The other spectrum of the stars

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Resumen

Abstract

I dedicate the prose to Trinidad,
for making the morning coffee
that fueled the writing of this document

But all the code is for Miguel
who will not be able to compile it anymore
but I think he would have liked it anyway

Acknowledgements

There were a lot of people who provided me with their guidance and support on the process of writing this document. It was not purely a research process, but a personal voyage of discovery and motivation.

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I am also grateful with my dearest friends: Miguel, Juan David, Valeria, Camilo, Juanita and the two Nathalias. My time at Bogotá would have been very sorrowful if not for them. Also my roommates, David, Kelly and Gabriel. On recent times of crisis, yet another David took care of me back in my hometown.

Finally, I write this last couple of words to attempt to express the unmeassurable gratitude I have for Laura.

Contents

Chapter 1

Introduction

Ancient stellar variability

It is undeniable that ancient civilizations looked to the night sky with great interest. Stars were considered innamobile and immutable, with the notable exceptions of planets and Novæ, respectively. But periodic stellar variability was probably known since antiquity too. For instance, egyptians knew the period of Algol three millenia ago (Jetsu & Porceddu 2015; Jetsu et al. 2013), and the mythology of several cultures seems to have some references to the phenomenon (Wilk 1996). On some cases, periodic variable stars were recorded as Novæ on some ancient sources (Ho Peng Yoke & Ho Ping-Yü 1962).

Western rediscovery

The rediscovery of stars having periodic changes on their brightness is accredited to Fabricius, who discovered Mira (o Ceti) in 1596 (Hoffleit 1997). That discovery was in direct contradiction with the classical philosophical view of the Universe, as in (Aristotle 350 BCE, book I, part 3): "so far as our inherited records reach, no change appears to have taken place either in the whole scheme of the outermost heaven or in any of its proper parts". On the following centuries several other stars were marked as candidates for periodic variables. Edward Pigott and his collaborator John Goodricke were verifying those candidates in 1784 (Hoskin 1979). Famously, Pigott (1785) observed η Aquilæ and confirmed its variability, while Goodricke (1786) observed δ Cephei, Algol, β Lyræ, and others.

Initial theories for stellar variablity

Pigott and Goodricke results are remarkable, as almost a century would pass until the formalization of the magnitude scale for brightness by Pogson (1856). But despite the lack truly (instrumental) quantitative measurments of brightness, there were plenty of theories regarding the mechanism behind variability. Those theories included planetary eclipses, star-star collisions, binary stars, meteor impacts, obfuscation by gas or dust clouds, and sun-like spots coupled with rotation and axial tilts (Hoffleit 1993). And although the eclipse conjecture was later proved to be the correct for Algol (Pickering 1880), the assymetric behaviour of the brightness of some stars (as those seen in Figure 1.1) could not be accounted for. If the change of brightness were the product of an eclipse, the star brightness would spend the same amount of time increasing as decreasing, as the transiting object covers and uncovers the star. On the same train of thought, if the star happened to have a side full of spots, or obscured by Nebulæ, no stable rotation or movement could make the brightness go from minimum to maximum faster than from maximum to minimum on a periodic manner.

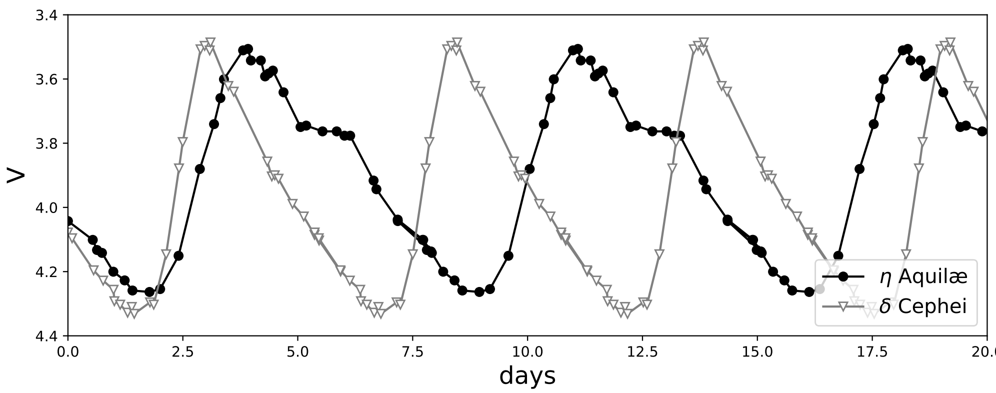

Figure 1.1: Modern light curves for the first two discovered Cepheid variable stars. η Aquilæ has a period of ~ 7.17 days, in contrast with the ~ 5.36 days of δ Cephei. Objects are brighter as magnitude (V) decreases (see chapter 2 for details). Note how both stars take more time decreasing their brightness than increasing it. Figure reconstructed from Kiss (1998) data.

Early classification

These variable stars were initially classified by Pickering (1880), only taking into account the shape of the light curve: Novæ, Mira-like, eclipsing, irregular variables, and class for the aforementioned irregular (but highly periodic) case, namely β Lyræ and δ Cephei. There was a need for further classification of these stars, with several attempts of break down Pickering classes (Lockyer 1896, 1897), but it would take several important discoveries in astronomy for the classification of variable stars to fully develop, resulting in δ Cephei as the prototype of its own class of variable stars.

Work and discoveries of the Harvard Computers

The next big steps on the field were done by Pickering's "computers" women at Harvard. Although the universities refused to let women study at the time, Pickering (then director of Harvard's observatory) needed people to process and analyze the sheer amount data in the observatory, on the form of stellar spectra and photographic plaques of the observations. Working there, Williamina Fleming prepared the Draper Catalogue of stellar spectra (Pickering 1890), which allowed her to classify Mira-type stars and Novæ with only their spectrum. This classification system was later reordered by Cannon & Pickering (1901) to reflect the temperature of the stars. Around that time Henrietta Leavitt joined the Harvard computers, with the task of searching for variable stars in the Magellanic Clouds, which at the time were classified as Nebulæ. There she discovered almost two thousand variables (Leavitt 1908), the majority of which turned out to be of the δ Cephei class. By calculating the periods of 25 of those stars and comparing them to their maximum and minimum magnitudes, Leavitt found a linear relationship (Figure 1.2).

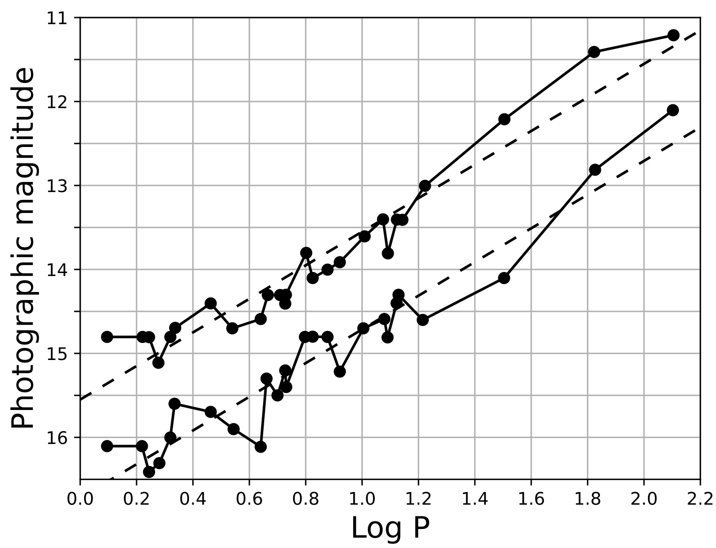

Figure 1.2: Leavitt & Pickering (1912) representation of the relationship between period and luminosity of 25 Cepehid stars in the Small Magellanic Cloud. The two data series refeer to the points of maximum and minimum brightness for each star. The period of the stars (P) is reported on days, so the abscissa is in units of log(days). The ordenate is given in photographic magnitude.

Period-Luminosity relation

Leavitt's discovery was of immense importance as a possible tool for measuring the distance to the farthest cepheid stars. She noted: "Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light" (Leavitt & Pickering 1912, page 3). Leavitt knew she was seeing the *apparent* brightness of the stars, as brightness decreases with distance. If distances to near cepeheids could be found by another method, this Period-Luminosity (PL) relation could be reversed to find the *absolute* brightness of the Cepheids in the Small Magellanic Cloud (SMC), finding the distance to the satellite galaxy (then called Nebulæ). Leavitt correctly proposed the method of parallaxes to solve this task, but his work on Harvard did not let her pursue this investigation.

fine-tuning the PR relation and the Magellanic clouds

The parallaxes for the nearest Cepheids were examined by (Hertzsprung 1913). He used Leavitt's PL relation to calculate the distance to the SMC, giving —after a "pen error" (Fernie 1969)— 30 kilo-lightyears (kly), which is a vast underestimation. Shapley (1918) improved further the precision of Leavitt's original PL relation, but its zero point (its accuracy) was assumed to be the correct one, despite having several sistematic and selection errors (Fernie 1969). Shapley used his results to calculate the distance to the Magellanic Clouds, obtaining 106 ± 5 kly for the Small Cloud (Shapley 1924a) and 112 ± 12 kly for the Large Cloud (Shapley 1924b).

The great debate, and Hubble measuring the size of the universe

Around this time, there was a big debate in the astronomical community around the nature of the so-called "spiral nebulæ". Were those nebulæ part of the Milky Way, or were they their own separate, distant galaxies? E. Hubble, using Shapley version of the PL relation, settled the matter when he found a distance of ~ 929 kly for M31 and M33 (now called the Andromeda and the Triangulum galaxies) and ~ 697 kly for NGC 6822 (Barnard's galaxy) (Hubble 1925a,b), surpassing Shapley's hypothesis that the galaxy was only 300 kly wide.

Space means time: the Cosmic age problem

With this results, Hubble (1929) measured the redshift of some extra-galactic Nebulæ, and encountered a linear relationship between distance as velocity. It was the first experimental evidence of the general relativity prediction of an expanding universe (Friedmann 1922; Lemaître 1927). Hubble estimate of this expanding rate was $H_0 \approx 550$(km/s)/Mpc (the Hubble constant), which implied the universe must have an age of 2×10^9 years. Meanwhile, geologists estimated the age of the earth as 4×10^9 years (see Dalrymple 1994, for an historical account). How could be the Earth older than the universe? There was a big problem in the figures, somewhere.

Baade correction

Hubble, again, had half the answer. He had some concerns about the zero point of Shapley's PL relation, an opinion shared with Baade (1944) after he divided the stars on two populations based on their metallicities. Baade realized that population I Cepheids were 1.5 magnitures brighter than population II (for the same period) so there were *two* different PL relations, shifted on their zero point by 1.5 magnitudes. He proved this hypothesis at Palomar Observatory, observing the Andromeda nebula (Baade 1956) (see Arp 1955, for another discussion). As a consequence of the distance-modulus equation, measurements made with population I Cepheids should be scaled by a factor of $10^{3/10} \approx 2$. The Hubble distances were based on population I Cepheids, and therefore his distances doubled, and consequently the observed age of the universe. Patterson et al. (1955) measured the age of the Earth as 4.5×10^9 years, so the problem was not solved yet.

Sandage correction

A second correction came from the work of Scandage. First reviewing Hubble's work with more data (Humason et al. 1956), and then correcting a problem: Hubble had made the calibration of the distance for the farthest nebulæ with the brightest resolvable stars he had, possible incurring in an identification mistakes with ionized Hydrogen regions or multiple nearby stars (Sandage 1958). This considerations amounted a total correction of 4.1 magnitudes, and produced a Hubble constant of $H_0 \approx 75$(km/s)/Mpc, or a timescale for the universe of $\sim 1.3 \times 10^{10}$ years, comparable to modern estimates (Freedman et al. 2001).

Present status of the distance ladder

In the present day, mainly two astronomical projects are entitled to the search of variable stars and the refinement of cosmic distances estimation: the OGLE project[1] and the Araucaria project[2]. While the Gaia space observatory measures parallaxes, the first step on the distance ladder, the OGLE project surveys the galaxy and the Magellanic Clouds in search of variable stars and gravitational microlensing. They have nearly completed Leavitt initial task of catalogue the Cepheid stars on the Magellanic Clouds (Soszyński et al. 2017), and their survey of Cepheids on the Milky Way has allowed to further study its structure (Skowron et al. 2019) and its dynamics (Mróz et al. 2019). On the other side, the Araucaria project focuses on the calibration of standard candles, comparing different methods: they have calibrated the distance to the SMC within a 3% of precision (Graczyk et al. 2014) and to the LMC within a 1% (Pietrzyński et al. 2019).

The other spectrum, the Fourier spectrum

Just one more particular problem has surfaced on the PL relation. As a consequence of the pulsation mechanism of these stars, the underlying physical machinery that makes their brightness oscillate, Cepheid variable stars can pulsate on several *overtones* of their natural frequency. This overtones displaces the PL relation, as is multiplicative operation on the period, which amounts on a different position on the $\log P$ axis. Therefore, stars with different modes of pulsation must be separated before attempting to calibrate a PL relation (Zabolotskikh et al. 2005). The most natural way of attacking this problem is using the other spectrum of the star: not the light-energy usual spectrum, but the Fourier spectrum, which allow us to see the frecuencies and phase properties of the light curve.

We have seen that as experimental techniques evolve and become more precise, the theoretical

[1] http://ogle.astrouw.edu.pl/
[2] https://araucaria.camk.edu.pl/

aspects of the PL relation became increasingly important for the accurate determination of distances on the universe. Even so, with the amount of observational data these projects are producing, the use of efficient and robust methods for analyzing it became imperative.

Although of capital importance, the methods of image reduction and magnitude determination lie outside the scope of this work. The aim of this monograph is to examine and implement the different methods for finding the period of a Cepheid variable star. Each method will be tested on real Cepheid data, in order to select the one better suited for the task of producing reliable PL relations. The resulting method (or combination of methods) will be used to replicate the PL relations of the Cepheids on the Magellanic Clouds given by Soszynski et al. (2016).

Chapter 2

Theoretical Framework

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