4 Observational Parameters

In order to determine the correct model of the Universe we need to know some key parameters from observations since the Big Bang model does not provide a unique description of the Universe.

4.1 The expansion rate H_0

H_0 gives us the present expansion rate of the Universe. Observationally, it is determined from $v = H_0 r$. The velocity is measured from the spectral redshift and is easy to measure accurately.

BUT galaxies have peculiar velocities (random) so we need to use galaxies at large distances so that the uniform expansion dominates.

e.g. v of Virgo cluster at 16 Mpc is 1100 $\mathrm{km\,s^{-1}}$ but peculiar velocities attain 600 $\mathrm{km\,s^{-1}}$.
v of Coma cluster at 100 Mpc is 6900 $\mathrm{km\,s^{-1}}$ so at this distance, the Hubble flow can be reliably measured and H_0 determined BUT to do this we need to know the distance to the Coma cluster independently and this is not reliably known.

4.2 Distance determination

4.2.1 Parallax

The only direct means of measuring distance is through parallax. A star 1 pc away has a parallax of 1 arc sec. Closest star = 1.3 pc or $\pi = 1/r = 0''.77$. Turbulence in the atmosphere blurs apparent diameter of a star $\approx 1''$ so parallaxes can only be measured for stars up to 30 pc ($0''.03$) away or just a few thousand stars.

The Hipparcos satellite launched in 1989 extended the measurement of parallaxes out to 100 pc and led to some fundamental revisions in the distance scale. Parallaxes were measured for 118,000 stars.

4.2.2 Luminosity Distance

To measure distances beyond 100 pc we rely on using "standard candles" i.e. objects which have some special property so that their intrinsic brightness or luminosity, L is known.

Apparent brightness, $l = L/(4\pi d_L^2)$ where d_L is the luminosity distance and l can be easily measured.

4.3 The Distance Ladder

4.3.1 Primary Distance Indicators

1. RR Lyrae stars: low mass, evolved stars often found in globular clusters which pulsate with periods of few hours to one day. These stars are identified by their variability and periodicity – mean brightness is measured. All RR Lyrae stars have similar value of L.

RR Lyrae stars are intrinsically quite faint and can only be used to determine distances out to 150 kpc.

2. Cepheid variables: pulsating stars with higher mass than RR Lyrae stars – periods of 2–200 days and a well-determined relationship between P and L. Technique adopted is to identify a Cepheid variable and measure its period and mean brightness. The Cepheid P-L relation is then used to give L and hence d_L from the mean apparent brightness. From the ground, distances using Cepheids are limited to 4 Mpc. i.e. much farther away than RR Lyrae stars but still not out to the Virgo cluster of galaxies at 16 Mpc.

These two types of variable stars are known as primary distance indicators. By using various other methods of distance determination, the distance to the small satellite galaxy of the Milky Way, the Large Magellanic Cloud is known to be 50 kpc. The period-luminosity relation for Cepheids is then determined for Cepheids in the LMC (all at effectively the same distance). The LMC is the anchor point of the extragalactic distance scale and any uncertainties in its distance will directly affect all distance determinations.

Thus, if we detect a Cepheid in another galaxy – measure period and mean brightness, use P–L relationship $\Rightarrow$ distance to galaxy. Cepheids occupy the first step of distance ladder. Extending the distance scale > 4 Mpc requires more steps in the distance ladder via use of secondary distance indicators. Many have been developed – the two most important ones are summarised below.

4.3.2 Secondary Distance Indicators

Tully-Fisher Relation

Tully and Fisher (1977) discovered a relationship between the luminosity L of a spiral galaxy and its rotation velocity V_r such that $L \propto V_r^4$. Spiral galaxies have flat rotation curves (presence of dark matter) so V_r is fairly easy to measure as it is independent of galaxy radius. Distances have been determined for ~ 2000 spiral galaxies extending velocity/distance scale to 100 Mpc. There are large uncertainties in this method because the calibration rests on 5 galaxies with Cepheid distances, of which only two are luminous spirals (M31, M81). The reason for $L \propto V_r^4$ is not totally understood so the intrinsic scatter is not known.

Peak Luminosity of Type Ia Supernovae (SN)

Two types of SNe: (1) massive star ($> 8\,M_\odot$) – Type II and (2) Type Ia which occur in binary systems where one star is a white dwarf so mass $< 1.4\,M_\odot$. Companion star transfers material to W.D. which eventually takes it over the Chandrasekhar limit. W.D. becomes unstable and explodes. Because the mass of the W.D. is always 1.4 $M_\odot$, the absolute luminosity of Type Ia SN is always the same.

Distances can be measured using SN Ia's to ~ 400 Mpc. Many galaxies are observable at these distances and thus SNe are a common occurrence – find SN and monitor it $\rightarrow$ peak brightness + light curve to ascertain it is Type Ia. Also need a spectrum to measure the redshift.

BUT problem is the small number of calibrators – only two nearby galaxies with Cepheid distances have had SNe and there is considerable debate over whether these SNe were typical Type Ia's.

Overall, at large distances (> 20 Mpc) secondary calibrators give accurate relative distances and extend well into the region of the Hubble flow. The big problem is in turning these relative distances into absolute distances as the calibrators are so few – huge discrepancy in the distance scale between 4–20 Mpc depending on which method is used.

4.4 The value of H_0

In the early 1980's most measurements fell into two groups – those near $H_0 = 50$ and those near $H_0 = 100$ km s^{-1} Mpc^{-1} – largely due to two different groups using different calibrations to tie in the different steps in the distance ladder. Distances based on SN Ia gave values near 50 whereas distances based on the Tully-Fisher method gave values near 100.

One of the main goals of the Hubble Space Telescope (hence name – Hubble) is to determine H_0 to an accuracy of 10%. The aim is to use its superb imaging abilities to find Cepheids in galaxies out to a distance of 30 Mpc and to (a) determine the distance to Virgo without any intermediate steps, and (b) to obtain Cepheid distances for more galaxies that have had SN Ia explosions to provide more calibrators for secondary distance indicators. The goals of the HST key project are to (1) obtain primary distances to galaxies in the 3–30 Mpc range; (2) increase the number of calibrators from 5 to 30 for the Tully-Fisher relation; and (3) increase number of calibrators from 2 to 6 for the SN Ia relation.

The HST key project has now finished. They find that

$$\underline{H_0 = 72 \pm 8\ \mathrm{km\,s^{-1}\,Mpc^{-1}}} \qquad (1\sigma \text{ error})$$

BUT this value is entirely based on the Cepheid period-luminosity relation and the assumption that the distance of the LMC is 50 ± 3 kpc.

Other methods generally give H_0 values of 60–80 km s^{-1} Mpc^{-1}.

Because of the uncertainties in H_0, it is usually parameterised as

$$H_0 = 100\, h\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \qquad (4.1)$$

where h probably lies in the range 0.6-0.8. The smaller the value of h, the more slowly the Universe is expanding. The failure to obtain an accurate value of H_0 introduces many uncertainties in cosmology. Note that even though the value of H_0 is not well determined, the Hubble Law of expansion is extremely well determined.