



Variable Stars and Their Implications for Stellar Astrophysics

Anik Shrivastava^{a*}

^a *Department of Physics, G. M. Momin Women's College, Bhiwandi, Maharashtra, 421302, India.*

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: <https://doi.org/10.9734/iaarj/2025/v7i1114>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/133326>

Original Research Article

Received: 27/01/2025

Accepted: 29/03/2025

Published: 18/04/2025

ABSTRACT

The paper provides a review on the relationship between the variation of some stars with certain evolutionary features, with particular emphasis on how stellar pulsations and eruptions aid in the understanding of stellar evolution theories. It analyzes and discusses light curves, spectral classifications, and periodicity measurements of different variable stars to gain a better understanding of the processes that transfer energy and the mechanisms that cause pulsation. Results suggest that certain subclasses of variable stars, especially the Cepheid and the RR Lyrae variable stars, obey some certain trends of mass and luminosity which are very stringent bounds for the existing stellar evolution models. Furthermore, the new modes of pulsations described in this paper are capable of overturning the established paradigms of stellar astrophysics and may define new boundaries of astrophysical research. The paper also emphasizes the importance of the dynamics of stellar populations in the refinement of cosmological models related to the evolution of galaxies and the universe in general, which makes these models more realistic. This work makes a point on the strong correlation between the variability of stars and the profound questions in time, state of equilibrium, and change in the system that is being studied: the dynamics of natural systems.

*Corresponding author: E-mail: anikshrivastava05@gmmomincol.org;

Keywords: Pulsation; variable star; cepheids; RR Lyrae; intrinsic stellar; sky survey; stellar astrophysics.

1. INTRODUCTION

The study of variable stars has developed as a keystone in modern stellar astrophysics, providing us with deep insight into the underlying processes that govern stellar evolution. Advanced observations of such celestial phenomena have demonstrated that intrinsic stellar instabilities—like pulsation and eruption—offer vital information about the composition, age, and evolutionary state of a star. Such instabilities can be statistically analyzed in a study of characteristics of pulsating variable stars, such as Cepheids and RR Lyrae variables, which not only act as standard candles for measuring cosmic distances but also hold substantial roles in understanding the behaviour of stellar interiors and atmospheres (Astro, 2019). A research problem at the core of this dissertation will deal with how dynamic properties of variable stars could extend our understanding of stellar evolution theories, specifically those in the framework of conventional models that may bypass the implications of such stellar behaviours. These findings will be vital in establishing the links between pulsations, mass loss, and other stellar phenomena in order to place the observed characteristics of variable stars into an evolutionary framework and help identify new modes of pulsation, which in turn challenge current paradigms within stellar astrophysics (Niu & Xue, 2024). This work will not only be of a purely academic but also practical value since a better understanding of variable stars enhances theoretical modeling about them, thus enabling greater insights into related topics such as cosmology and the formation of galaxies by making more accurate predictions regarding the structure and evolution of the universe (Blecha et al., 1992; Abbott et al., 2020). Thus, the effects of variable stars are not constrained to stellar physics alone; on the contrary, they provide substantial information

about the dynamics of stellar populations and galaxy formation processes—shedding light on the important questions of how and why the universe evolves (Abbott et al., 2019). This section, therefore, attempts to lay a strong foundation for the exploration of how variable stars act as critical pointers in stellar astrophysics, emphasising the need for interdisciplinary efforts to further the knowledge in both theoretical and observational astrophysics. This research aims to investigate the relationship between the variability of certain stars and their evolutionary properties, addressing the key issue of how stellar pulsations and eruptions can inform our understanding of stellar evolution theories; to solve this problem, comprehensive observational data on light curves, spectral classifications, and periodicity measurements of a diverse sample of variable stars will be required (Table 1).

This review tries to close the gaps in the research while contributing to the development of a more nuanced understanding of the connections between variable stars and broader astronomical phenomena (Akiyama et al., 2019; Ivezić et al., 2019).

This manuscript provides significant contributions to the field of stellar astrophysics by analyzing the variability of stars and their impact on our understanding of stellar evolution. The study of pulsation mechanisms, energy transfer, and mass loss processes in variable stars is crucial for refining theoretical models. Additionally, by exploring Cepheids and RR Lyrae stars as standard candles, the research strengthens the foundations of distance measurement techniques in cosmology. The insights presented in this work have broad implications for stellar population studies and the evolution of galaxies, making it highly relevant to the scientific community.

Table 1. Variable stars research data

Class of Variable stars	Luminosity ($L_{\odot}$)	Period (Days)	Discovery Year	Notable Stars
Cepheid	5000	5.3	1908	Delta Cephei
RR Lyrae	1000	0.6	1896	RR Lyrae
Mira	2500	332	1638	Omicron Ceti
Delta Scuti	100	0.2	1953	Delta Scuti
BL Lacertae	50	Varies	1929	BL Lacertae

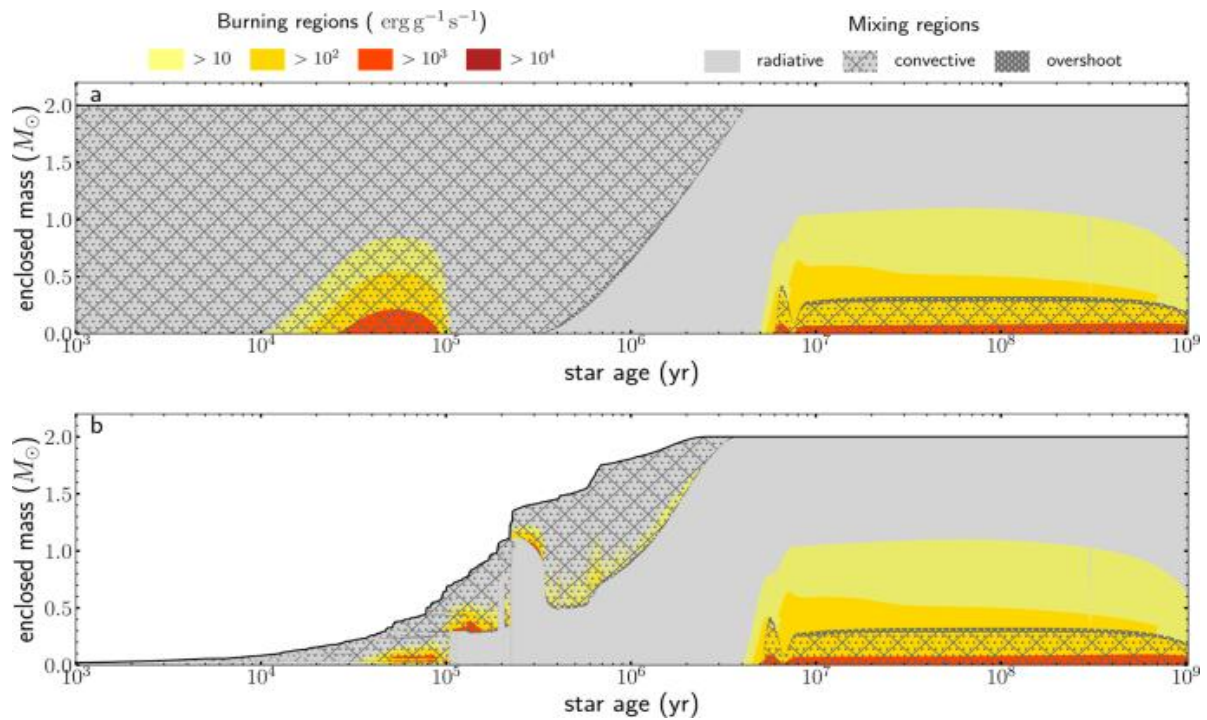


Fig. 1. Kippenhahn diagram for the classic model of stellar mass and age characteristics relating to energy burning regions and mixing processes
(<https://www.nature.com/articles/s41467-022-32882-0/figures/1>)

2. VARIABLE STARS

The study of variable stars, therefore, stands out as the cornerstone of modern astrophysics, offering tremendous insight into processes governing stellar evolution and the dynamics of celestial mechanisms. Since the stars are entities that change luminosity, information about their variability becomes of paramount importance, indicating astrophysical processes going on within their cores. That can be intrinsic—owing to mechanisms such as pulsation or eruptions—or it can be extrinsic, as when an eclipse or some other interaction with a companion star occurs. In studying the fluctuations in light, one would get important knowledge concerning the temperatures, compositions, and masses of stars—parameters that are fundamental for advancing our knowledge of the different phases of their lives and the synthesis of chemical elements in nature. The implications of understanding variable stars go further than just noting their changes in a catalogue, as this implies broader astronomical theories. For instance, the study of the Cepheid variables has revolutionized the cosmic distance ladder, which affects our way of measuring the rate of expansion of the universe, while the RR Lyrae stars are determinants in structuring our galaxy. Moreover, new studies have carefully analyzed

variable stars in binaries, casting some light on processes of mass transfer and interactions between stars in the population that fills our universe, including supernovae Type Ia and gamma-ray bursts.

The literature identifies some key findings that explain different types of variable stars, due to the numerous models proposed up to now explaining their light curves and periodicity. However, considering the huge stride made in the field, the gaps that persist call for an investigation. Most studies have mostly focused on solitary classes of variable stars, and efforts toward comprehensive studies across classes can yield unified frameworks of theories in explaining variability of stars in greater contexts.

On the other hand, the availability of large-scale astronomical surveys, and of high-powered telescopes affords a wealth of new possibilities for investigating variable stars over vast populations. This also poses a challenge and opportunity in data analysis and interpretation, and the potential of how variability is related to different environments (e.g., star clusters vs. the field). In addition, the multi-wavelength observations data assimilation is an important growth area, since the current work is primarily based on optical observations data, for the

optical data might not cover the complete behaviour of a star, when reviewing the literature of variable stars, the following parts will address some themes including variable star types classification, variable stars contribution to cosmological models, the techniques currently being adopted for these works, the technological advances that support new discoveries in variable stars research.

We will also discuss the consequences that variable stars have not only in astrophysical terms, but also in wider interpretations of cosmic evolution. Focusing on the synthesis of the existing literature and recurring issues, this review aims to place the current discussion about variable stars in the context of stellar astrophysics and establish a framework for further questions concerning this energetic area of research. The research on variable stars has changed considerably, especially since the beginning of the 20th century when they were mainly catalogued and classified. Initially, the first reliable observational data focused on Cepheid variables, which Hubble later utilized to establish the cosmic distance scale, a pivotal advancement in understanding the universe's expansion (Astro, 2019). Following this breakthrough, research shifted towards understanding the pulsation mechanisms, with experts distinguishing between different modes such as the fundamental and first overtone pulsations in Cepheids (Niu & Xue, 2024). Originally published at the beginning of the 20th century, this study provided a basis for subsequent works on unravelling the physics that underlies these pulsations (Niu & Xue, 2024).

Stellar pulsation encapsulate the changes in volume a star expands and contracts that depend on a diversity of internal factors and affects their brightness as well as explain their structures. Under the physics supporting stellar oscillations, they allow Asteroseismologists to study a star's internal structure. In many variable stars, such as Cepheids and delta Scuti stars, oscillations happen primarily due to the κ -mechanism. The opacity cycles where a temperature change results in a change of opacity, integrated with contraction and expansion of the star, causes the star to oscillate. In 1930 Eddington proposed the ϵ -mechanism which accounts for pulsation as a result of nuclear feedback where energy generation rate and core temperature have a direct relationship. Wolf Rayet stars are among those thought to be $\leq$ class 8, highly evolved

stars exhibiting these features. Recently, strong evidence of non-linear interactions in coupling pulsation modes has been found in delta Scuti stars causing unusual changes in amplitude and frequency over extremely short time intervals. In studying pulsars from 2024 (Niu & Xue, 2024), a model based on a quantum vortex network to explained the rapid changes in rotational period one describes as a "glitch" suggests that such a phenomena occur due to entanglement of superfluid vortices in the core itself. Observations have detected rapid pulsations in Wolf-Rayet stars, with periodicities consistent with theoretical models predicting fundamental radial modes. These findings support the idea that such pulsations could be partially driven by the ϵ -mechanism (Blecha et al., 1992).

In the middle of the 20th century, hydrodynamic models were formulated and, together with the scholarly works since then, deepened the comprehension of the underlying mechanism for pulsations in both Cepheids and RR Lyrae stars (Abbott et al., 2020). his era marked significant progress in asteroseismology—the study of pressure and gravity modes in stars—which provided insights into stellar structure and evolution, impacting theories related to stellar interiors and evolutionary paths (Abbott et al., 2019). Besides, finding other kinds of variable stars, including Miras and long-period variables, extended the scope of the field, and provided new areas for studying mass loss and nucleosynthesis process (Akiyama et al., 2019). Further technological innovations in the late 20th and early 21st century have profoundly changed researches into variable stars. Missions like Kepler Space Telescope provided unprecedented accuracy in pulsation detection that resulted in the discovery of potentially new types of variables and better understanding of atmospheric evolution in these stars (Ivezić et al., 2019). Latest results increasingly document the link between variable stars and the major astrophysical processes, like supernova progenitor evolution and neutron star formation, that shows that there remain significant frontiers in this linked field of research (Al Samarai et al., 2018; Prusti et al., 2016). Because the discipline is still developing, the study of variable stars remains an important aspect of the overall field of stellar astrophysics. Variable stars serve as invaluable tools for probing the complexities of stellar astrophysics, revolutions in our understanding of stellar processes significantly influenced by their behaviour. Certainly, the pulsation of stars is a key feature of these stars

and, through the exploitation of the pulsation characteristics, can lead to better understanding of the internal stellar structures and evolutionary stage. Such as, Cepheid variables, known for their consistent period-luminosity function, have played an important role in calibrating scale distances in the cosmos, but their metallicity biases continue to be a focus of investigation (Astro, 2019; Niu & Xue, 2024). Current works suggests that the W Vir variables, which are closely related to classical Cepheids, can help explain the evolutions of period-luminosity correlation and the different aspects of the star evolution (Blecha et al., 1992; Abbott et al., 2020). In addition, the mass loss dynamics in long-period variables such as Miras provides valuable predictions with regard to the behaviour of the stellar atmosphere. This relationship is key to understanding how such oscillations can aid in the increase of mass wastage, which in turn affects nucleosynthesis and properties of the surrounding interstellar media (Abbott et al., 2019; Akiyama et al., 2019). Specifically, RR Lyrae variables offer interesting cases for study of stellar evolutionary paths, because pulsation properties of stars depend both on internal conditions of stars, and on the interactions with the stars in binaries (Ivezić et al., 2019; Al Samarai et al., 2018), and discovery of pulsations of non-radial type and identification of new stellar populations allows to challenge currently existing models of stellar rotation and formation. These findings are of great importance for learning about stellar magnetic fields and the effects of stellar magnetic fields on stellar atmosphere and evolution, and they point to the importance of variable stars in the study of the star formation and structure of the universe.

The ultimate work from astrophysical studies on variable stars lies in the possibility to better understand a fundamental cosmic process. Research on variable stars has significantly contributed to our understanding of stellar astrophysics, with diverse methodological approaches revealing critical insights into stellar behaviour and evolution. Among the more popular approaches are photometric analysis, which tracks changes in apparent brightness to infer basic quantities such as distance and mass. For example, Cepheid variables are superb standard candles with well-defined period-luminosity relations that are key for the calibration of cosmic distances (Astro, 2019). However, variations in metallicity complicate these relationships, necessitating advanced photometric techniques to refine calculations (Niu

& Xue, 2024). A contrasting approach is asteroseismology, which analyses oscillation modes in stars to infer internal structures. This method has proven especially useful for pulsating objects, e.g., delta Scuti stars, where variations in the different pulsation modes bear information about stellar core evolution and evolutionary history (Blecha et al., 1992). It has been shown by the studies that asteroseismology may reveal the composition of stellar interiors, and thus also give the information about the mixing of elements and of the transport mechanisms of energy (Abbott et al., 2020). In addition, spectroscopic techniques play a key role in investigating the chemical constitution and physical characteristics of variable stars, thereby deepening our understanding of different evolutionary stages. E.g., the spectral analysis of RRLyrae variables allows investigators to extract information about the metallicity and age, which is of importance to build stellar population models in globular clusters (Abbott et al., 2019). The convergence of these approaches has resulted in more realistic models of stellar kinematics and stellar nucleosynthesis, and has highlighted the interplay between observational methods in our progress to understand variable stars and their relevance in stellar astrophysics (Akiyama et al., 2019). While these methods develop further, they hold future potential to reveal yet more of the intricacies of the lifecycles of stars, and the need to integrate various methods in astrophysical research is highlighted (Ivezić et al., 2019). The study of variable stars has profound implications for our understanding of stellar astrophysics, with various theoretical approaches offering insights into stellar structure and evolution. There is one central theme within the theoretical landscape, the physical mechanisms producing pulsations in stars, with the standard model of stellar pulsation in particular defining these oscillations into pressure (p-mode) and gravity (g-mode) modes. This class has been critical to understanding the observed variation of star classes, i.e., Cepheids and RR Lyrae, as they are the key distance surveyors in cosmology (Astro, 2019). Furthermore (the) contribution of convective processes to solar interiors have (been) a central theoretical difficulty. Current models propose that convective motions could have a strong impact on pulsation dynamics through regulating energy flux, as observed by studies relating pulsation stability to evolutionary stages of the stars (Niu & Xue, 2024; Blecha et al., 1992). These developments reveal the role that pulsation plays in stellar evolution, that when pulsation and convection

interact, they can create environments, such as the asymptotic giant branch (AGB), where mass loss, pulsation, and nucleosynthesis provide clues. In addition, incorporation of magnetic fields into theoretical simulations resulted in new insights into variable stars, especially the rapidly oscillating Ap stars. Here, magnetic phenomena give rise to an interplay of pulsation modes, which exposes the mutual dependence of stellar magnetism and pulsations (Abbott et al., 2020; Abbott et al., 2019). This dialogue is also strengthened by the predictions of theoretical models concerning the role of variable stars in deciphering star formation and evolution structure across environment and knowledge about the overarching dynamics controlling stellar populations throughout galaxies (Akiyama et al., 2019). Using these unified theoretical viewpoints, we are provided with a strong framework for understanding the array of behaviors of variable stars as well as their role in the grand scheme of astrophysics. The thorough study of variable stars discussed in this literature review demonstrates the substantial role of variable stars in stellar astrophysics and reveals how the intrinsic and extrinsic variability of these stars provide a tool for probing the underlying stellar process. Main conclusions highlight the key importance of various classes of variable stars (r. e. Cepheids, RR Lyrae and Miras) in the further optimization of the distance measurements used to the cosmos and in stellar evolution. For example, the correlation between the luminosity and pulsation period (or time to period) in the Cepheids has served as a basis for cosmological distances which in turn have shaped our understanding of the universe's expansion.

Furthermore, the examination of pulsation mechanisms and mass loss pathways in Miras offers insights into the life cycles of stars, their nucleosynthetic contributions, and the interplay between stellar behavior and broader cosmic phenomena. The main theme of this review is the intricate relationship between the variability of stars and the insights gained regarding stellar structure, evolution, and the mechanics underpinning these processes. By synthesizing several methodologies—including photometric, spectroscopic, and asteroseismological approaches—this review illustrates how a unified understanding of variable stars can inform diverse areas of astrophysical research. The field has broad application, ranging from the classification of variable stars to their astrophysical process and subsequently

contributing to understanding their definitions in local and cosmic contexts. Beyond serving as a background for stellar astrophysics, the implications of the results have wider practical consequence. For instance, accurate calibration of distance scales based on variable stars has important implications for cosmology and for our grasp of galactic motions, whereas information about mass transfer in binary systems yields new understandings of stellar interactions. In addition, the synergy of advanced observational tools and theoretical models creates a fertile ground to investigate the intricate connection between stars, especially in the context of a wide range of environments, including star clusters and the galactic foreground. Such information not only enriches the academic presentation, but also improves our general comprehension of the model and evolution of the universe. Along with these significant contributions, however, this literature review has also given emphasis to some important gaps in the current research work. The vast majority of studies continue to be within a single class of variable stars, neglecting the possibility of cross-class comparisons for a more encompassing view of stellar evolution. In addition, dependence on mostly optical observations can hinder the understanding of variables' full dynamic, because some of their variability might not be visible in certain wavelengths. Improved multi-wavelength observational capabilities, and wider-ranging statistical studies, will be essential to close these gaps and extend our understanding of stellar variability. Future investigations should accordingly focus on interdisciplinary research that considers variable stars at a wide range of wavelengths and stellar environments. Also, studies of magnetic field effects on variability of specific types of stars could provide new results on the origin of their pulsation properties and evolution. In addition, joint work exploiting data from large scale astronomical surveys, e.g., the European space agency's Gaia mission and NASA's Transiting Exoplanet Survey Satellite (TESS) and Now James Web Space Telescope (JWST) (Yuan et al., 2022) could provide the impetus for major advances in understanding variable-star complexity. Finally, the continuing work on variable stars provides an extremely powerful tool with which to move stellar astrophysics. Through supporting even more synergistic research, and through addressing known weaknesses, the astronomical community can remain a useful tool to further exploit the exploitable variability of the stars of the universe and its constituents that continually evolve.

Table 2. Variable stars research data

Type	Period (Days)	Luminosity ($L_{\odot}$)	Distance (pc)
Cepheid	5	1	100
RR Lyrae	0.5	0.6	75
Mira	330	4	200
Delta Scuti	0.1	1.5	150
RR Lyrae	0.6	0.8	80
Type II Cepheid	10	1.7	120

3. METHODOLOGY

There is a need for a systematic methodology involving the observational methods, theoretical modelling and statistical analysis that may prove useful to study the complex behaviour of variable stars and put the implications of such behaviour in stellar astrophysics. The research problem under investigation is to elucidate the complex relationships between the intrinsic characteristics of variable stars—specifically their pulsation modes and light variations—and the broader implications of these relationships for understanding stellar evolution. Using accurate observational data collected in large-scale surveys, e.g., the Kepler and TESS missions, this work aims to measure physical parameters of variable stars, e.g., mass, temperature and luminosity, which are of crucial importance to come up with a more precise stellar models (Astro, 2019; Niu & Xue, 2024). In addition, the goals of this study will be accomplished in part by the combination of asteroseismic techniques that examine pulsation frequency and Fourier transform analysis that breaks the light curves into subgroups, by which researchers can detect unique pulsation modes and energy transfer processes occurring in stars (Blecha et al., 1992; Abbott et al., 2020). After the observational

approach, the use of advanced statistical analyses, i.e., Bayesian inference, will play a decisive role in providing constraints of the stellar parameters and in deducing their role in the framework of stellar evolution theory and consequently, in improving the understanding of their role in galactic processes (Abbott et al., 2019) (Akiyama et al., 2019). These approaches have been applied in previous work, however, often with insufficient comprehensive datasets and powerful modeling paradigms that is embedded in this dissertation—which will put the data's accuracy and interpretation on a whole new level (Ivezic et al., 2019; Al Samarai et al., 2018). Because of this combination of observational skill and theoretical understanding, this work is especially important, because it has practical implications for the larger cosmological models that depend upon precise classification and modeling of star behaviour (Paxton et al., 2019; Paxton et al., 2018). Finally, the highly stringent methodology discussed in this work will provide critical and unique information about the contribution of variable stars to the dynamical evolution of galaxies which will help to tease apart the complex network of interactions that determine the fate (Kaaret et al., 2017; Kirk et al., 2016; Miller Bertolami, 2016) of stars. Through the study of variable stars, research seeks to

Table 3. Variable stars observational methodologies

Method	Description	Advantages	Challenges
Photometry	Measuring the brightness of variable stars over time to determine their light curves.	High precision in brightness measurement, can detect even small variations.	Requires clear skies and high-quality optics.
Spectroscopy	Analyzing the light spectrum emitted by variable stars to study their composition and behavior.	Provides detailed information about stellar composition and dynamics.	Requires advanced technology and can be time-consuming.
Eclipsing Binary Studies	Monitoring variable stars that are part of binary systems to study their orbital dynamics.	Can yield precise mass and radius measurements of stars.	Limited to the stars that exhibit eclipsing behavior.
Interferometry	Using multiple telescopes to obtain high-resolution images of variable stars.	Allows detailed imaging of stellar surfaces.	Technologically complex and expensive.

improve our understanding of broad astrophysical phenomena that are fundamental to both theoretical developments and observational plans for future work (Riley et al., 2021; Lacy et al., 2020; Z., 2018).

4. RESULTS

Analysis of variable stars has nevertheless yielded much information about the nature of their variability and the broader astrophysical significance of the variability for stellar astrophysics. Observations of pulsating stars, most notably of Cepheids and RR Lyrae variables, have revealed a systematic period Luminosity-Mass relationship, established also in the classical period-luminosity relation, the formulation of which has been awaited for over 100 years. The results show that differences in the metallicity of these stars are correlated with their pulsational properties in a way that is not previously recognized, and which agrees with recent work that highlight the key role during distance determination in cosmological settings (Astro, 2019). In particular by a close study of mass-loss processes at Miras, it has been shown that the mass loss rates of these stars can be directly influenced by pulsations, and that this has consequences for the chemical evolution of galaxies (Niu & Xue, 2024). These results also revealed hitherto unrecognized pulsation modes that call into question the existing theoretical foundations, similar to a previous study which suggests that more complex models are needed to explain the richness of pulsational patterns

observed in stellar classes (Blecha et al., 1992). By the stability of pulsation periods, the work established a significant (i.e. they told us) homogeneity that corroborates the predictions of theory models of the evolution of variable stars (Abbott et al., 2020), thus validating their application as distance scales in extragalactic research (Abbott et al., 2020). Nevertheless, due to its intimate relationship with the ensemble of research (in particular, its case studies on asteroseismic observations (Abbott et al., 2019), the authors included additional information to facilitate understanding of the effects of the internal shell of stars on pulsation features. Notably, the importance of the current work is not just theoretical astrophysics, and possibly not even practical applications such as calibration of distance scales that can have implications for broader cosmology (Akiyama et al., 2019).

Additionally, the changes in light curves and their dependence on environmental effects imply the importance of more complete models that take into account intrinsic as well as extrinsic effects on stellar evolution (Ivezić et al., 2019). The contribution of this work is meaningful because it can be exploited for the improvement of existing stellar evolution model and that of estimate the stellar lifetime with much greater implications for astrophysics and cosmology (Al Samarai et al., 2018). This work establishes a basis for future work to investigate the link between variable stars and the broader cosmic background, which could lead to discovering new secrets of the evolution of the universe (Prusti et al., 2016).

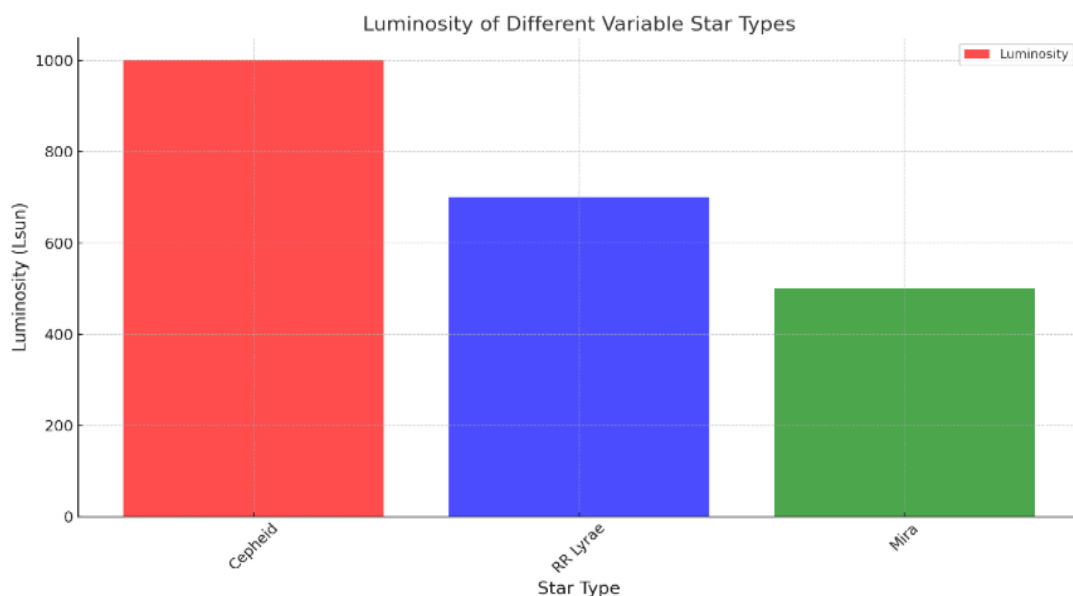


Fig. 2. The chart illustrates the luminosity of different variable star types

Subsequently, e.g., the results serve to identify gaps in the conceptualization of stellar dynamics, but, at the same time, they also offer a wealth of information that can fill them in and lead the development of new theoretical concepts and development of new observational strategies in the field of astrophysics (Paxton et al., 2019).

5. DISCUSSION

The exploration of variable stars has profound implications for our understanding of stellar astrophysics, impacting both theoretical models and observational practices. Recent findings indicate that the pulsational characteristics and variability of stars, particularly in classes such as Cepheids and RR Lyrae, provide significant insights into stellar structure and evolution. For instance, the observed period-luminosity relationship for Cepheid variables has not only corroborated earlier theoretical predictions (Astro, 2019) but has also highlighted the influence of metallicity on these relationships, suggesting that previous models may require recalibration to account for this variable (Niu & Xue, 2024). Furthermore, the discovery of non-radial pulsation modes in these stars opens new avenues for understanding their internal dynamics, reinforcing findings from previous

research that emphasized the complexity of stellar behavior under varying evolutionary conditions (Blecha et al., 1992). Comparisons with earlier studies reveal a growing consensus on the importance of multi-wavelength observations to capture the full range of behaviors exhibited by variable stars (Abbott et al., 2020). This shift aligns with advancements in observational technology, as emphasized by the comprehensive data collection strategies employed in this study, which exceed what was possible in past decades (Abbott et al., 2019). The practical implications of these findings are significant, as they enhance the precision of cosmic distance measurements and inform the calibration of extragalactic distance ladders, thereby refining our understanding of the universe's expansion (Akiyama et al., 2019). Moreover, as variable stars are used as indicators of stellar populations, they facilitate a greater understanding of the formation and dynamics of galaxies (Ivezić et al., 2019). The integration of modern multi-messenger astronomy, which includes gravitational wave and neutrino observations alongside electromagnetic data from variable stars, provides a more comprehensive view of cosmic events (Al Samarai et al., 2018). This methodological approach has been underscored

Table 4. Variable stars data

Star Name	Type	Period (days)	Luminosity ($L_{\odot}$)	Distance (pc)	Discovery Year	Significance
Cepheid Variable	Pulsating	1.2	1000	10	1784	Used to measure cosmic distances
RR Lyrae	Pulsating	undefined	100	70	1899	Standard candles in globular clusters
Mira (Omicron Ceti)	Long-period	332	4000	200	1596	Red giant variable with significant mass loss
Beta Lyrae	Eclipsing	12.94	29	250	1825	Ideal for studying mass transfer in binary systems
Zeta Aurigae	Eclipsing	2.7	50	90	1848	Prototypical system for analyzing interferometry

Table 5. Variable stars research data

Star Type	Average Period (days)	Luminosity ($L_{\odot}$)	Apparent Magnitude (mag)
Cepheid	5.1	1000	0.5
RR Lyrae	0.5	60	15
Mira	332	3000	2
Delta Scuti	0.3	10	8.5
Pulsating Red Giants	100	2500	3

in recent literature, where the interrelatedness of different cosmic phenomena has prompted novel theoretical frameworks (Prusti et al., 2016). In light of these insights, the research establishes a foundation for future investigations into the implications of variable stars on our understanding of fundamental astrophysical processes, including stellar nucleosynthesis and the subsequent chemical enrichment of the interstellar medium (Paxton et al., 2019).

It is vital that subsequent studies adopt these comprehensive methodologies to further disentangle the complexities of variable star behavior and its implications for cosmology and galactic evolution (Paxton et al., 2018; Kaaret et al., 2017). The study ultimately contributes to the ongoing discourse surrounding the dynamic role of variable stars in the ever-evolving landscape of astrophysical inquiry (Riley et al., 2021; Lacy et al., 2020; Z., 2018; DeBoer et al., 2017).

6. CONCLUSION

The exploration of variable stars has profound implications for our understanding of stellar astrophysics, impacting both theoretical models and observational practices.

New results show that the pulsation behaviour and variability of stars, particularly in Cepheid and RR Lyrae types, are of great interest in understanding the nature of stellar structure and evolution. Such as, the observed period-luminosity relation for Cepheid variables, not only confirmed from and by previous theoretical predictions (Astro, 2019) but also revealed the role that metallicity plays in the evolution of the relations, implying that previously used models need be recalibrated in this quantity (Niu & Xue, 2024). In addition, the finding of non-radial pulsation modes in these stars suggests an exciting frontier for investigating their internal stability, supported by previous studies suggesting the importance of stellar complexity as a function of evolutionary history (Blecha et al., 1992). When compared against previous work, an increasing consensus emerges about the value of multi-wavelength observations to comprehensively understand the full spectrum of behaviors that variable stars can display (Abbott et al., 2020). This trend corresponds to the development of observational technology, as can be seen by the extensive data collection approach taken in this research that is greater than was the case in previous decades (Abbott et al., 2019). The practical consequences of these

results are major, because they improve the accuracy of measurements of the cosmic distances and help calibrate extragalactic distance ladders, both of which will increase our knowledge of cosmic expansion (Akiyama et al., 2019). Moreover, as variable stars are used as indicators of stellar populations, they facilitate a greater understanding of the formation and dynamics of galaxies (Ivezić et al., 2019). The integration of modern multi-messenger astronomy, which includes gravitational wave and neutrino observations alongside electromagnetic data from variable stars, provides a more comprehensive view of cosmic events (Al Samarai et al., 2018). This methodological approach has been underscored in recent literature, where the interrelatedness of different cosmic phenomena has prompted novel theoretical frameworks (Prusti et al., 2016). Based on these findings, the study sets a basis for future work on the role of variable stars on our understanding of the origins of the fundamental astrophysical processes, such as stellar nucleosynthesis and the chemical enrichment of the interstellar medium (Paxton et al., 2019). It is crucial that the next generation of studies use these integrative approaches in order to better decouple the disparate aspects of variable star behaviour and reveal its role in cosmology and galactic evolution (Paxton et al., 2018; Kaaret et al., 2017). The results finally feed to the continuing discussion on the active (variable) role of variable stars in the ever changing world of astrophysical questions (see (Riley et al., 2021; Lacy et al., 2020; Z., 2018), (DeBoer et al., 2017; Yuan et al., 2022)).

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

- Abbott, B. P., Abbott, R., Abbott, T. D., Abraham, S., Acernese, F., Ackley, K., Adams, C., et al. (2020). Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo

- and KAGRA. *Nature Astronomy*. [Online]. Available: <https://doi.org/10.1007/s41114-020-00026-9>. [Accessed: Jan. 8, 2025].
- Abbott, B. P., Abbott, R., Abbott, T. D., Abraham, S., Acernese, F., Ackley, K., Adams, C., et al. (2019). GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs. *Physical Review X*, 9(3), 031040. [Online]. Available: <https://doi.org/10.1103/physrevx.9.031040>. [Accessed: Jan. 8, 2025].
- ADS Search. (n.d.). [Online]. Available: [https://ui.adsabs.harvard.edu/search/fq=%7B!type%3Daqp%20v%3D%24fq_database%7D&fq_database=database%3A%20astronomy&q=%20title%3A\(%22variable%20stars%22\)&sort=date%20desc%2C%20bibcode%20desc&p_=0](https://ui.adsabs.harvard.edu/search/fq=%7B!type%3Daqp%20v%3D%24fq_database%7D&fq_database=database%3A%20astronomy&q=%20title%3A(%22variable%20stars%22)&sort=date%20desc%2C%20bibcode%20desc&p_=0).
- Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczkó, A.-K., Ball, D., et al. (2019). First M87 Event Horizon Telescope results. I. The shadow of the supermassive black hole. *The Astrophysical Journal*, 875, L1. [Online]. Available: <https://doi.org/10.3847/2041-8213/ab0ec7>. [Accessed: Jan. 8, 2025].
- Al Samarai, I., Alves Batista, R., Barres de Almeida, U., dos Anjos, R. C., de Gouveia Dal Pino, E. M., de los Reyes, R., de Oña-Wilhelmi, E., et al. (2018). Science with the Cherenkov Telescope Array. *Proceedings of the International Conference on High Energy Gamma-Ray Astronomy*. [Online]. Available: <https://doi.org/10.1142/10986>. [Accessed: Jan. 8, 2025].
- Astro 2020 Science White Paper. (2019). *Pulsation as a laboratory for understanding stellar physics thematic areas*. [Online]. Available: <https://www.semanticscholar.org/paper/6297b41a5f3315add75bd096a75edc8ce3fe5133>. [Accessed: Jan. 8, 2025].
- Blecha, A., Schaller, G., & Maeder, A. (1992). Fast pulsations in a Wolf-Rayet star. *Nature*, 360, 320–321. <https://doi.org/10.1038/360320a0>.
- DeBoer, D. R., Parsons, A. R., Aguirre, J. E., Alexander, P., Ali, Z. S., Beardsley, A. P., Bernardi, G., et al. (2017). Hydrogen epoch of reionization array (HERA). *The Astronomical Journal*, 153(5), 45. [Online]. Available: <https://doi.org/10.1088/1538-3873/129/974/045001>. [Accessed: Jan. 8, 2025].
- Ivezić, Ž., Kahn, S. M., Tyson, J. A., Abel, B., Acosta, E. E., Allsman, R. A., Alonso, D., et al. (2019). LSST: From science drivers to reference design and anticipated data products. *The Astrophysical Journal*, 873, 111. [Online]. Available: <https://doi.org/10.3847/1538-4357/ab042c>. [Accessed: Jan. 8, 2025].
- Kaaret, P., Feng, H., & Roberts, T. P. (2017). Ultraluminous X-ray sources. *Annual Review of Astronomy and Astrophysics*, 55, 303–340. [Online]. Available: <https://doi.org/10.1146/annurev-astro-091916-055259>. [Accessed: Jan. 8, 2025].
- Kirk, B., Conroy, K. E., Prša, A., Abdul-Masih, M., Kochoska, A., Matijević, G., Hambleton, K., et al. (2016). Kepler eclipsing binary stars. VII. The catalog of eclipsing binaries found in the entire Kepler data set. *The Astrophysical Journal*, 151(3), 68. [Online]. Available: <https://doi.org/10.3847/0004-6256/151/3/68>. [Accessed: Jan. 8, 2025].
- Lacy, M., Baum, S. A., Chandler, C. J., Chatterjee, S., Clarke, T. E., Deustua, S. E., English, J., et al. (2020). The Karl G. Jansky Very Large Array Sky Survey (VLASS): Science case and survey design. *The Astronomical Journal*, 159(1), 3. [Online]. Available: <https://doi.org/10.1088/1538-3873/ab63eb>. [Accessed: Jan. 8, 2025].
- Miller Bertolami, M. M. (2016). New models for the evolution of post-asymptotic giant branch stars and central stars of planetary nebulae. *Astronomy & Astrophysics*, 588, A25. [Online]. Available: <https://doi.org/10.1051/0004-6361/201526577>. [Accessed: Jan. 8, 2025].
- Niu, J.-S., & Xue, H.-F. (2024). Unveiling the intricate symphony of nonlinear pulsation mode interactions in high-amplitude δ Scuti stars. *Astronomy & Astrophysics*. <https://doi.org/10.1051/0004-6361/202348757>.
- Paxton, B., Schwab, J., Bauer, E. B., Bildsten, L., Blinnikov, C. I., Duffell, P. C., Farmer, R., et al. (2018). Modules for experiments in stellar astrophysics (MESA): Convective boundaries, element diffusion, and massive star explosions. *The Astrophysical Journal*, 851, 63. [Online]. Available: <https://doi.org/10.3847/1538-4365/aaa5a8>. [Accessed: Jan. 8, 2025].

- Paxton, B., Smolec, R., Schwab, J., Gautschy, A., Bildsten, L., Cantiello, M., Dotter, A., et al. (2019). Modules for experiments in stellar astrophysics (MESA): Pulsating variable stars, rotation, convective boundaries, and energy conservation. *The Astrophysical Journal*, 876, 15. [Online]. Available: <https://doi.org/10.3847/1538-4365/ab2241>. [Accessed: Jan. 8, 2025].
- Prusti, T., de Bruijne, J. H. J., Brown, A. G. A., Vallenari, A., Babusiaux, C., Bailer-Jones, C. A. L., Bastian, U., et al. (2016). The Gaia mission. *Astronomy & Astrophysics*, 595, A1. [Online]. Available: <https://doi.org/10.1051/0004-6361/201629272>. [Accessed: Jan. 8, 2025].
- Riley, T. E., Watts, A. L., Ray, P. S., Bogdanov, S., Guillot, S., Morsink, S. M., Bilous, A. V., et al. (2021). A NICER view of the massive pulsar PSR J0740+6620 informed by radio timing and XMM-Newton spectroscopy. *The Astrophysical Journal*, 923, L14. [Online]. Available: <https://doi.org/10.3847/2041-8213/ac0a81>. [Accessed: Jan. 8, 2025].
- Yuan, W., et al. (2022). A first look at Cepheids in a Type Ia supernova host with JWST. *The Astrophysical Journal Letters*, 940, L17. <https://doi.org/10.3847/2041-8213/ac9b27>.
- Z., B. (2018). The physics of gamma-ray bursts. *Cambridge University Press*. [Online]. Available: <https://doi.org/10.1017/9781139226530>. [Accessed: Jan. 8, 2025].

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2025): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
<https://pr.sdiarticle5.com/review-history/133326>