Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

CHALLENGES TO MODELLING FROM GROUND-BREAKING NEW DATA OF PRESENT/FUTURE SPACE AND GROUND FACILITIES

G. Clementini[1], M. Marconi[2] and A. Garofalo[1]

Abstract. The sheer volume of high-accuracy, multi-band photometry, spectroscopy, astrometry and seismic data that space missions like *Kepler, Gaia, PLATO, TESS, JWST* and ground-based facilities under development such as MOONS, WEAVE and LSST will produce within the next decade brings big opportunities to improve current modelling; but there are also unprecedented challenges to overcome the present limitations in stelar evolution and pulsation models. Such an unprecedented harvest of data also requires multi-tasking and synergistic approaches to be interpreted and fully exploited. We review briefly the major output expected from ongoing and planned facilities and large sky surveys, and then focus specifically on *Gaia* and present a few examples of the impact that this mission is having on studies of stellar physics, Galactic structure and the cosmic distance ladder.

Keywords: Stars: general, oscillations, distances, Hertzsprung–Russell and C–M diagrams, variables: general, surveys, cosmology: distance scale

1 Introduction

The wealth and variety of datasets produced by ground/space-based facilities and large sky surveys under way or planned for the near future are trning Astronomy into a paradigm of "Big Data" science. Some of these facilities are reviewed briefly to show how their complementary data products can not only advance significantly our knowledge of stellar interiors, evolution and pulsation, but can also help constraining the structure and formation of our Galaxy, enable us to characterise the stellar populations in Galactic and extragalactic environments, and refine the cosmic distance ladder and gauge the expansion rate of the Universe.

Past, ongoing and future space facilities like *WIRE* (Hacking et al. 1999), *MOST* (Walker et al. 2003), *CoRoT* (Baglin 2003), *Kepler* (Koch et al. 2010), it K2 (Howell et al. 2014), *BRITE* (Pablo et al. 2016), *TESS* (Ricker et al. 2015), *Cheops* (Broeg et al. 2013) and *PLATO* (Rauer et al. 2014) are producing unprecedented, accurate light-curves that are revealing a very rich collection of stellar oscillations (gravity-modes, pressure-modes, rotation-related modes, etc.) for stars in different evolutionary stages. Asteroseismology is exploiting these data to provide seismic measurements of radii, masses, ages, distances and positions on the Hertzsprung–Russell diagram for thousands of stars within some tens of kpc. These measurements enable us to test distances derived from parallaxes, such as those measured by *Gaia*; they also provide a unique benchmark for testing and improving models for stellar evolution and pulsation. On the theoretical side, 3D model atmospheres are now starting to become available. They will enable a calibration of the empirical oscillations and convection parameters used in stellar-evolution codes (see e.g. Chaplin & Miglio 2013; Dupret 2019, and various contributions in this conference).

Several physical mechanisms (e.g. rotation and rotationally-induced mixing, magnetic fields, thermohaline mixing, internal gravity waves, mass loss, etc.) are still poorly understood and are not accounted for well in current stellar modelling. Including such effects into models is difficult because they are controlled by several physical parameters. However, it is no longer possible to ignore them if we wish to understand and interpret thoroughly the huge amount of high-accuracy photometric, spectroscopic, astrometric and seismic information that on-going and future surveys are providing. The development of 3-D stellar models and hydro-dynamical codes is also needed to describe convection and other dynamical phenomena realistically as they occur in stars; however, this is a very challenging and computationally expensive task (see e.g. Joyce et al. 2019, and references therein, and a number of talks at this conference).

---

[1] Osservatorio di Astrofisica e Scienza dello Spazio, Via Piero Gobetti 93/3, 40129 Bologna, Italy
[2] Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131, Naples, Italy

Large time-domain photometric surveys such as OGLE (Udalski et al. 1992), MACHO (Alcock et al. 1999), EROS (Tisserand et al. 2007), ASAS (Pojmanski 1997), Pan-STARRS (Chambers et al. 2016), *Hipparcos* (van Leeuwen 2007), SDSS (Stripe82; Annis et al. 2014), Catalina (Drake et al. 2014), PTF (Law et al. 2009), ZTF (Bellm et al. 2019), VVV (Minniti et al. 2010), VMC (Cioni et al. 2011) and *Gaia* (Gaia Collaboration et al. 2016) are providing a census of the variable stars in the Milky Way and its closest companions, revealing new features and new variability types. Starting full science operations in 2023, LSST (Ivezić et al. 2019 and references therein) will be *Gaia's deep complement in the southern hemisphere, providing parallaxes, proper motions and multiband photometry with uncertainties similar to Gaia's faint end (V∼20.5 mag) but reaching to about 5 magnitudes fainter than Gaia can.*

HERE

In parallel, large spectroscopic surveys such as SEGUE (Yanny et al. 2009), RAVE (Steinmetz et al. 2006), GALAH (De Silva et al. 2015), APOGEE (Allende Prieto et al. 2008), LAMOST (Deng et al. 2012) are measuring radial velocities and elemental abundances. Gaia-ESO (Gilmore et al. 2012), the only spectroscopic survey at an 8 m class telescope so far, is providing large samples of heavy-element abundances, both for s-process-dominated (Y-Zr-Ba-La-Ce), r-process-dominated (Sm-Eu), and mixed s&r (Pr-Nd) elements. In the near future, instruments under development such as WEAVE (Bonifacio et al. 2016) at the William Herschel Telescope (WHT), 4MOST (de Jong et al. 2019) at VISTA and MOONS (Cirasuolo et al. 2011) at the VLT will provide a detailed chemical characterisation for millions of stars in the Galactic halo and disk(s) (WEAVE) and accurate chemistry and kinematics for large samples of old giants spanning a wide portion of the red giant branch in the Magellanic Clouds and the Sagittarius dwarf spheroidal (MOONS). Accurate nucleosynthesis predictions, in particular for s-elements, require a detailed modelling of the asymptotic giant branch (AGB) evolutionary phase. The AGB phase is also critical for the interpretation of the infrared observations of the evolved populations in galaxies (e.g. the Magellanic Clouds and Local Group dwarf galaxies) and to study extinction properties. In the future, study of the circumstellar envelopes around massive stars in the Milky Way and in the Local Group will also become possible thanks to the high spatial resolution of next-generation facilities such as ELT in the optical and SKA in the radio. SKA will also allow one to measure the magnetic fields in stars of different evolutionary phases.

Such an unprecedented harvest of data requires synergistic and multivariate approaches to be fully exploited.

2 Gaia, three instruments in one mission: astrometry, (spectro-)photometry, spectroscopy

The stunning revolution being operated by Gaia has often been mentioned during the conference and examples have been shown in a number of talks (see, e.g. Eyer et al. contribution to this proceedings). Here, we would like to address two specific fields where Gaia is really astonishing: (i) the detailed monitoring of stellar populations in different evolutionary phases, and (ii) the distance scale.

The study of stellar populations can rely on Gaia 3-band time-series photometry (G, G_{BP} *and* G_{RP}*) and* G_{BP}*,* G_{RP} *spectro-photometry; on spectroscopy from the Radial Velocity Spectrometer (RVS; for sources brighter than G∼ 16-16.5 mag) and on astrometry (positions, proper motions and parallaxes, hence individual distances) for over 1 billion stars, that allow us to build accurate HR diagrams (see left panel of Fig. 1, showing the colour-magnitude diagram of the Large Magellanic Cloud – LMC, from Gaia Data Release 2 – DR2, data) as well as to estimate precise individual and mean distances. On this basis a 3D map of the Milky Way providing insight into the Galactic formation and evolution mechanisms is derived. Gaia is also a most powerful tool to discover and characterise all-sky variable sources, as shown by the catalogue and multiband time-series for more than half a million variables of different types (RR Lyrae stars, Cepheids, Long Period Variables – LPVs, Solar-like stars with rotation modulation, δ Scuti & SX Phoenicis and short period variables) released in Gaia DR2 (Holl et al. 2018). In the right panel of Fig. 1, we show RR Lyrae stars, Cepheids and LPVs released in DR2 which belong to the LMC plotted over the Galaxy CMD.*

A noteworthy product released in DR2, is the catalogue of about 150,000 rotational-modulation variable candidates of the BY Draconis class, an unprecedented sample to study stellar rotation, magnetic activity and stellar ages (Lanzafame et al. 2018, 2019).

Gaia DR2 contains also a catalogue of 140,784 confirmed RR Lyrae stars with full characterization: periods, amplitudes, mean magnitudes, Fourier parameters, photometric metal abundances (for a subsample of 64,932 sources) and interstellar absorption (for 54,272 of them) (Clementini et al. 2019). About 50,000 of these RR Lyrae stars are new discoveries by Gaia. In the DR2 variability tables there are more than 9,000 confirmed Cepheids fully characterized and with photometric metal abundances (for 3,738 for sources). About 350 of them are new discoveries by Gaia (Clementini et al. 2019; Ripepi et al. 2019).

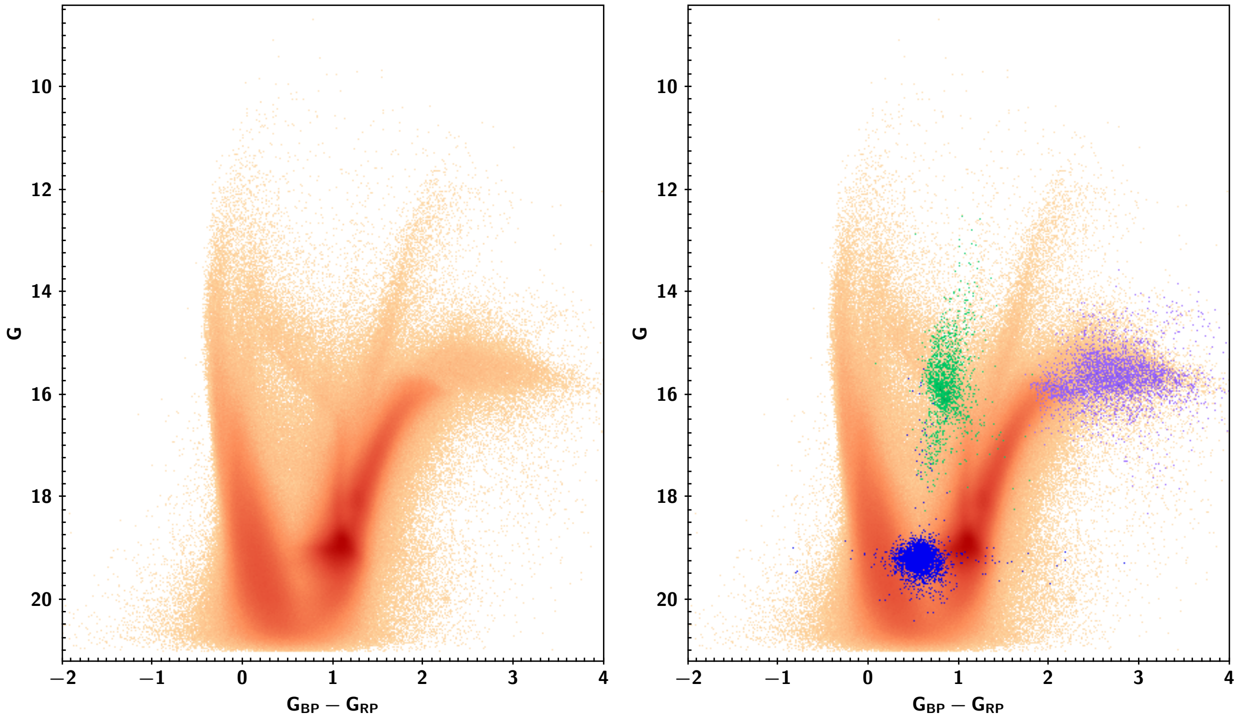

Fig. 1. Left: CMD of sources in the Gaia DR2 catalogue (selected by parallax and proper motions) contained in a region of about 8.8 degrees in radius around the Large Magellanic Cloud centre. Main features corresponding to the different evolutionary phases can be easily recognised: the main sequence, the red giant branch, the red clump, the horizontal branch. A sharp cut on the red giant branch marks the tip of the red giant branch (TRGB). The magnitude of the TRGB, which is set by the luminosity of the He core flash, may serve as a distance indicator for old stellar populations. Also very clearly visible are the blue loops of the core helium-burning evolutionary phase. **Right:** Same as in the right panel but with Cepheids, RR Lyrae stars, and LPVs (Soszyński et al. 2017, 2016, 2009, respectively) that cross-match with variable sources in the DR2 catalogue plotted as green, blue and purple filled circles, respectively, using G, $G_{BP}-G_{RP}$ mean magnitudes and colours from Gaia DR2 variability tables. The bulk of classical Cepheids are located on the central helium burning blue loop evolutionary phase, whereas RRLs nicely trace the LMC horizontal branch. Most of the LPVs are found above the TRGB, in the region of thermally-pulsing AGB stars.

In the case of pulsating stars, the distance information inferred from Gaia parallaxes can be used to provide stringent constraints on other debated quantities and relations such as the efficiency of superadiabatic convection or Mass-Luminosity relations, as well as, once complementary spectroscopic metallicities are available, the Helium to metal enrichment ratio. This will be possible through the comparison between observed and predicted pulsation properties including the model fitting of multi-filter light curves through non-linear convective pulsation models (see e.g. Marconi & Clementini 2005; Keller & Wood 2006; Marconi et al. 2013b,a, and references therein). Figure 2 shows the model fitting of the multiband light curves of the classical Cepheid RS Puppis. The best fit is obtained for a model with $T_{\rm eff} = 4875$ *K,* $\log L/L_\odot = 4.19$*,* $M/M_\odot=9$ *and mixing-length parameter* $\alpha = 1.5$*. The model fitting provides a parallax of 0.58± 0.03 mas in excellent agreement with the Tycho-Gaia Astrometric Solution (TGAS) parallax released with Gaia DR1 for this star, 0.63± 0.26 mas.*

Furthermore, once the distances are fixed, it will be possible to constrain the coefficients of the adopted extinction laws in current applications of the Period-Wesenheit relations. The comparison between predicted and observed radial velocity curves or Period-Radius relations will also allow us to directly measure the projection factor P, whose value and possible dependence on the pulsation period are debated in the literature.

Gaia distances are also adopted to calibrate Cepheid Period-Luminosity and Period-Wesenheit relations that in turn allow us to calibrate the extra-galactic distance ladder and to evaluate the Hubble constant through the calibration of secondary distance indicators.

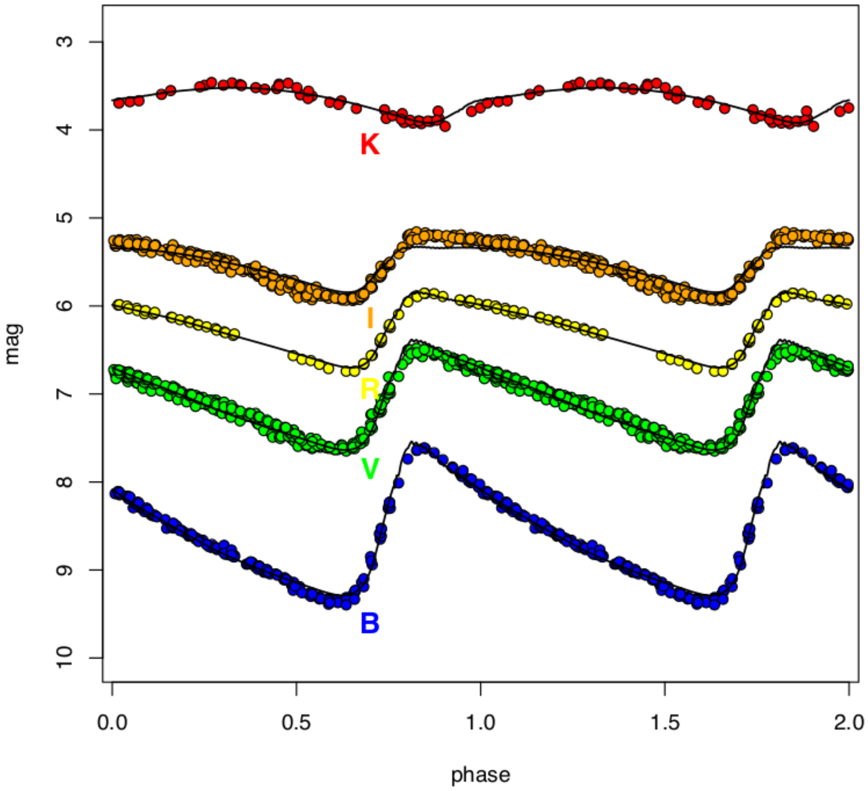

Fig. 2. Model fitting of the multi-wavelength light curves of the fundamental mode classical Cepheid RS Puppis (P=41.528 days) through non-linear convective pulsation models (adapted from Fig. 12 of Gaia Collaboration et al. 2017).

3 Parallaxes - Distances - H_0 and the H_0 'tension'

The Hubble constant, H_0, is the expansion rate of the Universe measured in units of inverse time. There is 'tension' between values of H_0 as derived from measurements of the anisotropy of the cosmic microwave background (CMB) radiation and as measured from a series of distance indicators in the local Universe. The CMB measures the age of the Universe at recombination. The distance ladder measures the age of the Universe now. If the standard model of cosmology is correct, these measurements should agree on the value of H_0 within the errors. Figure 3 summarises values of H_0 based on early- and late-Universe probes presented in the conference: "Tensions between the Early and the Late Universe", held at the Kavli Institute for Theoretical Physics, UC Santa Barbara in July 2019. The figure is an updated version of Fig. 1 in Verde et al. (2019) and shows that currently that 'tension' is between 4σ and 5.8σ. One thing is clear from Fig. 3 the onus to improve the accuracy of the H_0 measurements is on the distance ladder, rather than on the CMB. The error budget of the distance ladder must therefore be fully understood.

The Gaia contribution to understanding and quantifying the H_0 tension, as arising from the distance ladder side, will be unprecedented. This mission will allow us to raise the accuracy of the astronomical distance ladder by specifically tackling uncertainties and systematics in main stellar standard candles in order to cast light on the origin of the tension and at the same time better understand the underlying stellar physics.

The accuracy of local H_0 determinations will be significantly improved already by building on the data products in the forthcoming Gaia Data Releases 3 (EDR3 in the second half of 2020 and DR3 in the second half of 2021), and further boosted by subsequent releases (Gaia DR4, likely to occur in 2024) and the combination with data from TESS, JWST (Beichman et al. 2012) and the LSST.

Gaia will specifically improve the 'Anchors' of the distance ladder by directly measuring their distances through parallaxes. Examples of these improvements were already shown by the TGAS parallaxes released in Gaia

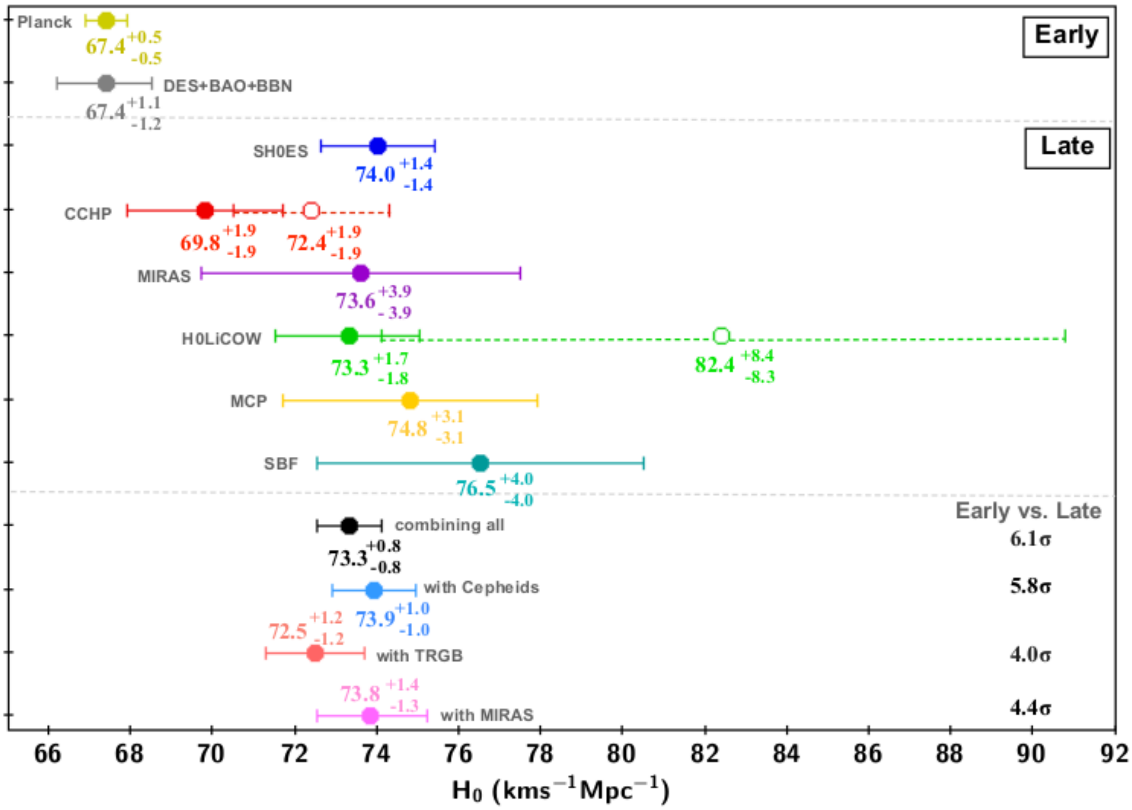

Fig. 3. Predictions and measurements of H_0 based on early- and late-Universe probes (adapted from Fig. 1 in Verde et al. 2019). The two independent predictions based on early-Universe data are from: Planck Collaboration et al. (2018), and Abbott et al. (2018), respectively. Results based on late-Universe data include: Riess et al. (2019) results for the SH0ES collaboration which uses geometric distances to calibrate Cepheids; Freedman et al. (2019) results for the CCHP collaboration which uses the TRGB to connect the distance ladder and, shown by the red dashed line, Jee et al. (2019) revision of the CCHP TRGB-based estimate of H_0; Huang et al. (2018) and Huang et al. (2019) results for Miras in NGC 4258 and NGC 1159, respectively; Wong et al. (2019) for the H0liCOW team that uses strong lensing time delays between multiple images of background quasars and, shown by the green dashed line, the new measurements from strong gravitational lenses by Jee et al. (2019) who recently increased the H_0 value by H0liCOW to H_0=82.4 +8.4/-8.3 km s^{-1} Mpc^{-1} (but note the large uncertainty); new results from the Megamaser Cosmology Project (MCP; Reid et al. 2009) which uses VLBI observations of water masers orbiting around supermassive black holes to measure geometric distances; and, Potter et al. (2018) results from IR Surface Brightness Fluctuations. Not shown in the figure, but potentially an additional tool to measure H_0, are gravitational waves and standard sirens. Recent results from this method were published by Mukherjee et al. (2019) who find $H_0 = 69.3^{+4.5}_{-4.0}$ km s^{-1} Mpc^{-1}.

DR1 (see, e.g. Gaia Collaboration et al. 2017) and by the Gaia-only parallaxes of RR Lyrae stars (Muraveva et al. 2018) and Cepheids (Riess et al. 2018) released in Gaia DR2.

According to current estimates of the error budget associated to each step of the cosmic ladder, the improvement that Gaia is going to provide can allow us to evaluate H_0 to ∼ 1%. This will occur through a number of progressive steps that are briefly listed below:

- *The exploitation of Gaia DR3 parallaxes along with a detailed investigation of the associated systematics, offsets (e.g. the offset with respect to QSOs, see fig. 12 in Lindegren et al. 2018) and relativistic effects, also relying on the comparison with asteroseismic parallaxes from Kepler, K2 and TESS*

- *The use of Gaia parallaxes along with NIR photometry for pulsating stars to re-calibrate Cepheid and RR Lyrae distance scales and their application to measure the distance to stellar systems containing different, independent primary and secondary distance indicators and, at the same time, bridging Gaia's distance range to those of LSST and JWST in a self-consistent path to H_0*

- *The simultaneous development and extension of fine grids of nonlinear convective pulsation models for variable stars in different evolutionary phases and environments that will allow us to theoretically constrain the distances and their dependence on physical and numerical assumptions, with relevant implications for the final error budget associated to* H_0
- *An improved treatment of population effects in various classes of standard candles associated to different stellar populations, namely, Cepheids, RR Lyrae stars, LPVs and the TRGB, directly calibrated through Gaia parallaxes locally, and all well represented in many external systems, like the Magellanic Clouds*
- *The investigation of possible alternative cosmic distance scale anchors to the traditionally adopted LMC, such as M31, and the use of different independent indicators for the same stellar system/anchor*
- *A rigorous quantification of systematic effects associated to the various adopted distance indicators and their impact on the final* H_0 *derivation.*

4 Conclusions

Synergy between different techniques, instruments and datasets is the key to tackle many of the issues affecting stellar evolution and pulsation modelling as well as to test empirical results (e.g. Gaia parallaxes). A bright future is in front of us thanks to present/future outstanding facilities and surveys, providing an unprecedented wealth of excellent photometry/astrometry/spectroscopy/asteroseismology datasets to challenge stellar evolution and pulsation modelling.

Acknowledgement: This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. We wish to warmly thank our colleagues and collaborators in the project "SH$_0$*T: the Stellar path to the* H_0 *Tension with whom many of the ideas presented in this proceedings are being developed.*

References

Abbott, T. M. C., Abdalla, F. B., Annis, J., et al. 2018, MNRAS, 480, 3879

Alcock, C., Allsman, R. A., Alves, D. R., et al. 1999, PASP, 111, 1539

Allende Prieto, C., Majewski, S. R., Schiavon, R., et al. 2008, AN, 329, 1018

Annis, J., Soares-Santos, M., Strauss, M. A., et al. 2014, ApJ, 794, 120

Baglin, A. 2003, Advances in Space Research, 31, 345

Beichman, C. A., Rieke, M., Eisenstein, D., et al. 2012, SPIE Conference Series, Vol. 8442, Science opportunities with the near-IR camera (NIRCam) on the James Webb Space Telescope (JWST) (SPIE), 84422N

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, PASP, 131, 018002

Bonifacio, P., Dalton, G., Trager, S., et al. 2016, in SF2A-2016: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse, & I. Vauglin, 267–270

Broeg, C., Fortier, A., Ehrenreich, D., et al. 2013, in EPJ Web of Conferences, Vol. 47, EPJ Web of Conferences, 03005

Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560

Chaplin, W. J. & Miglio, A. 2013, ARA&A, 51, 353

Cioni, M. R. L., Clementini, G., Girardi, L., et al. 2011, A&A, 527, A116

Cirasuolo, M., Afonso, J., Bender, R., et al. 2011, The Messenger, 145, 11

Clementini, G., Ripepi, V., Molinaro, R., et al. 2019, A&A, 622, A60

de Jong, R. S., Agertz, O., Berbel, A. A., et al. 2019, The Messenger, 175, 3

De Silva, G. M., Freeman, K. C., Bland-Hawthorn, J., et al. 2015, MNRAS, 449, 2604

Deng, L.-C., Newberg, H. J., Liu, C., et al. 2012, Research in A&A, 12, 735

Drake, A. J., Graham, M. J., Djorgovski, S. G., et al. 2014, ApJS, 213, 9

Dupret, M.-A. 2019, arXiv e-prints, arXiv:1901.08809

Freedman, W. L., Madore, B. F., Hatt, D., et al. 2019, ApJ, 882, 34

Gaia Collaboration, Clementini, G., Eyer, L., et al. 2017, A&A, 605, A79

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1

Gilmore, G., Randich, S., Asplund, M., et al. 2012, The Messenger, 147, 25

Hacking, P., Lonsdale, C., Gautier, T., et al. 1999, ASPCS, Vol. 177, The Wide-Field Infrared Explore (WIRE) Mission (ASP), 409

Holl, B., Audard, M., Nienartowicz, K., et al. 2018, A&A, 618, A30

Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 398

Huang, C. D., Riess, A. G., Hoffmann, S. L., et al. 2018, ApJ, 857, 67

Huang, C. D., Riess, A. G., Yuan, W., et al. 2019, arXiv e-prints, arXiv:1908.10883

Ivezić, Ž., Kahn, S. M., Tyson, J. A., et al. 2019, ApJ, 873, 111

Jee, I., Suyu, S. H., Komatsu, E., et al. 2019, Science, 365, 1134

Joyce, M., Lairmore, L., Price, D. J., Mohamed, S., & Reichardt, T. 2019, ApJ, 882, 63

Keller, S. C. & Wood, P. R. 2006, ApJ, 642, 834

Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJ, 713, L79

Lanzafame, A. C., Distefano, E., Barnes, S. A., & Spada, F. 2019, ApJ, 877, 157

Lanzafame, A. C., Distefano, E., Messina, S., et al. 2018, A&A, 616, A16

Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395

Lindegren, L., Hernández, J., Bombrun, A., et al. 2018, A&A, 616, A2

Marconi, M. & Clementini, G. 2005, AJ, 129, 2257

Marconi, M., Molinaro, R., Bono, G., et al. 2013a, ApJ, 768, L6

Marconi, M., Molinaro, R., Ripepi, V., Musella, I., & Brocato, E. 2013b, MNRAS, 428, 2185

Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, New A, 15, 433

Mukherjee, S., Lavaux, G., Bouchet, F. R., et al. 2019, arXiv e-prints, arXiv:1909.08627

Muraveva, T., Delgado, H. E., Clementini, G., Sarro, L. M., & Garofalo, A. 2018, MNRAS, 481, 1195

Pablo, H., Whittaker, G. N., Popowicz, A., et al. 2016, PASP, 128, 125001

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2018, arXiv e-prints, arXiv:1807.06209

Pojmanski, G. 1997, Acta Astron., 47, 467

Potter, C., Jensen, J. B., Blakeslee, J., et al. 2018, in AAS Meeting Abstracts, Vol. 232, AAS Meeting Abstracts #232, 319.02

Rauer, H., Catala, C., Aerts, C., et al. 2014, Experimental Astronomy, 38, 249

Reid, M. J., Braatz, J. A., Condon, J. J., et al. 2009, ApJ, 695, 287

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, JATIS, 1, 014003

Riess, A. G., Casertano, S., Yuan, W., et al. 2018, ApJ, 861, 126

Riess, A. G., Casertano, S., Yuan, W., Macri, L. M., & Scolnic, D. 2019, ApJ, 876, 85

Ripepi, V., Molinaro, R., Musella, I., et al. 2019, A&A, 625, A14

Soszyński, I., Udalski, A., Szymański, M. K., et al. 2009, Acta Astron., 59, 239

Soszyński, I., Udalski, A., Szymański, M. K., et al. 2016, Acta Astron., 66, 131

Soszyński, I., Udalski, A., Szymański, M. K., et al. 2017, Acta Astron., 67, 103

Steinmetz, M., Zwitter, T., Siebert, A., et al. 2006, AJ, 132, 1645

Tisserand, P., Le Guillou, L., Afonso, C., et al. 2007, A&A, 469, 387

Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., & Mateo, M. 1992, Acta Astron., 42, 253

van Leeuwen, F. 2007, ASSL, Vol. 350, Hipparcos, the New Reduction of the Raw Data (Springer Netherlands)

Verde, L., Treu, T., & Riess, A. G. 2019, Nature Astronomy, 3, 891

Walker, G., Matthews, J., Kuschnig, R., et al. 2003, PASP, 115, 1023

Wong, K. C., Suyu, S. H., Chen, G. C. F., et al. 2019, arXiv e-prints, arXiv:1907.04869

Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377