The Development of Early Pulsation Theory, or, How Cepheids Are Like Steam Engines

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Abstract The pulsation theory of Cepheid variable stars was a major breakthrough of early twentieth-century astrophysics. At the beginning of that century, the basic physics of normal stars was very poorly understood, and variable stars were even more mysterious. Breaking with accepted explanations in terms of eclipsing binaries, Harlow Shapley and A. S. Eddington pioneered novel theories that considered Cepheids as pulsating spheres of gas. Surprisingly, the pulsation theory not only depended on novel developments in stellar physics, but the theory also drove many of those developments. In particular, models of stars in radiative balance and theories of stellar energy were heavily inspired and shaped by ideas about variable stars. Further, the success of the pulsation theory helped justify the new approaches to astrophysics being developed before World War II.

1. Introduction

The idea that stars could change brightness was bizarre enough that Aristotle rejected it on general principles. Even at the end of the nineteenth century, with the existence of variable stars well documented, their exact nature remained mysterious and problematic. The key to solving this puzzle was the theoretical astrophysics developed in the early twentieth century, but in an important sense variable stars were also the keys to theoretical astrophysics. Cepheid variables inspired, framed, and functioned as laboratories for many of the critical investigations that established the discipline.

2. The Binary hypothesis

Cepheid variables were completely inexplicable until the discovery of periodic radial velocity shifts in their spectra. This led to the double-star interpretation of variability: given the evidence for regular motion toward and away from observers, it was the most natural interpretation of the data at hand. There were other suggestions offered, such as the close approach of two stars causing tidal variations and eruptions of gas at higher temperatures than the stellar surface (Renaudot 1917). But none of these had the conceptual clarity and ease of explanation of the binary theory.

Harlow Shapley in 1914 called it a “misfortune” that the lines could be so easily understood this way. This paper focused on the problems with the binary interpretation, which he called “insurmountable” (Shapley 1914). Chief among these problems was the irregularity of Cepheid light curves. He noted that the continual change of the shape of the light curve made it quite difficult to assign the hypothetical binary a normal periodic orbit. He objected that instead of these messy curves, “regularity and continuity” (Shapley 1914) would be expected of any orbital phenomena. Shapley also brought up the observed changes in spectral type, which seemed nonsensical for a binary.

Some astronomers (including Campbell, Plummer, and Ludendorff) had also argued that there were internal inconsistencies in the double star hypothesis. For example, the average Cepheid was 700 times brighter than the Sun, which yielded a volume between 15 and 20,000 times as great as the Sun. As binaries, they would thus have an orbit less than 1/10 the radii of the stars themselves, which seemed impossible.

Shapley admitted that he could “offer no complete explanation of Cepheid variability as a substitute for the existing theories that are shown to be more and more inadequate.” His paper was just suggesting new avenues of approach to these problems. He did offer one intriguing, if poorly defined, possibility. Perhaps the variability was caused by “internal or surface pulsations of isolated stellar bodies.” (Shapley 1914) Shapley listed points in favor of the pulsation hypothesis: as a result of some original disturbance there would be oscillations of several different periods, explaining the complex light curves; for pulsation maximum velocity and light would be correlated just as observed; ebb and flow of heat would explain the change of spectral type. It is important to understand that pulsation was only a hazy hypothesis at this point, without any clear technical articulation. Shapley said the difficulty of making the hypothesis more precise lay in the lack of knowledge of the processes inside stars.

3. Early pulsation theory

Martin and Plummer (1915, 1917) followed up on Shapley’s idea, integrating the Cepheid velocity curve to get a radial displacement function over time. Interpreting this displacement as actual movement of the star’s surface yielded an expansion of the order of hundreds of thousands of kilometers. Like Shapley, they did not claim any proof or decisive evidence, and their most important contribution was laying out the technical issues that needed to be solved for pulsation theory to be useful.

They argued that one of the benefits of the pulsation hypothesis was that it could explain a number of different types of variables: “There seems to be no very cogent reason against the view that, outside the eclipsing systems, the great majority of variable stars manifest the operation of one essentially uniform process in nature.” (Martin and Plummer 1917) The uniform process they were referring to was the struggle between radiative expenditure and mechanical equilibrium, a presumably fundamental process in stellar interiors. This demonstrates an important point in the early history of variable star theory. There was continual disagreement about whether Cepheids should be explained in terms of a process organic to the normal functioning of stars, or whether it should be a process outside ordinary stellar behavior.

Around the same time, A. S. Eddington had begun theoretical investigations into many of these fundamental processes, most importantly the radiative balance with gravity. In 1917 he followed Shapley to discuss the pulsation hypothesis explicitly. He noted the enormous amplitudes of expansion that would be required, commenting that since Cepheids were giant stars it was possible, “but the consequent internal changes in the star must be very far-reaching.” (Eddington 1917) This framed the problem in a definite way: the validity of the pulsation hypothesis was to be solved by understanding the stellar interior. The processes of the stellar interior were essentially unknown at this point, and Eddington was largely working with a blank slate.

He began by assessing a major difficulty key to the pulsation theory. Why do the pulsations not die out? It seemed unlikely that such massive alterations in the star’s structure would last for very long:

> The most difficult question is, how can these pulsations be maintained? It is suggested by Shapley that, if the pulsations were started by some cataclysm, there is one type which would decay extremely slowly; it might persist almost indefinitely with inappreciable dissipation. But I do not think this conclusion is warranted by such investigations as have been made. The problem is essentially a thermodynamical one. The main cause likely to lead to a decay of vibrations is thermal dissipation of energy due to the flow of heat between different parts of the star. (Eddington 1917)

That is, Shapley thought of this as a problem in wave mechanics. Eddington proposed treating this as a problem in energy transfer. The vibrations would presumably dissipate a great deal of energy, and there must be a system by which this energy was replaced. Stellar heat was clearly “continually liberated within the star and passes outward into space; this may be borrowed and converted into energy of pulsation.” (Eddington 1917) If these were the key issues, Eddington suggested, one should use an existing body of detailed theory developed for a physically different, but conceptually similar problem: the action of a steam engine. This helped clarify what a pulsation theory would require:

> But in order to convert heat of any kind into work, the star, or some part of it, must behave as an engine in the thermodynamical sense: that is to say, it must take in heat when it is at a higher temperature than the average and give out heat at a lower temperature - just the opposite of what usually happens in natural conditions. (Eddington 1917)

He pointed out that by means of radiation pressure a portion of this energy could be captured mechanically, just as a piston captured the expansion of steam.

Eddington confessed that understanding the vibrations of a star was "a very difficult analytical problem" and it has not yet been possible to figure out how a star could "behave in the manner of an engine." (Eddington 1917) However, he said, it was important not to obsess over certainty when conceptual progress could be made:

> Though we cannot offer any adequate theory as to how the star manages to behave as an engine, we can point out some evidence that it does so behave. I am not sure whether the following mode of regarding the question is strictly allowable; but I venture to put forward the suggestion tentatively. (Eddington 1917)

The key was to find a thermodynamic situation where the stellar waves neither decayed nor increased. He speculated that varying transparency inside the star could regulate the radiation pressure and therefore the expansion forces. Also, since the outflow of radiation was greatest when the star was expanding, that would help it expand, and vice versa, which would also help maintain vibrations. He explicitly avoided the question of the origin of the pulsations, only considering their survival: "How this comes about must be left unsolved; but since it is so, it seems clear that the pulsations are likely to be maintained." (Eddington 1917) It was clear that to proceed further more detailed studies of radiation pressure would be needed, and this drove Eddington's broader studies of radiation pressure in stars.

By 1918 the pulsation theory had made serious strides. The Council of the Royal Astronomical Society (CRAS) commented that the binary theory was imperiled, but that the pulsation hypothesis had not been proven (CRAS 1918). Eddington agreed that there was no proof while still stating that there was "little doubt" that Cepheid variation must be attributed to some form of pulsation (Eddington 1918). His new investigations used dimensional analysis to shows that "globes of fluid" would oscillate in periods inversely proportional to the square root of the density, a relation that he found to be fulfilled by nearly all the known Cepheids. This allowed determination of density changes in Cepheids by measuring the change of their period (which could be done very precisely). Noting that the most recent measurements of δ Cephei showed its period decreasing by about 1 in 9 million per year, this suggested it would take 10 million years to pass from type G to F (Eddington 1918). This seemingly minor detail had enormous implications:

> This is a far slower change than that derived from the assumption that a star's heat is provided by the energy of contraction. In fact, our time-scale is enlarged a thousand-fold, and becomes much more

> easily reconciled with current theories as to the age of terrestrial rocks, the development of the Earth-Moon system, and geological change. (Eddington 1918)

Thus measuring the periodicity of Cepheids could provide a clue to the critical question of the age of the stars, and therefore, of the universe. The time scale of stellar and cosmic evolution could finally be settled (Eddington 1918, 1919a). This link of stellar evolution to variable stars provided a useful hook on which new investigations of stellar aging could begin.

Another consequence of these calculations was the suggestion that if a star's energy came solely from gravitational contraction, then its change of period should be quite large. The observed change of period of δ Cephei was 0.1 second per year, while contraction theory predicted about 40 seconds per year. Eddington confidently asserted that "I see at present no escape from the conclusion that the energy radiated by a star comes mainly from some source other than contraction." (Eddington 1919b) Investigations of variable stars had unexpectedly advanced the long stalemated mystery of the energy source of stars.

By 1919 the pulsation theory had been developed far enough that Eddington was willing to state more firmly that:

> it is concluded that the binary hypothesis of Cepheids must be ruled out, because (a) the distance of the centres of the components would have to be less than the radius of one of them, (b) because there is a uniform relation between the period and density which seems to point to a cause intrinsic in the star. (Eddington 1919a)

He made the case that the hypothesis of pulsating stars leads to results in agreement with observation, specifically the absolute value of the periods, the advance of spectral type toward the red with increasing luminosity, and the asymmetric form of the velocity curve. Eddington had made a powerful case for the likelihood of the pulsation hypothesis, and along the way provided serious impetus to the longstanding problems of stellar evolution and stellar energy.

A handful of astronomers, including Shapley, Eddington, Martin, and Plummer, moved ahead with the pulsation theory. Even with the theory in an embryonic form, they were able to make significant progress. Their success drove other investigators to ask more detailed questions about the observational consequences of the pulsation theory and to present alternative ideas.

4. Objections and alternatives to pulsation

Despite its problems, many astronomers continued to do work with the binary hypothesis—its familiarity and conceptual straightforwardness kept it popular for some time (Henroteau 1919). Others, such as Walter Adams, were reluctant to accept the pulsation theory due to a number of unresolved issues, such as the narrow, well-defined spectral lines of Cepheids being unlikely given the enormous disruption that pulsations would be expected to cause (Adams 1919).

A characteristic example of both positions can be found in C. D. Perrine, director of the Argentine National Observatory. In 1919 he vigorously defended the binary hypothesis: "The closeness with which these variations are represented by orbital motion...is in itself, in the absence of proof to the contrary, almost conclusive evidence of their binary character." (Perrine 1919) He maintained that the characteristics of light curves of known binary systems were perfectly consistent with Cepheid curves. And like Adams, he found it difficult to believe that internal pulsations could be so uniform in length and period. Perrine pointed out that the light curves show no sign of violent disturbance, and sunspots and novae persuaded him that all forms of stellar brightness variation would be irregular. Further, it seemed impossible to reconcile the "quiescent spectra of the Cepheids with such violent activity as the hypothesis of pulsations demands" (Perrine 1921).

Perrine argued that so little was known about what was happening inside stars that one could not use the pulsation theory. Instead, he wrote, we should assume that even mysterious stars such as Cepheids did not involve any truly novel processes. Astronomers should rely on "strong presumption of a similarity in constitution and evolutionary processes among all stars" (Perrine 1919). On this reasoning, they should be treated as binary stars in the absence of extraordinary evidence. He closed by making the case that the "almost deciding factor as to the nature of Cepheid variation" was their preference for the plane of the Milky Way. This, he said, indicated that their variation did not come from "the operation of general physical or gravitational laws" but rather some external condition (Perrine 1919). That is, Cepheids were ordinary binaries driven to unusual behavior by some local property in their neighborhood of the universe.

Many of the critiques of pulsation theory were based on hopes that Cepheid variation could be explained solely through celestial mechanics and other well-understood physics. There was a wide realization that pulsation would require a great deal of messy, novel physics unpalatable to an older generation of scientists. For example, James Jeans proposed a well developed alternative that relied solely on classical astronomy and physics. In 1919 he derived a functional formula for the light curve of δ Cephei with two major terms.He proposed that the first term could be the rotation of a single elongated body and the second term was "arising from some sort of explosion which occurs whenever this body assumes a particular orientation." The observed changes of spectral type would just be the result of the progress of the explosion (Jeans 1919). On this hypothesis, a theory would require little more than traditional calculations of spinning bodies. The period of a Cepheid would simply be the period of rotation of an elongated body tidally locked to a companion. This suggested that Cepheids were merely one peculiar type of binary star (Jeans 1925).

There were plenty of more exotic proposals as well. Johann Hagen at the Vatican Observatory rejected both the pulsation and binary theories, instead suggesting cometary tidal forces (Hagen 1921). The notoriously heterodox American astronomer T. J. J. See argued that both sunspots and Cepheid variation were caused by tidal forces from Jovian planets (See 1922). Kyoto University's Shinzo Shinjo dismissed the pulsation theory and instead proposed the rotation of an "eccentrically condensed nucleus" moving in a spherical mass of meteoric material (Shinjo 1922).

A 1924 article by François Henroteau, working at the Allegheny Observatory and later the Dominion Observatory in Ottawa, provided a massive compilation of Cepheid observations and also assessed the competing theories:

> The present state of our knowledge of Cepheid variation is scarcely adequate to explain all the phenomena involved. The ordinary binary theory may almost certainly be definitely ruled out of court, while on the pulsation theory there are certain points not accounted for. (Henroteau 1924)

His assessment was fairly accurate. The binary theory had been wounded fatally, but the pulsation theory was only appealing to those investigators willing to grapple with strange new physics. The central continuing concern for everyone was whether Cepheids were a distinct class of star, a phase of a typical star's development, or some other possibility. The nature of δ Cephei remained uncertain.

5. A comprehensive pulsation theory

The full foundation of the pulsation theory was presented in Eddington's highly influential book *The Internal Constitution of the Stars* (1926). Its chapter on variable stars was strategically designed to remove competitors and leave the pulsation theory as the only option. He chose his words carefully, stating that it appeared "improbable" that Cepheids were binaries, and that the pulsation theory was now the "most plausible" (Eddington 1926). He warned that getting rid of the binary hypothesis did not necessarily mean the pulsation theory was correct. But, he said, doing so does leave a Cepheid as a single star, and the variation must therefore be intrinsic to it. If we have only one star, then pulsation and rotation were the only real options. The rotational theory (largely put forward by Eddington's archrival Jeans) was dismissed casually: "We do not know of any theory connecting the variations with the star's rotation, sufficiently plausible to be discussed here." The problem with rotational models was the expected but unobserved line broadening. He thus left the reader with pulsations as the only reasonable alternative:

> I have never regarded the hypothesis of symmetrical pulsations as conclusively established but I am not persuaded that anything has transpired in the recent discussions to weaken the case for it as here set forth. (Eddington 1926)

Eddington built his Cepheid theory on the same structure as his general theory of stellar constitution. The core of his Cepheid analysis was his calculation of adiabatic oscillations. He rejected the idea that the pulsations were just left over from a disaster, leaving the alternative that there were causes inside the star that tended to increase and maintain a pulsation. He followed the analogy of the heat engine quite closely—looking for the stellar equivalents of cylinders, valves, and so on (Eddington 1926; subsequent developments are described in Kawaler and Hansen 2012, this volume).

Eddington linked the critical question of energy transfer to the pulsations to the larger question of stellar energy generation in general. He pointed out that the values of density and temperature needed for the energy transfer to reinforce the pulsations were quite narrow. And interestingly, those values were virtually identical to the conditions necessary for energy liberation via the transmutation of hydrogen into helium (Eddington 1926). This calculation brought three important points forward. First, it was a major clue to the stellar energy source. Second, this calculation made Cepheids fairly rare, which was a point in its favor—it explained why most normal stars do not pulsate. Finally, it succeeded in calculating a size for Cepheids that closely matched observations. Eddington reminded his readers that investigating the Cepheids was not important just for themselves, but for their ability to help understand stars in general: “If this explanation is correct we have an opportunity of extending the study of the internal state of a star from static to disturbed conditions” (Eddington 1926).

6. Conclusion

The pulsation theory was on a firm footing by the late 1920s because the hypothesis was an integral part of the wider theory of stellar structure developed in that decade. Its deep connections to the successes of the broader theory made it highly plausible, and more appealing than invoking a hypothesis that thought of Cepheids as entities completely different from normal stars. And conversely, the success of stellar structure theory in explaining the bizarre behavior of Cepheids was a major feather in its cap. The ability of stellar structure theory to explain such strange objects was an important tool for convincing skeptics of its power, and also helped legitimate the use of the innovative approaches and methods critical to that theory. In particular, the Cepheid pulsation theory provided critical stimulus to develop the theory of radiative balance, the idea of fusion as the stellar energy source, and the timescale of the lifetime of stars.

References

Adams, W. S. 1919, *Observatory*, **42**, 167.

Council of the Royal Astronomical Society. 1918, *Mon. Not. Roy. Astron. Soc.*, **78**, 307.

Eddington, A. S. 1917, *Observatory*, **40**, 290.

Eddington, A. S. 1918, *Observatory*, **41**, 379.

Eddington, A. S. 1919a, *Mon. Not. Roy. Astron. Soc.*, **79**, 177.

Eddington, A. S. 1919b, *Observatory*, **42**, 338.

Eddington, A. S. 1926, *The Internal Constitution of the Stars*, Cambridge University Press, Cambridge.

Hagen, J. G. 1921, *Mon. Not. Roy. Astron. Soc.*, **81**, 226.

Henroteau, F. 1919, *Astron. J.*, **32**, 57.

Henroteau, F. 1924, *Publ. Dom. Obs. Ottawa*, **9**, 1.

Jeans, J. H. 1919, *Observatory*, **42**, 88.

Jeans, J. H. 1925, *Mon. Not. Roy. Astron. Soc.*, **85**, 797.

Kawaler, S. D., and Hansen, C. J., 2012, *J. Amer. Assoc. Var. Star Obs.*, **40**, 150.

Martin, C., and Plummer, H. C. 1915, *Mon. Not. Roy. Astron. Soc.*, **75**, 566.

Martin, C., and Plummer, H. C. 1917, *Mon. Not. Roy. Astron. Soc.*, **78**, 156.

Perrine, C. D. 1919, *Astrophys. J.*, **50**, 81.

Perrine, C. D. 1921, *Mon. Not. Roy. Astron. Soc.*, **81**, 442.

Renaudot, M. G. 1917, *Pop. Astron.*, **25**, 587.

See, T. J. J. 1922, *Astron. Nachr.*, **216**, 193.

Shapely, H. 1914, *Astrophys. J.*, **40**, 448.

Shinjo, S. 1922, *Jpn. J. Astron. Geophys.*, **1**, 7.