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Analysis and Comparison of Length Measurement Scenarios from the Solar System to the Galaxy

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Abstract. As a matter of fact, astronomical research depends heavily on distance measurement between the Earth and celestial objects, so it’s crucial to employ effective method along with advanced instrument for distance measurement. This study talks about the three most commonly used strategies to measure distance in space. Stellar parallax, based on trigonometry and the concept of stereoscopic vision, is the most conventional method to measure the distances within the Milky Way. Cepheid Variables, with their consistent period-luminosity relationship, become useful when measuring distances to nearby galaxies. Type 1a supernova that worked as standard candles can be used to measure distance that parallax and Cepheid variables cannot achieve. According to the analysis, these three methods each plays an important role in the cosmic distance ladder and excels in different distance ranges. Even though more accurate techniques are still needed for a more propound exploration of the universe, these methods become a foundation for future advancement in astronomical distance measurement.

Keywords: Astronomical distance measurement; parallax; Cepheid variable; Type 1a supernova.

1. Introduction

Astronomical distance measurement has a long history, tracing back to early times when astronomers used basic geometric method such as stellar parallax to estimate distances to adjacent planets. The method of parallax is similar to stereoscopic vision, which measures an object’s change in position when observed from different locations. In 1838, German astronomer Friedrich Bessel became the first person to successfully calculated the distance to the star 61 Cygni using parallax, marking the beginning of creating a detailed map of the Universe [1].

With the advancement of science and technology, astronomers have invented more sophisticated method to measure longer cosmic distances and at a higher precision. The Cepheid variables method, in which the variable stars are served as standard candles to measure the distances to nearby stars or galaxies, extended the capacity of distance measurement past the reach of parallax [2]. Additionally, radar ranging involves recording the time difference between sending electromagnetic energy to nearby planetary body and receiving part of it back. By multiplying the speed of light with its traveling time, scientists are able to measure distances within the Solar System with extremely high precision [3]. Later, Type 1a supernovae, utilized as standard candles, enables measurement to extend up to almost one billion light-years [4]. These methods have refreshed people’s understanding of the scale of the universe and set the foundation for developing new methods in the future. Astronomical distance measurement continues be a key component in modern astronomy, because it can help astronomers understand galaxy formation and evolution. Since distance is often the main uncertainty factor in determining a star’s inherent luminosity, mass, or other physical properties, a precise distance measurement will help determine accurate properties of the stars. Measuring the size and shape of the Milky Way allows astronomers to model its structure and understand the formation of the Milky Way, drawing parallel to other galaxies as well [5].

In recent years, the cosmic distance measurement technique has shown significant progress, especially in the exactness of measurement. Firstly, the use of interferometry with the advancement on gravitational wave detection such as LIGO and Vergo allows researchers to measure distances to binary neutron stars with high precision [6]. Interferometry combines the signal from multiple

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telescopes to simulate a more massive aperture. For example, the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO) recombines the light from the four VLT Unit telescopes and obtain milli-arcsec angular resolution. Its adaptive optics system, enhanced with lasers, helps minimize the impact of atmospheric distortion and improves clarity. Therefore, VLTI became a valuable instrument for astronomical research on extragalactic objects [7].

The precise measurement of astronomical distances is a main challenge in astrophysics, since it directly relates to scientists' understanding of the structure and the evolution of the universe. Among various distance measurement methods, parallax, Cepheid variables, and Type 1a supernovae stand out due to their significant contribution to cosmic distance ladder. This study will explore these three methods in depth, explaining their principles with specific laws and equations, introducing the main instruments for measurement and observation, and discussing recent outcomes. The study will also compare and examine the limitations and prospects of the methods in the later section, seeking to emphasize the ongoing importance and the need for future development of these method to refine the understanding of the universe.

2. Stellar Parallax

One of the most traditional and most reliable methods for calculating distances within the Milky Way is stellar parallax. It entails tracking the apparent movement of a star against a far-off background as the Earth orbits the Sun, as seen in Fig. 1. This shift results from the observer's changing position, and the two observations period are typically separated by six months [8]. As a result, the distance to a star can be calculate using trigonometric,

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

where d is the distance to the star in parsecs, and p is the parallax angle in arcseconds. Amongst, the Earth-Sun distance is typically 1 AU. This equation is the foundation of the stellar parallax method, allowing astronomers to calculate the distance to a star by measuring its parallax angle. For most stars, this parallax angle is extremely small, often less than 1 arcsecond, but a greater precision is still necessary.

Previously, parallax measurement was conducted using ground-based telescope. Nevertheless, atmospheric distortion constrained their accuracy. Nowadays, these measurements are often carried out in the space, where scientists can avoid atmospheric distortion and allows greater accuracy. One of the most significant progress in the field is the European Space Agency's Gaia mission. Gaia is equipped with highly sensitive astrometric instruments that are able to measure the parallax angles in micro arcsecond, much more precise than arcseconds. This level of precision enables astronomers to determine distances to stars located thousands of parsecs away, greatly improving people's understanding of the structure and shape of the Milky Way.

In particular, the Gaia mission provided the most comprehensive survey of the Milky Way galaxy. An essential step of the mission was the release of Gaia Data Release 2 (DR2) in 2018. It provides accurate parallax measurements for over 1.3 billion stars. The Gaia parallax data is also important for identifying potential asteroids and Solar System Objects (SSOs) through the observatory's alert system as well. Between 2016 and 2020, more than 1,700 alerts were published. In 2018, Gaia's precise parallax measurements were used to analyze a sample of 6.4 million F-G-K stars, giving a comprehensive information which includes but not limited to positions, velocities, and distances. This data has been crucial in the resolution of the incomplete models of adjacent stellar systems and the configuration of the Milky Way [9].

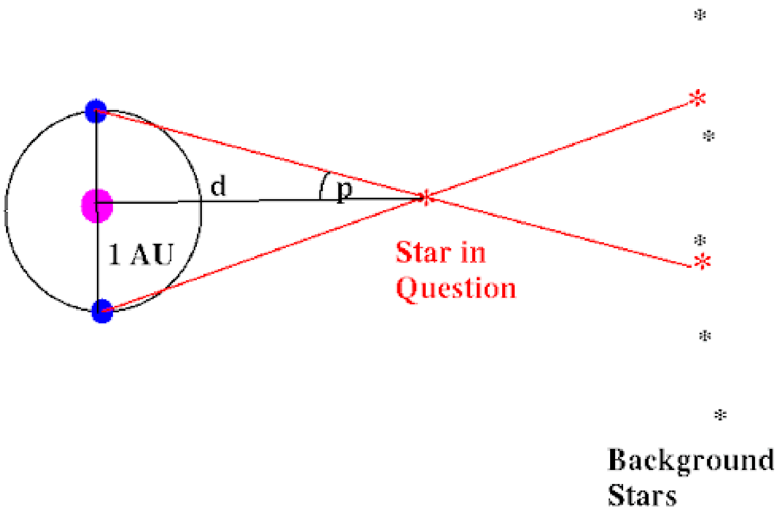

Fig. 1 A graphic demonstration of stellar parallax.

3. Cepheid Variables

The Cepheid variables are significant for extragalactic distance measurement, allowing astronomers to calculate the distances to nearby galaxies that host these variable stars. Cepheid variables are stars well-known for the strong relationship between their luminosity and pulsation period, known as the Leavitt Law, which states an important connection between a Cepheid's pulsation period and its luminosity. According to Leavitt Law, Cepheid variables with longer pulsation period are more luminous, and this period-luminosity relation can be expressed with equation:

$$M = a \log P + b, \tag{2}$$

where M is the absolute value, P is the pulsation rate, and a and b are constants depend on specific wavelength band of observation. As astronomers observe the Cepheid variable, they first record the light curve that shows how the star's light change overtime, and carefully measure the corresponding pulsation period, typically ranging from 1 to 100 days. Then, using the above period-luminosity relationship, they can determine the star's absolute magnitude. The apparent magnitude of the Cepheids is measured through observations, which represents the brightness of star observing from the Earth. With known apparent magnitude and absolute magnitude, they apply the distance modulus equation

$$\mu = m - M = 5 \log d - 5, \tag{3}$$

where μ is the distance modulus, m is the apparent magnitude, M is the absolute magnitude, and d is distance in parsecs [10].

An accurate distance measurement of Cepheid variables requires the innovative instruments and techniques. For instance, optical telescope equipped with highly sensitive CCD cameras are fundamental for observing Cepheid variables, as they provide clear photometric data to determine the light curve and period of these variable stars. One of the most powerful tools among them is Hubble Space Telescope, equipped with Wide Field Camera 3 (WFC3). WFC3 has both optical and near-infrared channels, so it can observe Cepheids through a great range of wavelengths. Its ability to capture high resolution photometry is also essential for recoding the light curve of Cepheid variables.

In 2016, the SH0ES (Supernovae and H_0 for the Equation of State) team used Hubble Space Telescope's WFC3 to refine measurements of Cepheid variables in nearby galaxies. By observing the Cepheids, they are able to calculate a value for the Hubble constant with an accuracy of 2.4% [11]. In 2020, WFC3 was used to improve distance measurement to galaxy NGC 4258, which hosts a mega maser that provides an independent geometric distance. By comparing Cepheid variables observed in NGC 4258 with the maser-based distance, astronomers further refined the calibration of the period-luminosity relationship [12].

4. Type 1a Supernovae

Because Type 1a supernovae have vast diversity in peak luminosity and the shape of light curve, they are especially well-suited for measuring cosmic distances [13]. Astronomers first observe the apparent magnitude (observed brightness) of Type 1a supernovae. Since they explode at a consistent Chandrasekhar mass, they have uniform peak absolute magnitude (intrinsic lightness), which is typically around -19.3. Knowing the values of both apparent magnitude and absolute magnitude, scientists can use the distance modulus equation to calculate the distances, similar to the process with Cepheid variables. Recall that the distance modulus equation is

$$m - M = 5 \log d - 5, \tag{4}$$

where m is observed apparent magnitude, M is known absolute magnitude, and d is distance to the Type 1a supernova in parsecs. Rearrange the equation and plug in the values for m and M, scientists can determine the precise distance.t

James Webb Space Telescope (JWST) is one of the most effective instruments for observing Type 1a supernovae at vast distances. JWSP has high infrared sensitivity, which allows it to observe high-redshift supernovae with $z > 2$. These supernovae are often redshifted out of the typical wavelength range, making it difficult for earlier telescopes including Hubble Space Telescope to see them, since those telescopes observe primarily in the optical and new-infrared range. However, with high infrared sensitivity, JWST can observe those supernovae that are invisible or hard to see in optical wavelength [14].

One of the most significant findings of JWST is the observation of supernovae at unprecedented redshift. In 2023, JWST observed a Type 1a supernova at a redshift of 2.9, which means the light from supernova's explosion has traveled 11.5 billion years. Until today, the JWST Advanced Deep Extragalactic Survey (JADES) has uncovered about 80 supernovae, including the farthest spectroscopically confirmed supernovae, at a redshift of 3.6 [14]. The detection of faraway supernovae at high redshift not only assist astronomers in cosmic distance measurement, but also help understand universe's expansion during early stages, resolving the ongoing Hubble tension.

5. Comparisons, Limitations, and Prospects

As for the three primary cosmic distance measurement methods (i.e., stellar parallax, Cepheid variables, and Type 1a supernovae), each has unique applicability, limitations, and prospects for future development. Stellar parallax is the most direct and geometrically based method. It has high accuracy in measuring distances within a few thousand parsecs, making it essential for fully exploring the own galaxy, the Milky Way. However, it's effectiveness diminished with farther distances due to the extremely small parallax angle with faraway stars which is difficult to measure even with the most sophisticated instruments. Although the new space-spaced observatories like Gaia greatly improved the parallax measurement, to a microarcsecond precision, which has pushed the limits of stellar parallax, the challenges still remain as it moves on to measuring stars beyond the Milky Way.

Cepheid variables contributed significantly to the cosmic distance ladder, becoming the most useful method to measure the distances to nearby galaxies. They are particularly useful within Local Group and nearby galaxy clusters, which is about few tens of millions of parsecs. However, its usefulness decreases as it measures the distant galaxies. First of all, Cepheid variables become difficult to detect and distinguish from other stars as distance increases. Moreover, interstellar stars can obscure these variables stars, leading to an inaccurate observation and brightness measurement. Lastly, the period-luminosity relationship differs among different types of Cepheid variables, and it shows some level of uncertainty. To extend the ability of Cepheid variables to measuring distant galaxies, future research may focus on refining the period-luminosity relationship and improve infrared observation to avoid the effects of dust.

Type 1a supernovae are the most effective tool for measuring vast distances, beyond the reach of both stellar parallax and Cepheid variables. It can measure distances to galaxies located billions of parsecs away, making it necessary for studying the large structure and evolution of the universe, including the Hubble Constant, which is the expansion rate of the universe. However, Type 1a supernovae do not exist that frequently, so there is a limitation on the applicable situations of this method. Scientists in the future may put effort into finding new standard candles to use at the situation when Type 1a supernovae are not available.

6. Conclusion

Overall, each of the three methods (i.e., stellar parallax, Cepheid variables, and Type 1a supernovae) are significant to cosmic distance ladder. Stellar parallax is effective when measuring distances within the Milky Way, but encounters limitations when trying to reach out to nearby galaxies. Cepheid variables extend the reach to nearby galaxy, utilizing Leavitt Law, though difficulties occur when measuring longer distances due to interstellar dust. Type 1a supernovae, served as standard candles, allows astronomers to measure enormous distances up to billions of parsecs away. However, since they do not exist frequently, the method is not applicable in numerous situations. The continuing improvement in space-based observatories and advanced instrument like Gaia, Hubble Space Telescope, and James Webb Space Telescope have enhanced some levels of precision in distance measurement. However, those methods still have apparent limitations and encounter challenges at different degrees, highlighting the need for developing new methods to further the boundary of distance measurement.

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