Distance Ladder

1. Basics & Nomenclature

Determination of distance is a fundamental problem in astronomy, to which is owed numerous breakthroughs. The distance to nearby galaxies has been established through a calibrated *distance ladder*, refined over the past century.

The distance ladder begins with the measurement of *parallax*, which is the apparent motion of sufficiently nearby stars due to the motion of the Earth around the Sun. Precise measurements of stars over time in a fixed reference frame yield *proper motions* and parallax-based distances. Most recently, the Gaia satellite has provided a large sample of stars with measured parallaxes reaching across our Galaxy.

To reach distances outside our galaxy, we must rely on less direct measurements of distance. Usually this involves finding objects or phenomena that have pairs of observables with a known relation but with different dependences on distance.

Many of these techniques fall into the *standard candle* category: a luminosity is estimated by some means, and a flux is measured, and the distance is inferred from the inverse-square law $f = L/4\pi D^2$. The most prominent standard candles are:

- *RR Lyrae* variable stars. These stars are relatively low mass horizontal branch stars. They vary due to the κ mechanism, which is an instability associated with the reaction of the atmospheric opacity to changes in pressure and density that causes oscillations in stellar size and luminosity. They have periods of order a day. They are prominent in globular clusters but can also be found throughout the Milky Way. Historically they have been most useful for determining distances within the Galaxy. However, the advent of Gaia and the James Webb Space Telescope opens up the possibility of observing these stars in nearby galaxies.

- *Cepheid* variable stars. These stars are high mass and luminous. They also vary due to the κ mechanism but have longer periods. Historically, they have provided one of the most direct links between local distance scales and distant galaxies.

- *Tip of the Red Giant Branch* stars. The red giant branch is commences when core hydrogen burning ends; at this point, shell hydrogen burning commences and the star becomes rapidly brighter and much larger. At a certain point the helium ash at the core ignites, moving the star to its next phase, the smaller and less luminous horizontal branch. The core ignites rapidly at a specific stage in evolution, so that at a given metallicity red giant stars all end this stage at the same luminosity. This leads to a rapid fall-off in the luminosity distribution of RGB stars and a clear tip of the red giant branch that can be used as a standard candle.

- *Type Ia supernovae.* These supernovae result from the nuclear detonation of white dwarfs,

probably due to accretion from or collision with a binary companion. The Phillips relation connects the time scale of the supernova light curve to the luminosity of the supernova. These sources were used to provide the first definitive evidence for the existence of cosmic acceleration.

Historically, a number of other distance measurements have also been used that could be categorized as standard candle distances. Some methods have relied on other supernova types. Other methods have generally capitalized on scaling relations of galaxies, such as the Tully-Fisher relation for spirals relating luminosity and circular velocity, and the Fundamental Plane for ellipticals relating luminosity, size, and velocity dispersion. The difficulty in implementing these methods in a way that is free of systematic errors generally has led to the use of supernovae for the most recent measurements of the distance ladder.

Several standard candle techniques prove useful, or may soon do so. I will discuss eclipsing binaries, masers, and gravitational waves:

- Some binary stars, like Algol, eclipse each other during their orbit. Their light curve alone yields a period P and their radii relative to the orbit size, r_1/a and r_2/a for any given eccentricity and phase of eclipse. If both their spectra can also be measured, this can yield velocities, which yields enough information to determine their total mass M, eccentricity e, and the line-of-sight semimajor axis of the orbit $a \sin i$. The mass and semimajor axis are related by:

$$M = \frac{4\pi^2 a^3}{GP^2}. \tag{1}$$

  For eclipsing binaries $i \approx 90°$. Thus, from gravitational and geometric considerations, you can determine the sizes of the stars. Spectra can yield constraints on their surface temperatures. The sizes and temperatures determines the luminosities, which combined with fluxes determines the distance.

- Under certain conditions the supermassive black holes at the centers of galaxies may contain H_2O masers. Under even more special conditions, these systems can be sufficiently clean that one may measure velocities and accelerations over time of clouds in circular orbits, which yields a physical distance. Combined , this combination yields the mass of the black hole and the distance. Only one clean enough system is known, about 8 Mpc away in NGC 4258.

- Colliding compact objects whose gravitational waves are detected can yield constraints on distance from the gravitational waveform, because the total mass of the system is related to both the waveform frequency and the total energy. If the redshift is known from an electromagnetic counterpart, then the rest-frame waveform frequency can be determined, and the object can be placed on the redshift-distance relation.

A major application of these methods is to compare the redshifts and distances of local galaxies.

This comparison led Hubble to the Hubble Law:

$$v = H_0 d \tag{2}$$

where v is velocity, H_0 is the Hubble constant, and d is the distance. Gravitational attraction causes galaxies to move toward each other with respect to this flow, with *peculiar velocities* of 100s of km s^{-1}. For example, M31 is moving toward us at 400 km s^{-1}, and large clusters, such as Virgo and Coma, have internal motions and thus peculiar velocities of 1000s of km s^{-1}. Thus, determinations of the Hubble constant need to use galaxies sufficiently far to reduce this effect. Alternatively, they need to estimate and correct for these peculiar velocities, using the density field of galaxies itself to estimate the magnitudes and directions of the expected velocities.

The Hubble Law is a fundamental measurement of the nature of the

universe we are in, but it also is a tool to map the universe on larger scales, since measuring Doppler shifts is relatively easy compared to galactic distances.

2. Commentary

Briefly, the most precise current estimates of the local Hubble constant come from the Riess et al. (2016) group. These use a number of Milky Way Cepheids with parallax distances, along with eclipsing binaries and NGC 4258, to anchor extragalactic Cepheids in galaxies with SNe Ia, and use those to anchor a much larger SN Ia data set. As of 2018, the results for H_0 from these analyses tend to be considerably higher (several sigma) than those inferred from cosmic microwave background and large scale structure measurements, using standard cosmological models to extrapolate to $z = 0$. The cause of this discrepancy is not known.

The current ladder to a precise H_0 is strongly dependent on the Cepheid step. There are several important issues with the interpretation of the Cepheid distance scale, the most prominent of which is that the period-luminosity relation is metallicity dependent. The LMC has a much lower metallicity than the other galaxies in the analysis, and so if improperly modelled the metallicity dependence can cause a bias.

Beaton et al. (2016) present an alternative path using different indicators (RR Lyrae and TRGB) to calibrate the SN Ia, both of which tend to trace an older, more metal poor population even within metal rich galaxies. This path may soon become competitive. This second indepedent measurement will be critical in assessing the existing discrepancy.

The detection of much more distant masing systems suitable for an analysis similar to that of NGC 4258, or a sufficient number of gravitational wave sources, could provide a "one step" alternative to the distance ladder for the purpose of determining the cosmological constant.

3. Key References

- *A 2.4% Determination of the Local Value of the Hubble Constant*, Riess et al. (2016)

- *The Carnegie-Chicago Hubble Program. I. An Independent Approach to the Extragalactic Distance Scale Using Only Population II Distance Indicators*, Beaton et al. (2016)

4. Order-of-magnitude Exercises

1. Estimate age of the universe from the Hubble constant assuming constant expansion.

2. What is the maximum parallax at 1 pc, 10 pc, 1 kpc, and 1 Mpc? Assuming you can get good positions to with a few hundredths of a FWHM, what size telescopes do you need so that you can measure parallax at these distances?

3. If the typical peculiar velocity of a galaxy is ~ 300 km s^{-1}, at what redshift does its contribution to the distance error drop below 5%?

4. Based on their luminosities, what are the relative distances to which you should be able to determine distances to RR Lyrae, TRGB stars, Cepheids, and SN Type Ia?

5. Numerics and Data Exercises

1. Allen Sandage used to use brightest galaxies in clusters as a standard candle. Download redmapper, a modern catalog of galaxy clusters from SDSS. Select the brightest cluster galaxies for massive clusters. Based on looking at these galaxies within a narrow range of redshift, are they reasonable standard candles? Show a Hubble diagram assuming that they are and compare to a standard Planck cosmology.

2. Clementini et al. (2018) publish a catalog of RR Lyrae variables from Gaia DR2. Use that RR Lyrae stars in that catalog to estimate the ratio of the distance from us of the Sculptor dwarf galaxy to the Messier 62 globular cluuster.

REFERENCES

Beaton, R. L., Freedman, W. L., Madore, B. F., et al. 2016, ApJ, 832, 210

Clementini, G., Ripepi, V., Molinaro, R., et al. 2018, ArXiv e-prints, arXiv:1805.02079

Riess, A. G., Macri, L. M., Hoffmann, S. L., et al. 2016, ApJ, 826, 56

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