other recent studies related to *Gaia* parallax systematics. Notably, we see that L21 corrections are adequate for stars fainter than G = 11 in *Kepler*, but some shortcomings appear for brighter stars.

Circumstellar Matter around RR Lyrae Variables

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We present the first detection of circumstellar matter around a sample of RR Lyrae stars, identified through their variable mean magnitudes. While other phenomena, such as blending with other sources, may lead to a similar change of the mean magnitudes of RR Lyrae stars, the unchanging light-curve shapes and amplitudes lead to an unambiguous separation between them and variable extinction from circumstellar matter. Preliminary analysis shows that the extinction ratios calculated from multi-wavelength light curves possess a wide range, hinting at a similarly wide variety of dust properties. We discuss the prevalence, implications, and possible formation mechanisms of circumstellar matter around RR Lyrae variables, with special attention to its connection to binarity.

Pulsation of Chemically Peculiar Stars

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Up to now, there are only a very few, if any, chemically peculiar (CP) stars known which also show classical pulsations of delta Scuti, gamma Doradus, and beta Cephei type. The only exceptions are Am – Fm stars which have been found to show gamma Doradus type pulsation. However, even this group is quite rare.

The CP stars of the upper main sequence have been targets for astrophysical studies since the discovery of these objects by the American astronomer Antonia Maury (1897). Most of this early research was devoted to the detection of peculiar features in their spectra and photometric behaviour. The main characteristics of the classical CP stars are: peculiar and often variable line strengths, quadrature of line variability with radial velocity changes, photometric variability with the same periodicity and coincidence of extrema. Slow rotation was inferred from the sharpness of spectral lines. Overabundances of several orders of magnitude compared to the Sun were derived for Silicon, Chromium, Strontium, and Europium, and for other heavy elements.

We will analyse the known pulsating CP stars and compare their astrophysical properties with other known "normal" pulsating stars. The compilation is based on the newest *Gaia* DR3 and the VSX catalogue.

A Study of Stellar Photosphere – Hydrogen Ionisation Front Interaction in δ Scuti Stars

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δ Scuti stars are intermediate-mass pulsating variable stars with mass range 1.0–3.0 solar masses having spectral types between A2 and F2 located at the intersection of the Cepheid instability strip with the main sequence. We can use them as astrophysical laboratories to test the theories of stellar evolution and pulsation. The single-mode δ Scuti stars obey a period–luminosity (PL) relation, which make them reliable distance estimators (McNamara 1997, 2011; Ziaali et al. 2019; Poro et al. 2021; Barac et al. 2022) to our Galaxy, as well as to nearby galaxies, while the multimode δ Scuti stars provide an important astrophysical tool to understand the properties of deep stellar interiors (Breger & Pamyatnykh 1998). In this work, we have investigated the observed Period-Colour-Amplitude-Colour (PCAC) relations at maximum/mean/minimum light of Galactic bulge and LMC δ Scuti stars for the first time and tested the hydrogen ionization front (HIF)–photosphere interaction theory of Simon et al. (1993) using MESA - RSP code. The PCAC relations as a function of pulsation phase are crucial probes of the structure of the outer envelope and offer an insight into the physics of stellar pulsation and evolution. The observed behaviour of the δ Scuti PCAC relations are consistent with the theory of the interaction of the HIF and stellar photosphere. Another important result, we found from this study is that the bulge δ Scutis are comparatively hotter than the LMC δ Scutis.

A Multiwavelength Analysis of BL Her Stars: Models vs Observations

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We present new theoretical period-luminosity (*PL*), period-Wesenheit (*PW*) amd period-radius (*PR*) relations at multiple wavelengths (Johnson-Cousins-Glass bands *UBVRIJHKLL'M* and *Gaia* passbands $GG_{BP}G_{RP}$) for a fine grid of convective BL Herculis models computed using the non-linear radial stellar pulsation tool MESA-RSP. The non-linear models were computed for periods typical ofor BL Her stars, i.e. 1≤P (days)≤4 covering a wide range of input parameters: metallicity (-2.0 dex ≤ [Fe/H] ≤ 0.0 dex), stellar mass ($0.5M_{\odot}$-$0.8M_{\odot}$), luminosity ($50L_{\odot}$-$300L_{\odot}$) and effective temperature (full extent of the instability strip; in steps of 50K). We investigate the impact of four sets of different convection parameters on multi-wavelength properties. Most empirical relations match well with the theoretical *PL*, *PW* and *PR* relations from the BL Her models computed using the four sets of convection parameters. However, *PL* slopes of the models with radiative cooling provide a better match to empirical relations for BL Her stars in the LMC in the *G*-band and the HK_S bands. No significant metallicity effects are seen in the *PR* relations. Another important result from our grid of BL Her models is that it supports the equivalence of the *PL* relations of RR Lyrae and T2Cs, thereby providing us the opportunity of adopting RRLs + T2Cs together as an alternative to classical Cepheids for the extragalactic distance scale calibration.

How ‘Accurate’ is ‘Precise’? The Effect of Period Fluctuations on PL Relations

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Cepheid period-luminosity relations provide arguably the most important step in the cosmic distance ladder formalism, as they build up the necessary transition between local and Hubble-flow distance estimation techniques. Over the years, the method has been tested and improved several times to be able to provide the current day’s precise estimates; however, out of these, only a few studies investigated errors and biases along the period values in the context of these relations. One such effect, that can cause uncertainties in the estimated period value of a Cepheid, is the fluctuations in the pulsation.

The fluctuations and instabilities of the pulsation period have been known for a long time, mostly in the context of longer-period pulsating stars. Recent studies showed, however, that they are quite common and detectable in Classical Cepheids as well, and they modify the exhibited pulsation period slightly, changing it from the “physical” value (i.e., from the one which is directly connected to the luminosity). Albeit this effect is not only negligible but barely noticeable for shorter period Cepheids, it leads to changes on per cent levels for stars at the other end of the period distribution. And while their effect is small, they put a precision limit on the period-luminosity relations and may even bias it slightly in extreme cases. Removing these fluctuations and estimating true physical period values require observations to be taken at longer temporal baselines, which enable constructing *O-C* diagrams; something that is barely available for extragalactic Cepheids to date.

Since the fluctuations are not removable from the period values otherwise, it is important to constrain their effect. In this work, we simulated fluctuations on mock period-luminosity data and evaluated their effects on the obtainable distance moduli. Our results show that, generally, fluctuations merely set a small precision limit which is smaller than or negligible compared to the currently estimated fit uncertainties. However, we also give examples of extreme cases, when only long-period Cepheids are used for constructing the PL relations, where the presence of fluctuations also leads to noticeable biases. Hence keeping these instabilities in mind and understanding their limiting effect may be important in future higher-precision studies.

Impact of the ESA *Gaia* Mission on the Primary Period – Luminosity Relation Calibrators in the Milky Way: Cepheids and RR Lyrae

Gisella Clementini

INAF OAS, Bologna, Italy

I will discuss the impact of *Gaia*, the cornerstone mission of the European Space Agency, on the calibration of the period-luminosity and luminosity-metallicity relations of Cepheids and RR Lyrae stars with specific emphasis about data published in *Gaia's* most recent releases: the Early Data Release 3 (EDR3) on 19 December 2020 and the DR3 on 13 June 2022. Then I will give some perspectives about future *Gaia* data releases that will take place within the next years.

Primary Period – Luminosity Relation Calibrators in the Milky Way: Cepheids and RR Lyrae – Physical basis, Calibration, and Applications

Martin Groenewegen

Koninklijke Sterrenwacht van Belgie, Brussels, Belgium

I will review recent work on the calibration and application of the period-luminosity relation of Cepheids and RR Lyrae stars in the Milky Way. This will include a discussion on the *Gaia* parallax zero-point offset as well as the application of the PL-relation in kinematical studies and studies of the metallicity gradient.

Cepheids with Giant Companions – A New Abundant Source of Cepheid Astrophysics

Bogumił Pilecki

Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, Poland

We will present the progress of our project which aim is to increase the number of known Cepheids in double-lined binary (SB2) systems from 6 to even 100 or more, that will allow us, among others, to measure Cepheid masses for a large sample of these important stars. Currently only 6 accurate masses are available, which hinders our understanding of physical properties of Cepheids and renders their mass-luminosity relation poorly constrained. At the same time, Cepheids are widely used for very essential measurements (extragalactic distances, the Hubble constant).

Examining Cepheid period-luminosity relations we selected as binary candidates, outlying Cepheids that are too bright for their periods. Up to now, we confirmed more than 50 as SB2 systems, while for almost 30 we detected a significant orbital motion of the components.

We will show preliminary orbits of these systems and summarize their orbital and inferred Cepheid properties. We identified systems with orbital periods even 5 times shorter than the shortest reported before as well as those with mass ratios significantly different from 1 (suggesting merging events in the past). Both these features are essential to understand how multiplicity affects the creation and destruction of Cepheids' progenitors and what effect it has on global properties of Cepheids. We will also present several new systems composed of two Cepheids (only one such system is currently known).

A 0.9% Calibration of the Galactic Cepheid Luminosity Scale based on *Gaia* DR3 Open Cluster Astrometry

Mauricio Cruz Reyes, Richard I. Anderson

EPFL, Lausanne, Switzerland

We present a study that calibrates the Galactic Leavitt law to the highest available accuracy using Cepheids residing in open star clusters. We developed a method for detecting open clusters near Cepheids. This has allowed us to discover 3 new host clusters and update the parameters of 31 previously discovered ones. Cluster member stars span a similar magnitude and color range as the LMC stars and quasars used by Lindegren et al. (2021) (hereafter L21) to determine *Gaia* parallax systematics, are non-variable, and are not subject to other complicating factors of *Gaia* data processing, such as the gating mechanism to avoid saturation of stars brighter than $G \sim 12$. Using this approach, we find an average uncertainty in the cluster parallaxes of 7μas, an improvement of a factor of three over the parallax uncertainties of individual field Cepheids. Using the known distance to the Large Magellanic Cloud based on detached eclipsing binaries as a cross-check, we find that the L21 corrections accurately describe the parallax offset for this sample of clusters to within $-4 \pm 6\mu$as.

Using 26 cluster Cepheids and 225 MW Cepheids with recent *Gaia* DR3 astrometry and photometry, we obtain the most accurate calibration of the Galactic LL to date. We measure the field Cepheid residual parallax offset (after applying L21 corrections) to a significance of 6σ, and our results are in excellent agreement with the results determined by the *SH0ES* distance ladder. Lastly, we simultaneously calibrate the Leavitt law in several photometric bands (*Bp, V, G, Rp, I, F160W*) while solving for the parallax offset, we calibrate the fiducial absolute magnitude of 10-d Cepheids to within 0.019 mag using both *Gaia* and *HST* Wesenheit magnitudes, enabling distance determinations with relative errors as low as 0.9%.

Cepheid Metallicity in the Leavitt Law (C- MetaLL) Survey. The Metallicity Dependence of Cepheid Period-Luminosity Relations

Erasmo Trentin[1], Vincenzo Ripepi, Giovanni Catanzaro, Roberto Molinaro, Marcella Marconi, Ilaria Musella, Jesper Storm, Giulia De Somma, Anupam Bhardwaj, Massimiliano Gatto, C-MetaLL Team

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Classical Cepheids (DCEPs) are the first fundamental step in the calibration of the cosmological distance ladder and represent powerful tracers in the context of Galactic studies. In the context of the C-MetaLL (Cepheids-Metallicity in the Leavitt Law) survey, we calculated detailed abundances for a sample of 65 distant anti-center DCEPs, based on UVES@VLT high-resolution spectroscopy. We complemented this data with literature, obtaining a total sample of 633 DCEPs with metallicity from high-resolution spectroscopy. Furthermore, we considered a second sample comprehensive of the previous one plus 508 stars with *Gaia* metallicities obtained at mid-resolution with the *Gaia* RVS instrument.

Taking advantage of literature data, *Gaia* DR3 and 2MASS surveys, we collected photometry in the V, I, G, GBP, GRP, J, H, Ks bands for all the DCEPs in our sample. These data were used to build a variety of reddening-free Wesenheit magnitudes. We use all these photometric and spectroscopic data, in conjunction with *Gaia* DR3 parallaxes to calibrate a variety of PLZ and PWZ relations and study the metallicity dependence of both the zero point (γ) and slope (δ) of these relations. Generally, for the sample including *Gaia* metallicities we obtain a strong negative effect of the metallicity for the former parameter (γ~ −0.5 mag*dex-1) and no clear dependence on the band used, while in almost all the cases, the δ term seems unsignificant within the error. The sample without *Gaia* metallicities presents similar results.

Concluding, our investigation confirms a larger metallicity dependence with respect to that used in the measure of H0 by the SH0ES collaboration. The origin of such a discrepancy is still unexplained.

RR Lyrae Stars as Distance Indicators in the *Gaia* Era

Tatiana Muraveva

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RR Lyrae variables are particularly important since they can be used to study the age, formation, and structure of their parent stellar systems. Moreover, they are perfect tools to measure the distances and establish the cosmic distance ladder since they conform to a number of the fundamental relations, such as an optical luminosity-metallicity (MV – [Fe/H]) relation and infrared period–luminosity (PL) and PL-metallicity (PLZ) relations. An outstanding contribution to the study of the RR Lyrae fundamental relations is provided by the European Space Agency (ESA) mission *Gaia*, which delivers unprecedently accurate parallaxes for a large amount of RR Lyrae stars. The extraordinary quality and volume of these data pose novel challenges. Thus, the application of advanced techniques such as machine learning (ML) and the Bayesian approach becomes highly needed and timely. In my talk, I will outline the revolutionary progress achieved thanks to *Gaia* in the field of RR Lyrae stars and the future prospects expected with the *Gaia* DR4 currently foreseen for the end of 2025.

Exploring the Complexities of Determining Mean Luminosity in Variable Stars: The Impact of Biased Means in Weighted Procedures

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Accurately determining the period-luminosity relation requires accurate measurements of both period and luminosity. As we deal with variable stars, we need to compute the mean flux/magnitude from several measurements in a given photometric filter, then come successive steps to convert to bolometric quantities and then to luminosity when the distance is known. Though this seems simple, each step has its own complexity.

Here we show that even the very first step i.e., the determination of the mean when we have varying uncertainties, is an astonishingly complex topic. This does not only affect the mean but many other basic statistical estimators.

RRLs to Trace Early Galaxy Formation

Giuliana Fiorentino[1], V.F. Braga, G. Bono, M. Fabrizio, V. D'Orazio

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The first Gyrs of our Galactic halo can be probed by using ancient stellar population as traced by RR Lyrae stars (RRLs). Today, with the advancement in our knowledge of RR Lyrae properties belonging to the Halo and to nearby stellar systems (globular clusters, dwarf galaxies) we can provide sound constraints on the link between these stellar systems and the early formation of the Galactic spheroid. We plan to present recent results by using a detailed evolutionary analysis of RR Lyrae for which both optical and near infrared time-series and spectroscopic chemical abundances are available. In particular, we plan to focus our attention on the dependence of the pulsation properties when moving from the very metal-poor to the metal-rich regime. Finally, we plan to present preliminary results of a large photometric and spectroscopic survey of Bulge RRLs by using the new Adaptive Optics assisted NIR/MIR imager and integral field spectrograph ERIS available at ESO/VLT. This means new quantitative constraints on the impact of stellar crowding on the mean magnitude of RRLs, and in turn, a new look on the 3D structure of the Bulge.

Near-infrared Period-Luminosity Relations for Galactic RR Lyrae based on Photometry from OCA and *Gaia* DR3 Parallaxes

Bartłomiej Zgirski

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RR Lyrae stars are important distance indicators that serve us to test the calibration of the cosmic distance ladder in the direct neighborhood of the Milky Way. We present a new calibration of period-luminosity and period-luminosity-metallicity relations for Galactic RR Lyrae in JHKs bands based on the photometry gathered using the 0.8 m IRIS telescope from the Cerro Armazones Observatory in Chile and *Gaia* DR3 parallaxes. Metallicities of 23 stars had been taken from the work of Crestani et al. (2021). We compare the new relations with those available in the literature. The zero point of the new calibration is in very good agreement with the very accurate distance to the Large Magellanic Cloud (LMC) based on eclipsing binaries (Pietrzyński et al. 2019) and the VMC photometry of RR Lyrae stars from the LMC (e.g., Cusano et al. 2021). Finally, we discuss the impact of the new relations on distance determinations to a few nearby galaxies: LMC, SMC, Sculptor dSph, Fornax, and Carina.

The Cepheid Based Cosmic Distance Scale: New Constraints from Updated Synthetic Multi-filter Cepheid PL Relations

Musella Ilaria[1], Marconi Marcella, De Somma Giulia, Molinaro Roberto, Ripepi Vincenzo, Leccia Silvio

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In this work, I will present an updated set of synthetic Period-Luminosity (PL) relations, based on recently published non-linear and convective pulsating models for Classical Cepheids able to predict all the relevant observables (mean magnitude, period, amplitude, light curves) in any bands we are interested in.

These synthetic relations will be applied to observational Cepheid samples (both space- and ground-based) present in literature to obtain fundamental constraints on their distances and stellar properties, but also to point out the possible existence of systematic errors possibly affecting the Hubble constant determination. The application to the HST samples will allow us to compare our results with Riess et al. determinations, whereas the possibility to predict synthetic PL relations in the forthcoming Rubin-LSST filters and their dependence on both chemical compositions and model physical assumptions, will be crucial to optimize the scientific exploitation of this challenging survey.

Finally, I will also analyze the behavior of multi-filter synthetic PL relations of Ultra-Long Period Cepheids (ULPs) (Period > 80 d) that are suggested to be the extension at longer periods and higher mass of Classical Cepheids. Thanks to their luminosity, ULPs are observable up to cosmological distances (larger than 100 Mpc) allowing us, in principle, to measure the Hubble constant without the need for secondary distance indicators. Currently, the number of known ULPs is small (72), often lacking homogeneous and accurate photometry and their role as standard candles and their theoretical properties are not completely understood, but Rubin-LSST will offer the (unique) possibility to improve their knowledge.

Photometrical and Spectroscopic Measurement Campaign on the Stars RR Lyr (RR Lyrae) and R Scuti (RV Tauri), at the Oukaimeden Observatory in Morocco

Abdelmajid Benhida

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Since 2015, we have carried out intensive photometric and spectroscopic observation campaigns focused on the variable stars RR Lyr and RSct. For photometry, a 25-cm ASA 10N telescope was used with a QSI CCD camera. For spectroscopy, a 35.5-cm C14 telescope was used along with an eShel spectrograph (125mm F/5 collimator, R2 echelle Grating, cross-dispersing prism, 85mm F/1.8 objective). We have obtained a large database of spectra covering a large part of the visible domain (between orders 32 and 52, from 4100 to 7200 Å), with a resolving power of about 12000. With an exposure duration of 300 s, the signal-to-noise (S/N) ratio is approximately 30.

We focused on the atmospheric dynamics of large amplitude pulsations like RR Lyr and R Sct, to establish new models of the mechanical and thermal behavior of their atmospheres (shock waves, relaxation time, energy loss...). The aim of the campaign was to monitor the behavior of several observational signatures of shockwave propagation in the atmosphere of RR Lyr and R Sct.

In this talk, I will summarize our recent findings, including:
**For the star RR Lyr:
- The study of the evolution of the Hα profile and helium emission in different phases of Blazhko.
**For R Sct star
-The Hα profile in the optical spectrum of this star exhibits a striking degree of variability,
-Ti I λ6554.239 & Ca I λ6572.797 lines display emission components which change from an inverse P Cygni profile to a P Cygni profile.

Period-Luminosity Relations for Galactic Classical Cepheids in the Sloan Bands

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The Sloan photometric system is gaining in importance due to its adoption for large-scale photometric surveys of the sky, such as the Legacy Survey of Space and Time (LSST). With the LSST, large amounts of pulsating variable stars, especially Cepheids and RR Lyrae stars, are going to be uncovered in the outer halo of the Milky Way, as well as in other galaxies of the Local Group. In order to best utilize this mine of opportunities, the accurate period-luminosity (PL) and period-Wesenheit (PW) relations of pulsating stars in the Sloan bands are required. Therefore, we have derived PL and PW relations for Galactic Classical Cepheids in the Sloan *gri* bands based on time-series photometry of about 100 stars obtained with the 40 cm telescope network of the Las Cumbres Observatory and *Gaia* parallaxes.

On the Origin of Galactic Anomalous Cepheids

Vincenzo Ripepi[1], Giovanni Catanzaro[2], Erasmo Trentin[3], Oscar Straniero[4], Marcella Marconi[1]
& the C-MetaLL collaboration

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We investigate the origin of a sample of 12 Galactic Anomalous Cepheids whose chemical abundance has been determined through high-resolution spectroscopy.
We find an enhancement of alpha-elements which is consistent with the Galactic Halo distribution, but we also find a surprising enhancement in the abundance of Sodium which is only seen in Galactic Globular Clusters. We discuss in general the origin of the abundance patterns for the investigated objects in comparison with a large sample of stars belonging to both the Milky Way and several Local Group galaxies, finding that the excess of Sodium can only be explained by a scenario in which the investigated Anomalous Cepheids were formed in binary systems with an exchange of matter through a Roche Lobe overflow. We explore some possible evolutionary scenarios able to explain the observations.

Milky Way Components with RR Lyrae

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RR Lyrae have been used in the past to shed some light onto the properties of the oldest Galactic component, the halo. Thanks to *Gaia*, we can now use its enormous all-sky sample of RR Lyrae to build a comprehensive, uninterrupted panorama of the entire Galaxy. With this powerful data, the halo is revealed to have complex and multi-component make-up. Most surprisingly, many RR Lyrae have turned in the least expected place - the disk of the Milky Way. Im this presentation, I will discuss the most recent progress in our understating of the various Galactic components based on RR Lyrae.

Implication of the Period-Magnitude Relation for Massive AGB Stars and its Astronomical Applications

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We will present astrometric VLBI studies of the Galactic AGB stars conducted with VERA VLBI array, and also present an implication of a new Period-Magnitude relation found in mid-infrared wavelengths applied to massive pulsating AGB stars.

In the last stage of stellar evolution with initial masses of 0.8-10 solar masses, they spend a part of their lives as Asymptotic Giant Branch (AGB) stars. The Mira variables are well known AGB stars showing narrow Period-Magnitude relation in near infrared and recognized as a fundamental distance estimator. As they evolve, Mira variables scatter large amount of dust and gas to their outer layers, and they will soon be enshrouded by thick circumstellar envelopes. At this stage, they are recognized as OH/IR stars because they show emission excess in infrared and accompanied by OH masers. Due to extinction caused by the dust, trigonometric parallax measurements of OH/IR stars in visible band will be difficult. On the other hand, observations in the radio band are very effective. For now, astrometric VLBI observations towards H_2O and SiO masers frequently associated with dust-enshrouded massive OH/IR stars are effective way to measure their parallaxes.

Our studies with VERA VLBI array at 22 and 43 GHz have revealed distances of dozens of dusty AGB stars in our Galaxy. From 2003 to 2017, we have mainly observed Mira variables with pulsation periods around 300 to 400 days and revealed Period-Magnitude relation. Now, we aim to establish a Period-Magnitude relation as a distance estimator for more massive, long-period AGB stars by determining absolute magnitudes based on our parallax measurements. Absolute magnitudes obtained in the mid-infrared imply presence of a Period-Magnitude relation in long-period regions where there have not been sufficient numbers of stars to study. In addition, it is possible to study the galactic structure by observing massive, long-period AGB stars. As an example, we will present our study of an OH/IR star, NSV 17351.

The Structure of the Milky Way from Period-luminosity Relations

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Disentangling the structural components of the Milky Way requires knowledge of distances to various classes of objects, both young, which trace the galactic disk, and old, which trace the galactic bulge and halo. Variable stars that obey period-luminosity relations are perfect distance indicators for such studies. I will discuss recent findings on the structure of our Galaxy, inferred from period-luminosity relations for both young, old, and intermediate age variable stars, including Cepheids, RR Lyrae stars, delta Scuti stars and Long Period Variables.

Variability Properties of the *Gaia* DR3 Catalogue of Galactic AGB Stars

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Asymptotic Giant Branch (AGB) stars are very common and very luminous pulsating stars. This type of star has been proposed as a possible cosmic distant indicator able to reach longer distances than Cepheids due to their higher luminosities. However, details on their variability properties are not well known and the period-luminosity relationship is not yet well characterized. Due to the lack of accurate distances to galactic AGB stars, studies on the AGB variability properties have been in the past mainly done using the Magellanic Cloud population of AGB stars. Now, thanks to the *Gaia* mission, we are able to explore the galactic AGB population on a larger scale, taking advantage of the distances provided by *Gaia*.

We present a study of a sample of thousands of galactic AGB stars with O- or C-rich chemistries, built by cross-matching available literature compilations of AGB stars and the *Gaia* DR3 catalogue. We built their spectral energy distributions from the Virtual Observatory and obtained their luminosity using the distances derived from the *Gaia* data. In addition, we analysed the *Gaia* DR3 light curves to characterize their variability properties.

In this talk I will present the results of this study, with special emphasis on the comparison between the properties shown by O- and C-rich galactic AGB populations. We will also discuss the possible Period-Luminosity-Amplitude relationships.

Granulation in Red Supergiants: The Scaling Relations

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The mechanisms and characteristics of the irregular variations of red supergiants (RSGs) are studied based on the most complete RSG samples in the Small Magellanic Cloud (SMC), Large Magellanic Cloud (LMC), and M31. With the timeseries data from the ASAS-SN, OGLE, and iPTF. We use the continuous time autoregressive moving average model or Generalized Lomb–Scargle periodogram method to estimate the variability features of the light curves and their power spectral density (PSD). The characteristic evolution timescale and amplitude of granulations are further derived from fitting the PSD with the COR function, which is a Harvey-like granulation model. The consistency of theoretical predictions and results is checked to verify the correctness of the assumption that granulations on RSGs contribute to irregular variation. The relations between granulation and stellar parameters (i.e., the scaling relations) are obtained and compared with the results of red giant branch (RGB) stars and Betelgeuse. It is found that the relations are in agreement with predictions from basic physical process of granulation and fall close to the extrapolated relations of RGB stars.

The results imply that the irregular variations of RSGs can be attributed to the evolution of granulations. At the same time, the scaling relations of RSGs provide a new method to infer stellar parameters (luminosity, mass, surface gravity, effective temperature, radius) by using the characteristic timescale and amplitude of granulations.

Towards Homogeneous Distances in the Local Group

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In the last years we have been running a long-term project aimed at deriving the properties of RR Lyrae stars in all bright Local Group galaxies. Nearby Milky Way satellites have been studied with highly homogeneous photometry from the database of P.B. Stetson. More distant objects have been observed with the Hubble Space Telescope, and the data have been reduced with similar prescriptions. One of the objectives of the project is to provide homogeneous distances, anchored to *Gaia*-calibrated indicators, for a large number of systems. In this talk I will present the last galaxies included, Eridanus II and Leo II, and the first global results.

The Distance Scales of Anomalous and Type 2 Cepheids from Near Infrared Observations in the Magellanic Clouds

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One of the most debated issues in modern astrophysics is the so-called Hubble tension, i.e., the 5σ discrepancy between the value H_0 obtained by means of the extragalactic distance scale, typically based on the Classical Cepheids and supernovae Ia, and that derived with the Cosmic Microwave Background (see e.g., Riess et al. 2022, ApJ, 934, L7). In this context, it is possible to use old standard candles such as RR Lyrae variables, type II Cepheids and tip of the Red Giant Branch (TRGB), to provide independent constraints on the extragalactic distance scale and thus verify the possible presence of systematic errors in the distances derived from the younger Classical Cepheid. Particular relevance is assumed in this framework by the Large and Small Magellanic Clouds (LMC and SMC). Indeed, these galaxies are fundamental anchors of the extragalactic distance scale and, hosting Classical, Type II, Anomalous Cepheids (intermediate-to-old age pulsating stars with characteristics similar to Classical Cepheids) and RR Lyrae, are the ideal laboratory to compare the distance scales obtained for each standard candle.

In this work, we exploit the time-series photometry in the near-Infrared (NIR) bands Y, J and K_S for a sample of type II (BL Herculis, W Virginis, RV Tauri sub-classes) and Anomalous Cepheids, comprising more than 530 objects and located both in the LMC and SMC. These data were acquired in the context of the "The VISTA near-infrared YJKs survey of the Magellanic System" (VMC, P.I. M.R. Cioni) which has been carried out with the VIRCAM@VISTA instrument. We determined the intensity-averaged magnitudes for all the stars in our sample by using a template technique. To this aim we built the multi-band templates from our own data. Reliable uncertainties on these quantities were obtained through a bootstrap technique. Our NIR photometry was complemented with the V, I magnitudes from the OGLE IV survey and G, G_{BP}, G_{RP} magnitudes from the *Gaia* mission. All the magnitudes were dereddened by means of up-to-date reddening maps of the Magellanic Clouds available in the literature. These data allowed us to build a variety of period-luminosity (PL), period-luminosity-colour (PLC) and period-Wesenheit (PW) relationships, including any combination of the available photometric bands.

We investigated the behaviour of the slope and zero point of the quoted relationships as a function of wavelength, verifying that, in analogy to Classical Cepheids, both for type II and Anomalous Cepheids, the PL/PW relations become steeper (higher absolute slope value) and tighter (smaller dispersion) going from blue to NIR bands.

Absolute zero points for selected relationships have been obtained by adopting a geometric distance to the LMC. These relations were tested using type II Cepheids both belonging to Galactic Globular Clusters (GGCs) and to the Galactic field. We calculated the distances of 24 GGCs and compared them with the literature values, mainly based on RR Lyrae stars, finding good agreement well within 1 σ and an overall dispersion of the order of 0.3-0.5 kpc, depending on the PL/PW relation used. The same relations were applied to a sample of 21 field type II Cepheids with good multi-band photometry and parallax from the *Gaia* mission, to calculate their distances and in turn their photometric parallaxes. The comparison between the latter and the *Gaia* ones allowed us to estimate the absolute zero-point offset of the *Gaia* parallaxes. A similar procedure was carried out with Anomalous Cepheids in several dwarf galaxies of the Local Group, finding again good agreement with the distances coming from RR Lyrae stars.

Early-type Eclipsing Binaries as Distance Indicators

Mónica Taormina

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In the goal to measure precise distances to galaxies farther than LMC, and determine the accurate value of the Hubble constant, the eclipsing binary systems composed of early-type stars can play an important role. However, it is fundamental as a first step to get a reliable and empirical surface brightness-color relation (SBCR) for this type of stars. For this purpose, we carried out a spectroscopic and photometric analysis of a sample of O- and B-type detached eclipsing binaries located in the LMC and obtained accurate physical parameters of their components. Based on that, and including the additional modeling of infrared light curves we prepared the calibration of the SBCR for stars with V-Ks < 0 mag. This is the first such calibration done for stars similar to those that will be used in the future for distance determination to other galaxies, i.e., fast-rotating components of massive binary systems.

Sub-percent Binary Star Masses and Distances from Interferometric Observations

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Our knowledge of stellar evolution relies on constraints provided by measurements of the physical stellar properties such that the mass, effective temperature, and radii. The most fundamental parameter, the stellar mass, is rarely available or has a low accuracy, providing poor constraints on the stellar structure and evolution. Observing binary stars combining astrometry and spectroscopy offers the unique opportunity to measure very precise masses. In addition, double-lined spectroscopic binaries provide independent distance measurements with an extreme accuracy, allowing to test the *Gaia* parallaxes and the P-L relations. I will show that masses and distances as high as 0.05% accuracy level can be obtained by combining interferometric and spectroscopic observations for different type of binary systems, i.e., binary Cepheids, eclipsing and normal binaries.

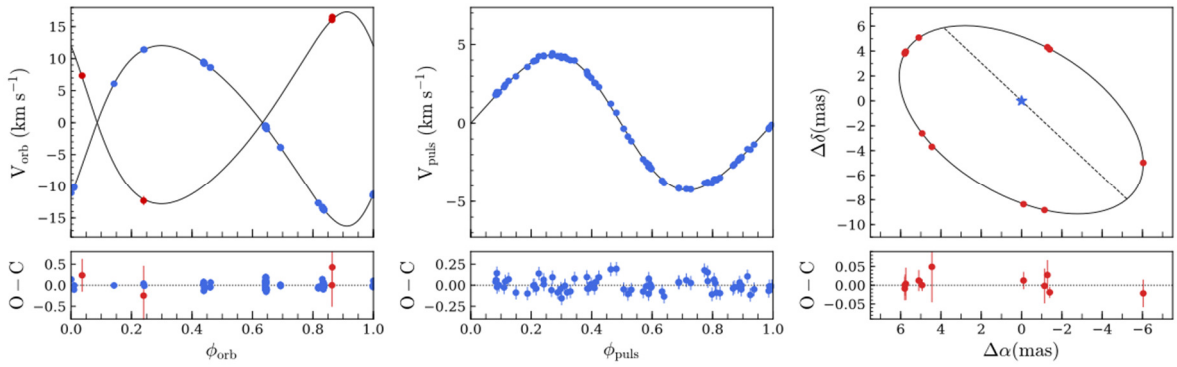

Figure 1: *Left: fitted (solid lines) and extracted primary (blue dots) and secondary (red dots) orbital velocity. Middle: fitted (solid line) and extracted (blue dots) pulsation velocity. Right: relative astrometric orbit of V1334 Cyg Ab.*

On the Use of the Mean J-band Magnitude of Carbon Stars as a Distance Indicator

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The use of Carbon Stars (CS) as distance indicators in the optical regime was suggested in the early 80s by Richer and collaborators. During the last few years this distance indicator received special attention from the astronomical community, since the accuracy of near infrared (NIR) measurements significantly improved and also because the current ground- and space-based observing facilities allow us to identify CS in Local Group (LG) and in Local Volume galaxies (Lee et al. 2022). In spite of these key advantages, we still lack a solid theoretical framework to constrain the dependence on stellar ages, chemical enrichment and on dust formation. We plan to present a new and homogeneous theoretical framework to investigate the possible occurrence of systematics covering both optical, NIR and mid-infrared (MIR) photometric bands. Moreover, and even more importantly, we will discuss the selection criteria we adopted to select CS in the dwarf irregular galaxy NGC 6822 (Tantalo et al. 2022) and we will also provide new distances by using CS, the tip of the red Giant Branch (i-band), optical/NIR/MIR Period-Luminosity (PL) relations of Classical Cepheids and the I-band PL relations for RR Lyrae stars. This means that NGC 6822 becomes one of the very few LG galaxies for which we can constrain the intrinsic accuracy of distance indicators tracing old, intermediate and young stellar populations.

RR Lyrae Light Curves and their Role in the Globular Cluster Metallicity and Distance Determination

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For more than a decade CCD time series of selected globular clusters have been systematically employed to Fourier decompose the light curves of cluster member RR Lyrae stars.

Well known semi-empirical calibrations of [Fe/H] and Mv in terms of the Fourier parameters lead to homogeneous determinations of the metallicity and distance. Particular care has been taken in defining the zero points of the luminosity calibrations. We present the results for 37 globular clusters and discuss the implications in the nature of the [Fe/H]-Mv relation, which seems substantially different for RRab and RRc stars. The role of the horizontal branch structure in the estimation of the distance is considered. Finally, the resulting values of [Fe/H] and distance compared favourably with sound independent estimates from high resolution spectroscopy and recent *Gaia* parallax distance determinations, respectively.

In the process of the above strategy numerous other aspects of astrophysical interest emerge; stars cluster membership, evolutionary time scales from Main sequence to ZAHB, inner mass distribution of certain variables, RR Lyraes distribution of the HB and the Oosterhoff cluster type connection, P-L relationship for SX Phe stars and certainly the discovery of many previously undetected variables. Time permitting, I shall discuss some of these aspects.

Using Classical Cepheids to Study the Far Side of the Milky Way Disk

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We are currently experiencing an era where distances are precisely being measured for more than one billion stars in our Galaxy by the *Gaia* mission. However, our knowledge of the MW innermost regions, and those lying beyond them, in the disk on the other side of the Galactic center, is far from complete. The difficulty to unveil these regions mainly arises from our location in the disk mid-plane and the large distances involved. A number of open questions are still pending an answer: What is the spiral structure of the MW? Are the properties of the young stellar populations of the disk similar in the far and near side of the Galaxy? And their radial extent? What is causing the warp of the disk?

Classical Cepheids (CCs) can help us to improve this situation, since they are young, luminous, and - relatively - easy identifiable standard candles, which makes them ideal tracers of the Galactic disk. Their location at the Milky Way disk complicates their identification, mainly due to the substantial reddening they are subject to. This is particularly true when studying them at the far side of the Galactic disk, but it can be surpassed with the use of infrared (IR) photometry. However, the classification based solely on near-IR light curves has proven difficult, and prone to providing highly contaminated samples.

We will show how the use of additional observable properties aids in the light-curve based classification process and present two different approaches to obtain clean samples of CCs: (1) Using spectroscopic follow-up data for a sample of CC candidates. (2) Using proper motions and colors obtained from the Vista Variables in the Vía Láctea Survey. Consequently, we have been able to significantly increase the number of bona fide CCs at the far disk. We present our results on the properties of the far Galactic disk (its structure, metallicity gradient and rotation curve) using these young tracers and discuss the prospects of this project.

The PL Diagram for dSct: Back in Business as Distance Estimators

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Delta Scuti pulsators are A-F type stars located where the instability strip crosses the main sequence in the HR diagram. Thus, they were considered as potential distance estimators as their most luminous "cousins", the Cepheids. However, the variety and quantity of modes showed by these stars complicate the identification of the fundamental radial mode (F0).

Gaia's precise luminosities helped to place Delta Scuti in the period-luminosity (PL) diagram (as previous works have shown, such as Ziaali+2019, Poro+2021, Barac+2022). Still, obtaining a unique PL relation (PLR) is not an easy task due to (1) the presence on nonradial modes, and (2) gravity darkening effects for rapid rotators (Royer+2007).

Here we demonstrate how to spot the fundamental radial mode in a PL diagram, and hence constraining the location of the Delta Scuti pulsation regime so it can be used for classification purposes. Moreover, we use the large separation-mean density relation for Delta Scuti stars discovered by our team (see for example, Suárez+2014; Garcia Hernández+2015, 2017) and the F0-large separation tight relation (presented here for the first time) to pointing out the position of other radial orders in the PL diagram. And, finally, we use the luminosity from *Gaia* affected by gravity darkening and the PLR to determine rotation rates and inclination angles.

Thus, spotting F0 and solving the gravity darkening effect, a reliable PLR for Delta Scuti stars can be used as distance estimator.

Theoretical Stellar Pulsation Physics

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Pulsating stars play a crucial role in the calibration of the cosmic distance scale as well as in tracing the properties of the associated stellar populations. In the era of large observational surveys and precise astrometric missions, it is crucial to rely on accurate stellar pulsation models able to predict the observed behaviors for different physical assumptions.

Indeed, the relations currently used in the literature to derive individual and mean distances of mainly radially pulsating stars such as Cepheids and RR Lyrae are well physically understood but are also known to depend on a number of often unknown parameters. Recent extensive sets of stellar pulsation models developed by various authors show how variations in the physical assumptions can affect the theoretical prediction of the instability strip boundaries, the morphology and amplitude of light and radial velocity curves and the consequent Period-Luminosity, Period-Luminosity-Color ad Period-Wesenheit relations. These aspects are discussed in the framework of current open problems in the field of classical pulsating stars.

Period-Luminosity-Metallicity Relations for Classical Pulsators at Near-infrared Wavelengths

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Classical Cepheids and RR Lyrae variables are the most vital tools for the extragalactic distance scale thanks to their tight Period-Luminosity-Metallicity (PLZ) relations at near-infrared (NIR) wavelengths. The absolute calibration of PLZ relations for these classical pulsating stars is crucial for the first step of the cosmic distance ladder measuring the Hubble constant. Despite the improvements in *Gaia* parallaxes, the precision of the absolute calibration of Galactic PLZ relations for Cepheids and RR Lyrae variables is limited due to inhomogeneous NIR photometry and spectroscopy of Milky Way field variables. We present a summary of an observational program on NIR monitoring of 1000 RR Lyrae and Type II Cepheid variables in 10 globular clusters covering a wide metallicity range (-0.4 < [Fe/H] < -2.4 dex) using the CFHT and Gemini telescopes. The empirically derived NIR PLZ relations for RR Lyrae variables show excellent agreement with theoretical predictions confirming a strong metallicity effect on their luminosities. Homogeneous high resolution spectroscopic metallicities and multiband time-series photometry for 60 Milky Way Cepheid standards were also obtained to empirically calibrate their NIR PLZ relations. We discuss the implications of newly calibrated PLZ relations for Cepheid and RR Lyrae variables using NIR observations of these variables in the Magellanic Clouds and nearby dwarf spheroidal galaxies.

First Direct Measurement of the Stellar Association Bias in the SN Host Galaxy M101

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We measure directly for the first time the stellar association bias caused by the physical association of Cepheids with their birth clusters in order to validate and improve the stellar association bias corrections applied to the late-Universe Ho measurement. For this purpose, we quantify the occurrence of Cepheids in (or near) open clusters in the SNeI a host anchor M101. We used HST/WFC3 UV observations of the Cepheids previously identified by the SH0ES project. UV observations allow to discover clusters that would not be detectable without UV photometry. We visually inspected the UV images for UV flux at the location of the Cepheids and checked whether there was evidence of that flux in the other available passbands (optical and near-IR). We evaluated the properties of the Cepheids occurring in open clusters in terms of period, magnitude and galactic location (e.g., star forming regions) and created an inventory with the properties of the Cepheids in the WFC3 footprint. We projected the M101 images to greater distances and measured the changes in amplitude and color with PSF photometry for both field and cluster Cepheids. Early results show that the fraction of Cepheids in open clusters in M101 is higher than the equivalent one measured in M31, however the fraction of clustered Cepheids found within 2 kpc of the Sun is not an outlier with respect to clustered Cepheid fractions on similar scales in M101. We found that the majority of the Cepheids found in open clusters are in star forming regions and have periods larger than 10 days. We estimated the effect of the stellar association bias on the distance ladder and our results agree with the corrections currently applied in the measurement of H0. These observations, enable the first direct measurement of stellar association bias in a SN host galaxy, provide a crucial sanity check for the measurement of H0 and allow the development of improved selection criteria that could further reduce the impact of stellar association bias at distances beyond the Local Group.

An Independent Analysis of the Multi-Wavelength Cepheid PL Relations in NGC 7250

Kayla Owens[1], Wendy Freedman, In Sung Jang, Barry Madore, Taylor Hoyt, Abigail Lee

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The Cepheid period-luminosity (PL) relation is the basis of the currently most precise measurement of the Hubble constant (H0), as determined by the SH0ES team (Riess et al. 2022). Despite the precision of the measurement, there are known issues with the data, including unexpectedly large scatter in the infrared PL relations. To investigate this, we have conducted a full reanalysis of the Cepheids in the supernova calibrator galaxy NGC 7250. We re-reduced all of the HST images using the photometry software DOLPHOT. We performed an independent variable identification using different methodologies and *newly-constructed* templates, and we redetermined all properties of the identified variables using these new templates. For the first time, we will show period-luminosity relations and light curves for the Cepheids in all four filters (F350LP, F555W, F814W, and F160W) in this galaxy. Further, using new data from JWST, we will show a single-epoch F115W PL relation for these same Cepheids, which reduces the infrared scatter (compared to HST F160W) by more than a factor of 2. This scatter is now consistent with the intrinsic scatter expected in the infrared. Finally, we use the 4x increased resolution of JWST to identify unresolved crowding stars on the HST infrared images that may explain the increased scatter in the F160W PL relation. These early results are part of a larger program targeting 11 of the supernova calibrator galaxies, and they show great promise for the success of the overall program in reducing statistical and systematic errors in the distance scale.

A Multi-phase Study of Theoretical and Observed Light Curves of Classical Cepheids in the Magellanic Clouds

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This work presents the study of multi-phase Period Colour (MPPC)/Period Luminosity (MPPL) relations of classical Cepheids (Cepheids) for short periods (log $P < 1$), long periods (log $P > 1$) and all periods in the Magellanic Clouds. The observed light curves are taken from the OGLE-IV database. MESA has been utilized to generate the theoretical light curves of Cepheids for metallicity appropriate for the LMC ($Z = 0.008$) and SMC ($Z = 0.004$) in V I-bands using four sets of convection parameters. From the analysis, it has been found that the multi-phase relations obtained using the models as well as observations in the PC/PL plane are dynamic in nature with pulsational phase with the effect more pronounced at $\Phi \sim 0.75 - 0.85$. MPPC and MPPL relations using the observed light curves and the models across the four convection sets for short and long periods are seen to display contrasting behaviour for both LMC and SMC. It has been observed that the multi-phase relations obtained from the Cepheid models display a clear distinction among different sets in most phases. The multi-phase relations obtained using the models in all the sets are found to agree better with the observations in the PC plane. In the PL plane, some discrepancy between the models and observations is observed. Comparison of the multi-phase relations obtained from the models and observations is one way to test the models with the observations and to constrain the theory of pulsation.

Metallicity Estimations of MW, SMC, and LMC Classical Cepheids from the Shape of the V- and I-band Light Curves

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Estimating the metallicity of classical Cepheids is of prime importance for studying metallicity effects on stellar evolution and the chemical evolution of galaxies, as well as on the period-luminosity relation used on the extragalactic distance scale. Until now, high-resolution spectroscopic observations have led to determinations of the iron-to-hydrogen ratio [Fe/H] for several hundreds of Cepheids, which are mostly within about 5 kpc (see Figure, left). Indeed, these observations are difficult to apply to faint stars that are distant or that are located in the line of sight of a significantly reddened environment such as the Galactic Center. An interesting alternative to spectroscopy is to carry out estimations of the metallicity of the Cepheids using the light curve shape. Although this method can be less precise, it has the advantage to be easily applied for a large number of Cepheids which are not accessible via spectroscopy (see Figure). I□Hocdé et al. 2023, we prese□t a□i□□ovative calibratio□of these empirical relatio□s i□the V a□d I ba□ds, from an extensive dataset gathered in literature. I will show that these relations for short and long-period Cepheids are able to distinguish metallicity population from MW, SMC and LMC. Furthermore, these relations are able to reconstruct the metallicity gradient in the MW, and thus could be useful for galactic archaeology and studying the metallicity effect on the PL relation.

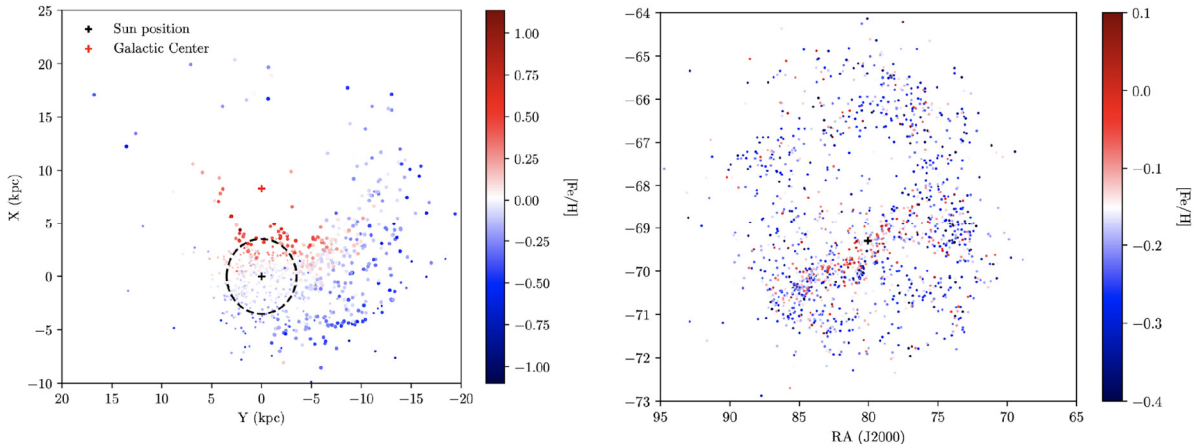

Figure 1: *Metallicity distribution of MW (left, 863 stars) and LMC (right, 1678 stars) from empirical metallicity relations in the I-band (Hocdé et al. 2023). On the left small points are values from literature (HR spectroscopy), bigger points are estimations.*

Double-mode RR Lyrae Star – A Robust Distance and Metallicity Indicator

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RR Lyrae stars are one of the primary distance indicators for old stellar populations such as globular clusters, dwarf galaxies, and galaxies. Typically, fundamental-mode RR Lyrae stars (RRab) are used for distance measurements, and their accuracy is strongly limited by the dependence of absolute magnitudes on metallicity, both in the optical and infrared bands. Here, we report the discovery of a period–(period ratio)–metallicity relation for double-mode RR Lyrae stars (RRd), which can predict metallicity as accurately as the low-resolution spectra. With theoretical and observational evidence, we propose that the period–luminosity relation (PLR) of RRd stars is not affected by the metallicity. Combining the Large Magellanic Cloud distance and *Gaia* parallaxes, we calibrate the zero point of the PLR to an error of 0.022 mag, which means that in the best case, RRd stars can anchor galaxy distances to an accuracy of 1.0%. For four globular clusters and two dwarf galaxies, we obtain distances using RRd stars with a distance accuracy of 2-3% and 1-2%, respectively. With future telescopes such as CSST and LSST, RRd stars will be established as an independent distance ladder in the near-field universe.

Empirical Constraints for the Instability Strip from the Analysis of LMC Cepheids

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The comparison of the theoretical instability strip (IS) edges with those obtained empirically, using the most recent Cepheid catalogs available, can provide us with insight into the physical processes that determine the position of the IS boundaries. The shape of the IS is also connected with the shape of the P-L relation. We obtained an empirical IS for the classical Cepheids in the Large Magellanic Cloud (LMC) using data of classical fundamental-mode (F) and first overtone (1O) LMC Cepheids from the OGLE-IV variable star catalog. After careful cleaning, our final sample includes 1929 F and 1268 1O Cepheids. We studied their position on the color-magnitude diagram and determined the intrinsic IS borders taking into account their distribution and reddening from a recent reddening map. We found a break in the IS located at a period of about 3 days. This phenomenon coincides with the break reported in the literature for the period-luminosity relation and adds complexity to the typically assumed shape of the IS. In addition, we compare our empirical borders with theoretical predictions published in the literature. For particular choices of model parameters, we obtained a good agreement between theory and observations.

The Period-Luminosity Relation of Red Supergiants

Biwei Jiang[1], Ming Yang, Yi Ren, Zehao Zhang

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Red supergiants (RSGs) are the brightest variable stars in near infrared (NIR) to be potential cosmic candle. In particular, the extinction in NIR is about one order of magnitude smaller than in optical, which reduces greatly the uncertainty of distance induced by interstellar extinction. With the development of large-scale time-domain surveys like ASAS-SN, OGLE and ZTF, the time coverage of observation is extended to as long as 10 years so that the long-time variation of RSGs can be investigated with higher accuracy. New methods in combination with deep photometry and numerous astrometry by e.g., UKIRT and *Gaia* lead to much more complete samples of RSGs. In addition, the accurate distance measurements imply the improved calibration of the zero point of the P-L relation. This talk will discuss the P-L relations of RSGs in the Milky Way and the nearby galaxies including the Magellanic Clouds, M31 and M33, and their dependence on the galactic environment.

Period-Luminosity Relations Formed by Contact and Close Binary Systems

Michał Pawlak

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Contact and close binary stars are known to form period-luminosity or period-luminosity-colour relations due to the correlation between the radius of the orbit and the size of the components of the system. While these relations are usually less tight than the ones formed by classical pulsators, they also have certain advantage. Close binary system are very abundant, relatively easy to detect with time-series photometric data. They appear among practically all types of stars, and not restricted to a particular population or evolutionary stage. In recent years, large sky surveys like OGLE, *Gaia* and ASAS-SN have provided unprecedented amount of data, allowing for calibration and analysis of a broad range of binary period-luminosity relations.

In this presentation I will give an overview of the known period-luminosity relations formed by contact and close binary stars. These include ellipsoidal red giants and early-type main-sequence stars in the Magellanic Clouds, as well as galactic W UMa-type systems. I will also present some of the possible applications of the binary period-luminosity relations.

Comprehensive Analysis of Mira-type Stars Variability and the Structure of the Milky Way

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We conducted a detailed analysis of the variability of Mira-type stars in the Large Magellanic Cloud by examining light curves in 14 different bands ranging from 0.5 to 24 microns. Utilizing data from the Optical Gravitational Lensing Experiment (OGLE), we modeled densely covered 20-year-long *I*-band light curves for over 1600 Miras and used this information to fit templates to near- and mid-infrared data from surveys such as VMC, WISE, and Spitzer. Our findings revealed that the variability amplitude ratio decreases with increasing wavelength, while the phase lag between bands slightly increases with wavelength. Additionally, we analyzed Spectral Energy Distributions for 140 Miras and using synthetic light curves derived Period-Luminosity Relations (PLRs) in 42 bands from existing and future sky surveys. By searching the OGLE databases, we discovered almost 66,000 Miras in the Milky Way's bulge and disk, with two-thirds of them being new discoveries. Our results on the Miras' variability, PLRs in mid-infrared bands, and mid-infrared observations from WISE and Spitzer allowed us to determine distances to each Galactic Mira star. This, in combination with precise measurements of pulsation periods and coordinates, enabled us to analyze the three-dimensional structure of the Milky Way as seen through the Mira variable stars.

Distance Estimates for AGB Stars - *Gaia* DR3 Parallax and PL Relation

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Determining the distances to asymptotic giant branch (AGB) stars is not a trivial task. The parallaxes of AGB stars measured with optical telescopes such as *Gaia* are bound to have large errors. Indeed, the intrinsic properties of these variable stars, such as their large size, colour, surface brightness variability, and circumstellar dust, bring significant uncertainties to their parallax measurements. In some cases, the extent of these uncertainties makes the derived distances unreliable. This highlights the need for a well-calibrated period-luminosity (PL) relation as an alternative distance estimator for these variables. In this talk, I will present the results of our statistical analysis of the parallaxes, and the corresponding distances, of a sample of nearby AGB stars measured by *Gaia* DR3. In particular, *Gaia* DR3 parallaxes were calibrated using more-robust parallax measurements from maser emission for a sub-sample of these stars. In addition, I will present and discuss the newly-calibrated bolometric PL relation that we derived for Galactic oxygen-rich Mira variables.

Breaking the Law:
A Segmented Period – Luminosity Relation in delta Scuti Stars

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Delta Scuti stars are variable stars located at the intersection of the classical instability strip and the main sequence, with periods between 0.008 - 0.42 days and amplitudes between 0.001 - 1.7 mag in the V-band. This kind of variable stars near the main sequence turn-off (MSTO) has been targeted as possibly being responsible, in part, for extended or split MSTOs observed in intermediate-age clusters and have also been used to constrain the age of star clusters. Delta Scuti are radially pulsating stars that have been shown to follow a period-luminosity relation in the visible and are thus potentially useful distance indicators. They have been extensively studied in the Milky Way, but far less in extragalactic systems. Their period-luminosity dependency had always been described by a linear relation; however, when studying ~4000 extragalactic delta Scuti stars from the Magellanic Clouds and a few other Milky Way dwarf satellite galaxies, we noticed a non-linear behavior in the period-luminosity relation of delta Scuti stars. The best fit to the period-luminosity plane is given by a piecewise linear relation with a break at log P = –1.03 +/- 0.01 (or –0.093 +/- 0.002 days).
Geometric or depth effects in the Large Magellanic Clouds, metallicity dependence, or different pulsation modes are discarded as possible causes of this segmented relation seen in nearby extragalactic delta Scuti stars. Although the origin of the segmented relation with a break at ~0.09 days remains unexplained, the behavior has proven to be not spurious, visible not only in extragalactic but in Galactic fields as well.

Long-Period Variables as Distance and Age Indicators in the Era of *Gaia* and LSST

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[6]*Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia*

Low- and intermediate-mass stars terminate their evolution on the Asymptotic Giant Branch (AGB) as Long-Period Variables (LPVs): bright red giants pulsating on timescales between about a month and a few years. Their variability is known as a powerful diagnostic for constraining stellar physics (most importantly dust formation and mass loss, key to galaxy evolution) and estimating elusive stellar properties (masses, radii, ...). LPVs obey period-age and period-luminosity relations enabling their use as distance indicators and for mapping young- and intermediate-age stellar populations. Miras, a class of highly luminous LPVs characterized by large visual amplitudes, are especially promising for reaching further distances than those accessible to Classical Cepheids. In this talk I will provide an overview of our recent research in this active field, with focus on two main subjects. I will discuss the current status and prospects of the theoretical machinery developed by the Padova stellar research group. This highly integrated framework of evolutionary tracks, pulsation models, and stellar population synthesis tools was crucial to attain a self-consistent interpretation of the global properties of LPVs observed by OGLE and *Gaia* in the Magellanic Clouds and will be foundational to analyze the massive amount of data from upcoming large-scale variability surveys such as Rubin-LSST. At the same time, the understanding obtained from these models is instrumental for the extraction of a substantial wealth of information still buried in existing observational catalogs. This is especially true for the Semi-Regular Variables (SRVs), the somewhat neglected progenitors of Miras that have the potential to complement the latter as distance indicators. Compared to Miras, SRVs are more numerous in any given stellar population, follow the same period-luminosity relation as well as an additional one and suffer from shallower circumstellar extinction. Moreover, they are found in older stellar populations, often probed with RR Lyrae variables, compared to which the SRVs are substantially brighter. These arguments motivated a project aimed at assessing their potential as standard candles, the results of which I will present in the second part of this talk.

The Mira Distance to M101

Caroline Huang[1], Wenlong Yuan, Adam Riess, Warren Hack, Randall Smith, Nadia Zakamska, Stefano Casertano, Lucas Macri

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The increasing discordance between local measurements of the Hubble constant and the value inferred from observations of the cosmic microwave background has posed a serious challenge to LambdaCDM. Direct, distance-ladder measurements of the Hubble constant rely primarily on Cepheid variables and the Tip of the Red Giant Branch (TRGB) to calibrate the luminosity of Type Ia supernovae. Mira variables—highly-evolved, radially-pulsating asymptotic giant branch stars, which follow tight Period-Luminosity Relations in the near-infrared—can provide an independent approach. Short-period, Oxygen-rich Miras are a ubiquitous, highly-luminous stellar population that can serve as a complement or check to the existing Cepheid and TRGB distances, while increasing the number of local calibrators for Type Ia Supernovae. I will discuss the methodology used in the Mira-based H0 measurement and present the results of the most recent Mira search in the nearby spiral galaxy M101, host to SN 2011fe.

Near-infrared Period-Luminosity Relations for Type II and Anomalous Cepheids in the Solar Neighbourhood

Piotr Wielgórski[1], Grzegorz Pietrzyński[1], Wolfgang Gieren[2], Bogumił Pilecki[1], Bartłomiej Zgirski[1], Marek Górski[1], Gergely Hajdu[1], Weronika Narloch[2], Karczmarek Paulina[2], Pierre Kervella[3], Radosław Smolec[1], Jesper Storm[4], Alexandre Gallenne[5], Louise Breuval[6], Wojtek Pych[1], Rolf Chini[7]

[1]*Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, Poland*
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Type II and Anomalous Cepheids are old population pulsating stars which lie about 1-2 mag below Classical Cepheids on the period-luminosity diagram. Accurate calibration of period-luminosity relations of these stars will allow to measure precise distances of globular clusters, dwarf spheroidal galaxies and galaxies within the Local Group. I will show recent results of the Araucaria project where we use *Gaia* DR3 parallaxes of nearby Type II and Anomalous Cepheids and near-infrared photometry obtained in the Cerro Armazones Observatory in order to improve the accuracy of the zero-point of period-luminosity relations for these stars.

Possible Studies on Variable Stars based on CSST

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[2]*School of Mathematical and Physical Sciences, Macquarie University, Sydney, Australia*

China Space Station Telescope (CSST) is a 2-meter space telescope scheduled for launch next year. Its main survey will perform multi-band photometry of 17,500 square degrees of sky in ten years. We have also planned a small amount of dedicated time to search for variable stars in nearby galaxies. Here we discuss what benefits CSST can bring to variable star research, mainly about discovering new periodic variable stars, establishing period-luminosity relations for distance tracers, and measuring galaxies' distances and Hubble constants. We also present the preliminary work that we will do before CSST.

OH/IR Stars and the Period-Luminosity-Relation of Mira Variables

Dieter Engels

Hamburger Sternwarte, Universität Hamburg, Germany

OH/IR stars are evolved stars with strong OH maser and infrared emission, but they are optically dim due to obscuration by circumstellar dust. They show two types of variability characteristics. They are either large-amplitude long-period variables, akin the much better-known Mira variables, or small-amplitude non-regular pulsators. The former are stars in the final stage of AGB evolution, while the latter are young post-AGB stars. The OH/IR stars on the AGB have periods significantly longer than those of the Mira variables, in the range of 500 to 2000 days. Attempts to extend the Mira Period-Luminosity Relation (PLR) to these longer periods did not yield to satisfying results, in part due to lacking distances. I will present the variability properties of OH/IR stars, based on an ongoing monitoring program of their 1612-MHz OH masers with the Nançay Radio Telescope started in 2008, and discuss constraints for a PLR for periods longer than those of the Mira variables.

An Uncharted but Valuable Distance Indicator: Period-Luminosity Relation of W Ursae Majoris Type Contact Binaries

Fangzhou Ren[1], Xiaodian Chen, Richard de Grijs, Huawei Zhang, Licai Deng

[1]*University of Chinese Academy of Sciences, Beijing, China*

W Ursa Majoris (W UMa)-type contact binaries (CBs) are one of the most numerous variables in the Galaxy since they cover the evolutionary phases of binaries with long orbital timescales. Both components of W UMa-type CBs fill their Roche lobes and have similar temperatures. W UMas can be used as distance indicators, because they follow a well-defined period–luminosity relation (PLR). Since Eggen (1967), a number of attempts have been made to use W UMa period–luminosity–color relations as potential distance indicators. Rucinski made several attempts to derive PLRs from nearby W UMa-type CBs (Rucinski 1994), with Hipparcos parallaxes (Rucinski & Duerbeck 1997), ASAS catalogs (Rucinski 2006), and TGAS parallaxes (Mateo & Rucinski 2017).

We adopt optical to mid-infrared PLRs based on 183 nearby W UMa- type CBs with TGAS parallaxes to unify the PLRs obtained from different bands (Chen et al. 2018). The minimum scatter, 0.16 mag, implies that W UMa-type CBs can be used to recover distances to 7% precision. Utilizing this distance indicator, various scientific studies have been conducted: in different environments, the luminosity function of W UMa-type CBs may be different; the stellar distribution appears inhomogeneous as a function of direction along the Galactic plane (Ren et al. 2021a); the detailed zero-point offset of *Gaia* parallax (Ren et al. 2021b).

Galactic Center Miras: Period-Luminosity Relations and Circumstellar Effects

Megan Lewis

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Maser-based parallax distances help to anchor Mira period-luminosity relations (PLRs); therefore, studying a large sample of maser-bearing Mira variables is critical if we are to understand the biases that maser stars have as compared to the general Mira population. We explore PLRs for a sample of over 300 SiO-maser-bearing Mira variables that likely lie near the Galactic center. Using preexisting K_s-band PLRs derived in the LMC we show that circumstellar extinction can be severe (sometimes more than 2 magnitudes in the K_s band) and span a large range of values in these sources. Thus, we explore PLRs at the longer wavelengths of the WISE bands and show that circumstellar *emission* may contribute to observed magnitudes at wavelengths longer than about 3 μm. Finally, ideas to mitigate circumstellar effects via careful sample selection are presented, and we comment on the reddening laws in the Mira circumstellar environment.

Abstracts of poster presentations

Poster Session 1.

P-01 – Helen Sawyer Hogg and the Globular Cluster Period-Luminosity Relation

Christine Clement

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Helen Sawyer Hogg (HSH) was a well-known astronomer whose research focussed on globular clusters and their variable stars. Her astronomical career began in 1926 at the Harvard College Observatory where she worked with Harlow Shapley. Shapley was famous for his research on deriving the distances of the Milky Way globular clusters, for which the P-L relation was an important tool (1918, ApJ, Vol. 48, p.89). In his study, his modus operandi was to match the P-L relation of the long period Cepheids in globular clusters to the relation that Leavitt derived for Cepheids in the SMC (1912, Harv. Circ. No. 173).

However, at the time, some astronomers were concerned that Shapley's P-L relation was based on so few clusters and so few variables that it had little meaning. When HSH heard about this at an AAS meeting in 1927, it came as quite a shock because Shapley was her mentor. It motivated her to investigate the literature on the subject and she soon realized there was too little material to warrant the significance being given to it. HSH related this story in an address to the Canadian Astronomical Society (1973, JRASC, Vol. 67, p.8). It turned out that, in Shapley's investigation, Omega Centauri was the only cluster that had long period Cepheids with a range of periods suitable for testing the slope of the P-L relation.

In 1931, HSH set up her own observing program, first at the DAO in Victoria and later at the DDO in Richmond Hill. In the ensuing years, she discovered and characterized the variable star population in a number of globular clusters. Among these were three clusters that contained long period Cepheids with a range in periods: M2, M14 and M13. In all three clusters, the slope she derived for the P-L relation was in good agreement with the one that Shapley derived for Omega Centauri. In addition, she discovered longer period variables in a few other clusters: M10, M12, M22, M28, M56 and M80. All of these stars were observed spectroscopically by Joy (1949, ApJ, Vol. 110, p. 105) and the results revealed significant differences between globular cluster (population II) and classical Cepheids. Based on period distribution and spectral properties, it was apparent that the two groups might follow different P-L relations.

The existence of two P-L relations was subsequently confirmed by other criteria (see Baade 1956, PASP, Vol. 68, p.5). On average, a classical Cepheid is about 1.5 magnitudes brighter than a population II Cepheid (type II Cepheid) of the same period. This discovery had important consequences for the Universal distance scale. Extragalactic distances that had been derived from classical Cepheids had been underestimated by a factor of two. As a result, the size of the Universe was doubled!

P-02 – Distance Measurements of Type Ia Supernovae from Light Curve Fitting

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Type Ia supernovae are thermonuclear explosions of C/O white dwarfs that are commonly used as distance indicators on cosmological scales. Utilizing the correlation between the peak luminosity and light curve width using different methods, we can determine the luminosity distance of these supernovae.

The 0.8m Ritchey-Chrétien telescope at Piszkéstető Observatory, Hungary has been operating since late 2019 to observe astronomical transients, including Type Ia supernovae, in B, V, g, r, i and z bands. We present the photometric analysis and inferred luminosity distances for 18 nearby Type Ia SNe, observed between 2019 and 2021.

We compare distances obtained using the latest calibration of the Spectral Adaptive Lightcurve Template (SALT3) with the distance moduli produced by the MLCS2k2 code, and find that despite their different approach and calibration, the fitted distances are in agreement within 2 sigma of each other. Even though the fitted value of H0 is lower than its latest estimate using the distance ladder because of the small size of our sample, the precise distances we obtained are still useful to assemble reliable bolometric light curves and study the physics of Type Ia SNe.

P-03 – Decreasing the Scatter of SN Ia Host Cepheid PL Relations

Anton Afanasiev

LESIA, Paris Observatory, France

The long-persistent problem of Hubble constant tension is of paramount importance to the astrophysical community. We plan to contribute to the verification of the local H0 measurement by reanalyzing existing HST data for 37 SH0ES galaxies aiming at increasing the accuracy of the Cepheid PL relation and consequently the distance moduli measurements. This can be achieved by more precise estimates of crowding bias, metallicity and reddening as well as reevaluating the Cepheid identification quality and sample completeness. In the poster we will demonstrate the first steps in this work regarding progress in Cepheid identification and present the preliminary results of several tested algorithmic implementations.

P-04 – Population Age Origin of the Host Mass Step in Type Ia Supernovae

Chul Chung[1], Seunhyun Park, Seunghyeon An, Suk-Jin Yoon, Young-Wook Lee

[1]*Department of Astronomy & Center for Galaxy Evolution Research, Yonsei University, Seoul, Korea*

The standardization of type Ia supernovae (SNe) is one of the crucial parts of the research on the cosmic distance scale. Recently, we found a strong correlation between the luminosity of type Ia SNe and their progenitor age. Here, we present that the host mass step employed in the standardization of type Ia SNe originates from the difference in stellar population age based on the well-established highly nonlinear empirical age-mass relationship (AMR) of galaxies. Our simulations indicate that the inflected nonlinear AMR results in the bimodal age distribution of galaxies with a significant age difference. This age difference could be the stellar astrophysical explanation for the observed luminosity difference in type Ia SNe, depending on their host mass. We further simulate the Hubble residual distribution inferred from type Ia SN progenitor ages and discuss how this new relationship should be applied to the standardization of type Ia SNe.

P-05 – Evidence for Strong Progenitor Age Bias in Type Ia Supernova Distance Scale: Lessons from Cepheids

Seunghyun Park, Young-Wook Lee, Chul Chung, Junhyuk Son, Hyejeon Cho, Seunghyun An

Department of Astronomy, Yonsei University, Seoul, Korea

Supernova (SN) cosmology is based on the assumption that the width-luminosity relation (WLR) and the color-luminosity relation (CLR) in the type Ia SN luminosity standardization would not show zero-point offsets with progenitor age. Unlike this expectation, recent age datings of stellar populations in host galaxies have shown significant correlations between progenitor age and Hubble residual (HR). Here we show that this correlation originates from a strong progenitor age dependence of the zero-points of the WLR and CLR, in the sense that SNe from younger progenitors are fainter each at given light-curve parameters x1 and c. This 4.6 sigma result is reminiscent of Baade's discovery of the zero-point variation of the Cepheid period-luminosity relation with population type/age, and, as such, causes a serious systematic bias with redshift in SN cosmology. Other host properties show substantially smaller and insignificant offsets in the WLR and CLR for the same dataset. We illustrate that the differences between the high-z and low-z SNe in the WLR and CLR, and in HR after the standardization, are fully comparable to those between the correspondingly young and old SNe at intermediate redshift, indicating that the observed dimming of SNe with redshift may well be an artifact of over-correction in the luminosity standardization. When this systematic bias with redshift is properly taken into account, there is little evidence left for an accelerating universe, urging the follow-up investigations with larger samples at different redshift bins.

P-07 – First Detection of CO Emission from Cepheid Variables: A Step to Reducing the H_0 Error Budget

Steve Ardern[1], Stephen Leslie Hamer, Victoria Scowcroft

[1]*University of Bath, United Kingdom*

We present the first detection of CO emission in Cepheids, found using observations from the IRAM 30 m Telescope, of the CO(1-0) and CO(2-1) emission lines in a sample of eight Cepheid variable stars. The CO(1-0) line is detected in four of the eight targets at a signal-to-noise of >3.5 confirming the presence of CO in Cepheid atmospheres. Two sources show strong absorption in both CO lines; this is likely related to contamination by cold molecular gas clouds along or close to the line of sight. The remaining two targets showed no strong features related to either CO line.

These detections represent the first direct evidence for the presence of CO in Cepheid atmospheres, providing strong evidence for the mechanism proposed to explain the observed mid-infrared colour variation seen in Cepheids. Further, these detections support the proposed use of mid-IR colour as a robust photometric metallicity indicator for Cepheids, potentially leading to the elimination of metallicity systematics from the □$_0$ error budget. We discuss the future studies needed in this area and how our observations can be used to inform optimal observing strategies for large-scale dedicated studies.

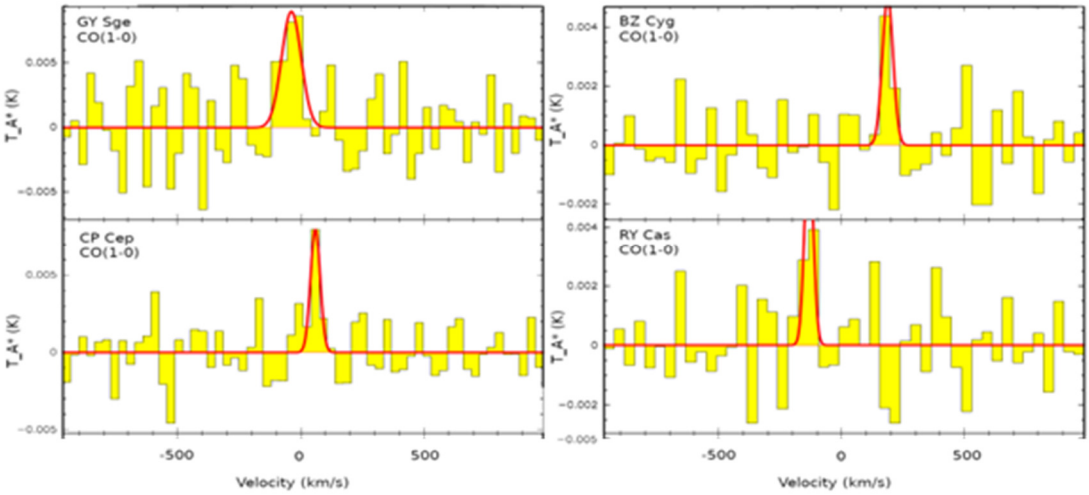

Figure 1: *Our CO(1-0) emission detections at a signal-to-noise of greater than 3 produced using CLASS/GILDAS. Yellow bars show the smoothed spectra (antenna Temperature in K). Fits to detected features are shown as a red line.*

P-08 – A Proposal for the Absorption of Light by Dark Matter to Explain the Hubble Tension

John Baruch[1,2]

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It is conjectured that just as the gradient in the gravitational field around black holes can emit photons as suggested by Stephen Hawking (1974), that the reverse is possible and where the gravitational field is quantised, such a quantised field can have an absorption cross section for photons above a threshold energy.

The failure to find dark matter particles in any form has led to suggestions that they exist as Gravitationally Interacting Massive Particles (GIMP)s with a mass in the region of 10^{23} eV. Such particles will not be seen by current detectors looking for Weakly Interacting Massive Particles (WIMPs).

It is conjectured that the gravitational field holding two GIMPs together governed by gravity and would be quantised according to the laws of quantum mechanics. Such binary particles would have an absorption cross-section for photons above a threshold energy with the surplus energy transferred to the individual dark matter GIMPs in a way similar to the ionisation of atoms by energetic photons. In this way such binary GIMPs would contribute significantly to the absorption of light from Cepheids and other stars within our galaxy and less from stars in the LMC. Such absorption can explain the Hubble tension and enables the mass of the dark matter particles to be calculated. The density of intergalactic dark matter is about 10^5 times less than within the galaxy and its halo. The absorption of light by intergalactic dark matter would only detract significantly from the intensity of light received from galaxies, and their supernovae at $z>0.4$.

P-09 – Is the Period-Luminosity Relation for Cepheids Upset by a Small Threshold for the Absorption of Light by Dark Matter?

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It is conjectured that above an energy threshold in the far infra-red dark matter has a small absorption coefficient for light. Such a conjecture if upheld could explain the Hubble tension and the claimed acceleration in the rate of expansion of the Universe at z< 0.4. This paper reviews current data in the relevant areas to see if there are any contra indications and how strong current data supports such a conjecture. e.g. Re-analysis of the Reiss and *Gaia* data (Reiss et al. ApJL 908.L6 (2021)) suggests an average absorption of 8% for Milky Way Cepheids. A wide range of current data is reviewed around Cepheids, Tip of the Red Giant Branch stars, eclipsing W Ursa Majoris binaries, Maser Galaxies, the Hubble tension, galaxy number counts and Hubble deep fields.

P-10 – Cepheids in M51: Cross-Checking the PLR Distance with Independent Estimates

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The Whirlpool Galaxy (or Messier 51, M51) is one of the best-known extragalactic objects in the sky for professional and amateur astronomers. Despite its proximity, and many observations conducted by generations of astronomers, the distance of this galaxy remains uncertain compared to the state-of-the-art and other well-known galaxies, with little agreement between the different methods, such as the tip of the red giant branch (TRGB) or the supernova expanding photosphere method (EPM), as shown for example by McQuinn et al. (2016). To date, no Cepheid analysis was conducted for M51.

Recently, Conroy et al. (2018) published an extremely rich catalogue of variable stars in M51, which was derived based on several epochs taken over almost a year by the *Hubble Space Telescope* (*HST*). Not only numerous Cepheids are present in this catalogue, but the number of available epochs for the individual stars makes this dataset one of the richest among those of other, farther away galaxies. In this work, we analyzed this catalogue with the goal of estimating a Cepheid distance to M51.

This estimation not only provides an accurate distance M51, but it also allows for a direct cross-check between independent methods, namely the TRGB and the EPM. To facilitate such a check, we also estimated the distance to one of the past supernovae in M51, SN 2005cs, through the augmented version of EPM (see e.g., Csörnyei et al. 2023), then compared these distances to the most recent TRGB estimates. We find that the Cepheid and the supernova estimates are in good agreement with one another, and they are both in significant tension with TRGB. This finding validates well empirically both the augmented supernova method as well as the calibration of the Cepheid PRL, while highlighting the possible difficulties related to the TRGB analysis.

References:

McQuinn et al. 2016, ApJ, 826, 21
Conroy et al. 2018, ApJ, 864, 111
Csörnyei et al. 2023, arXiv:2302.03112

P-11 – Variable Stars in NGC 6822

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We provide and discuss a number of light curves of different kind pulsating variable stars found in the Local Group dwarf irregular galaxy NGC 6822. We used a catalogue with BVI photometry which consists of 127 B, 102 V and 149 I images. The catalogue matches most of the variables previously identified and available in the literature: Long-Period variables (LPVs) by Mennickent et al. 2006 and Battinelli and Demers 2011, Mira variables by Baldacci et al. 2005 and Whitelock et al. 2013, and Cepheid and RR Lyrae stars by Baldacci et al. 2005. However, the most important result of this study is the identification of 385 new candidate variables, which are mainly bright stars, and according to their position on the Colour-Magnitude diagram (CMD) they may be Cepheids, Mira variables or LPVs and eclipsing binaries. We present preliminary results concerning their light curves, their classification and estimates of the pulsation parameters.

P-12 – Variable Stars in an Irregular Dwarf Galaxy, IC 10

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To identify the variable stars in IC 10 as the nearest starburst galaxy of the Local Group, we conducted an optical monitoring survey using the 2.5-m Isaac Newton Telescope with the wide-field camera in the i-band and V-band from 2015 to 2017. Within an area of 0.07 deg^2, we obtained photometric catalogs for 53579 stars, of which 762 are classified as variable candidates, and 457 are within two half-light radii ($2r_h$) of the galaxy center. Also, 424 variable candidates are identified as long-period variables based on their amplitude variability in i-band magnitude, mostly asymptotic giant branch stars and red supergiants within $2r_h$ of IC 10. Since this galaxy is located near the Galactic plane, there is significant foreground extinction, so the reddening has been corrected for all the stars using a dust map (SFD98). The reddening of most of the stars in our catalog is about 1.5 mag corresponding to $A_V \sim 4.65$ mag. We also defined the level of foreground contamination in the direction of the galaxy. To achieve this aim, we simulated the foreground stars' spatial distribution in the direction of the galaxy (l= 118˚.9, b= -3˚.3) with TRILEGAL (TRIdimensional modeL of thE GALaxy) code as a theoretical tool to synthesize the stellar population. A more realistic amount of foregrounds was obtained by using the *Gaia* Early Data Release 3 catalog and applying criteria based on the parallaxes, proper motion, and RUWE parameters for each common source between our photometric catalog and *Gaia* catalog. Moreover, by comparing our output catalog to optical catalogs, we calculated the accuracy of our detection method for our sources. In this paper, we investigate the variable star survey's methodology and our photometric catalog.

P-13 – Detection of Long-Period Variable Stars in And IX to Study Star Formation History and Dust Production Rate

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In this paper, we studied the photometric results of the dSph galaxy And IX, one of the metal-poor dwarf spheroidal satellites of M31. A distance modulus of ~ $24.56_{-0.15}^{+0.05}$ mag (~ $816.58_{-54.50}^{+19.02}$ kpc) was calculated using the Sobel kernel [-2, -1, 0, 1, 2] to detect the tip of the RGB through edge detection procedures. We detected 50 long period variable (LPV) stars within two half-light radii in And IX using the Isaac Newton Telescope (INT) in two filters, Sloan (i') and Harris (V). LPVs with amplitude in the range of 0.2-2.12 mag in the i-band between the RGB-tip and AGB-tip are detected using the variability index. The period of LPVs ranges from 100 to 1000 days, with the birth mass between 0.8 and 3 $M_\odot$. Asymptotic giant branch (AGB) stars as easily detectable and reliable tracers are selected to reconstruct the star formation history (SFH) of the galaxy. The star formation rates (SFRs) in more metal-poor estimation (Z = 0.0001) reached a maximum of $8.2\pm3.1\times10^{-4}$ $M_\odot$ yr^{-1} in 6 Gyr ago, which is 57% more than the maximum peak in more metal-rich estimation (Z = 0.0003).

An outside-in galaxy formation scenario was concluded for And IX with a quenching occurring $3.65_{-1.52}^{+0.13}$ Gyr ago with SFR in the order of 0.0002 $M_\odot$ yr^{-1} at redshift < 0.5. We also calculate the total stellar mass by integrating the SFRs within two half-light radii for three metallicities ~ 3.0×10^5 $M_\odot$ (Z = 0.0001), 2.4×10^5 $M_\odot$ (Z = 0.0002), and 2.3×10^5 $M_\odot$ (Z = 0.0003). By employing the spectral energy distribution (SED) fitting for observed LPVs in And IX, we evaluate mass-loss rate in the range of $10^{-7} \leq \dot{M} \leq 10^{-5}$ $M_\odot$ yr^{-1}. The total mass deposition to the interstellar medium (ISM) is ~ 2.4×10^{-4} $M_\odot$ yr^{-1} from the C- and O-rich type of dust-enshrouded LPVs.

P-15 – The Effect of Metallicity on the PL Relation from a Baade-Wesselink Type Analysis of a Cepheids in the Milky Way and the Magellanic Clouds

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We have acquired new radial velocity curves for a significant sample of nearby (<5kpc) Milky Way Cepheids. This data combined with photometric and radial velocity data from the literature has expanded the sample of Milky Way Cepheid for which we can apply the near-IR surface-brightness method from 70 to 150 stars. The near-IR surface-brightness method is a Baade-Wesselink type of method and allows direct distance and radius determination to individual stars and thus absolute magnitudes. We combine the results from the new dataset with our previous analysis of Cepheids in the LMC and SMC and the extensive range of metallicities allows us to put significant constraints on the effect of metallicity on the PL and PW relations. As an example, we find that for Cepheids with logP>0.9 the effect amounts to -0.32±0.11 mag/dex in the K-band and -0.41±0.11 mag/dex in the *Gaia* Wesenheit pseudo-magnitude. With the large Milky Way sample, we can re-calibrate the method using *Gaia* DR3. This changes the zero point of the resulting PL relations a bit, depending on the adopted parallax zero-point offset, but the effect of metallicity on the resulting PL relations are very robust to these changes.

P-16 – The Star Formation History and Chemical Enrichment of Sagittarius Dwarf Irregular Galaxy Derived from Long-period Variable Stars

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We present a study of constructing the star formation history of Sagittarius dwarf irregular galaxy (SagDIG) employing the PARSEC–COLIBRI stellar evolutionary model and the mass-luminosity relation of long-period variable stars (LPVs). These stars are at the final stage of evolution, and their period-luminosity relation is a reliable distance estimator. To identify the LPVs in SagDIG, we performed multi-epoch observations using the 2.5 m Isaac Newton Telescope at La Palma. We detected 27 LPV candidates within two half-light radii of SagDIG, ten of them were in common with previous studies. By adopting the metallicity Z = 0.0002 for older populations and Z = 0.0004 for younger ages, we estimated that the star formation rate changes from 0.0005 ± 0.0002 $M_{\odot}$ yr^{-1} kpc^{-2} (13 Gyr ago) to 0.0021 ± 0.0010 $M_{\odot}$ yr^{-1} kpc^{-2} (0.06 Gyr ago). Moreover, by combining our time-averaged photometry and other available catalogs, such as Spitzer Space Telescope Mid- Infrared photometry, we modeled the spectral energy distribution of our LPV candidates, estimated their mass-loss rate, and investigated its correlation with luminosity, amplitude, color, and optical depth. We also determined a distance modulus of μ = 25.27 ± 0.05 mag, using the tip of the red giant branch.

P-18 – RR Lyrae Stars as Standard Candles and Tools to Disentangle the Milky Way's History

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In the Lambda cold dark matter framework, galaxies are formed hierarchically through the accretion of smaller systems. Evidence of these interactions can be observed in the chemo-dynamics of stars in the Milky Way's halo as tidal remnants. However, reliable tracers of the halo at large distances are required to uncover the Milky Way's history, and remote halo tracers are scarce, and their distances typically suffer from large uncertainties. The period-luminosity relation of pulsating stars has given them the status of fundamental tools for the study of the local universe through precise distance estimations. RR Lyrae stars, in particular, have played a major role in disentangling our Galaxy's assembly history, as they are known old-population standard candles ubiquitous in the halo and numerously detected in recent Galactic surveys. In this contribution, I will summarize the results of our recent studies relying on halo RR Lyrae as tracers of the outer halo, which combine state-of-the-art astrometric, photometric, and spectroscopic measurements, from public and proprietary surveys. I will present the analysis of well-characterized RR Lyrae known in the Milky Way's halo, emphasizing their connection to tidal streams as means to recover their parent population properties (e.g., dwarf galaxies and/or globular clusters). Lastly, I will highlight the important role that these stars and the calibration of their period-luminosity relation will play in the upcoming era of large photometric and spectroscopic surveys.

P-19 – On the Consistency of the Cepheid and TRGB Distance Scales

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We developed a code in order to analyze and understand the different models and effects considered on the cosmic distance ladder and the resulting Hubble value.

The main goal of this code is to measure the Hubble constant as well as the various parameters related to the considered distance ladder. In an automatic way, it is possible to integrate different modifications to the Cepheid distance ladder and fit multiple models to the same dataset. We can for example mention the introduction of a break in the PLR of the Cepheids, the consideration of Redshift Leavitt Bias, the introduction of TRGB as a second distance indicator, and so on.

We then use this code to compare and test the sensitivity to the different parameters and models used, and then assess the consistency of the different ladders one can use, in particular the consistency between the Cepheid and the TRGB distance scales.

P-20 – Dependence of Pulsation Mode of Cepheids on Metallicity

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The Cepheid variables in the Small Magellanic Cloud (SMC), the Large Magellanic Cloud (LMC), the Milky Way, M33, and M31 are used to examine the dependence of pulsation mode on metallicity, which was previously found in red supergiants. The initial samples of Cepheids are collected from the Cepheid catalogs identified from the OGLE, PS1, DIRECT, WISE and ZTF surveys. The contaminants are removed with the help of the *Gaia*/EDR3 astrometric information for extra galaxies or by comparing the geometric distance and the distance from the period-luminosity relation for the Milky Way. The division of fundamental (FU) and first-overtone (1O) modes is refined according to the gap between the two modes in the P-L diagram of the objects in each galaxy. The ratio of FU/(FU+1O) is found to be 0.59, 0.60, 0.69, 0.83, and 0.85 for the SMC, the LMC, the Milky Way, M33, and M31, respectively, in order of metallicity, which confirms that the pulsation mode depends on metallicity in the way that the ratio of FU/(FU+1O) increases with metallicity. This dependence is not changed if the incompleteness of the samples is taken into account.

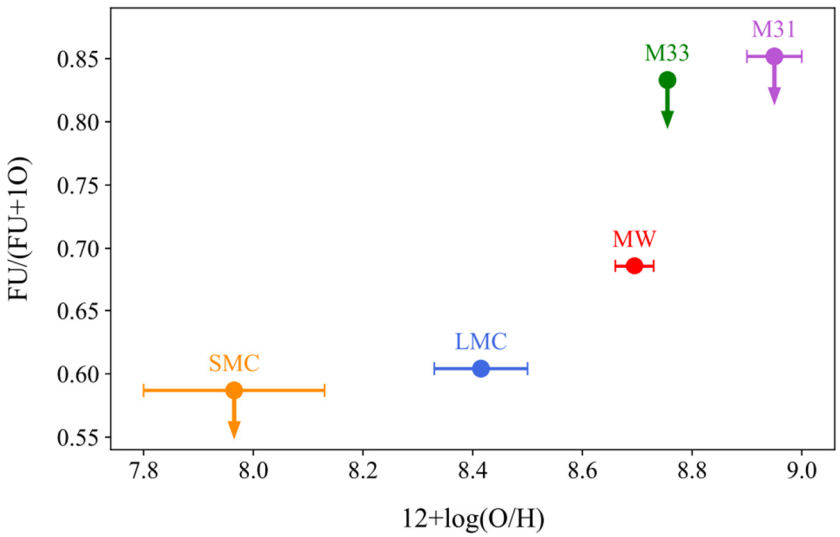

Figure 1: *The FU/(FU+1O) ratio of Cepheids vs. the metallicity represented by 12+log(O/H) in the target galaxies. The arrows indicate trends that may change after considering incompleteness.*

P-21 – Non-Radial Modes in Classical Pulsators – Perspectives for Asteroseismology

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RR Lyrae stars and classical Cepheids are essential astrophysical tools as they obey period-luminosity relations. However, due to their relatively simple pulsations, they were rarely studied with asteroseismic methods. The new possibilities to study these stars with asteroseismology emerged with the detection of additional signals in them. According to the most recent hypothesis, these signals are due to non-radial modes of degrees 8 or 9. Here we present seismic modelling of RR Lyrae stars with non-radial modes that have their physical parameters observationally constrained. In particular, we tested whether, using the proposed hypothesis, we can correctly model observed periods and period ratios of the selected targets.

P-22 – Classifying Milky Way Cepheids with *TESS*

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To improve Cepheid PL relations in the Milky Way we require not only precise distance measurements but the proper identification of the Cepheid types and pulsation modes too. By comparing the variability catalogs of different large sky surveys, we experience disagreements between classifications for a significant amount of Cepheids stars. The Transiting Exoplanet Survey Satellite provides us with precise, high-cadence space photometry for the majority of Milky Way Cepheids. The detailed *TESS* light curves are reliable classifiers that work best at the short-period end of the PL relation due to the instrumental constraints of the data length and the brightness limit. Here we present some examples where *TESS* data unambiguously resolved uncertainties in the Cepheid classification.

P-23 – Testing Ultra-low Amplitude Cepheid Candidates in the Galactic Disk by *TESS* and *Gaia*

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Ultra-low amplitude (ULA) Cepheids are thought to be pulsating variable stars that show millimagnitude-level light variations. These stars are thought to be near to or at the edges of the classical instability strip. Until now, only a few dozen such variable star candidates have been found both in the Large Magellanic Cloud and the Galactic disk. The latter were found by Szabó et al. (2009), based on CoRoT and 2MASS data. In this work, we test the six known ULA Cepheid candidates in the Milky Way based on their CoRoT, 2MASS, *Gaia* and *TESS* data. We calculated their reddening-free absolute magnitudes and identified their positions on the color—magnitude diagram. Furthermore, we calculated their relative Fourier parameters and investigated the long-term phase shifts for four out of the six stars. Based on the results, we conclude that none of the six ULA Cepheid candidates are pulsating variable stars but show rotation-induced variability instead (spotted and α^2 Canum Venaticorum variables) that are either bluer or fainter than Cepheids would be.

P-24 – Thousand Faces of Convection

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As it turned out in the eighties, turbulent convection has a crucial role in the energy balance of the classical pulsators. This also affects stars evolving from the horizontal branch within the instability strip which have their own PL relations, while they have the same behaviour despite mass and evolutionary differences.

Understanding the details of convective processes is achievable through mul- tidimensional codes, while 1D codes can reproduce most of the features of these stars. Also, there are some aspects of these particular convective processes that differ from the usual picture of core or envelope convection.

In the present work, we show these phenomena i.e., the time-dependent nature of this narrow region, the merging and separating of the H and He convective layers, also their coupling with the pulsation phase. In addition, we show what effects the 1D convective parameters have on PL relations alongside with the key differences between stellar envelopes of HB (RR Lyrae), AGB (Type II Cepheids) and Cepheid stars which obey different PL relations.

Abstracts of poster presentations

Poster Session 2.

P-26 – How Accurate Are those Periods?

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The various versions of the period-luminosity relations for Cepheids and RR Lyrae stars usually assume that the period of these variable stars can be easily and accurately determined. In this presentation we point out that there are a number of physical effects that limit the accuracy that can be achieved. For example, the (often multi-periodic) Blazhko effect, quasi-periodic period changes due to non-radial modes, or period changes due to the binarity. Each effect causes systematic errors in the periods and these systematic errors can be much larger than formal errors. Of course, the systematic errors can be reduced by considering time series of appropriate length, but in practice this is often not possible, so the existence of these errors should always be kept in mind.

P-27 – VELOcities of Cepheids (VELOCE) DR1: An Unprecedented View of Cepheid RV Variability and Spectroscopic Binarity

Giordano Viviani, Richard I. Anderson, Shreeya Shetye

EPFL, Lausanne, Switzerland

VELOCE is a project dedicated to measuring high-precision radial velocities (RVs) of Galactic classical Cepheids from both hemispheres over up to 10-year baselines targeting dense phase coverage. The first data release is currently in preparation and comprises more than 18,100 individual observations of 256 bona fide classical Cepheids, with RV uncertainties that can be as low as 2 m/s. As such, VELOCE is the largest single catalog of RV time series of classical Cepheids to date. The sheer amount of data and the long observational baseline provide good phase coverage of the pulsation phase for most targets, enabling new insights into the pulsational variability of Cepheids, including a high-definition view of the Hertzsprung progression in RVs, the identification of double-peaked bumps in the pulsation curve, and modulated variability. VELOCE further includes new reference RV curves of Cepheids of unprecedented precision that provide new insights into the calibration of the Baade-Wesselink projection factor. Using VELOCE data, we identified 75 single-lined spectroscopic binaries and determined 36 precise orbital solutions, including 22 for the first time. This allows a unique view of orbital statistics for classical Cepheids and comparisons with other indications of binarity. In this talk, we present an overview of VELOCE DR1, highlighting the role of RV data in relation to the period-luminosity relations of Cepheids.

P-28 – Review of BOAO Short Period Variable Star Surveys to Calibrate Period-Luminosity Relation

Young-Beom Jeon

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Short-period SX Phoenicis variables and delta Scuti variables in globular and open clusters that show good period-luminosity relations are used as distance indicators. I review the period-luminosity relation between SX Phoenicis variable stars in globular clusters and delta Scuti variable stars in open clusters, which have been observed and studied at the Bohyunsan Optical Astronomy Observatory and examine the zero point of the period-luminosity relation using recent *Gaia* parallax data. In particular, the globular cluster's SX Phoenicis variable stars showed a good period-luminosity relation when the effect of metal abundance was corrected.

P-29 – Metallicity Determination from IGRINS Spectra for a Sample of Galactic Cepheids

Giovanni Catanzaro [1], Anupam Bhardwaj, Vincenzo Ripepi, Erasmo Trentin, Soung-Chul Yang, Noriyuki Matsunaga

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We present preliminary results on elemental abundances determination in 22 Galactic and 2 LMC cepheids using high-resolution (R=45000), high signal-to-noise ratio (S/N=150-200) H-and K-band spectra obtained with the Immersion Grating Infrared Spectrograph (IGRINS). We have determined the abundances of 21 elements, including alpha (Mg, Si, Ca, S), odd-Z (Na, Al, P, K), Fe-group (Sc, Ti, Cr, Co, Ni), neutron-capture (Ce, Nd, Yb), and CNO- group elements. When possible, we compare the abundances derived in the IR with those derived in the optical spectral range. For some elements, the CNO- group just as an example, IR provides more reliable lines with respect the optical spectral range.

P-30 – The Mass of the Cepheid S Mus

Nancy Evans[1], A. Gallenne, C. Proffitt, J. Kuraszkiewicz, P. Kervella, J. Monnier, A. Mérand, T. Gardner, R. I. Anderson

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S Mus is the classical Cepheid with the longest pulsation period (P = 9.6d) for which we currently have an orbit, which provides the possibility of measuring its mass. For S Mus we have photometric light curves and radial velocity pulsation and orbital curves, as well as interferometry around the orbit and ultraviolet STIS velocities for the hot companion. The mass resulting from this data suite will be discussed.

Cepheid masses remain a test of evolutionary tracks, including new the insights from asteroseismology. In addition, most Cepheids will become white dwarfs, however the most massive may become neutron stars. The mass of the shorter period Cepheid V1334 Cyg (P =3.3d) is smaller than predicted by evolutionary calculations. If this is true of longer period more massive Cepheids such as S Mus, the predicted frequency of neutron stars decreases, with implications for objects such as short gamma-ray bursts, gravitational waves, and X-ray binaries.

P-31 – Spectral Energy Distribution Fitting to Find and Characterize Cepheids in Binary Systems

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The determination of precise and consistent parameters of classical Cepheids is key to improving our understanding of the physical properties and the evolution of this important class of pulsating variable stars. In particular, Cepheids in detached eclipsing and spectroscopic double-lined binary (SB2) systems allow us to measure their physical parameters very accurately, which can be then compared with the results obtained with other methods. For this reason, we are focusing our efforts in finding new candidate Cepheids in SB2 systems, confirming them, and measuring their physical parameters using different techniques.

We have started a project to construct spectral energy distributions (SEDs) for classical Cepheids in binary systems using photometric information available in the literature and fit them to find signatures of binarity. For this purpose, we used the virtual observatory SED analyzer (VOSA) to construct and analyze the SEDs of our sample of binary Cepheids. This code allows to fit both single and binary model atmospheres to the observed SED. The analyzed sample consists of well-known Cepheids in eclipsing SB2 systems and those of candidate SB2 systems with giant companions in the Large Magellanic Cloud and in the Milky Way.

We find evidence in favor of a good fraction of the candidates having parameters (effective temperature and luminosity) consistent with the binarity hypothesis. These findings also indicate that SED fitting can be used to search for new binary systems with one of the components being a pulsating star.

P-32 – Observational Calibration of the Projection Factor of RR Lyrae Stars Using the SPIPS Pulsation Modeling

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The Baade-Wesselink technique (also known as parallax-of-pulsation) is commonly used to determine the distances of pulsating stars. The projection factor, used to convert disk-integrated radial velocities into pulsation velocities, is an essential component of this technique, that is currently poorly calibrated. Trahin et al. (2021) showed that the p-factors of Cepheids are affected by a large dispersion, but a comparable study has not been conducted for RR Lyrae stars.

The recent third *Gaia* Data Release provides precise parallaxes for thousands of RR Lyrae stars, enabling the calibration of their p-factors. Together with photometric and radial velocity data from the literature, we obtained new radial velocity measurements of a sample of 16 stars from the SOPHIE instrument at Haute-Provence Observatory. These data, combined in a pulsating model using the SPIPS code (Mérand et al. 2015), lead us to determine the p-factors of these RR Lyrae stars.

Such a measurement of the p-factor requires attention as it depends on the method used to determine radial velocities. We studied the cross-correlation and broadening functions approaches, as well as different templates and methods to measure the peak of these functions and will report on our results.

P-33 – Multiband Photometry and Spectroscopy of RR Lyrae Field Stars

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Pulsating variable stars provide further, complementary constraints to the properties of the parent populations, in terms of their age and metallicity. RR Lyrae stars, Cepheids (Classical, Anomalous, Type II), Delta Scuti, Mira (and other long period variable stars) can be used to trace different stellar populations. In particular, RR Lyrae are low-mass, centrally He-burning Horizontal Branch stars, and are the best tracers of old (> 10 Gyr) stellar populations. They are therefore direct witnesses of the early evolutionary stages of the host galaxies; moreover, they are a key instrument to measure distances up to a few Mpc.

In this context, we are preparing a catalog of 95 bright RR Lyrae field stars specifically targeted so that *Gaia* has produced high precision parallaxes for them. The main aim of the project is to characterise newly calibrated period-luminosity-metallicity multiwavelength relations in the optical and infrared. Data has been collected by our group in the last years: optical photometry with the IAC80 telescope, located at the Teide Observatory (Tenerife); infrared photometry with the IRSF telescope, located at the SAAO (South African Astronomical Observatory); spectra with Mercator, TNG and NOT, located at Roque de los Muchachos Observatory (La Palma), and Stella from Teide Observatory.

P-34 – Improving the *Gaia* RR Lyrae Photometric Metallicities

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For tracking and modeling Galactic Chemical Evolution, it is crucial to know the chemical abundance distributions of stellar populations at different ages. RR Lyrae stars offer a great opportunity for this purpose, as their metallicity can be estimated based solely on photometric measurements, which are available for numerous stars thanks to large-scale surveys such as the *Gaia* mission. The empirical relation used for deriving these so-called photometric metallicities should, however, be calibrated separately for different photometric passbands.

To this day, a relation calibrated for the *Kepler* space telescope is being used for the *Gaia* G band, despite the differences of the passbands and the small parameter space covered in case of the RRab subtype. In our work, we fitted the relation directly on *Gaia* G photometric data, both for the RRab and the RRc subtypes, using data from four high-resolution spectroscopic surveys. We managed to significantly improve the fit in the case of RRab stars, especially in the long-period and low-amplitude domains, where the previous relation was only extrapolated to. The new calibration fixes the metal-rich regions in the *Gaia* Bailey diagram that contradicts direct spectroscopic observations. As a first test, we use the newly derived relations to detect the metallicity gradient in the Large Magellanic Cloud's old stellar population.

P-35 – Calibrating RR Lyrae Absolute Magnitudes as a Function of Period Shift to Correct Post-ZAHB Evolution Systematics

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RR Lyrae (RRL) stars of Oosterhoff type II (OoII) are known to be intrinsically more luminous than those of type I (OoI), by approximately 0.2 mag in the V-band (e.g. Lee et al. 1990; Kunder & Chaboyer 2009), this over-luminosity of OoII~RRLs probably owing to a more advanced evolutionary state, with OoI RRL tracing the Zero Age Horizontal Branch (ZAHB) and OoII~stars having evolved off the ZAHB on their way to the Asymptotic Giant Branch (Lee et al. 1990, Clement & Shelton 1999).

Currently, most studies using RRLs as tracers of Milky Way structure use optical surveys and M-[Fe/H] relations (or, most commonly, fixed absolute magnitude values) to derive distances to RRLs. These relations, however, cannot account for the difference in luminosity as a function of the Oosterhoff type, translating into a systematic distance underestimation of ~10% for OoII stars, which amount to about a quarter of all RRL in the Galactic halo. Although the difference may be small enough to be neglected for many purposes, the fact that it is systematic could compromise the interpretation of analyses based on the distribution of RRL by Oosterhoff type as well as the detection of new substructures (e.g. tidal streams, clouds, etc.) that may contain mixed-type RRLs (as the majority of Galactic satellites and even many globular clusters do), by washing out their distance signature or causing confusion between distinct ones.

In this contribution we explore calibrating RRL absolute magnitudes as a function of period-shift, as first proposed by Kunder et al. 2009. Period-shift characterises the location in the Period-Amplitude diagram (e.g., Sandage 2006) and correlates with Oosterhoff type, having the potential to account for both the evolutionary and the metallicity dependence of the luminosity. We will explore here the performance of the absolute-magnitude-period-shift calibration for the *Gaia* G-band — the most widely used currently for Galactic structure purposes— using RRLs in globular clusters and comparing against the traditional absolute-magnitude-metallicity calibration benchmark.

P-36 – WUMaCat – The Largest Catalog of Individually Studied W UMa Stars

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WUMaCat is the largest catalog of individually studied late-type contact binaries known as W UMa stars. These intriguing objects, whose characteristics, evolution, and membership in multiple stellar systems are not fully understood even after decades of research, are a favorite target for observations with ground-based telescopes due to their short periods. But they are even more relevant now, in the age of space photometry and large sky surveys, because the masses and radii of their components can in favorable conditions be estimated without spectroscopic follow-up. At the time of publication, in April 2021, the catalog contained the orbital and stellar parameters of about 700 W UMa stars, carefully curated from over 450 publications and supplemented by data from LAMOST and *Gaia* archives. We have been working on expanding the catalog ever since. In this contribution, we will present some of the interesting statistics of this growing sample and discuss the factors limiting the reliability of the theoretical period-luminosity relation for W UMa stars.

P-38 – IR Spectroscopy of Stars in Various Instability Strips

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Using the 3.5-m of the Astrophysical Research Consortium (ARC) located in New Mexico, USA, we have begun a program to obtain spectra of pulsating variable stars over a number of instability strips. This includes the traditional instability strip of Cepheids, RR Lyrae, and delta Scuti variables, the gamma Doradus stars, and beta Cephei stars. Observations were secured with the *TripleSpec* camera system that provides coverage from about 0.95 microns to 2.45 microns, with the normal atmospheric gaps. A sample spectrum for RZ Cas is shown in Figure 1.

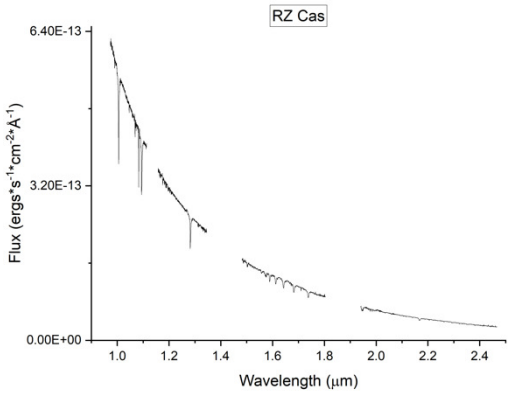

Figure 1: *IR Spectrum of RZ Cas – A delta Scuti in a Binary System*

Within the overall spectra we find 3 prominant lines from the Hydrogen Paschen sequence P-beta, P-gamma and P-delta. These are seen as the three strong lines to the left in Figure 1. Further to the red we find 7-10 Hydrogren Brackett lines starting with the gamma line. The number of lines seen is dependent on the temperature of the object. We are using these observations to examine the atmophere of these pulsating variable stars. This includes a magnitude limited sample for each group for targets reachable by the ARC telescope. This will provide 1-3 observations per target. However, the observations will not be targeted to specific phase points. Beyond an examination of the atmospheric conditions for these stars, these observations will be used to search for faint red companions. We have found a number of examples with CO band heads, showing a cool companion. For a smaller sample of targets, we have obtained observations that fully sample the phased light curve.

We will present preliminary results from all aspects of this program. This will include targets with newly found companions and a discussion of atmospheric conditions. Once data from this program are published the individual spectra will be make available for download.

P-39 – Validation of the RR Lyrae Identifications in the PanSTARRS PS1 3π Survey with K2 and *Gaia*

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Pan-STARRS observed a large number of RR Lyrae stars during its PS1 3π survey. The identification and period determination of these stars, however, were based on light curves that are sparsely sampled and contain only a few (~ a dozen or so) data points in each of the 5 filters. The *Kepler* space telescope observed a subset of these variable stars during its K2 campaigns and provided us with continuous light curves with significantly higher sampling frequency.

The two catalogs that list the RR Lyrae stars identified from the Pan-STARRS data sets (Hernitschek et al. 2016 and Sesar et al. 2017) were first cross-matched with the list of RR Lyrae stars that were observed by the K2 mission in at least one of the campaigns and there is available Automated Extended Aperture Photometry light curve (Bódi et al. 2022). Then the selection was cross-matched with the *Gaia* DR3 catalog.

In total we found 1438 stars. Analyzing their frequency spectra, we found that for the majority of the stars, the periods calculated from the K2 light curves are in accordance with those derived from the Pan-STARRS data. However, for a subset of stars, an alias frequency with ± 1 or 2 c/d offset was found instead of the true one, most likely due to the fact that Pan-STARRS observed from the ground, causing regular gaps in the data during daytime. Among the subtypes, the RRc variables were found to be the ones that are the most likely to have alias frequencies because of their less sharp light curve shapes.

P-40 – Combined *Gaia* and K2 Studies of Globular Cluster Variables

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Globular clusters allow us to study old stellar populations with strong constraints on their distances and metallicities. The *Kepler* space telescope observed multiple globular clusters during its K2 mission, providing us with a unique opportunity to collect space-based time-series photometry for their member stars. Although extracting precise photometry from the dense stellar fields can be challenging, were able to retrieve numerous light curves. Here we show examples where we were able to gather detailed seismic signatures from variable stars. The combination of the mode content with accurate distances and color-magnitude diagram positions from the *Gaia* mission will allow us to construct well-constrained seismic and/or pulsation models for these stars.

P-41 – Catalogue of Variable Stars in Open Cluster Fields

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Knowledge of the variable star contents in open clusters is a significant advantage in their study. Analysing variability of cluster members and fields stars also allows us to study the characteristics of stars and clusters together. This catalogue of variable stars in open cluster fields is the first step in supporting such studies.

We present a homogeneous catalogue of known variable stars in open cluster regions and with up to two times the given cluster radius. This gives basic information about the distribution of variable stars in cluster fields for the complete sky.

The compilation is based on the newest *Gaia* DR3 and the VSX catalogue.

P-42 – The Classification Intricacy of Different Type of Cepheid Variable Stars and the Case of RU Camelopardalis

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Variable stars with “Cepheid“ in their names are three different types of pulsating stars: classical, type II and anomalous. Each form a separate period-luminosity relation. The most known of these types are the classical Cepheids, which are sometimes called *Cepheids*. They are medium mass stars (4 – 20 $M_\odot$) that cross the instability strip (IS) as they evolve igniting their He core after the main sequence, hence their relatively young age. Type II Cepheids are old (10 – 12 Gyrs) pulsating stars with low masses (~0.5 $M_\odot$) crossing the IS in the stage when leave the horizontal branch on their final path to their final stage of evolution. Anomalous Cepheids have up 1.8 $M_\odot$ and their actual evolutionary status is not completely known. All these stars can pulsate fundamental and first overtone mode, and classical Cepheids in even more modes. There is a period range around three days where they could be mixed up (even with RR Lyrae variable stars). Here we will explore how this can happen and what additional data would be useful for classification. They can be found in different galactic structures in the Milky Way, globular clusters and dwarf galaxies, which will play a role in new observations such as the LSST survey.

RU Camelopardalis is a well-known Type II Cepheids (W Virginis subtype) which displays a lot of behaviours untypical of any other Type II Cepheids and it is still referred to as such. Studying the long-term light curve, the spectral analysis from the literature, the Spectral Energy Distribution and evolutionary models we will show that these stars should be considered for reclassification as most probably a post-RGB or post-AGB star with a mass of around 1.0 to 3.0 $M_\odot$. It was referred in many publications as a text-book example of ongoing period change in Type II Cepheids, but if its classification is wrong indeed then we should reconsider the narrative around it.

P-43 – Hierarchical Classification of Variable Stars Using Deep Convolutional Neural Networks

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The importance of using fast and automatic methods to classify variable stars for large amounts of data is undeniable. There have been many attempts to classify variable stars by traditional algorithms like Random Forest. In recent years, neural networks as classifiers have come to notice. This paper uses the Hierarchical Classification technique, which contains several models with same network structure. Our pre-processing method uses light curves and period of stars as input data. We consider most of the classes and subclasses of variable stars in OGLE-IV database and show that using Hierarchical Classification technique and designing appropriate preprocessing can increase accuracy of predicting smaller classes. We obtain an accuracy of 98% for class classification and 93% for subclasses classification.

P-45 – Light Curve's Recovery with the Rubin Observatory's LSST

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Recently our team developed a new tool, called PulsationStarRecovery, to quantify the recovery of the light curve period and amplitude from a LSST simulated time series. The output of this code are pulsation parameters (period, amplitude, mean magnitude) together with quantitative information concerning the difference between the shape of the light curve and template light curves. I will describe the first applications of this newborn metric to simulate Rubin Observatory's LSST observations and recovery of different types of pulsating stars (RR Lyrae, Classical Cepheids and LPV) hosted by selected massive stellar systems to show how the recovery changes according to distance and variable star type. I will show that this exercise is essential to understand the potential of LSST since an excellent recovery is necessary to optimize the use of predicted Period-Luminosity relations to constrain the cosmic distance scale and the color-color planes to constrain the metallicity distribution function of different stellar populations.

P-46 – Light Curve Templates of RR Lyrae in the LSST Photometric System

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RR Lyrae (RRLs) are low-mass (0.54-0.82 Msun), old (>10 Gyr) pulsating stars (Catelan&Smith 2015) in the central Helium burning phase. Their periods are very regular, between 0.2 and 1.2 days and, most importantly, they obey to tight period-luminosity relations (PLs) of the form $M_X = a + b*logP$, where M_X is the apparent magnitude in the X band, in passbands redder than R (Longmore+ 1986, Catelan 2009, Braga+ 2015). This makes them excellent stellar tracers of the old population and probes of the Galactic evolution and assembly history (Iorio&Belokurov 2019, Ablimit+ 2022). On top of this, the PLs of RRLs are also the best tool to provide an independent calibration of the extragalactic distance scale (Beaton+ 2016) and, in turn, an estimate of H_0, which is crucial to settle the issue of the ever- increasing H_0-tension (Riess+ 2022).

RRLs are ubiquitous in all the components of the Milky Way (MW, see Fig. 1), especially in the Halo and Bulge, and most of its satellite Globular clusters (GCs) and dwarf Spheroidals (dSphs). To date, more than 300,000 RRLs are known in the MW and Magellanic Clouds, mostly from the *Gaia* DR3 (Clementini+ 2022) and OGLE-IV (Soszynski+ 2019). However, the sample is incomplete, especially concerning the Galactic Bulge and the outermost regions of the Halo.

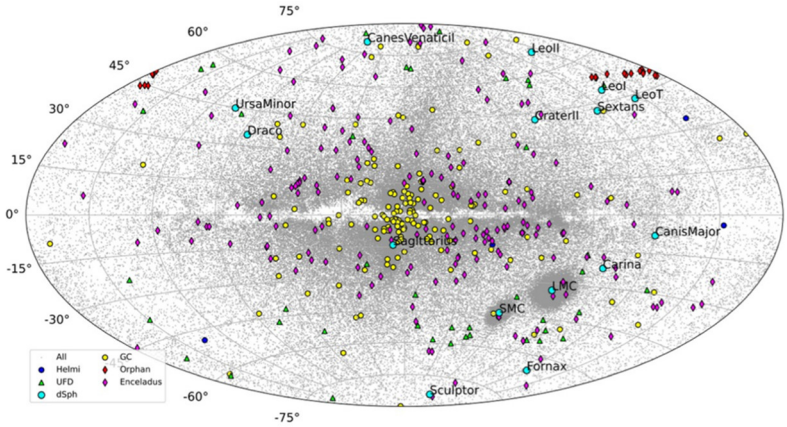

Figure 1: *Aitoff projection, in galactic coordinates, of RRLs in the MW and its satellites*

P-47 – The Post-mass Transfer Eclipsing Binary WASP 1814+48: Absolute Properties and Multiperiodic Pulsations

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For the EL CVn candidate WASP 1814+48, we obtained the first spectroscopic observations between 2015 April and 2021 March. Using the echelle spectra, the radial velocities (RVs) of the primary star were measured with its atmospheric parameters of $T_{\rm eff,1}$=7770±130 K and $v_1 \sin i$=47±6 km s^{-1}. We fitted our single-lined RVs and the *TESS* light curve simultaneously. From the binary modeling, we determined the following fundamental parameters for each star: M_1=1.659±0.048 M$_\odot$, R_1=1.945±0.027 R$_\odot$, and L_1=12.35±0.90 L$_\odot$ for WASP 1814+48 A, and M_2=0.172±0.005 M$_\odot$, R_2=0.194±0.005 R$_\odot$, and L_2=0.69±0.07 L$_\odot$ for WASP 1814+48 B. The surface gravity of log g_2=5.098±0.026 obtained from M_2 and R_2 is concurrent with 5.097±0.025 computed directly from the observable quantities. WASP 1814+48 B is well-matched with the 0.176 M$_\odot$ white dwarf (WD) evolutionary model for Z=0.01. The metallicity and our Galactic kinematics indicate that the program target is a thin-disk star. The whole light residuals after removal of the binary trend were analyzed and found to oscillate at a total of 52 frequencies. Among these, most of the low frequencies below 24 day^{-1} are aliases and orbital harmonics. The five significant frequencies between 32 and 36 day^{-1} are the pulsation modes of WASP 1814+48 A located in the δ Sct domain on ZAMS, and the high frequencies of 128-288 day^{-1} arise from WASP 1814+48 B in the pre-He WD instability strip. Our results reveal that WASP 1814+48 is the fifth EL CVn star that is composed of a δ Sct-type primary and a pre-ELMV (extremely low-mass pre-He WD variable).

P-48 – Spectroscopic Analysis of the Variable Star CO Aurigae with the GATS Telescope

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CO Aurigae is an unusual delta Cepheid star pulsating in double modes. In the years 2007–2015, a spectroscopic observation campaign of CO Aurigae was carried out, which resulted in several hundred spectral data. The observations were performed by the Global Astrophysical Telescope System (GATS), which consist of two telescopes; PST1 (the Poznan Spectroscopic Telescope) (Baranowski et al., 2009) located near Poznań (Poland), and RBT/PST2 (the Roman Baranowski Telescope) in Winer Observatory in Arizona (USA). Both telescopes operate in robotic mode and are equipped with fibre-fed echelle spectrographs of resolution R□35000 and 40000.

We would like to present the preliminary results of the analysis of the received data for CO Aur. It will concern the determination of pulsation frequencies and amplitudes, as well as the determination of the star's atmospheric parameters and the abundance of selected elements, from averaged spectra. To estimate parameters of stellar atmosphere and abundances, we will use the iSpec program (Blanco-Cuaresma et al., 2014, Blanco-Cuaresma, 2019) and spectrum synthesis method (with models ATLAS9 Kurucz/Castelli (Kurucz, 2005)).

P-49 – Non-Variable Stars

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Theory predicts, that if we look very closely on the brightness of any arbitrarily chosen star, we will find variability. The detection limit of the corresponding amplitude only depends on the instrumentation and accuracy of the measurements. This means that variable stars can be found at all locations across the Hertzsprung-Russell diagram (HRD). Countless papers over the last 150 years have been dedicated to the search for and detection of new variable stars. Most astrophysical theories including stellar formation and evolution can be tested with variable stars because they allow a look deep in the stellar interior (e.g., asteroseismology).

Nowadays, we know of millions of variable stars in our Milky Way and other Galaxies, especially due to large photometric surveys. In such a situation, it is more and more difficult to find really stable (constant), non-variable stars. However, do we need such stars? Just as an example, non-variable stars can be counted as boundary conditions of stellar models such as evolutionary tracks. It is therefore necessary to know the distribution of non-variable stars across the HRD answering questions like why there are variable together with non-variable stars in the classical instability strip.

In this talk, we present the photometric time-series of the *Kepler* satellite mission which are still the most accurate available and excellently suited to search for non-variable stars. We analysed all Long Cadence light curves for stars not reported as variable so far from the *Kepler* satellite mission. Using the known characteristics and flaws of these data sets, we defined three different frequency ranges in which we searched for nonvariability. We used the Lomb-Scargle periodogram and the False-Alarm probability (FAP) to analyse the cleaned data sets of 138 451 light curves. We then used log FAP ≥ –2 for defining a star not being variable in the ranges below 0.1 c/d, 0.1 to 2.0 c/d, and 2.0 to 25.0 c/d, respectively. Furthermore, we also calculated the standard deviation of the mean light curve to provide another parameter. In total, we found 14 154 stars which fulfil the set criteria. These objects are mainly cooler than 7000K populating the whole Main Sequence to the Red Giant Branch.

We assess the possible causes for stars pulsating and non-pulsating in the same regions of the HRD using our sample of stars.