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6 min read

How do we measure distances across the universe? | Explained

The Pillars of Creation structure in the Eagle Nebula 6,500-7,000 lightyears away, as imaged by the James Webb Space Telescope, November 30, 2022. | Photo Credit: NASA, ESA, CSA, STScI

Ask any elementary schooler reared on YouTube and they will tell you that the edge of the observable universe is 46.5 billion light years away. But have you ever wondered *how* we know this?

Come to think of it, how do we even know the distance to our nearest galaxy Andromeda (2.5 million lightyears)? Or for that matter how far out the stars in our own Milky Way are. After all, no human probe has travelled much beyond the Solar System.

There is a set of special tape measures that astronomers use to judge the extent of the sky. To make sense of them, we first need to get the hang of the scales involved.

Let's consider the distance from the earth to Pluto, about 5 billion km, to be as long as your fingernail. This will be our base unit, and we will discuss cosmic distances in terms of this "fingernail scale". For example, in this model, the star Proxima Centauri – which is 4.2 lightyears away – will be a walk to your neighbour's house across the road.

Cosmic distances

Roughly speaking, scientists can *directly* measure the distances to nearby celestial objects and *indirectly* measure those to faraway bodies, the latter thanks to something we know about these bodies.

The clearest illustration of a direct measurement is the use of parallax. We perceive depth in vision because we have two eyes. Similarly, if two telescopes watch a star, scientists can estimate its farness with simple geometry. The more the telescopes are separated, the farther they can together 'see'.

In practice, instead of two telescopes, we often use just one telescope and observe a star with it from two well-separated points.

The distances to most stars are measured just this way, with widely separated viewpoints (provided for free by the earth's motion around the sun). Thus, by simply knowing the distance between the earth and the sun and observing the same star from either side of the sun, we will have precise distances to stars that are closer than tens of thousands of light years away. In our "fingernail scale", that's how far Benguluru is from Chennai.

(How do we know the earth-sun separation? Distances between Solar System bodies are measured with radar and the transmissions from interplanetary spacecraft.)

Standard candles

The aforementioned parallax method is limited by the resolution of the cameras on the telescope, quite like how, to our own vision, objects too far away appear to be blurred. The best data have come from the Hipparcos satellite and the Hubble Space Telescope. The newer Gaia satellite has better resolution and is expected to map many more stars.

To measure the distance to a galaxy further away, we need a reference body in that galaxy. The most well-known class of such bodies is what astronomer Henrietta Leavitt called standard candles.

On a clear night, a sailor at sea can gauge the distance to the coast by how faint a familiar lighthouse lamp is. Similarly, an astronomer can gauge the distance to a galaxy by looking for a type of resident star that periodically pulsates in brightness, called a Cepheid variable.

In 1908, Leavitt noticed a strong relationship between the rate of pulsation and the true brightness of a Cepheid variable. So the brightness of a Cepheid variable as seen from the earth can produce an estimate of the distance to its parent galaxy, since the apparent brightness of an object falls as the inverse of the square of the distance.

This method is good for objects up to 100 million lightyears away – or more than twice the distance to the moon on our “fingernail scale”.

The most well-known standard candle is the Type Ia supernova, an explosion that occurs when a white-dwarf star accumulates interstellar material and exceeds the maximum mass at which it can support its own gravity.

Astrophysicists understand these explosions well. In particular, by studying how the intensity of a Type Ia supernova evolves in real time, they can calculate its true brightness. So as with Cepheid variables, their apparent brightness in the sky can indicate how far away the explosion was. This method reaches up to 11 billion lightyears, or the earth-sun distance in our scale.

Cosmic distance ladder

Eleven billion lightyears is a great distance. In the 1990s, astronomer teams made unprecedented measurements of the speeds with which faraway galaxies are receding from us. The leaders of these teams won the 2011 Nobel Prize in physics because their work established a remarkable fact: our universe’s expansion is accelerating.

One fortunate detail about standard candles is crucial to establish these colossal distances. To fix the true brightness of Cepheid variables, astronomers first use parallax measurements of Cepheids within the Milky Way. Using this, they infer the true brightness of Type Ia supernovae outside our galaxy from their parent galaxies that also harbour Cepheid variables.

That is, obtaining smaller distances in turn helps determine longer ones, with each technique helping to make up the rungs of a cosmic distance ladder.

Since 2016, astronomers have also been dealing with the idea of standard sirens. These are black holes or neutron stars in a paired system that merge and emit powerful ripples in spacetime called gravitational waves. On the earth, the LIGO and Virgo detectors detect them.

By studying the waves' shapes, scientists can reconstruct the masses and separation of the colliding bodies, and from there the power emitted in the waves. By comparing this with their power as recorded on the earth, and once again using the fact that the apparent power falls as the inverse of the square of the distance, they can estimate how far the source was.

This method also reaches out to the earth-sun distance in the fingernail scale, and can thus be used to estimate how fast the universe is expanding.

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