Measure by Measure they touched the heaven

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Abstract – **The measure of distances is a recurring theme in astrophysics. The interpretation of the light coming from a luminous object in the sky can be very different depending on the distance of the object. Two stars or galaxies may have a different real brightness, although they may look similar. The correct measures came by women computers a century ago. Special mention to Williamina Fleming who supervised an observatory for 30 years working on the first system to classify stars by spectrum. Antonia Maury helped locate the first double star and developed her classification system. Henrietta Leavitt found a law to determine stellar distances. The most famous of the Harvard computers was Annie Jump Cannon. An expert in photography, she catalogued over 350,000 stars and expanded the classification system used today but was Henrietta Leavitt to leave an indelible mark.**

I. INTRODUCTION

Why today there are only women in labs where electronic boards are prototyped? The reason is embedded in the requested precision that generally women apply. The same precision that was requested to women computers for astronomical measures. At the beginning of 1900 the Harvard computer women computers, workers at Harvard Observatory, went beyond their calculation functions to find a different and still used methods to measure the distances of the stars and to classify them. They used Cepheids as Distance Markers. The important feature of a Cepheid Variable that allows it to be used for distance measurements is that its period is related directly to its luminosity. This relation allows us to work out how much brighter than the Sun the star is.
The discovered connection between these variable stars and distance, passed through several steps:

- Distances in astrophysics are notoriously difficult to calculate.
- Visual astronomical measurements introduced subjective uncertainties. The photography overcame the problem of subjectivity by creating an enormous quantity of photos to analyze.
- Women-computer executed calculations and measure-by-measure they unveil new laws that expanded the universe.

II. DISTANCE IN ASTROPHYSICS

Distances in astrophysics are notoriously difficult to calculate. It is possible to use geometric methods to determine the objects that are in the proximity of the solar system, we say within a distance of about 150 light-years from us. Beyond it is impossible to use any simple method to calculate distances. And this was the situation in astronomical research at the beginning of the last century. Many new objects had been discovered, but without knowing their distances, it was impossible to put them in any stellar systems model. At that time, before 1900, it was not known that we live in a galaxy called the Milky Way, and there are other galaxies.

This big handicap was elegantly removed by a very important discovery made by the American woman computer Henrietta Swan Leavitt in 1912 who found a way to determine the real brightness of a particular type of star and she was not the unique lady of the stars. The extent of this discovery can be evaluated by connecting three different elements: variable stars, astronomical photography and women computers.

III. THE CEPHEIDS

For the calculation of the distance of nearby stars a geometric method consists in observing the star on two occasions, six months apart from each other (so that the earth is in two opposite positions with respect to the sun); the star, compared to the background composed of other more distant stars, will be in two different positions and from the measure of the subtended angle it is possible to go back to the distance. But how to measure the remote stars on the sky background? And those whose brightness varies?

The apparent brightness of a star is how bright it seems when viewed from the Earth, but a large, bright star can appear dim if it is a long way from the Earth and a dim star can appear to be bright if it is close to the Earth. Therefore, the apparent magnitude has no bearing on the distance from the Earth. To give an accurate measurement of the brightness of a star we need to make an absolute magnitude scale.

Moreover, not all stars have a constant brightness over time: many of them show a variable brightness (the causes of variability are many). In 1784, at the time of Messier, a very young British amateur astronomer, John

Goodricke, discovered that the Delta star of the constellation Cepheus was a variable star whose brightness oscillated in a very regular manner. In fact, this star reaches a maximum of brightness then fades until it reaches a minimum; later the brightness begin to grow again until it reaches its maximum again and so on, like a clock.

This particular type of variable stars was called Cepheids in honour of the constellation. The Cepheids are very numerous and above all, they are scattered everywhere; their period of change in brightness varies from few hours to few days up to about two months. We now know that these variations are due to perturbations in the inner part of these stars and constitute a temporary phase of their life.

Until the mid-nineteenth century, every measure was meticulously performed based on the astronomer's observational abilities but with an unavoidable subjectivity component, until it was possible to take photographs and thus have available a database to work with.

IV. ASTRONOMICAL PHOTOGRAPHY

Between 1847 and 1852, photographer John Adams Whipple and astronomer William Cranch Bond, at the time director of the Harvard College Observatory, used the observatory's large refracting telescope to produce images of the Moon of considerable detail and clarity. On July 16, 1850, Whipple and Bond made the first daguerreotype of a star: Vega. It was the beginning of astronomical photography. Although the glass-plate photographs was instantly less sensitive than the eye, it had the advantage of having memory: what the eye does not see in a tenth of a second will never see it; instead the photons that arrive at a given moment on the plate add up their action to those that came before, that's why photography makes possible long exposure times, which allows to capture more information.

In 1872 the first photography of the spectrum of a star was obtained and the study of stellar spectra opened a new frontier. Thus it started the enormous work that Edward Pickering undertook at the Harvard College observatory (HCO) in the United States. At HCO a large prism was used to disperse light and to obtain the spectra of many stars at once. The Observatory organized for the systematic observation of the brightest stars both in the southern hemisphere and in the northern hemisphere; the collected data were so many even for the astronomers of today, and much of the work of cataloguing and analyzing the data was carried out by the Harvard computers, that is by several dozen of women, hired to carry out the most tedious tasks of astronomical data analysis and paid about half of their male counterparts [5].

In 1928, astronomers worked on spectra of 250,000 stars thanks to women computers measurements!

V. WOMEN COMPUTERS

For two centuries, the computers were mental workers who could efficiently grind logarithms. A large percentage of them were women. The male scientists of that time considered creative mathematics beyond feminine abilities, but found women perfect for this type of numerical "embroidery". A calculation time was measured in "girl hours": a complex calculation could even require "kilo-girl-hours".

Most human-computers have left no memory of their personal life. One of the first was Nicole-Reine Lepaute, the wife of a watchmaker of the King of France. In 1750, paired with two male colleagues, she foresaw the return of Halley's comet in 1758 after an absence of 76 years. The estimation was incorrect for just one month.

Human-computers learned to execute complex tasks. Someone cross-checked to screen errors and a human-computer, called the comparator, verified the work and searched for discrepancies.

As late as 1940, a giant mathematical table project was active, employing more than 300 human-computers, half of which used only paper and pencil. In 1952, IBM began selling its electronic computer model 701 for scientific activities. By 1960, almost all numerical calculations were being performed by calculating machines.

Coming back to the Harvard computers, the most remarkable woman computer was Miss Henrietta Leavitt, the daughter of a congregation minister, graduated at the Radcliffe College, hired as a computer at the University of Harvard Observatory in 1880. Her job was to compare photographic plates of Magellanic Clouds to detect small differences in the brightness of the stars. Now we know them as neighbouring galaxies, the companions of our Milky Way. At that time no one was quite sure what they were. Curved over the plates in an observatory laboratory, Miss Leavitt found the model that led to the answer. She discovered a way to make measurements beyond our galaxy and begin to map the universe[1].

Leavitt determined that some stars have a consistent brightness no matter where they are located – making it easy to figure out their distance from Earth.

The visual brightness of a star depends on its size or its distance from the Earth: stars with similar apparent magnitudes could be at different distances. But Leavitt had also noticed that variable stars emit pulses of light and that the true brightness of a star can be measured by the speed of its pulses. Brighter stars flash more slowly. Comparing the times with apparent brightness of the star, one can estimate how far is it.

PERIODS OF VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

H.	Max.	Min.	Epoch.	Period.	Res. M.	Res. m.	H.	Max.	Min.	Epoch.	Period.	Res. M.	Res. m.
1505	14.8	16.1	0.02	1.25336	-0.6	-0.5	1400	14.1	14.8	4.0	6.650	+0.2	-0.3
1436	14.8	16.4	0.02	1.6637	-0.3	+0.1	1355	14.0	14.8	4.8	7.483	+0.2	-0.2
1446	14.8	16.4	1.38	1.7620	-0.3	+0.1	1374	13.9	15.2	6.0	8.397	+0.2	-0.3
1506	15.1	16.3	1.08	1.87502	+0.1	+0.1	818	13.6	14.7	4.0	10.336	0.0	0.0
1413	14.7	15.6	0.35	2.17352	-0.2	-0.5	1610	13.4	14.6	11.0	11.645	0.0	0.0
1460	14.4	15.7	0.00	2.913	-0.3	-0.1	1365	13.8	14.8	9.6	12.417	+0.4	+0.2
1422	14.7	15.9	0.6	3.501	+0.2	+0.2	1351	13.4	14.4	4.0	13.08	+0.1	-0.1
842	14.6	16.1	2.61	4.2897	+0.3	+0.6	827	13.4	14.3	11.6	13.47	+0.1	-0.2
1425	14.3	15.3	2.8	4.547	0.0	-0.1	822	13.6	14.6	13.0	16.75	-0.1	+0.3
1742	14.3	15.5	0.95	4.9866	+0.1	+0.2	823	12.2	14.1	2.9	31.94	-0.3	+0.4
1646	14.4	15.4	4.30	5.311	+0.3	+0.1	824	11.4	12.8	4.	65.8	-0.4	-0.2
1649	14.3	15.2	5.05	5.323	+0.2	-0.1	821	11.2	12.1	97.	127.0	-0.1	-0.4
1492	13.8	14.8	0.6	6.2926	-0.2	-0.4							

Figure 1 period of variables stars published by HARVARD COLLEGE OBSERVATORY - Circular 173 - Edward C. Pickering, March 3, 1912

The astronomers were impressed. "What a variable star 'friend' Miss Leavitt is. One can't keep up with the roll of the new discoveries", with these words a Princeton astronomer expressed himself in a letter to his boss.

Although she had been praised for her excellent work, Miss Leavitt earned neither a promotion nor any privilege to pursue her research. She quietly continued her human-computer activities, remaining single and living the appropriate life for a distinguished Bostonian young lady. Even her emotions of her important discovery remain a mystery, she left no diaries or letters.

Figure 2 Harvard Computers, courtesy of Center for astrophysics Harvard and Smithsonian Wolbach library

Other women computers left written testimonies that sometimes expressed their frustration because they were not allowed to explore the deeper implications of what they had found.

Of course, not all human-computers were women. Some were men, mostly young and looking for a stable job: they were mathematicians, not scientists.

Harvard computers became known as 'the Pickering harem' [6].

This expression illustrates the consideration of their work. More than 80 women worked for Pickering at the Harvard Observatory, putting in six-day weeks poring over photographs, and earning 25 to 50 cents an hour (half what a man would have been paid). The daily work was largely clerical: some women would reduce the photographs, taking into account things like atmospheric refraction, to render the image as clear and unadulterated as possible. Others would classify the stars comparing the photographs to known catalogues. Others catalogued the photographs themselves, making careful notes of each image's date of exposure and the region of the sky. The notes were then meticulously copied into tables, which included the star's location in the sky and its magnitude.

Many of the women were bright and inquisitive and quickly expanded their roles. Williamina Fleming, who headed the group, discovered the Horsehead Nebula.

But few, like Miss Leavitt, looked up at the stars and turned the human-computer into something much more.

Many other women at HCO made the history of astronomical research. In particular, Annie Jump Cannon, originally hired to do mathematical calculations by hand and examine photographs, was able to make a great contribution in the field of stellar classification. Other women that deserve mention are, Antonia Maury and Cecilia Payne-Gaposchkin. They discovered hundreds of variable stars and many novae stars, these last were revealed analyzing the enlarged emission lines of their spectrum.[2]

They introduced a new classification of stellar spectra that included most of the stars, and that was related to the star physical properties.

The sequence of spectral types was described by Annie Cannon in 1912, in the article "Classification of 1477 stars by means of their photographic spectra"[3]; for mnemonic use, she invented the phrase O Be A Fine Girl Kiss Me. In substance, this acronym is still in use today, O B A F G K M.

The first scheme of spectroscopic classification, dating back to the nineteenth century, was based only on absorption lines and divided the stars into various classes called with the letters of the alphabet, from A to P. The modern Cannon system eliminated many classes and reordered the remaining ones creating a sequence-dependent on the effective surface temperature of the stars. The classes still in use are:

O: 30.000 - 60.000 K blue stars

B: 10.000 - 30.000 K blue-white stars

A: 7.500 - 10.000 K white-stars

F: 6.000 - 7.500 K yellow-white stars

G: 5.000 - 6.000 K yellow stars (like our Sun)

K: 3.500 - 5.000 K light orange stars

M: < 3.500 K orange stars

Then 3 new classes have been added: N, R and S that correspond to stars more orange and colder.

Figure 3 Annie Cannon with plate- courtesy of Center for astrophysics Harvard and Smithsonian Wolbach library

A. The law of Leavitt

The absolute magnitude (M, also called absolute luminosity) is the apparent magnitude (m) that an object would have if it were at a distance of 10 parsecs (32.616 light-years) or 3×10^{14} kilometres from the observer. The Leavitt's law expresses the dependence of the absolute magnitude on the apparent one and the logarithm of the distance:

$$M = m + 5 - 5 \log d \quad (1)$$

where m is the apparent magnitude and d is the real distance of the star expressed in parsecs.

Her discovery allowed to calculate distances between 100 and 10 million light-years, thus paving the way for the fundamental works of the astronomers Hubble and Shapley that revolutionized our knowledge of the Galaxy and the Universe, while the period-luminosity relationship of Cepheids represents today the foundation of our extragalactic distance scale.
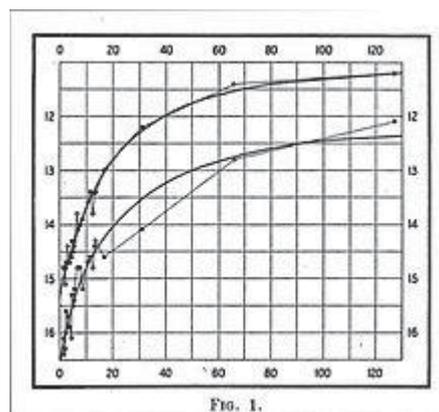

Figure 4 Periods of 25 Variable Stars in the Small Magellanic Cloud" Harvard College Observatory Circular, vol. 173 from Wikimedia Commons

Throughout her career, Leavitt discovered over 2400 variable stars and provided the basis for scientists to further research and learn more about the cosmos. Leavitt continued to work at the Harvard College Observatory until 1921 when she died of cancer at the age of 53 years. Perhaps also because of his premature death in 1921, her name did not receive the recognition she deserved in the scientific community of the time. She was proposed as Nobel Prize winner four years after her death by a committee member who did not know of his untimely end, so the award went to Shapley.

The importance of this law was immediately appreciated. A year after the discovery, the Danish astronomer Ejnar Hertzsprung determined the distances of some Cepheids in the proximity of our Milky Way, using geometric methods. (Today we know that this measure also depends on some factors at that time unknown. For example, we realized later that the measure depends in some way on the quantity of heavy elements in the stars.)

Within the next 5 years Harlow Shapley applied the law of Leavitt to globular clusters and was able to produce the first map of the Milky Way. He made a picture of a vast system of stars, about a hundred billion structured in a disk, whose center is far from our solar system. Shapley had created a whole new chapter in astronomy, and this was only possible because of Leavitt's crucial discovery.

Since then, astronomers have devised a series of other relationships between the properties of different astronomical objects (supernovae, HII regions, just to name a few), which can be used to determine even greater distances of objects where Cepheids are difficult to locate. The period-luminosity relationship of Cepheids, however, remains the least uncertain method of determining distances.

In 1924 Edwin P. Hubble, with the new 254 cm diameter Mount Wilson telescope (at that time the largest in the world) was able to resolve the outer parts of the

Andromeda nebula and Hubble discovered dozens of Cepheids; in the hypothesis (very reasonable) that the Cepheids of the Andromeda nebula behave like those of our galaxy we finally had a method for calculating the distance of the nebula. The result literally made the astronomers pale: the nebula was distant between 700,000 and 1,000,000 light-years which, for those times, was an immense distance.

Furthermore, the application of Leavitt's law allowed the classification of g celestial phenomena previously seen as spots in the night sky and provided substantial evidence that the universe is expanding.

B. The Leavitt's legacy

One of the key projects of the Hubble space telescope, launched more than a decade ago, was the identification of the Cepheid variable stars in the Virgo galaxies cluster (the nearest galaxy cluster in the Milky Way, at a distance of about 50 million light-years) to determine their distance more precisely. The Cepheid variables are the most useful stars in the sky, they are the "standard candles".

Even today, after a century, thanks to the fundamental contribution of Henrietta Leavitt, the Cepheid variable stars remain a reference in astronomical research for the estimation of cosmological distances.

VI.   AT THE END

The fiction literature introduced computational devices when women computers were at the top. "The machine Stops" by E.M. Forster is a short story about the role of technology in our lives (1909) and then the fiction of XX century will be rich of these roles (Heinlein, Asimov, van Vogth and the others). The success and the limits of

manual computing was a source of inspiration for writers of the positivism period. Camille Flammarion who began his carrier as human-computer as well, in his book "The Planet Mars" mentioned computer devices. Did their scientific effort influence the vision for the future?

We cannot learn how to solve specific scientific problems from history, but we can better understand our contemporary science and frame it within its social context.

"By the serious attempt to put ourselves back into the intellectual situation of the ancient thinkers, far less experienced as regards the actual behavior of the nature, but also very often much less biased, we may regain from them the freedom of thought"[4].

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