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.

- *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 on the horizon may prove useful in the coming years. I will discuss masers and gravitational waves:

- Under certain conditions the supermassive black holes at the centers of galaxies may contain H_2O masers. Under certain conditions, these systems can be sufficiently clean that one may measure angular velocities of circular orbits and angular sizes, which yields a period. Combined with a Doppler velocity, 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:

$$v = H_0 d \tag{1}$$

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 best current estimates of the local Hubble constant come from the Riess et al. papers. These use a number of Milky Way Cepheids with parallax distances 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.

3. Key References

- *Riess et al*
- *Kitchin*

Gunn et al. (2006)

4. Order-of-magnitude Exercises

1. Typical parallax at 1pc, 10pc, 1kpc, 1 Mpc; diffraction limit necessary to determine them.
2. Translation between error of individual object to error in Hubble
3. Estimate age of the universe from the Hubble constant

5. Analytic Exercises

1. Something about the masers?

6. Numerics and Data Exercises

1.

REFERENCES

Gunn, J. E., et al. 2006, AJ, 131, 2332

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