Comparing Primary Distance Indicators

By Tiffany Zhang

AUTHOR BIO

Tiffany Zhang is a junior at Great Neck South High School and has been part of her school's research program since freshman year. She is interested in astrophysics, computer science, and math. She is the co-founder, website manager, and instructor at AlphaMath, a non-profit organization that hosts free online sessions to make learning math more accessible and fun during the pandemic. She actively participates in her school's Women in STEM club 'SHE' by hosting events and organizing fundraisers. She interned in the ReWild Long Island Summer Program to promote biodiversity, climate change resilience, and food security by reintroducing native plants to attract a variety of animals, following organic and regenerative practices of recycling and composting, and donating grown fruits and vegetables to the hungry. She qualified for AIME, represented her school in various math competitions, and has participated in physics and programming competitions. Acknowledgement: The author thanks Dr. Shyamal Mitra, Arnav Sharma, and Eleanor Liu for their feedback and constant support.

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ABSTRACT

Measuring distances to astronomical objects is crucial for collecting and analyzing their properties. Different distance methods form the distance ladder, in which methods for shorter distances calibrate methods for larger distances. Parallax, main sequence fitting, variable stars, and red clump stars form the lower portion of the distance ladder. Reviews on these methods were compiled and evaluated. The distance methods played a significant role in astronomical discoveries (especially parallax), though controversies and discrepancies limit their reliability (especially for red clump stars). Red clump stars are not a firmly established distance indicator because of varying strengths in the relationships of specific photometric bands, or passbands, with other stellar properties between studies. These discrepancies are likely due to contamination of the data and the heterogeneous nature of red clump stars; hence, future research should explore different ways to isolate the red clump for more accurate and decisive data analyses on whether red clump stars are a plausible distance indicator.

Keywords: *distance indicator, distance ladder, parallax, main sequence fitting, HR diagram, star clusters, variable stars, Cepheids, RR Lyrae, period-luminosity relation, red clump, metallicity.*

INTRODUCTION

In an expanding universe, distances to astronomical objects become a barrier to observing these objects' properties, so consistent recalibration of distance methods is needed to increase their accuracies. However, each method has a limited range in which it is applicable because the distance indicator might not be present within a certain distance or become too faint outside a certain distance, so farther distance methods rely on closer distance methods for calibration in the distance ladder.

Parallax lies at the bottom of this ladder, as it is the only method for measuring absolute distance. Main sequence (MS) fitting is on the next rung of this ladder, relying on known distances calculated from parallax for calibration. The distance indicators of Cepheids and red clump stars are on the subsequent rung of this ladder and rely on distances calculated from either parallax or MS fitting to these objects for calibration. The reliance on shorter distance methods to calibrate farther distance methods continues on the subsequent rungs. As our understanding of cosmology and evolution progresses, studying farther astronomical objects becomes more important to clarify and confirm the findings, emphasizing the need for increasingly accurate distance measurements.

Despite recent advances in these distance calibrations and measurements, they are influenced by systematic errors and discrepancies left unresolved. Red clump stars are a promising distance indicator as they are luminous and prominent on the HR Diagram (HRD). This review aims to evaluate the mentioned methods of distance measurement: parallax, MS fitting, variable stars, and red clump stars. Specifically, this review outlines their history in Sections 2, 3, 4, and 5, respectively, and evaluates them in Section 6.

1. Parallax

Parallax is the only method to measure distance directly as other distance measurements rely on relative distances and recalibration. Since Earth's revolution causes angular displacement of an astronomical object with respect to background stars as shown in Fig. 1, this can be measured to calculate the distance with the small angle formula:

$$d = \frac{1}{p}$$

where d is the distance in parsecs and p is the parallax in arcseconds. However, using parallax for distance measurements is limited: as the distance of the target object increases, the observed angular displacement diminishes, becoming negligible and impossible to measure for distance calculations.

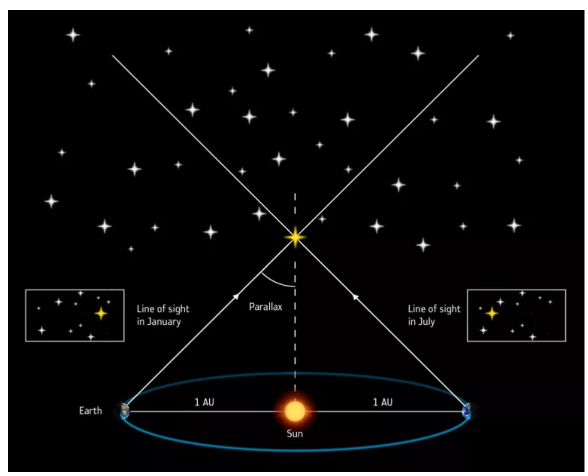

Figure 1: As the Earth revolves around the Sun, parallax motion is observed in the yellow star as its position shifts with respect to background stars with negligible parallax. This figure is from Pultarova (2022).

Gaia and Hipparcos are two significant space missions with the accurate and efficient collection of parallax measurements of 1,811,709,771 and 118,218 objects, respectively (Lindegren et al., 1997; Vallenari et al., 2022).

Moreover, they both contributed to many novel discoveries. Hipparcos aided in the confirmation of the Vogt-Russel Theorem, the hypothesis that absolute magnitude (luminosity) and color (effective temperature) are a function of metallicity, by expanding the sample size and providing more accurate distance measurements for calculating absolute magnitude (Reid, 1999). Gaia allowed for the discovery of new open clusters as it provided a large data set of proper motions and parallaxes where unsupervised machine learning can be applied (Cantat-Gaudin et al., 2019).

2. Main Sequence Fitting

Main sequence fitting relies on the Vogt-Russell Theorem and the HRD of a star cluster by assuming stars with similar colors have equal luminosities and stars in the same star cluster have equal distances (Reid, 1999). Consequently, after plotting the cluster's HRD, the amount shifted to align it with the zero-age main sequence (ZAMS) is the distance modulus, or m - M, where m and M are the apparent and absolute magnitudes, respectively. This can be used to derive the distance using the following equation:

$$m - M = -5 + 5\log d$$

This method may be inaccurate for individual stars as there are various possible luminosities for a given color or effective temperature (for example, a red main-sequence star and a red giant with the same color or effective temperature). However, this is not a problem when analyzing the star cluster as relative magnitudes between stars become apparent. For example, Oralhan (2021) studied the properties of open cluster Berkeley 55, including distance, age, radius, star membership, and reddening. MS fitting was used to determine the distance modulus by shifting the ZAMS vertically in increments of 0.1 mag until it is fitted with the lower edge of the MS in the bands $IJHK_S$ with the V band as shown in Fig. 2. Hence, MS fitting is widely used to calculate distances for star clusters.

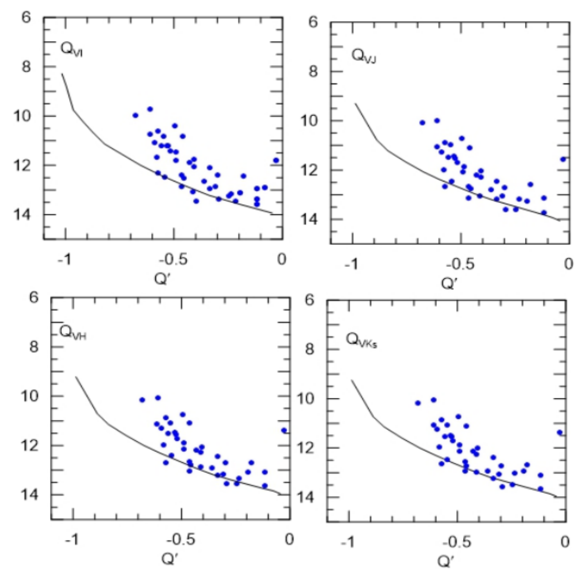

Figure 2: $Q_{V\lambda}$ versus Q' graph where Q represents reddening-independent quantities for their respective bands and λ represents the $IJHK_S$ filters. The early-type stars in the open star cluster Berkeley 55 and ZAMS are plotted as blue dots and a line, respectively. This figure is from figure 10 of Oralhan (2021).

3. Variable Stars

Variable stars fluctuate in luminosity in a regular pattern and serve as crucial distance indicators as they usually follow a relation between some physical characteristic (e.g. period, metallicity, color) and luminosity, which varies with distance. Two of the variable stars most popularly used as distance indicators are Cepheids and RR Lyrae.

Cepheids exhibit a correlation between the period of their luminosity fluctuations and their absolute luminosity described by a Period-Luminosity (P-L) relation. The light curve of Cepheid can be recorded, as shown in Fig. 3, to obtain the period and derive the absolute luminosity. Along with the measurement of apparent luminosity, the equation of the distance modulus can be used to calculate the distance.

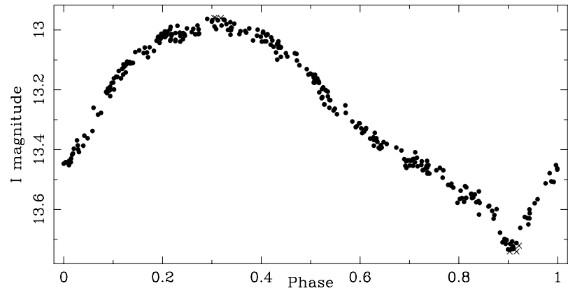

Figure 3: Light curve of a Population II Cepheid in the I band from the OGLE survey. The period of the light curve 9.94431 days. This figure is from figure 1 of Groenewegen (2008).

However, P-L relations will differ in slope or zero-point across different colors with respect to the photometric band as revealed in the calibrated P-L relations of Galactic Cepheids selected by Sandage & Tammann (2016) in the B, V, and I bands shown in Fig. 4, which are

$$M_B = -(2.692 \pm 0.093)\log P - (0.575 \pm 0.107)$$
(1)

$$M_V = -(3.087 \pm 0.085)\log P - (0.914 \pm 0.098)$$
(2)

$$M_I = -(3.348 \pm 0.083)\log P - (1.429 \pm 0.097)$$
(3)

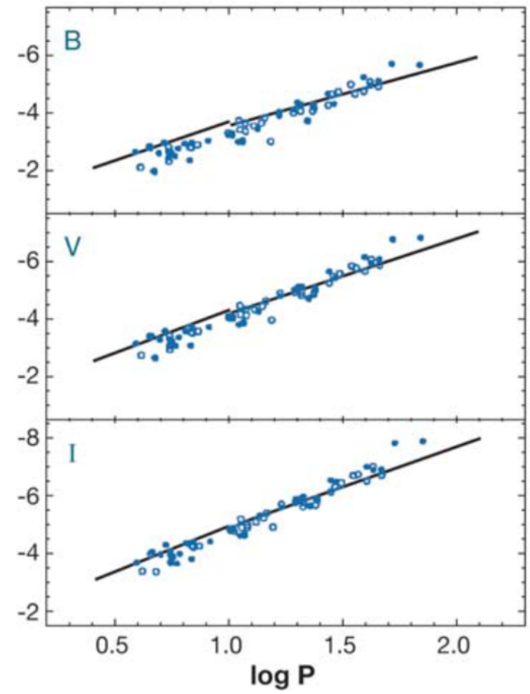

Figure 4: Fitted P-L relation for Galactic Cepheids in the B, V, and I bands. These calibrations are equations (1), (2), and (3), respectively. This figure is from figure 8 of Sandage & Tammann (2016).

RR Lyrae exhibits a relation between absolute magnitude and metallicity [Fe/H] (the iron to hydrogen ratio with respect to that of the Sun), which was originally assumed to be linear. However, recent research found that a parabolic metallicity-luminosity relation demonstrated a better fit (Sandage & Tammann, 2016; and references therein). One of these relations selected by Sandage & Tammann (2016) is

$$M_V = 1.109 + 0.600([Fe/H]) + 0.140([Fe/H])^2$$

and is favored for longer distances.

4. Red Clump Stars

Red clump (RC) stars are core He-burning stars with masses below the He-flash limit M_{HeF}, or the maximum mass of a star that can have a degenerate yet He-burning core to cause the He-flash (Girardi, 2016). Since a specific small range of masses allow for degeneracy, consistencies of RC luminosity and effective temperature. Consequently, the RC makes up ⅓ of all red giants, forming a prominent clump in the HRD as shown in Fig. 6. Moreover, high metallicity and low mass create the RC's characteristic large red convective envelope. The use of RC as a distance indicator was first suggested by Cannon (1970), and the first significant study on the RC by Paczyński & Stanek (1998) found their mean I-band magnitude with little uncertainties. Since the RC's luminosity increases as it transitions from mainly H-burning to He-burning overtime, the RC should exhibit a metallicity-luminosity relation where absolute luminosity is represented as a linear function of metallicity (Girardi, 2016). Note that metallicity is defined as the concentration of all elements heavier than He relative to the Sun. Hence, it is possible to derive a red clump star's absolute magnitude from metallicity and calculate its distance.

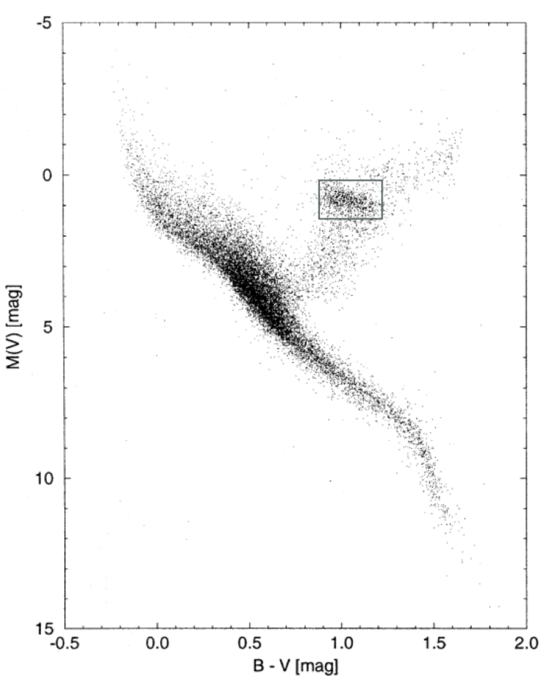

Figure 6: HR Diagram in the B and V bands using Hipparcos data. A box is drawn around the red clump. This figure is from figure 3 of Lindegren (1997) and edited by the author.

Despite their proximity to the RC in the CMD, the different structures shown in Fig. 7 have their distinct characteristics. The secondary red clump (SRC) and vertical structure (VS) are substructures of the RC: The secondary red clump (SRC) has masses between M_{HeF} and M_{HeF} + 0.3 $M_{\odot}$ and stretch below the RC, while the vertical structure (VS) has masses greater than M_{HeF} + 0.3 $M_{\odot}$, are slightly brighter than the RC, and extend above the RC as shown in Fig. 7 (Girardi, 2016). The red giant branch (RGB) bump, horizontal branch (HB), and early asymptotic giant branch (EAGB) bump are main structures in the CMD as they represent crucial points of a star's life: stars in the RGB passed the main sequence phase but haven't experienced He ignition, those in the HB passed the RGB and undergo He fusion, and those in the EAGB passed the HB and undergo fusion of heavier elements like carbon. Hence, these stars may contaminate RC data and cause inaccuracies.

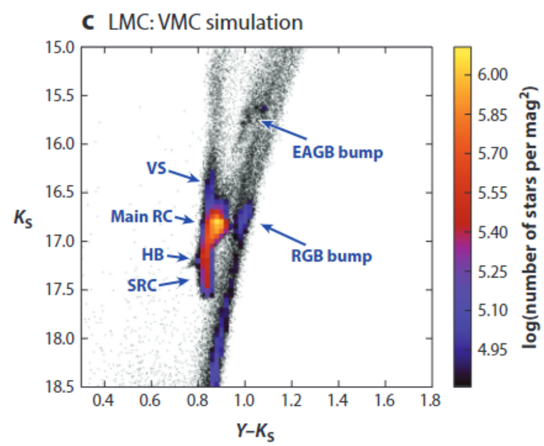

Figure 7: Color-magnitude diagrams of a simulation of the Large Magellanic Cloud (LMC). Distinctive features on the color-magnitude diagram are labeled: main red clump (RC), horizontal branch (HB), secondary red clump (SRC), vertical structure (VS), red giant branch (RGB) bump, and early asymptotic giant branch (EAGB) bump. This figure is from figure 10c of Girardi (2016).

5. Conclusion

Parallax surveys led to various significant discoveries in multiple astronomic subfields, such as the HRD, exoplanets, proto-planetary disks, white dwarfs, the Milky Way, stellar streams, clusters, the Solar System, and active galactic nuclei (Brown, 2021; and references therein). Moreover, it contributes to the calibration of other distance indicators, including Cepheids and RC stars, allowing farther distances to be measured. However, gravitational lensing and aberration may affect the observed parallax motion by bending and blurring the observed light, deviating from the true motion of the object. These effects must be predicted to ~1 μas accuracy to consider their impact on astrometry as negligible (Brown, 2021). Hence, future surveys should investigate and refine methods to automate the recognition and correction of these effects to address this issue.

MS fitting is frequently used for distance measurements to star clusters and calibrating distance indicator relations, including the Cepheid P-L relation. However, unresolved binaries may lead to inaccuracies in the stars' absolute magnitude and color. In addition, the accuracy of MS fitting is dependent on reddening: if reddening is overestimated, the distance modulus is overestimated (Reid, 1999). Hence, future surveys should recognize and flag unresolved binaries in the data processing.

The Cepheid P-L relation is commonly used to measure distances to star clusters and galaxies. However, the P-L relations of the Milky Way and LMC differ in both zero-point and slope, and the latter even exhibits a break at the period of 10 days (Sandage, 2004). Consequently, the uncertainty in selecting an equation—calibrated with Galactic or LMC Cepheids—will influence the accuracy of distance measurements to unknown objects. One theory for these discrepancies is metallicity differences. Many studies have incorporated metallicities into their calibrations; however, no changes that can explain the inconsistencies in the P-L relation between Galactic Cepheids and the LMC were observed (Groenewegen, 2018; Sandage & Tammann, 2016; and references therein). Future research should investigate whether metallicity plays a role in the P-L relation and analyze other differences in the features of Galactic and LMC Cepheids.

Red clump stars exhibit potential as a distance indicator because they are luminous and distinguishable on the HRD. However, they are not a firmly established distance indicator: since the first paper on analyzing this relationship of red clump stars by Paczyński & Stanek (1998), the metallicity-luminosity relationship was shown to range from a strong correlation to a weak correlation as noted by Girardi (2016). For example, Alves (2000), Grocholski & Sarajedini (2002), and Helshoecht & Groenewegen (2005) found that the K-band magnitude exhibited an insignificant correlation with metallicity. However, models suggest a significant dependence of K-band magnitudes with metallicity (Salaris & Girardi, 2002). These discrepancies are likely due to contamination of SRC and RGB stars, shown in Fig. 7 (Girardi, 2016). Asteroseismic graphs exhibit clustering that can distinguish these stars from the RC better than spectroscopic data, such as the effective temperature T_{eff} versus surface gravity log *g* plot. Another possible factor in the discrepancies is the heterogeneous nature of red clump stars as they span a wide range of initial masses, initial metallicities, and ages, possibly causing sample variations that weaken the metallicity-luminosity relation (Girardi, 2016). Because of the persistence of these discrepancies, repeating similar analyses will likely lead to the same inconsistencies, so the approach must be modified. Future research should address removing these contaminants, especially SRC and RGB stars, by collecting more asteroseismic data and searching for other distinguishable characteristics from the RC until their effects are near negligible. Only until then can the reliability of the metallicity-luminosity relation be evaluated.

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