The following was originally an assignment for the course PHYS08039: Discovering Astronomy at the University of Edinburgh, fall 2012. It received a mark of 73, equivalent to an A.

The Cosmic Distance Ladder

Prompt: Imagine you work for a government department, and the minister wants a briefing on what we know about the size of the universe. Assume that the minister has good scientific training but happens to know very little about this particular subject. Write a short technical report (no more than 2-3 sides of A4) on the astronomical distance scale to provide such a briefing. Describe very briefly in turn how we know the distance of planets, of stars, and of galaxies, and then explain the current debate on the expansion rate of the universe, and its size and age. You may include diagrams (but dont go beyond 4 sides of A4).

The tools and practices of astronomical measurement have come a long way since the Greek philosopher Anaxagoras declared the sun to be comparable in size to the Peloponnese. Today, we know the distances and sizes of objects out to several billion light-years from Earth with reasonable confidence, and have taken images of galaxies that formed over 13 billion years ago. It is only within the last few centuries that we have been able to obtain accurate measurements of astronomical scales, and only within the last century that we have been able to measure beyond our own galaxy at all.

One of the most historically useful ways to measure distances is that of parallax, which has many applications in astronomy and other disciplines as well. Parallax describes the apparent change in location an object experiences against a fixed background when observed from two different points; for example, if one holds a finger up to one's face and blinks each eye in succession, the finger will appear to move. If the distance between the two observing points is known and the angle between the two places the object appears at is measured, then one can use simple trigonometry to determine the distance to the object.

Planetary distances can be measured with parallax, although not in quite the same way as stellar parallaxes, as in the half a year it takes for the earth to travel between the extremes of its orbit, the planet one is trying to observe will move significantly as well. In the eighteenth century, the distance to Venus was calculated with reasonable accuracy for the first time when observations were made from Tahiti, Canada, and several locations in Europe of a transit of Venus (a phenomenon last seen in June 2012, when Venus and Earth's orbits align such that Venus appears to pass in front of the sun). The observation points on Earth were far enough apart that Venus appeared at slightly different points on the sun, and from this parallax measurement astronomers were able to determine the distance to Venus, and thus the rest of the known planets and the sun, using Kepler's laws of orbital motion.

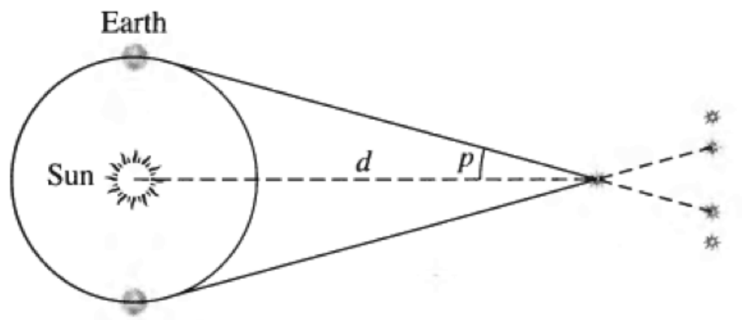

Figure 1: A visual explanation of stellar parallax, where the distance d is found using the observed parallax angle p and the known distance between the two extremes of Earth's orbit. Image: *An Introduction to Modern Astrophysics*, Carroll & Ostlie, p. 58, 2ed.

Stellar parallaxes are taken as pictured above. Parallax angles for extrasolar objects are measured in arcseconds (1 arcsecond, denoted $1''$, is 1/3600 of a degree), and the distance to an object with a parallax angle of 1 is defined as one parsec, or about 3.26 light-years (3.09×10^{16} m). The nearest star to the sun, Proxima Centauri, is about 1.29 parsecs away.

Parallax is only effective out to a certain point: beyond a distance of approximately a thousand parsecs, the parallax angle grows too small to measure. For objects within the outer reaches of the Milky Way and in nearby galaxies, objects called standard candles are the most effective distance indicator. Standard candles are categories of stellar bodies that have known brightnesses, such as Cepheid variable stars and Type Ia supernovae. If a standard candle is detected, astronomers can use the distance modulus, a relation between apparent and absolute magnitude, to find its distance. Apparent and absolute magnitude are two measures of a body's brightness, the former being the brightness as seen from earth and the latter of its brightness as seen from a distance of 10 kiloparsecs. Given that all standard candles of any given type have the same absolute magnitude, their distances are easy to determine once their magnitude from Earth is measured. There is some debate as to whether Type Ia supernovae all have exactly the same magnitude, and many distance calculations had to be reworked when it was found that there were two types of Cepheids, one of which was much brighter than the other, but on the whole they are excellent scale indicators. With current technology Cepheids are observable out to about 10^7 light-years, encompassing the supercluster of galaxies in which the Milky Way resides, and Type Ia supernovae are observable out to almost 10^9 light-years, well beyond the local supercluster.

Beyond the Milky Way and local galaxy clusters, still more measurement techniques are required. When parallax and standard candles fail, a galaxy's redshift is the best indicator of its distance, according to Hubble's Law. Redshift occurs when an object is moving away from an observer, and thus according to the Doppler effect the light from the object takes on a longer wavelength relative to the observer (i.e. it is shifted towards the redder end of the electromagnetic spectrum). Galactic redshift is calculated by taking a galaxy's spectra, which indicates the wavelengths of the light it emits. Spectra are dependent on atomic energy levels, and since galaxies are overwhelmingly composed of hydrogen, we know what set of wavelengths to expect from a hydrogen body that is at rest. The amount the observed wavelengths are shifted from the known rest wavelengths determines the redshift, and Hubble's Law states that the larger the redshift, the more distant the galaxy, in accordance with the relation $v = H_0 D$ where v is the velocity in kilometers per second, H_0 is Hubble's constant, and D is the distance in megaparsecs. H_0, despite being termed a constant, is not a fixed quantity, but time-dependent. Current measurements place it at approximately 74 kilometers per second per megaparsec; that is, for every megaparsec further from Earth an object is, its recessional velocity increases by 74 km/s at present. One can extrapolate from this to calculate the age and size of the universe; current estimates say the universe is approximately 13.7 billion years old, and the observable universe is about 46 billion light-years in radius.

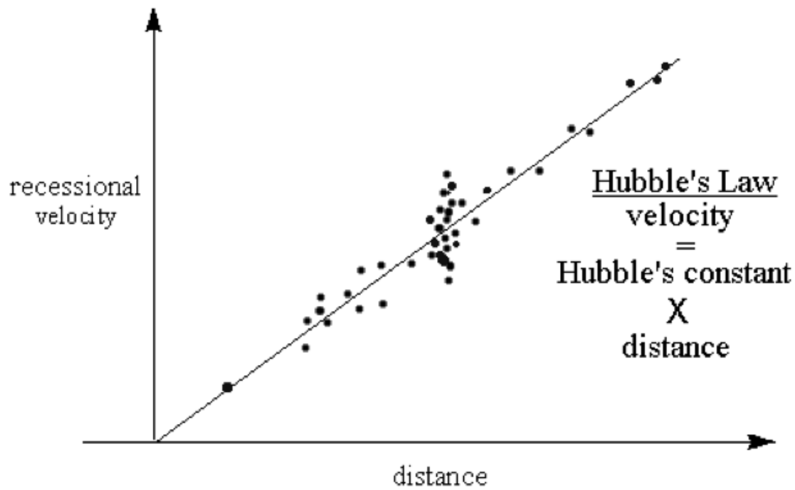

Figure 2: A plot of Hubble's Law as fitted to observational data; each dot represents a galaxy. Image: Cornell University.

It is somewhat misleading to say that these galaxies are moving away from us. Rather, space itself is expanding at every point in the universe and carrying the galaxies with it; there is nothing special or central about the Milky Way's location. All galaxies are moving away from each other roughly equally on large enough scales. The current evidence suggests that not only is the universe expanding, it is accelerating in that expansion. There is no concretely observed property of the universe that can readily account for this, which has led astronomers to hypothesize the existence of dark energy, a kind of energy that causes a net outward pressure on space and accelerates expansion. The problem with any hypothesis about what exactly constitutes dark energy is that it is extremely difficult to experimentally or observationally verify, given that dark energy is essentially an ad hoc construction to explain a phenomenon that defies explanation by known physical properties or laws. Current cosmology suggests that whatever dark energy may be, it will continue to push the universe outwards indefinitely, and that the universe does not have enough self-gravity to reverse the expansion.

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