Nearest Search: Distance to the Nearby Stars

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Why This Paper?

Possibilities; Humanity's future is ripe with them. Thousands of years ago our ancestor's world was Africa till they decided to cross Red sea. Imagine, 70 thousand years ago, a curious teen like me sitting at the shore of the Red sea with an anxiety to explore. To go beyond, what was then the infinity; the horizons of Red sea. To stretch the infinity and find possibilities of existence in the new found space of old infinity and new infinity. I have same curiosities when I gaze the stars, how can we reach them? NASA's New Horizon rocket broke the speed record when it blasted off towards Pluto with speed of 45 KM per second, but even that is not enough to reach other galaxies. Today, I feel much like that teen sitting at the bank of Red sea 70 thousands years ago. The twinkle of the stars appear as a challenge. The Homo Sapiens on the bank of Red sea would have had many trials and errors, but, thanks to humanity and its centuries of advancement in science, I can structure my attempt of intergalactic wanderlust in a phased manner. At this nascent stage, I in this paper, attempt to understand and execute the process of scientific enquiry, for which I have chosen the 'Nearest Search'. Find a star and figure out methods to calculate its distance from earth.

Introduction

The universe came into existence around 14 billion year ago with elements such as hydrogen, helium, and traces of lithium, beryllium, and boron. At some point in time, the first stars were formed, and within their core heavier element were produced by nucleosynthesis. The stars started to evolve based on their nuclear fuel and initial mass. Mid-size stars ejected planetary nebulae, while more massive stars exploded as supernova. The elements created within the core of stars were ejected into space, which provided the raw material for the formation of new generations of stars. Eventually, these elements became incorporated into the large clouds of gas and dust that condensed and formed protostars.

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This never-ending cycle of stellar formation and destruction continues-each new generation further enriching the interstellar medium with heavy elements that become incorporated into the next generation.

The stars in the sky appear to the naked eye as points of light affixed to the celestial sphere, whose apparent positions relative to each other never seem to change. However, the positions of nearby stars actually do move by tiny amounts, and if we can measure this apparent motion, we can calculate the distance to these stars using some simple trigonometry. The apparent distance between two points in the sky, is an angle, measured between the two imaginary lines running from your eyes to the points as shown in Figure 1.

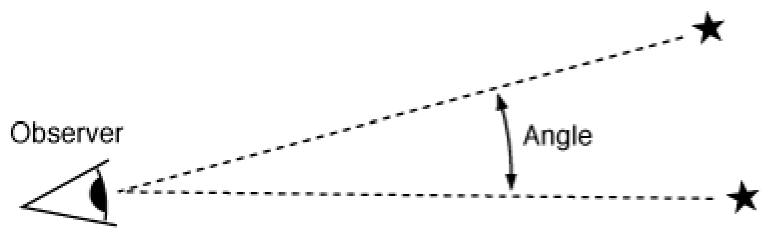

Figure 1. *The apparent distance between two points in the sky*

The most common way to measure the distance to a star within a few hundred light-years of earth is using the parallax method or triangulation. By observing the distance of the parallax shift and knowing the diameter of the earth's orbit, one can calculate the parallax angle across the sky. The smaller the parallax shift, the farther a star is from earth.

The method of measuring distance to stars beyond 100 light-years is to use Cepheid variable stars and supernovae. These stars pulsate in a predictable way, which allows astronomers to figure out the true brightness. The comparison of the apparent brightness of the star to the true brightness allows the astronomer to calculate the distance to the star.

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Parallax method

Parallax method sometimes also known as triangulation usage our brain to judge the distance to object around us- so called “depth perception”. Because our eye are separated by a few inches, our left eye sees a slightly different view of an object than your right eye. When our brain interprets the two images from our eyes, it allows us to estimate distance to the objects.

However, stars are so far away that the separation between our eyes does not make a difference in their appearance or parallax shift. We can use Earth’s orbit as a baseline to create separate images of nearby stars. In January, the Earth is on one side of the Sun, and 6 months later, in July, the Earth is on the other side of the Sun. The distance between the Earth’s position in January and its position in July is twice the Earth/Sun distance, or 2 AU. When we observe a nearby star in January, and then again in July, its position with respect to much more distant, background stars will have changed by a measurable amount.

Using trigonometry, we can calculate the lengths of the sides of a triangle. A right triangle is formed if we use half of the measured angle that the star appears to move in 6 months. The distance to the star (D), the angle by which the star appears to have moved (θ), and the length of the baseline (B) are related in the following way

$$\tan\left(\frac{\theta}{2}\right) = \frac{B}{D}$$

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The angle θ/2 is called as parallax angle (θ_p) of a star. The Figure 2. Shows the trigonometric parallax method to calculate the distance of the stars.

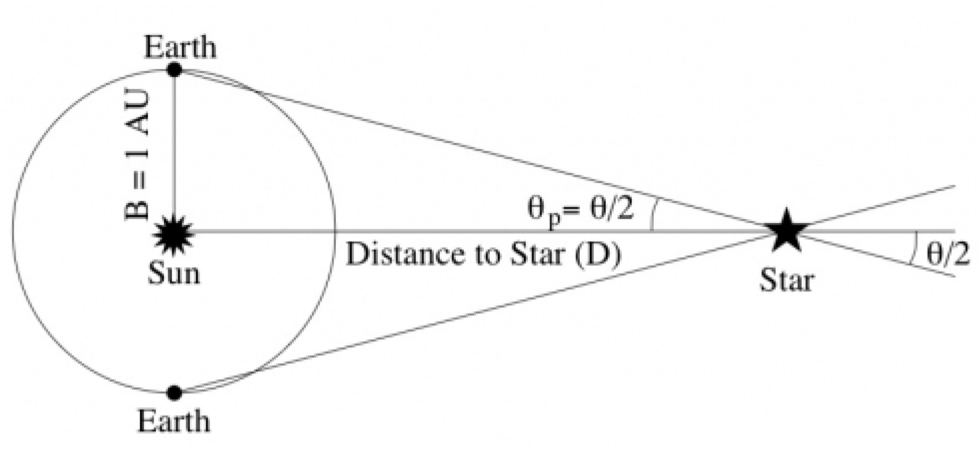

Figure 2.
Diagram showing the earth orbiting the sun and our changing line of sight to a distant star (Parallax Phenomenon)

The parallax angles that we measure are incredibly tiny. The nearest star to Earth, Proxima Centauri, undergoes a shift of 0.76813 arcseconds (~0.000213369°) in apparent position every 6 months. So every other star in the sky has an angular shift smaller than the Proxima Centauri!

The unit of measurement for distance is defined in parsec (pc) and light-years. One parsec is the distance to a star with a parallax angle of 1 arcsecond, and one light-year, is the distance a photon of light travels in 1 year. These two measurements are similar, and related as:

$$1\,parsec = 3.26 lightyears = 206264.8AU = 3.086x10^{13}km$$

We can calculate the distance of the star using the above two equations having only the arcseconds measurement.

$$D = \frac{1parsec}{p(inarcseconds)}$$

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Hence, the distance of the Proxima Centauri from earth is 1.302 parsecs, which equals 4.24 light years.

Luminosity and Apparent Brightness

Luminosity is an intrinsic property (amount of light it emits from its surface) of the star means that the radiant power emitted by star is independent of an observer's distance from the star.

However, apparent brightness is not an intrinsic property of the star; it depends on observer's location. So, everyone will measure a different apparent brightness for the same star if they are all different distances away from that star.

The apparent brightness of Stars is a consequence of geometry. As light rays emerge from a star, they spread out through the inverse square law of brightness. The variation in their brightness is caused by both variations in their luminosity and variations in their distance. An intrinsically faint, nearby star can appear to be just as bright to us on Earth as an intrinsically luminous, distant star.

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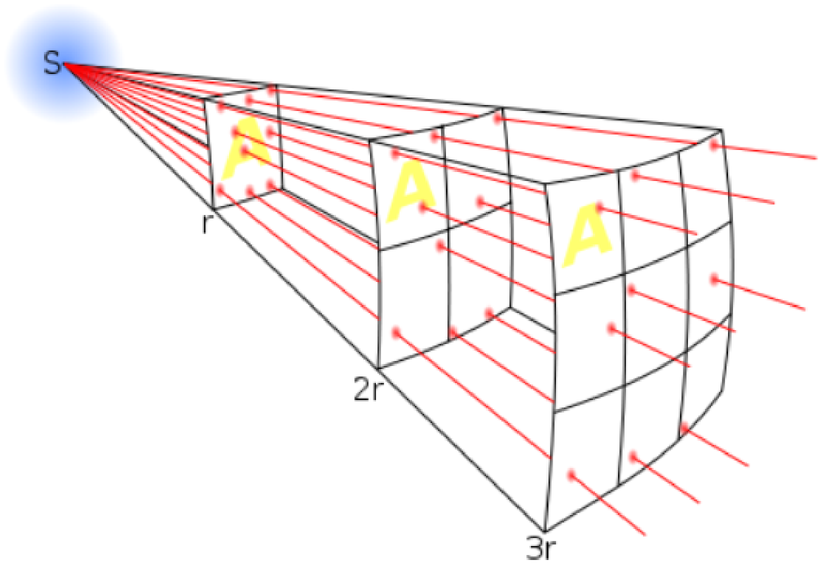

Figure 3. *Inverse Square law of brightness*

As the light gets emitted, we can picture it passing through spherical shells centered on the star. In the Figure 3, each shell placed at a distance of r, 2r, 3r should receive the same total amount of light energy per second from the star, but since each successive sphere is larger than previous sphere, the light hitting (per square meter) to a distant sphere (3r) will be diluted compared to the amount of light hitting nearby sphere (r). The amount of dilution is related to the surface area of the spheres, which is given by:

$$A = 4\pi r^2$$

As the surface area of the sphere increases, the same total amount of light illuminating each spherical shell has to spread out to cover 4 times or 9 times as much area for a shell twice or thrice as large in radius. Hence, a star light will appear four times fainter if you are twice as far away from it as someone else, and it will appear nine times fainter if you are three times as far away from it as someone else.

Thus, the equation for the measuring distance (D) of star having known the apparent brightness (B) and the luminosity (L) can be given by,

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$$D = \sqrt{\frac{L}{4\pi B}}$$

Given the measured value of the Sun having a luminosity of $3.9x10^{26}$ W, and the apparent brightness (solar constant) received on earth is 1379 W per square meter. We can calculate the distance between sun and earth as

$$D = \sqrt{\frac{3.9x10^{26}}{5516\pi}} = 1.5x10^{11}\ m$$

The value of this distance from sun to earth is referred as 1 astronomical unit (AU).

The process of measuring the apparent brightness of object is called photometry. Stellar magnitude and Absolute fluxes are two ways to express apparent brightness. Nowadays, Solid state Detector are used to measure the absolute fluxes (apparent brightness).

Apparent and Absolute Magnitude

Magnitude system is a traditional system from classical times, invented by Hipparchus to measure the relative brightness of stars. The star were ranked into "magnitudes" based on eye-to-eye observations of brightness. The 1^{st} magnitude of stars were brightest stars, lightly fainter stars were second magnitude, and the faintest stars the eye could see were listed as sixth magnitude.

However, astronomers still use a system of measuring stellar brightness called the magnitude system in the modern magnitude scale, so for every 5 magnitudes of difference in the brightness of two objects, the objects differ by a factor of 100 in

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apparent brightness (flux). If object A is 10 magnitudes fainter than object B, it is (100 x 100) or 10,000 times fainter. If object A is 15 magnitudes fainter than object B, it is (100 x 100 x 100) or 1,000,000 times fainter.

Apparent magnitude (m) of star is a number that tells how bright the star appears from the earth. It depends on its distance from earth. The closer the star is to Earth, the brighter its magnitude will be. That is, the apparent magnitude of a star is its magnitude (*flux, or apparent brightness*) measured on Earth.

Absolute magnitudes (M) is the apparent magnitude the star would have if it were placed at a distance of 10 parsec from the earth. For example, if a star is precisely 10 pc away from us, its apparent magnitude will be the same as its absolute magnitude. If the star is closer to us than 10 pc, it will appear brighter than if it were at 10 pc, so its apparent magnitude will be smaller than its absolute magnitude. The absolute magnitude of a star is equivalent to its *luminosity.*

$$M = m - 2.5 \log[(D/_{10})^2]$$

The above relation can be used to determine the distance to a star if both its apparent and absolute magnitude are known. This would be the case when one uses Cepheid or other variable stars for distance determination. For a Cepheid variable with M= -4, and m=18, the distance of the star is

$$D = 10 * 10^{\frac{[18-(-4)]}{5}} = 2.51 * 10^5\ pc$$

Supernovae

At distances up to about 1 billion light-years, methods such as parallax or Cepheid variables can no longer be used as the stars are no longer visible. All Type Ia supernovae reach nearly the same brightness at the peak of their outburst with an absolute magnitude of -19.3±0.03. They also follow a distinct curve as they decrease in brightness. These type Ia supernova are called “standard candles”, because their brightening and dimming is very regular and the maximum brightness at a distance of 1 light-year is (calculated using the known distance and the inverse square rule), about the same for all stars.

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To calculate distance of a far away galaxy, one must first locate a type Ia supernova in it and then measure its observed brightness. Then, by comparing the relative intensity of light observed with that of expected based on its assumed absolute magnitude, the distance modulus can be used to infer the distance.

Due to extremely bright nature of supernovae, this method is useful to very large distances, up to one billion light-years.

Redshift and Hubble's Law

For very far objects, beyond 1 billion light-years, none of the above methods seems to work. The theory used to determine these very great distances in the universe is based on the discovery by Edwin Hubble –"the universe is expanding". This phenomenon is observed as a redshift, which appears to be larger for faint, presumably further, galaxies. Hence, the farther a galaxy, the faster it is receding from Earth. The velocity of a galaxy could be expressed mathematically as

$$v = H\, x\, D$$

Where v is the galaxy's radial outward velocity, D is the galaxy's distance from Earth, and H is the constant of proportionality called the Hubble constant.

Galaxy's radial outward velocity is measurable using Doppler shift in the spectrum of a distant galaxy. Putting this velocity into the Hubble equation, we can determine the distance. Hubble law works only for the distant galaxies/objects.

Conclusion

There are now different ways to calculate the distance of celestial body, depending on the time how long it takes radar signals to travel from earth to the surface of a planet or other body and vice versa. For stars that are relatively nearby, we can "triangulate" the distances from a baseline created by earth's annual motion around the sun. Half the shift in a nearby star's position relative to a very distant background stars, as viewed from opposite sides of Earth's orbit, is called the parallax of that star and is a measure of its distance. The first successful measurements of stellar parallaxes were reported in 1838. Parallax measurements

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are a fundamental link in the chain of cosmic distances. The Hipparcos satellite and Gaia mission has allowed us to measure accurate parallaxes for stars out to about 30,000 light-years. Cepheids and RR lyrae stars are two types of pulsating variable stars. Light curves of these stars show that their luminosities vary with a regular repeating period. RR lyrae stars can be used as standard bulbs, and Cepheid variables obey a period-luminosity relations, so measuring their periods can tell us their luminosities. Then, we can calculate their distance by comparing their luminosities with their apparent bright nesses, and this allow us to measure distances to the stars out to about 60 million light-years. For stars beyond 1 billion light year supernovae method, spectral H-R diagram, Hubble law, can be used to measure distance. Spectrum allow us to pinpoint where the star is located on an H-R diagram and establish its luminosity. This with the star's apparent brightness, again yields its distance. The various distance methods can be used to check one against another and thus make a kind of distance ladder which allows us to find even larger distances.

Further advancing this science, most recently, the James Webb Space Telescope's (JWST) images are explaining the creation of first galaxies or stars. The James Webb Space Telescope uses its infrared cameras to see through dust in our universe. Stars and planets form inside those dust clouds, so peeking inside could lead to exciting new discoveries! It will also be able to see objects that are so far away that the expansion of the universe has made their light shift from visible to infrared! Stargazers are now more than ever need to heed the dual legacy left by "Sir William Herschel" – to approach the heavens with a sense of wonder and awe, as well as with scientific curiosity and scrutiny.

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