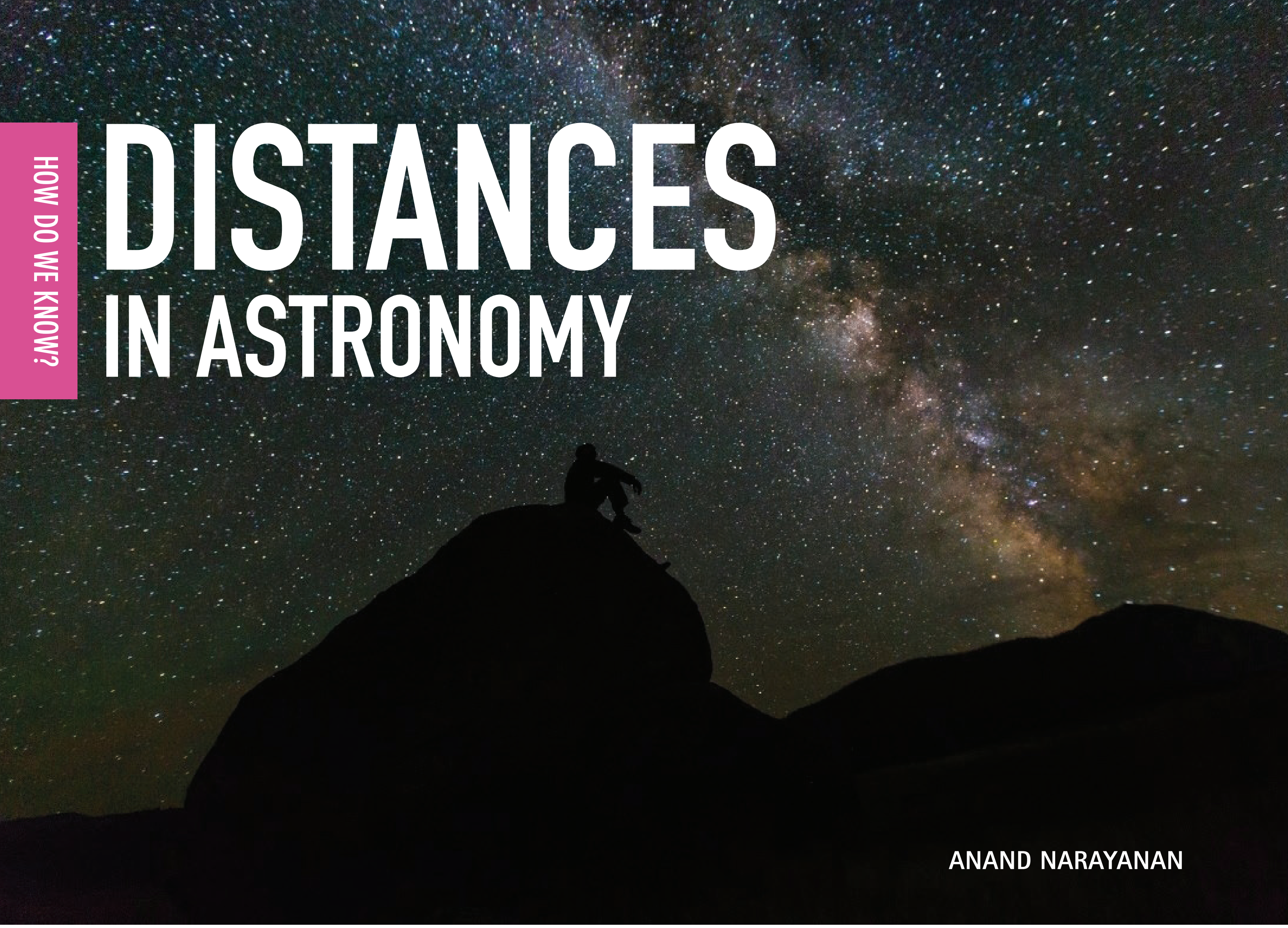
HOW DO WE KNOW?

DISTANCES IN ASTRONOMY



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How do we know the distance of the sun from the earth? Or that of the nearest galaxy to our own? This article introduces four methods that astronomers use to measure distances in space.

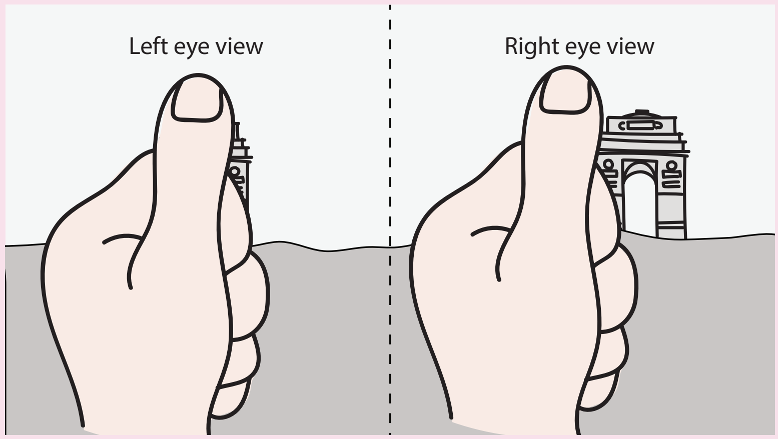
Much of our knowledge of astronomy is based on our ability to measure distances in space. Knowing astronomical distances helps us understand, among other things, how stars, star clusters, nebulae, galaxies are distributed in space; or, how bright they truly are as opposed to how bright they appear to us. However, given the scale of this task, estimating distances to objects in outer space is not a trivial task.

Over time, astronomers have come up with some really interesting ways to pin down distances to stars in our own as well as other galaxies. These include:

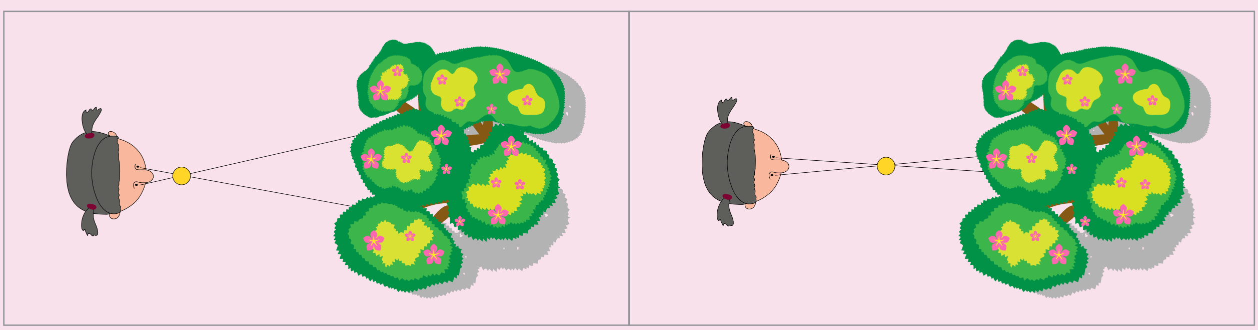
1. Trigonometric parallax: this technique is useful in estimating distances to stars within a few 100 light-years from us (see **Box 1**).
2. Observations of variable stars: this technique is useful in estimating distances to variable stars, or star clusters with variable stars, in our own as well as neighbouring galaxies (see **Box 2**).
3. Observations of standard candles in the dark: this technique is useful in estimating distances to galaxies in which supernova explosions (standard candles) are underway (see **Box 3**).
4. Estimation of the velocity with which galaxies are receding from us: this technique is useful in estimating distances of galaxies that are >100 million light-years away (see **Box 4**).

Box 1. Trigonometric parallax:

Stretch out your hand, fist closed, with your thumb pointing upwards. Try looking at your thumb first through your left eye, and then through your right eye. Against the backdrop of more distant objects, the position of your thumb will appear to shift. This shift, referred to as trigonometric parallax, happens because you are looking at your thumb from two slightly different viewing angles.



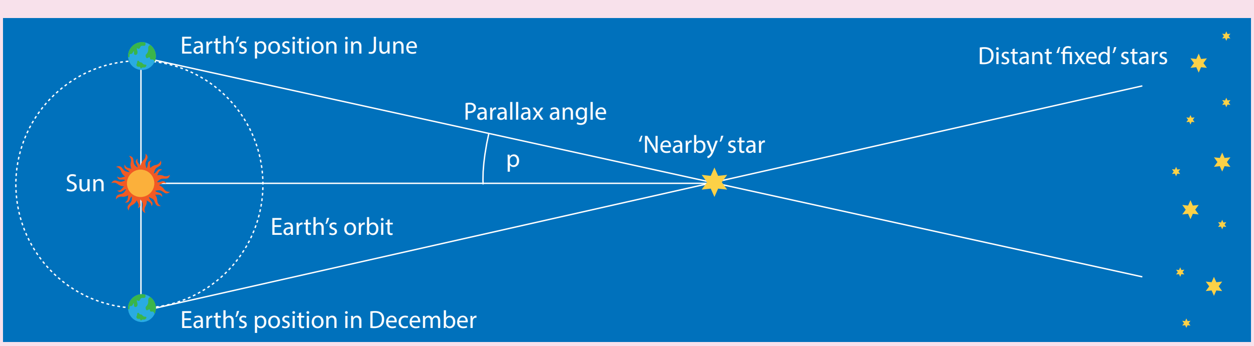
When you repeat this with another object, like a ball instead of your thumb, held at some distance from you, you may still see some shift. But the shift will be much less than what you see for your thumb. In fact, if the ball is held sufficiently far away from you, you may not notice any shift at all. Thus, the extent of shift in position seems to be telling us, in relative terms, how far or close an object is to us.



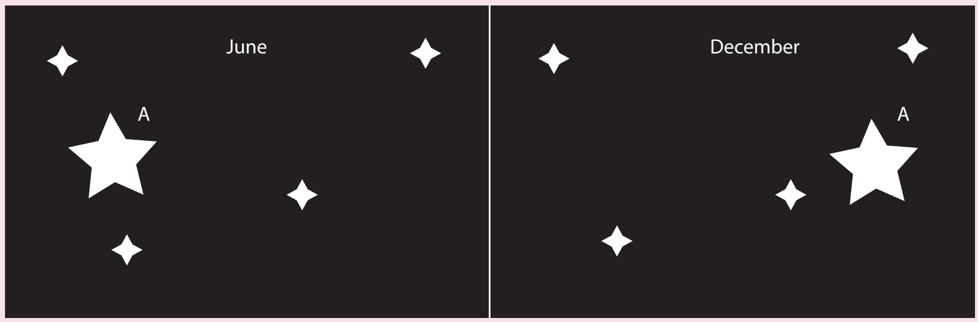
If we could measure angle 'p', then we could determine how far away the pencil is from us by using the trigonometric identity for a right-angled triangle:

$$\tan\theta = \frac{\text{Half the distance between the eyes}}{\text{Distance of the ball from us}}$$

How do we use this for measuring the distance to a star? Since stars are very far away from us, we may not be able to detect a shift in their position in the sky merely by viewing them through our naked eyes. Instead, we need a much broader binocular vision. That vision is provided by the earth's orbit around the sun. If you pick any two days in a year that are six months apart – the earth will be at opposite points in its orbit around the sun.



Thus, if you were to take photos of the night sky during June and December, the position of star A will appear to have shifted compared to other stars in the same field of view.



This shift is also due to parallax. Thus, the distance to the star A can be calculated by estimating the value of angle 'p' through some basic principles of spherical trigonometry:

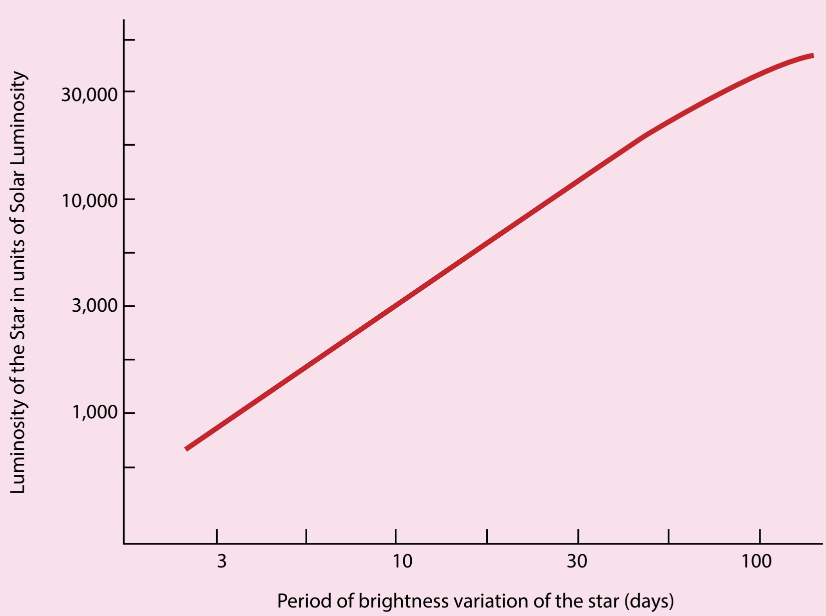
$$\tan(p) = \frac{\text{Distance between earth \& sun}}{\text{Distance to the star}}$$

In principle, all stars exhibit some parallax shift. However, the shift for ones that are very far away is too tiny for our telescopes to provide reliable measurements. Only stars that are relatively near (within a few 100 light-years of distance from) us, show an observable parallax shift.

Box 2. Observations of variable stars:

Stars known to vary in brightness – brightening and dimming in a periodic manner – are called **variable stars**. The periodicity of these variations is related to the average brightness of these stars. Stars which show a slow change in in their brightness (or, stars with a long time period of variability) tend to be intrinsically brighter than stars that show rapid variations in brightness.

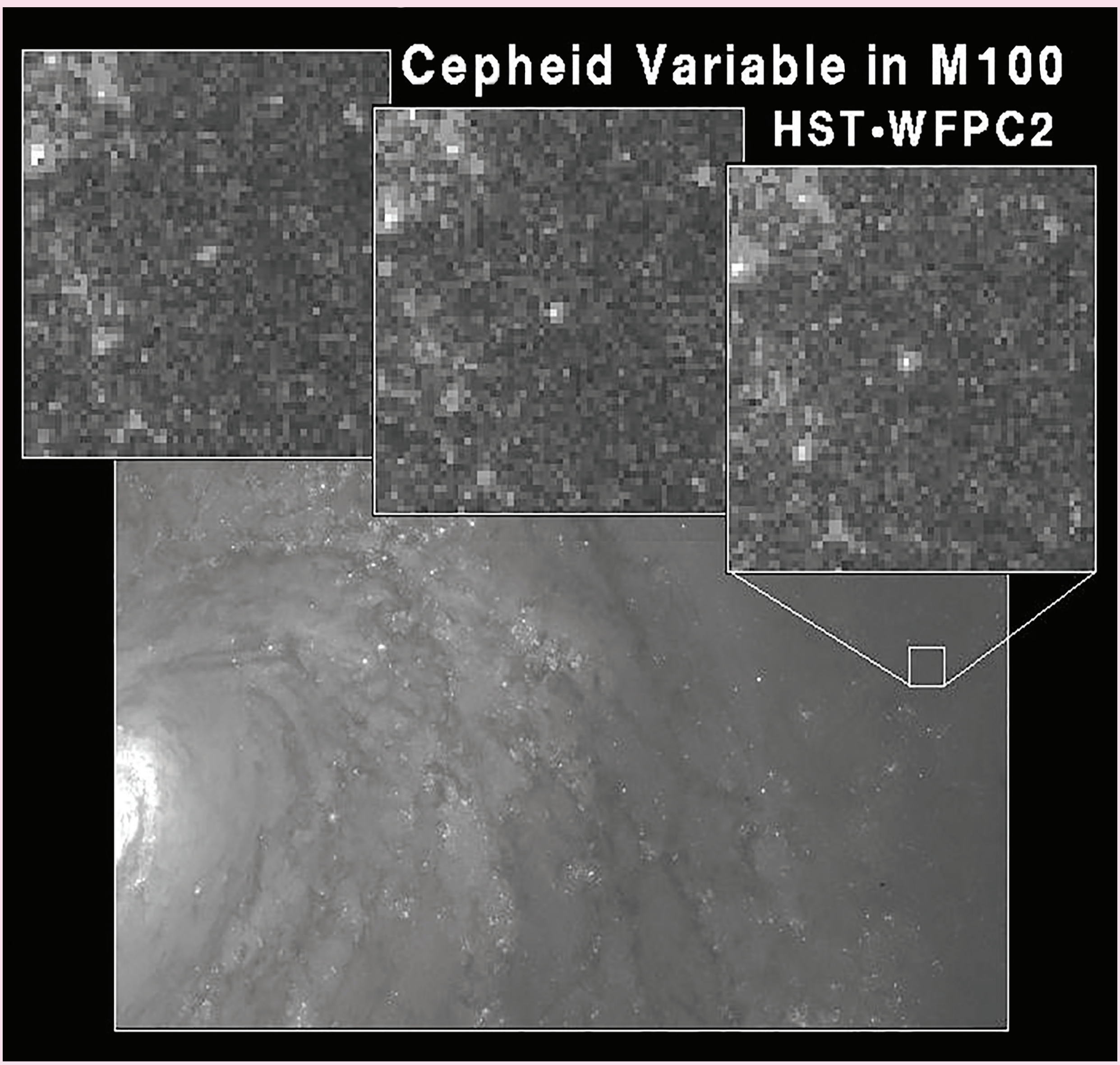
The true brightness (known as **luminosity**) of stars (in units relative to the sun's luminosity) is positively correlated with the observed time period for brightness variation (in units of earth days). This trend means that if we find out the time period of variation in the brightness of a variable star through observations, we can estimate the star's luminosity.



The luminosity of a star (how bright it actually is) is related to its observed brightness (how bright it appears to us in the sky) by way of this simple expression:

$$\text{How bright the star appears in the sky (directly observable)} = \frac{\text{The true brightness of the star as estimated from its time period of brightness variability}}{4 \times \pi \times (\text{distance to the star, the quantity to be estimated})^2}$$

If the variable star belongs to a star cluster, then by determining our distance to it, we also end up establishing our distance to the cluster. Similarly, if a variable star is identified in another galaxy, we can estimate the distance to not just the star, but the galaxy in which the star resides. For e.g., three images of a variable star in the outskirts of the spiral galaxy M100 taken by the Hubble Space Telescope at time intervals of a few weeks shows it slowly growing in brightness. Based on observations of this and other variable stars in the galaxy, astronomers have estimated that M100 is at a distance of 56 million light-years from us.



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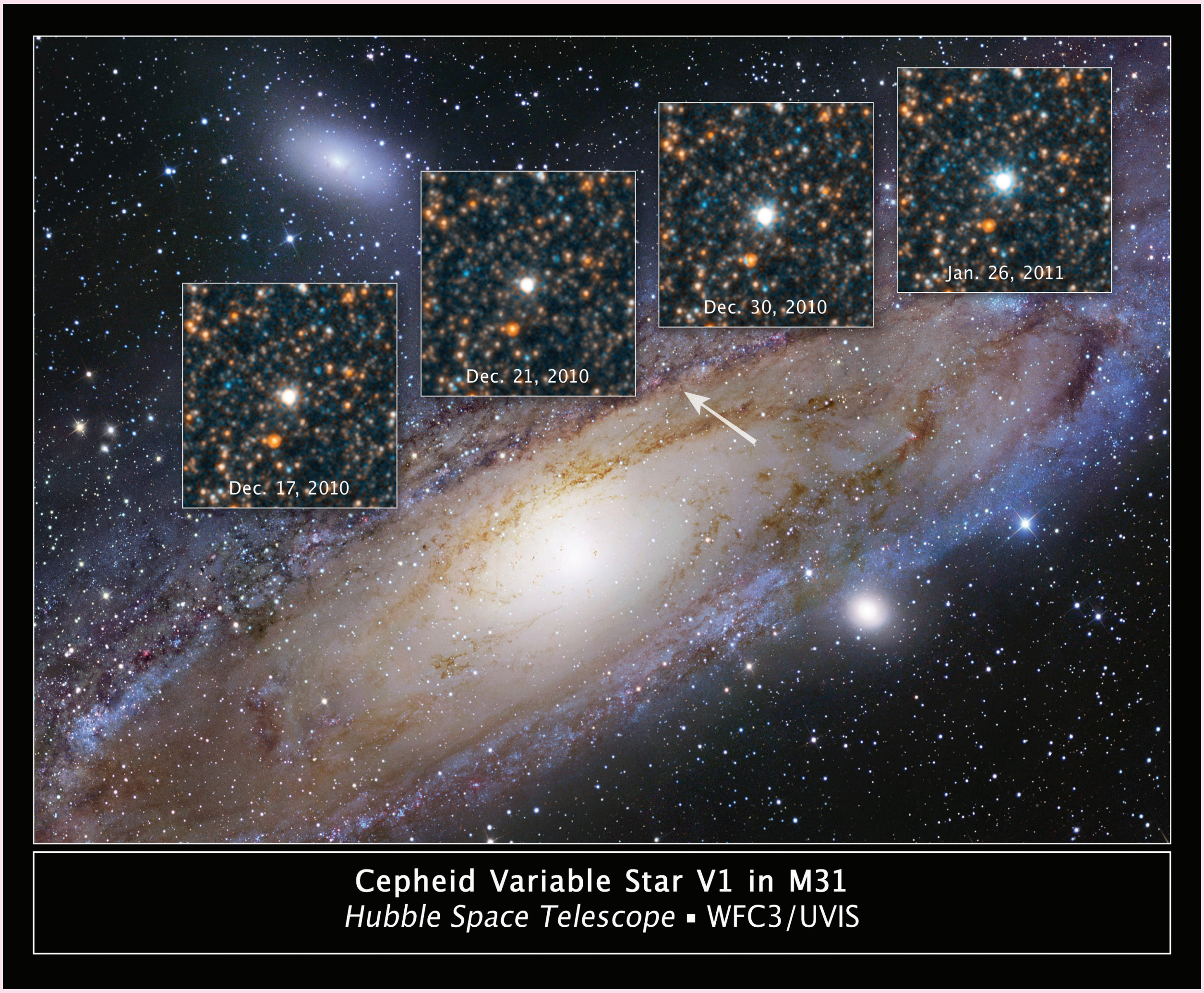
Similarly, images of the star V1 in the Andromeda Galaxy (also called M31, and the nearest big galaxy to the Milky Way) taken several days apart show it growing in brightness. This indicates that it is a variable star that can be used to determine the distance to this galaxy.



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This technique is limited to the local universe since it is not possible to discern individual stars in galaxies that are beyond a distance of a few tens of million light-years from us (considered "nearby" in astronomy).

Box 3. Observations of standard candles in the dark:

A supernova is the explosion that marks the death of a star. One type of supernovae, called **Type Ia supernovae,** results from the explosion of a white dwarf when it exceeds a certain mass limit. This mass limit, called the **Chandrasekhar limit,** is an exact value. In other words, every Type Ia supernova will be the result of the explosion of a star of the same mass.

Since a star's mass is what gets converted to energy, every Type Ia supernova explosion tends to shine with the same brightness or have the same luminosity. These explosions are so energetic that they continue to outshine the light from all the stars in the galaxy in which the exploding star resides till a few days after the event. It is because of their luminosity that our telescopes can detect these explosions even at distances that are so far from us that it is often difficult for us to detect any galaxies there.

For e.g., based on the constant peak brightness of a Type I supernova in the outskirts of the spiral galaxy NGC 4526, seen from earth in the year 1994, astronomers have accurately estimated that NGC 4526 is 50 million light-years away from us.

Credits: © NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team.

Similarly, an extremely bright Type I supernova could be seen from earth, through the thick shroud of gas and dust that obscured individual stars, in the galaxy M82 in 2014. Astronomers used this sighting to measure the distance to M82 accurately.

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So, how do these supernovae aid in distance estimation? Since every Type Ia supernova shines with the same brightness, a supernova in a nearby galaxy will appear fairly bright compared to one in a galaxy that is farther away. Thus, the distance to the supernova can be calculated using this relationship:

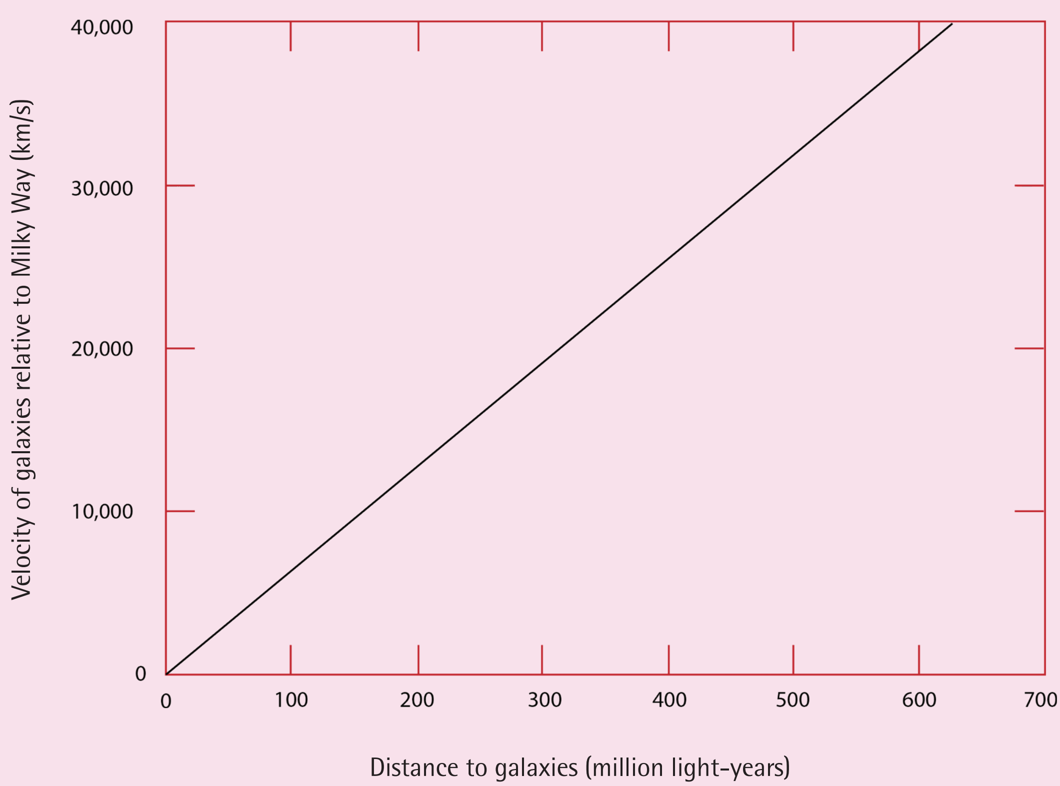
$$\text{How bright the star appears in the sky (directly observable)} = \frac{\text{The true brightness of the star as estimated from its time period of brightness variability}}{4 \times \pi \times (\text{distance to the star, the quantity to be estimated})^2}$$

This relationship also allows us to estimate our distance to the galaxy in which the explosion is happening. Type Ia supernovae thus serve as standard candles — a term used by physicists to talk about objects with the same inherent brightness.

Box 4. Estimation of the velocity with which galaxies are receding from us:

We live in an expanding universe. This startling realization came from the observation that (most, if not all) galaxies are moving away from each other. We also know that the further away a galaxy is from us, the faster the rate at which it tends to move away from us.

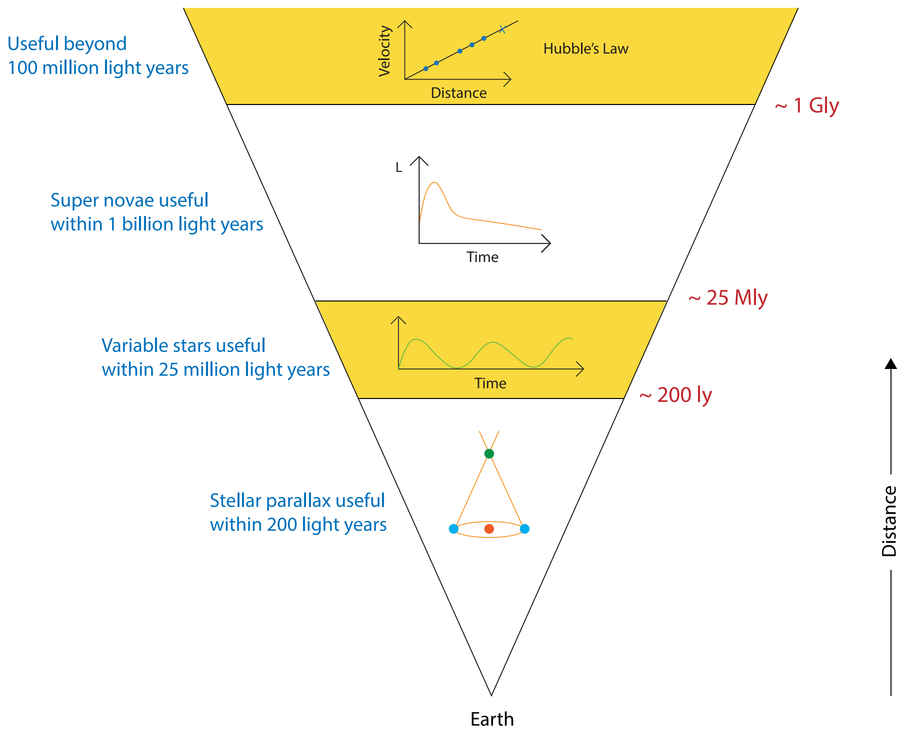
Thus, the distance to a galaxy can be estimated by recording the light from it as a spectrum. This spectrum reveals the velocity of the galaxy relative to the Milky Way (the vertical axis in the graph). We can establish the galaxy's distance from us (the horizontal axis in the graph) based on this correlation.



This relationship can be expressed mathematically as:

$$\text{How bright the star appears in the sky (directly observable)} = \frac{\text{The true brightness of the star as estimated from its time period of brightness variability}}{4 \times \pi \times (\text{distance to the star, the quantity to be estimated})^2}$$

This technique is most often used to find distances to galaxies >100 million light-years away from us, a distance scale at which the expansion of the universe becomes evident.



A simplified version of the cosmic distance ladder.

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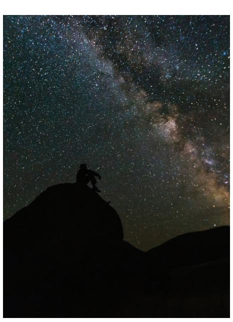
To conclude

The universe is vast and every technique to measure distances to objects in space is suited to an optimal range. Some techniques work well for the estimation of distances to objects that are very close to us, while others work best for objects that are far away. This range is captured in a sequence that astronomers often refer to as the **cosmic distance ladder.**

Techniques to estimate distances in space may help answer some of our most foundational questions about the universe. For e.g., we estimate the current age of the universe to be around 13.8 billion years. How do we know if this is true? Can we see the universe in its early stages? We can, at present, measure distances to galaxies that are >100 million light-years away from us. This means that we can see these galaxies as they were more than 100 million years ago. Will we one day be able to see even further back into our past than that? Only time will tell.

Key takeaways



- Much of our knowledge of astronomy is based on our ability to measure distances in space.
- Distances in space can be measured from the earth in multiple ways:
  - Using images of the same star, taken six months apart to estimate parallax shift.
  - Measuring how long it takes for the brightness of a variable star to change to determine the star's luminosity and, thereby, its distance from us.
  - Measuring the brightness of Type Ia supernovae – the greater their brightness, the closer the star, and vice versa.
  - By determining the velocity with which a galaxy moves away from our own through a shift in its spectrum.
- Determining distances in astronomy can help us understand how stars, star clusters, nebulae, galaxies are distributed in space; how bright they truly are as opposed to how bright they appear to be; and answer foundational questions such as the age of the universe.

Anand Narayanan teaches astrophysics at the Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram. His research is on understanding how baryonic matter is distributed outside of galaxies at large scales. He regularly contributes to astronomy-related educational and public outreach activities. Every so often he likes to travel, exploring the cultural history of South India.