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COMMISSION G4 PULSATING STARS

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TRIENNIAL REPORT 2018-2021

1. Introduction

We are witnessing a renaissance of pulsating stars. These objects are cornerstones of stellar astrophysics – asteroseismology, galactic archaeology, and extragalactic science, as well. The renewed interest in pulsations and oscillations are boosted by the fact that more precise observations are being gathered than ever, more stars are monitored than ever before, and more continuous data sets are available than a mere few years ago. Both hardware (information technology and computing power) and software (machine learning and artificial intelligence) developments make it easier to cope with and analyze the large data sets (and models!), and synergies with Solar System studies and exoplanet hunting manifest in large surveys particularly useful for studying pulsations and oscillations. The European Space Agency's Gaia mission brought a revolution in stellar astrophysics in general, and in the astrophysics of pulsating and oscillating stars in particular. Homogeneous and high-precision astrometric, photometric, and some low-resolution spectroscopic data are now available across all the sky, as well as across galactic and extragalactic environments waiting to be explored and used to stellar astrophysics, galactic structure and formation studies.

2. Notable scientific results and publications

Below we present an admittedly subjective and incomplete list of the latest, most important and interesting results on pulsating and oscillating stars:

Aerts (2021) published an excellent **review about asteroseismology** highlighting the most important results and with the aim to make this research field accessible to graduate students and readers coming from other fields of physics. Two **collections of articles** related to asteroseismology have been published as special topics in Frontiers in Astronomy and Space Sciences open access journal. These are: *The Future of Asteroseismology*†, eds. J.A. Guzik and M. Roth, and *Asteroseismology in the Kepler Era*‡, eds. A.S. Baran, E.A. Lynas-Gray, and K. Kinemuchi.

† https://www.frontiersin.org/research-topics/7390/the-future-of-asteroseismology
‡ https://www.frontiersin.org/research-topics/11509/asteroseismology-in-the-kepler-era

Gaia. Eyer et al. (2019) provided the most complete description of the colour-absolute magnitude diagram and its variability induced changes based on variable (including pulsating) stars using Gaia DR2. Clementini et al. (2019) analyzed an all-sky sample of selected Cepheids and RR Lyrae stars observed by Gaia, over 50 000 of which (1/3 of the sample) are new discoveries. Kervella et al. (2019a) and Kervella et al. (2019b) established binarity from proper motion anomaly and based on common proper motion pairs is investigated in these classical pulsating stars using Gaia DR2 data.

TESS. Many TESS *first light* variable star papers have been published, covering discoveries for δ Sct and γ Dor variables by Antoci et al. (2019), rapidly oscillating Ap stars by Cunha et al. (2019), Cepheids by Plachy et al. (2021), red giants by Silva Aguirre et al. (2020), and white dwarfs by Bell et al. (2019) and Bognár et al. (2020). In addition, Handler et al. (2020) reported the discovery of tidally trapped pulsations in the ellipsoidal variable HD 74423 in Transiting Exoplanet Survey Satellite (TESS) space photometry data. The system contains a δ Scuti pulsator in a 1.6-d orbit, whose pulsation mode amplitude is strongly modulated at the orbital frequency, which can be explained if the pulsations have a much larger amplitude in one hemisphere of the star. They interpreted this as an obliquely pulsating distorted dipole oscillation with a pulsation axis aligned with the tidal axis. Bedding et al. (2020) used TESS 2-minute cadence data to discover a new class of high-frequency δ Scuti stars with regular frequency spacings which allow systematic mode identification. The space motions of some of these stars indicate that they are members of known associations of young stars, enabling the opportunity to derive asteroseismic ages for these associations. Chaplin et al. (2020) demonstrated how to put constraints on an ancient galactic collision by using asteroseismic age dating of a single bright, naked-eye star (ν Indi) observed by TESS.

MESA. An important development is that the 1-D Warsaw pulsational code was incorporated into MESA as the RSP module by Paxton et al. (2021). In a work by Molnár et al. (2019) the combination of state-of-the-art modelling techniques using MESA and GYRE with data assimilated from observations collected by amateur astronomers over many decades provided, for the first time, the opportunity to establish that the rapid pulsation period change and associated reduction in radius in T UMi are caused by the recent onset of a thermal pulse. Also, the most precise mass and age determinations for a single asymptotic giant branch star ever are obtained in this work. Joyce et al. (2020) conducted a rigorous examination of the nearby red supergiant Betelgeuse by drawing on the synthesis of new observational data and three different modeling techniques (self-consistent results from multi-timescale evolutionary, oscillatory, and hydrodynamic simulations conducted with the MESA software suite). Through their modeling efforts they provided a precise prediction for the star's radius and distance. The new results place Betelgeuse definitively in the early core helium-burning phase of the red supergiant branch. They report a present-day mass of 16.5–19 solar masses – slightly lower than typical literature values.

Machine learning. Bellinger et al. (2020) showed that machine learning can be used effectively to relate input physical parameters to output light curve parameters for a set of synthetic RR Lyrae and Cepheid light curves produced in the V and I photometric bands simultaneously, emulating the two-colour measurements of the OGLE survey. Szklenár et al. (2020) developed a method to classify variable star light curves – including pulsating variables – based on deep convolutional neural networks, i.e., artificial intelligence. They used images of phase-folded light curves from the OGLE survey. The novelty of the method is that it is image-based, as opposed to other existing method based on various pre-computed statistics and light curve parameters. The method mimics the human brain: it learns larger and smaller scale characteristics of the light curves.

3. Conferences

The COVID pandemic situation dramatically changed the landscape of conferences and meetings worldwide in early 2020. Some conferences have been cancelled, some have been postponed, and many of them was or are planned to be held online (or in a hybrid form). Without doubt, this has profound consequences on the way we, as a community will organize conferences in the future with the possible benefits of decreasing significantly the carbon footprint of our conferences, and also making them more accessible to everyone including underprivileged countries/groups. The obvious downside is the lack of personal meetings and social interactions. Several excellent initiatives have been undertaken to counteract the disruption of professional interactions. One such example in the realm of pulsating stars is the Good Vibrations seminar series† that provides a venue for PhD students to present their work, start new collaborations and talk to people working in their field.

3.1. *Pre-covid meetings*

- The ESO Workshop *"A Revolution in Stellar Physics with Gaia and Large Surveys"* held in Warsaw, Poland, 3–7 September 2018, included several talks on asteroseismology and its connection to large spectroscopic surveys in the Gaia era.

- An international symposium *"PHOST: Physics of Oscillating Stars"* was held in Banyuls-sur-mer, France, 3-7 September 2018. More than 100 participants gathered to discuss what physics we can learn from oscillating stars.

- The Kepler/K2 Science Conference in Glendale CA, USA, 4-8 March 2019 had several presentations, including four invited talks highlighting asteroseismology.

- The KITP program *"Better Stars, Better Planets: Exploiting the Stellar-Exoplanetary Synergy*, in Santa Barbara, CA, USA Apr-Jun 2019 featured a related conference in May (Planet-Star Connections in the era of TESS and Gaia), both the program and the meeting had a strong seismology component.

- The next in the Los Alamos pulsation conference series *"Grand Challenges in Stellar Physics: Pulsating Stars in the Universe"* was planned to be held in France, Nice, in April 2019, but it was cancelled.

- The TESS Science Conference and the yearly TASC5/KASC12 (Kepler/TESS Asteroseismic Science Consortia) conferences were held back-to-back in Boston in July 2019. While the first one had two asteroseismology sessions, the latter is by and large was dedicated to seismology and its applications.

- The *"Stars and Their Variability from Space"* Conference held in Vienna, Austria, from August 19-23, 2019 discussed the history and recent advances in asteroseismology from space-based telescopes such as MOST, CoRoT, Kepler/K2 and BRITE.

- The ''*Dynamics of the Sun & Stars: Honoring the Life & Work of Michel Thompson"* conference was held at NCAR, Boulder CO, USA featured several helio- and asteroseismology talks.

- RRL/CEP2019 conference – *"Frontiers of Classical Pulsators: Theory and Observations"* – was held in Cloudcroft, NM, USA 13-18 October 2019. This is a series of biannual meetings dedicated to RR Lyrae and Cepheid science in a broad sense.

- The AAS#235 meeting was held in Honolulu, HI between 4-8 January 2020. The diverse program had a Pulsating Variable Stars session with six talks and a plenary talk on stellar physics and seismology by Jennifer van Saders.

† https://sites.lesia.obspm.fr/the-good-vibrations-seminars/

3.2. *Covid-affected meetings*

- The LSST@Europe4 conference originally planned for June, 2020 in Rome, Italy was cancelled.

- The pulsation conference *"The Rising stars of Asteroseismology"*, originally planned for July, 2020 in Liège, Belgium was postponed to a later date.

- The annual conference of the Kepler and TESS Asteroseismic Science Consortia (TASC6/KASC13), titled *"Asteroseismology in the Era of Surveys from Space and the Ground: Stars, Planets, and the Milky Way"* was first postponed to 2021, then again by another year.

- MOBSTER-1 virtual conference (*"Stellar variability as a probe of magnetic fields in massive stars"*) in July 2020 had a strong pulsation/seismology component. The event was a great success: 220 participant registered from 36 countries.

- The annual meeting of the European Astronomical Society (EAS) first online meeting in June/July 2020 was a huge success, more than 1700 colleagues participated. The conference had pulsation-related sections: (S10) Gaia: *"The (two) billion star galaxy census: The promise of (E)DR3"*, (SS5) *"New insights of angular momentum transport in stellar interiors"*.

- An international workshop *"Pulsations in intermediate-mass, massive and/or multiple stars"* was held online 18-22 January 2021, sponsored by the Royal Astronomical Society and the Institute of Advanced Studies, University of Surrey, UK. The potential of asteroseismology in the analysis of binary stars was deeply discussed.

- EAS 2021 will be held online, as well, offering several sessions of interest for our community: (S15) Gaia: *The (TWO) Billion Star Galaxy Census: The Science of EDR3 and the promise of DR3"*, (S16) *"Massive stars: birth, rotation, and chemical evolution, (SS22) "The Great Dimming of Betelgeuse: news from the mass loss of red supergiants"*.

- RRL/CEP2021 conference dedicated to RR Lyrae stars and Cepheids – originally planned for 2021 in La Palma (Canary Islands), was postponed to September, 2022.

- TESS Science conference II will be held online in August, 2021. Asteroseismology and pulsating stars are usually integral part of the scientific program of these conferences.

- Similarly, the PLATO Science conference in October 2021 has *"Asteroseismology and stellar characterisation"*, as well as *"Complementary science topics benefitting from PLATO high-precision photometry"* including pulsating stars among the major topics advertised.

3.3. *Meetings in preparation*

Two IAU symposium proposals related to pulsating stars have been submitted in 2019: *At the cross-roads of astrophysics and cosmology: Period–luminosity relations in the 2020s* (submitted by Richard de Grijs, location: Budapest, Hungary) and *Winds from close-in exoplanet to massive stars* (submitted by Aline Vidotto, location: IAU GA, Busan, South Korea). These proposals were resubmitted in 2020 and are waiting for decision.

4. Awards and prizes

In 2020 the American Astronomical Society instituted a new type of fellowships among its senior members. The following IAU members associated with Commission G4 were honored (in alphabetic order): Anne Cowley, Nancy R. Evans, Arne Henden, Steven Kawaler, Arlo Landolt. In 2021 Conny Aerts joined the AAS fellows. We congratulate to all of them for their outstanding work and exemplary careers.

5. Ph.D. theses

A number of students have published excellent Ph.D. theses during the triennium. A few examples of these are: Cole Johnston, Interior Modelling of Massive Stars in Multiple Systems† and May Gade Pedersen, Interior rotation, mixing, and ages of a sample of Slowly Pulsating B Stars from gravity-mode asteroseismology‡.

6. Developments within the past triennium

6.1. *Projects in space*

The highly successful Canadian MOST satellite was decommissioned in March 2019 after more than 15 years of operations. NASA's revolutionary Kepler/K2 missions also stopped operations in late 2019. The BRITE-Constellation nanosatellite fleet in Austrian-Polish-Canadian cooperation continues to observe bright stars. Launched in 2018, NASA's Transiting Exoplanet Survey Satellite (TESS) mission finished observations of both the southern and the northern ecliptic hemispheres observing many pulsating variable stars while searching for transiting exoplanets. The mission was extended by the NASA Senior Review through 2022. In the extended mission the satellite will cover again the southern and northern hemisphere and also ecliptic regions with modified cadence and target lists. ESA's M4 mission, PLATO with a strong seismology component is on track for its launch scheduled for the year 2026.

6.2. *Projects on the ground*

The Danish-led Stellar Observations Network Group (**SONG**) installed a new node with two telescopes in Mt. Kent, Australia to obtain spectroscopic time-series data of pulsating and oscillating stars. The US-led Vera C. Rubin Observatory in Chile will start its 10-yr multi-color **Legacy Survey of Space and Time** photometric survey in October 2023. The *Transients and Variable Stars*, as well as the *Stars, Milky Way, Local Volume* Science Collaborations cover science cases involving pulsating stars. The multi-object spectrograph of the **WEAVE** survey to be installed on the 4.2m William Herschel Telescope on La Palma, Canary Islands will have its first light sometime in 2021. The WEAVE survey will observe Cepheids and RR Lyrae stars as part of its SCIP (Stellar, Circumstellar and Interstellar Physics) and Galactic Archeology programs, respectively. SDSS-IV has finished its operation in 2020, while SDSS-V started to operate with the Milky Way Mapper – a time-domain optical+IR spectroscopic survey of Milky Way stars of all types – relevant for this Commission. Large number of pulsating stars are being or will be delivered by other large sky surveys, like ZTF, SuperWASP, ASAS-SN, and Everyscope. Last, but not least, AAVSO¶ – The American Association of Variable Star Observers — continues to collect ground-based data on pulsating — and other — variable stars. In several cases the light curves span more than a century.

6.3. *Journals*

Starting from 10 March 2019 **IBVS (International Bulletin on Variable Stars)** is no longer accepting new submissions. There are multiple reasons behind the decision to discontinue the journal. Konkoly Observatory maintained and edited IBVS since its conception in 1961. The number of the submitted manuscripts have steadily declined

† https://fys.kuleuven.be/ster/pub/phd-cole-johnston/johnston-thesis-online.pdf
‡ https://fys.kuleuven.be/ster/pub/phd-thesis-may-pedersen/phd-thesis-may-pedersen
¶ http://aavso.org

since the heydays in the 1990s and early 2000s. New possibilities arose to publish short papers and notes regarding variable stars. And, while quality of the papers is much more subjective to assess than quantity, editors felt that the overall level of the journal has also lowered. The Discovery and Observation reports formats started to get outdated, as we have entered the era of big, time-resolved surveys with hundreds of thousands of new variable detections, and these reports presented extra work for the editorial staff with diminishing returns. The journal also run into human resources issues. IBVS was too little to employ dedicated staff, so editorial work was distributed among a few post-docs (on temporary contracts), and IT personnel at the observatory. This was not a sustainable path on the long term. At this point, Konkoly Observatory management felt that resuscitating the journal would require expensive investments that are not justified by the number and quality of recently published papers. Instead, the objectives become to:

- provide an archived version of the journal,
- deposit all pdf versions to ADS, and
- deposit the data files at CDS.

The Editorial Board and all recent authors were notified about the closure, and the latter were pointed towards similar options elsewhere (e.g., JAAVSO, OEJV and RNAAS for papers, the AAVSO VSX and AID databases for observation data and reports). During the almost 60 years of operations more than 6200 IBVS issues were published.

The **Open European Journal on Variable Stars** (OEJV, Czech Republic) also stopped operations in October 2019. However, the journal was restarted in 2020 at Masaryk University. The editor in chief is Ernst Paunzen.

7. About the future

The US astronomy community initiated the Astro2020 Decadal Survey on Astronomy and Astrophysics during the triennium. Huber et al. (2020) describe a white paper on stellar physics and galactic archaeology using Asteroseismology in the 2020's, including current facilities such as SONG and next-generation high-precision RV instruments such as the Keck Planet Finder. On the other side of the Atlantic, the HAYDN (High-precision AsteroseismologY of DeNse stellar fields) concept was submitted by Miglio et al. (2021) as a white paper in response to Voyage 2050 long-term plan in the European Space Agency Science Programme. A mission like HAYDN, dedicated to gathering high-precision, high-cadence, long photometric series in dense stellar fields would lead to breakthroughs in stellar astrophysics, especially in the metal poor regime, providing insight to the evolution and formation of open and globular clusters, and aid our understanding of the assembly history and chemodynamics of the Milky Way's bulge and even nearby dwarf galaxies. Regardless of the adoption of the mission, asteroseismology and studying pulsating variable stars have a bright future.

Róbert Szabó
Acting President of the Commission

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