GRESHAM

COLLEGE

HOW BIG IS SPACE?

A Lecture by

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When you're out at night with an astronomer, you'll hear statements like 'that planet is 500 million miles away', or 'that star is 1800 light years from Earth.' Yet all the stars and planets look just like points of light stuck to the inside of a big dome. How can astronomers measure their distances, and how do they cope with the enormous numbers involved? After all, Concorde takes us to Australia in half a day, but it would take three million years to reach even the nearest star.

The important thing is not to get fazed. And the astronomers' method of measuring distances in the Universe helps us feel at home even with the largest distances. They have perfected a method of pushing out in gradual steps, each building on the one before. This 'ladder of distances' can take us from the Earth to the farthest quasars in the Universe.

So let's begin right at home. We all use a ruler or tape measure without a second thought, and these are calibrated by 'standards of length', such as the engraved brass plate outside the Old Royal Observatory in Greenwich (though the British yard is now defined in terms of the metre, which is based on measurements of the vibrations of atoms!). But if we buy a house, the estate agent doesn't measure up the rooms with a tape measure any more. He or she puts a small box to one wall, presses a button, and reads off the size. This device is an infrared laser, which bounces a beam of radiation off the far end of the room and measures how long it takes to return. Divide by the speed of the radiation (which is the same as the speed of light) and divide by two (to allow for the round trip) and - hey presto - you have the length of the room

Astronomers use precisely this method to measure the distance to our nearest neighbour in space, the Moon. They have been helped by the Apollo missions of 1969-72: each visiting astrononaut crew left a set of reflectors, designed to reflect light back exactly the way it has come. Again there is a familiar example of this technology: the reflectors on the back of a car.

Powerful lasers shoot light towards the Moon. After reflection, it arrives back at a telescope attached to the laser about two and a half seconds later. By measuring this time extremely accurately, astronomers can tell the distance to the Moon with almost unbelievable accuracy: to within a couple of inches, at a distance of quarter of a million miles. And they have confirmed a theoretical prediction that the Moon is gradually moving away from the Earth, at a rate of just over an inch per year.

The next step outwards is to find the distance of the Sun from the Earth - a distance so fundamental that astronomers dignify it with the name 'the Astronomical Unit'. We can't bounce a laser beam off the brilliant Sun and expect to see the faint reflection, so astronomers turn to another kind of radiation. From huge radio telescopes around the world, they can despatch radio waves - also travelling at the speed of light - and wait to receive a faint radio echo. It's exactly the same as the radar systems used to detect aircraft around airports, but naturally on a much bigger scale.

Although astronomers have 'radar-ranged' the Sun, the answers they've got are not very useful. The radio waves are reflected not from the sharp edge of the Sun that we see at visible wavelengths, but from layers in its outer atmosphere, and the location of the reflecting layer is always changing.

So a more subtle approach is needed. Here we call on the fact that the Earth is not alone circling the Sun. As the other planets move in its gravitational field, they all obey certain 'laws'. Of particular importance to this talk is Kepler's Third Law, which states that the time taken for a planet to orbit the Sun depends on its distance. Mathematically, $P^2=a^3$, where P is the period (in years) and a is the distance from the Sun (in astronomical units).

Astronomers can easily measure the time it takes each planet to orbit the Sun, and so we can use Kepler's law to build a scale model of the Solar System. For example, Venus orbits the Sun in 224.7 days. From Kepler's law, we can then calculate that its orbit is 0.723 AU in radius. At its closest to Earth, Venus is therefore 0.277 AU away. Now, if we can measure the actual distance to Venus at its closest, in miles or kilometres, then we can equate that to 0.277 AU, and easily work out what 1 AU is.

This is where interplanetary radar really comes into its own. Venus has a rocky surface that reflects radio waves well, so the distance to this planet can be measured with high precision. Radio waves take about four minutes to make the round trip. Plugging the exact value into Kepler's law, astronomers have found that the Astronomical Unit is 149,597,870 kilometres (92,955,730 miles) - another astoundingly accurate result.

Moving out the edges of the Solar System, we now have two tools to use. Radar can reach out as far as Saturn: this planet itself is made of gas and doesn't reflect radio waves, but its famous rings are composed of billions of chunks of solid ice, and astronomers have successfully radar-ranged Saturn's rings. This planet is so far away that - even travelling at the speed of light - the radio waves take three hours to get there and back. For Uranus, Neptune, Pluto and other objects out here, we can use Kepler's law the other way round - now that we know the value of the Astronomical Unit - working from their period of revolution to the distance. This takes us almost four billion miles from home.

But even the nearest star is thousands of times further away. Astronomers now turn to another method - but one that relies on the previous rung of the ladder, the measurement of the Astronomical Unit.

The method of *parallax* involves carefully measuring the position of a nearby star against the background of distant stars. As the Earth moves round its orbit, say from January to July, our viewpoint changes, and the nearby star seems to shift in the opposite direction. Here's a simple experiment. Hold a finger in front of your face, to represent the star. View it with each eye in turn, representing the Earth's positions at opposite side of its orbit, and you'll see the finger/star seem to jump from side to side.

In the case of astronomical parallax, the shift is of course much smaller, about the diameter of a 1p coin seen at a distance of several miles!

In addition, telescopes on the Earth have a blurred view of the sky as they observe through the Earth's shifting atmosphere. It's like performing the finger-parallax experiment when you suffer from acute short-sightedness. Now, however, a satellite called Hipparcos (high-precision parallax collecting satellite) is observing from above the atmosphere, seeing the stars in crisp focus, and when its data collection is complete in a couple of years astronomers will know the distances to 100,000 stars with unprecedented accuracy.

The nearest star, Proxima Centauri, turns out to be some 25 million million miles away. That's a huge distance, but it *is* comprehensible. The trick is to use a different unit of measurement. If you were travelling across the USA, you wouldn't measure the distance from Los Angeles to Albuquerque in inches, but in miles. Similarly, astronomers find the mile (or kilometre) far too small. Instead, we can use the *light year*.

Despite its name, this is not a unit of time, but of length. It's the distance that light travels in one year - around 6 million million miles. So we can say Proxima Centauri is just over four light years away. For comparison, the whole Milky Way Galaxy in which we live is 100,000 light years across - a figure which is big, but still comprehensible.

Even Hipparcos, however, takes us only part-way out into the Milky Way Galaxy - just 1000 light years. How do we get further? Astronomers turn to a method which - in various guises - takes us up several more rungs. It's called the *standard candle* method. If you find two objects you know shine with the same brightness, but appear to be different, then the fainter one must lie further away - and from its relative faintness, you can calculate how much further off it is.

The first use of this method involves star clusters, for example the lovely pair in Taurus, the Hyades and the Pleiades (the Seven Sisters). The Hyades is the nearest of all star clusters, and parallax measurements put it at 149 light years. (There's another way of measuring the distance to the Hyades, called the *moving cluster method*, but I won't describe it as it will be overtaken shortly by Hipparcos's extremely accurate parallaxes.) The Pleiades are clearly further off.

If we find a star of a particular colour (indicating its temperature) in the Hyades, and compare it with a star of the same colour in the Pleiades, we find that the latter is naturally fainter. Astronomers refine this method by plotting a graph of the brightnesses of stars against their colour. The stars in the Hyades fall along a narrow band, called the main sequence (the reason for this would be a whole talk in itself!).

The graph of the Pleiades has a similar main sequence, running parallel but consistently fainter. If we put the two graphs together, we can slide the Pleiades graph upwards to fit the Hyades: the amount of sliding shows how much fainter the Pleiades are. Instead of comparing just one star at a time, this *main sequence fitting* gives us a way of matching up dozens of stars at once, providing an instant average of them all.

Main sequence fitting shows that the Pleiades are 410 light years off. The method can be used for any cluster in our Galaxy, out to distances of literally thousands of light years.

As we measure more star distances by parallax or main sequence fitting, we can add them to one 'master graph' of brightness against temperature, a so-called Hertzsprung-Russell diagram. Running across this graph is the main sequence, with a few oddities scattered elsewhere, such as red giants and white dwarfs.

This master graph is the key to measuring the distance to any star. First, check the star's colour - say, white (meaning it's shining at a temperature of 10,000 C). Then break its light into a spectrum, and look for telltale signs as to whether it's a white main sequence star, or possibly a white giant or a white dwarf. We can now pinpoint the star's position on the Hertzsprung-Russell diagram. Each position corresponds to a different luminosity: from the master graph we can read off how bright the star really is. Then we compare that with the star's apparent brightness in the sky to work out how far away it lies.

This immensely powerful method means we can find the distance to any star in the Milky Way, and even in neighbouring galaxies, such as the Large Magellanic Cloud, some 170,000 light years off.

To penetrate to further galaxies, we need a really brilliant kind of star, visible at immense distances, and with some characteristics that indicate it is a standard candle. Fortunately, nature has provided such a beast, a rare kind of variable star called *Cepheid variables.* These stars change in brightness over a period in the range of a few days to three months: the quickest are the faintest while the slowest are the brightest. Astronomers have found Cepheids in some of the Milky Way's star clusters, with known distances, so we can calculate the actual brightness of Cepheids with different periods. They range from 1,000 to 100,000 times the Sun's brightness.

The next step in the distance ladder is to pick out Cepheid variables in other galaxies. These standard candles tell us, for example, that the nearest spiral galaxy, Andromeda, is 2.2 million light years away. The light we see from Andromeda today left that galaxy when humans were just beginning to tread the Earth.

Astronomers have devised a number of ingenious steps to build outwards from nearby galaxies like Andromeda to greater distances. For example, we can use radio telescopes to measure the rate at which a galaxy is rotating. It turns out that spiral galaxies rotating at the same speed have the same luminosity, and this *Tully-Fisher* relation (named for the American astronomers who discovered it) gives us a new standard candle - whole spiral galaxies.

But I won't dwell too much on these methods, because the sharp eye of the Hubble Space Telescope is now seeking out Cepheid variables in more remote galaxies, out to almost 100 million light years. In a couple of years, it will provide a much more reliable step outwards.

Within this region of space lie several clusters of galaxies (our Milky Way, along with Andromeda and the Large Magellanic Cloud form part of a cluster called the Local Group). The biggest clusters often contain one huge central galaxy, a cannibal that has grown fat by literally swallowing up smaller galaxies around. These are the largest and brightest galaxies. By using them as standard candles, astronomers can penetrate to the furthest distances we can see galaxies in the Universe - almost 10,000 million light years.

But there's one further tool in the astronomical armoury. In the 1920s, Edwin Hubble spread out the light from galaxies into a spectrum (like a rainbow). Each was crossed by dark lines where particular atoms absorb light. To Hubble's surprise, these lines were moved towards to the red end of the spectrum, when compared to the position as measure in the lab on Earth (or in stars of the Milky Way). And the more distant the galaxy was, the greater the *redshift*. Mathematically, we can say that the redshift is proportional to the distance.

Hubble concluded that the wavelengths of light from galaxies are being stretched as they rush away from us. The redshift indicated the Universe was expanding - and that's still the interpretation today.

Regardless of the cause of the redshift, however, it provides a powerful tool for finding distances to the remotest objects in the Universe. By measuring the redshift of galaxies with a known distance, astronomers can establish exactly how to convert a redshift to a distance (it involves multiplying by a number called the Hubble Constant). For example, when the first quasar was discovered in the 1962, there was no obvious way to measure its distance. Its light, however, turned out to be redshifted by an enormous amount, indicating it lay 2000 million light years away.

But what of the title of this lecture? How big *is* space? The answer is, probably, 'bigger than we can ever measure'. We can see quasars (and the occasional galaxy) out to a distance of almost 15,000 million light years. This is the *observable Universe*: it's limited by the faintness of light coming from such distances, and also because the light from any further galaxies has not had time to reach us since the time of the Big Bang, some 15,000 million years ago. The actual Universe may be millions of times bigger still: it may even be infinite.

With their diverse arsenal of methods, astronomers are now beginning to plot the distribution of millions of galaxies in a three-dimensional map of the entire observable Universe. When we combine the distribution of the galaxies with the rate at the Universe is expanding, we can begin to understand not just its 'geography', but the 'history' of the Universe, from the Big Bang to an ultimate fate that is still uncertain. But that's the cue for another talk!

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