Astro2020 Science White Paper

Pulsation as a Laboratory for Understanding Stellar Physics

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
XStars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract (optional):

This paper presents a brief review of stellar pulsation across the H-R diagram and the critical importance of investigations of pulsation in order to make important inroads into understanding many fundamental processes in stellar physics. This particular area of astrophysics has been largely overlooked by the community and is ripe for new discoveries over the next Decade.

1. Background:

Intrinsic stellar instabilities leading to pulsations are one of astronomy's most powerful tools to interrogate detailed questions of stellar physics. Stellar pulsational instabilities can be recognized at nearly every phase of stellar evolution, over a broad range of time scales, and occurring across a wide range of stellar masses and densities. Pulsations can be regular, irregular, interacting, or stochastic in nature and generally stem from an interplay between thermodynamics and gravitational forces. The two main types of pulsations are termed p-mode (pressure restoring forces) and g-mode (gravity/buoyancy restoring forces). Both the envelopes and interiors of the stars can experience these instabilities leading to pulsational variations which manifest as changes in intrinsic magnitude, stellar angular diameter, mass-loss, star spot distribution and even detailed evolutionary status.

2. Physical Manifestations:

Pulsations can be used to test a wide variety of questions about the evolutionary state of a star in a real-time setting. The most basic tests include confirmations of stellar size, flux, radial surface velocities, and distribution of material between core and envelope. Focusing on stellar atmospheres, pulsations are known to enhance mass-loss in AGB variables [1] and mass-transfer in near-Eddington limit binary systems [2]. The details of the pulsation affect the efficiency/yields of nucleosynthesis processes changing the products measured in the atmosphere or during mass-loss [3],[4] . Pulsations are expected to couple to convective motions, but may be further excited or damped by turbulence/mixing-lengths located in these convective layers [5]. Stellar rotation is seen to couple to pulsation causing a circulation of the atmospheres to create other mixing effects which in turn create atmospheric observables [6]. Finally, the hydrodynamical piston driving the atmospheres of pulsating stars may produce shocks which in turn extend the stellar atmospheres and create non-spherical distributions of matter [7].

We also find strong evidence for how pulsations affect stellar interiors giving us valuable insights into stellar evolution. For instance, the interplay/distribution between p- and g-modes can tell us about the locations of the convective and radiative layers inside the stars. Multi-mode pulsations and beat phenomena demonstrate how stellar instabilities can reveal opacity-driven changes [8]. Beyond the fundamental and first overtone radial pulsations, there are the non-radial oscillations and other modes (e.g. quadrupole) which lead us to re-evaluate the physics operating in many variable stars [9]. Finally, pulsational information helps us make conclusions about the stellar dynamos from which we can infer the formation process and stability of stellar magnetic fields [10].

3. Some Outstanding Astrophysical Questions:

In Figure 1 we include an H-R diagram with named stars as well as the locations of many of the most common classes of pulsating variables stars. Each class of variable stars has a particular set of unsolved problems being addressed by the community using a variety of techniques. We briefly outline a few of these and later discuss observational approaches to them.

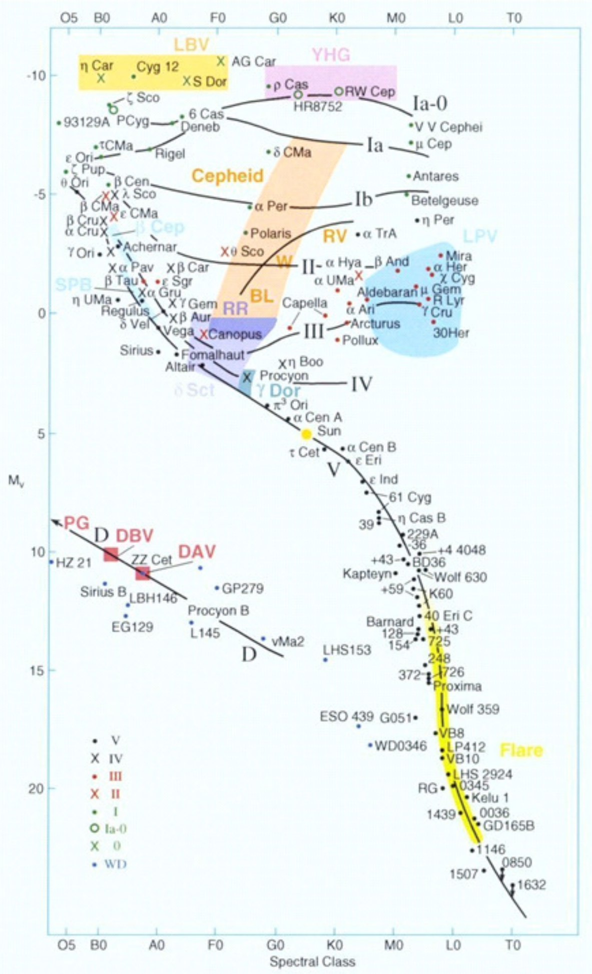

Figure 1: H-R Diagram including the major classes of variable stars. The classical instability strip is represented by the salmon and dark blue colored region. Other regions are represented by the colors associated with the abbreviations. Named stars in many of the sections of the diagram are included. From the top down, left to right, the variable stars categories are: LBV = Luminous Blue Variables, YHG = Yellow Hyper Giants, Cepheids, B Cep = Beta Cepheids, RV = RV Tauri, LPV = Long Period Variable including Miras, SPB = Slowly Pulsating B Stars, W = W Virginis, BL = BL Herculis, RR = RR Lyrae, del Sct = Delta Scuti, gam Dor = gamma Doradus, PG = PG 1159 stars, DBV = He White Dwarfs, DAV = H White Dwarfs or ZZ Ceti, Flare = K, M and L Dwarf Flare Stars. (Kaler, 2006 [11]).

3.1 Cepheid Variables: Arguably the most important variable stars owing to their use as standard candles, the period-luminosity (PL) relation for Cepheids still has several unresolved issues. Fundamentally, the relation needs to be well-calibrated, with stellar metallicity (referred to as color - C) still being an outstanding issue today [12]. Here the W Vir variables, the lower-mass, lower-metallicity cousins of the Classical Cepheids, become important in our attempts to quantify the PLC relationships. Absolute measurements can be problematic because fundamental parameters such as luminosity and spectral energy distribution are often not measured in a uniform way between investigations, requiring careful tracking to intercompare. Recent suggestions that some Cepheids may have episodic or long-term mass-loss [13],[14] has cast doubt about their use as standard candles at the 1-2% level (see Figure 2). This has profound implications for astrophysical conclusions based on distance scales derived from Cepheids.

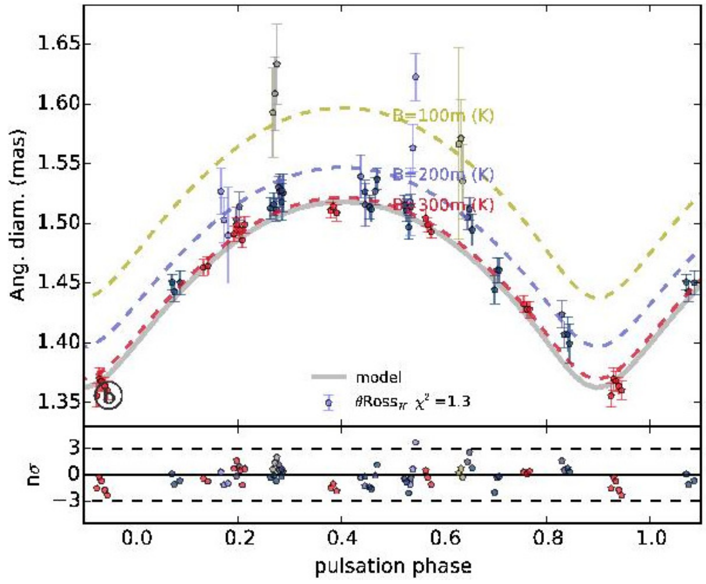

Figure 2: Pulsations of delta Cephei taken with the CHARA Array long-baseline interferometer. Overlaid on the base model (grey) are circumstellar envelope models associated with different baselines and distributions of material. Unambiguous pulsations of approximately 100 microarcseconds amplitude are detected over the pulsation period. (Merand et al. 2015 [13])

3.2 RR Lyrae Variables: These stars are smaller and have shorter periods than Cepheids, and are principally used to measure distances to globular clusters. They present us with a long-standing puzzle called the Blazhko effect, a secular variation in the form and amplitude of the fundamental mode pulsation which lasts tens to hundreds of days and is seen in a large fraction of RR Lyrae [15]. Multiple explanations have been put forth as explanations including metallicity [16], multi-level non-radial mode pulsations [17], and instabilities driven by turbulent convection [18]. Multiple complementary techniques and concentrated efforts from many investigators will likely be required to sort out these issues.

3.3 Mira Variables: Miras are the regular pulsators among the LPV class with periods over 200 days. Being very extended, low-to-intermediate mass giant stars, they are luminous enough to be seen at much greater distances than Cepheids. The ability to unambiguously identify the types of pulsations in Miras to develop PL relations, and also for individual objects, could render them as better distance calibrators. Arguments continue today about fundamental [19] versus first-overtone pulsation status [20]. Adding to this complication is the strong mass-loss and dust production, sometimes with peculiar nucleosynthetic signatures [21], as well as atmospheric convection in Miras [22] which could help theorists develop better approaches for mixing-length theory.

3.4 Solar-type Variables: Solar-type variables should be the easiest for astronomers to understand given detailed studies of the Sun, and therefore they are elevated to the most important variables for which to obtain high-precision measurements and large statistical samples. They will become the calibrators for all future conclusions that use the Sun as the reference model. An excellent review by Houdek [23] demonstrates the vast diagnostic power of understanding these solar cousins in order to understand what physics drives dwarf star convection, pulsational damping processes, stochastic excitation and turbulence, magnetic field generation and stellar-cycling effects.

3.5 roAp Variables: Rapidly oscillating peculiar A stars have long been a puzzle for the astrophysics community. These stars pulsate with periods of minutes, demonstrate spectra lines motions of ~10 km/s, and are strongly magnetic with field strengths up to tens of kiloGauss [24]. They represent special astrophysical laboratories because their magnetic and rotation/pulsation axes are not aligned rendering them as “an oblique pulsator”. This type of geometric degeneracy-breaking allows us to better comprehend the effects of magnetic fields on stellar atmospheres. Further, ions of peculiar species such as Nd and Pr are radiatively levitated in these atmospheres, allowing for the rare opportunity to study atmospheric diffusion in the stellar photosphere [25].

3.6 White Dwarf Variables: A wide range of temperatures (8,000-40,000 K) and chemistries (H, He, C, O, Ne) exist among the variable white dwarf stars. The numerous subgroups here exhibit pulsational periods of seconds to minutes and serve as excellent laboratories for studying matter distribution and nuclear reaction rates in (partially-) degenerate objects [26]. They may be one of the few places where crystallization of degenerate material [27], as well as the existence and depth of unanticipated convection zones on the surfaces of these dense objects [28], can be studied.

4. Future Needs to Address Pulsation Questions:

We list some of the most promising ways the astrophysics community can strive to solve these issues in the 2020s.

4.1 High Cadence Time-series, RV studies and Asteroseismology:The past decade’s advances designed for exoplanet scientific inquiries have helped tremendously in pushing the sensitivities and precisions needed for nearly all high-precision measurements of pulsating stars. Success of Kepler, CoRoT and OGLE are finally allowing for statistical analyses of asteroseismic data (see Figure 3). To continue making progress, additional high-cadence, high-precision instruments (few ppm level for photometry or few cm/s for RV) capable of deeper sensitivities (to match Gaia -- 14th mag or deeper) , as well as dedicated programs (e.g. TESS), will be required.

4.2 Long-Baseline Optical Interferometry: A unique and under-utilized opportunity exists in the astrophysics community measuring the angular diameters, tangential motions, and imaging non-spherical modes of pulsation in these types of stars. As sensitivities improve (approaching 14th mag over the next decade[29]) with the US LBOI interferometric arrays, as well as associated efficiency gains in observing cadence, variable stars in the angular size scales down to 0.5 milliarcseconds (with 5-10% errors), periods as short as a few hours, and spectrally resolved lines, will be routinely imaged. The addition of parallaxes from Hipparcos and Gaia will resolve the ambiguities in physical scales and allow unprecedented flux calibration of these variable systems.

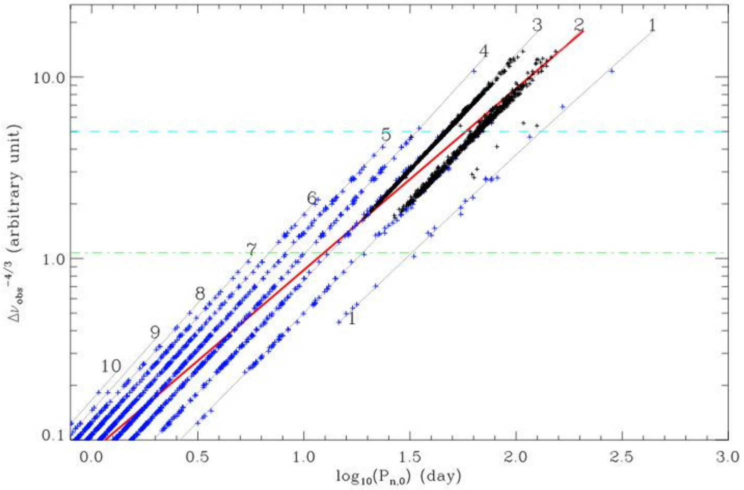

Figure 3: PL relations for AGB and RGB star radial solar-like oscillations taken with Kepler (blue) and OGLE (black). The y-axis corresponds to a proxy for luminosity. Each numbered grey line corresponds to a different radial pulsation order for these stars. (Mosser et al. 2013 [30])

4.3 Laboratory Astrophysics and Improved Modeling: There is still a strong and largely unmet need for laboratory measurements to expand our knowledge of detailed opacities, oscillator strengths of quantum transitions, and cross-sections for many common components in the stellar atmospheres. Finally an irony exists here that just as many of the truly interesting questions about stellar physics were being uncovered in the 1970's, and computer technology was becoming helpful for computationally difficult problems, much of the astrophysics community turned away from stellar physics. We finally have the synergy of computer technology and observing and data reduction approaches to address these issues in the 2020s.

Today's still relatively sparse data on variable stars show that these unsolved questions are the fertile field we need to make real insights into stellar physics. Understanding the interiors and atmospheres of the stars underpins all other conclusions we make in the astrophysics community and so it is imperative that we address these issues soon.

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