

Chapter 18. The Expansion and Structure of the Universe

The Velocity-Distance Relation

In 1912 V.M. Slipher measured the first Doppler shift for a spiral galaxy, M31. By 1925 he had observed 41 galaxies, and found all but three exhibited redshifts in their spectra, implying that most galaxies are moving away from us except M31, M32, and M33.

Edwin Hubble measured distances for 24 galaxies within 2 Mpc, and found a velocity-distance relation: the farther away the galaxies are the faster they move away from us – *the Hubble relation or the Hubble law*.

At distances larger than $\sim 100\text{Mpc}$, the Hubble relation is plotted as redshift vs visual magnitude. The modern plots of redshift vs. magnitude show observational points along a straight line up to a redshift of $z = 0.5$. This relation applies to clusters in all directions, and indicates that *the Universe is expanding isotropically*. We are NOT at the center of expansion; there is no favored position in the expansion.

The Meaning of the Redshift

Clusters of galaxies are not expanding *into* space but *with* space, in a smooth motion called the *Hubble flow*. The redshift is not a Doppler shift. It is caused by the expansion of the coordinate space itself. For small z , the redshifts are good approximations of velocities. For large z , the relation between z and velocity depends on the exact spacetime curvature of the Universe.

The Hubble Constant

The Hubble Constant (H_0) is the slope of the velocity-distance plot. It is the rate of expansion of the Universe. Hubble found an H_0 of 500 km/s/Mpc based on many erroneous distances and velocities. The currently favored value of H_0 is 65 km/s/Mpc.

The Hubble constant is difficult to determine because the distance itself is difficult to measure and the gravitational motions of galaxy clusters can confuse the Hubble flow. For example, the Local Group cluster, belonging to the Virgo supercluster, is “falling” toward Virgo at 150-300 km/s. The Virgo supercluster is falling toward a *Great Attractor* at roughly 600 km/s.

The Big Bang and the Age of the Universe

The isotropic expansion of the Universe implies that the Universe was concentrated into a small volume and dispersed in a sudden event now called the *Big Bang*. The time elapse since the Big Bang is called the *Hubble time*, which has been adopted to approximate the age of the Universe (t_0). $t_0 = 1/H_0 = 978 \times 10^9/H_0$ yr.

For a Hubble constant $H_0 = 65$ km/s/Mpc, the age of the Universe is $t_0 = 15 \times 10^9$ yr. This is only an approximation of the age of the Universe; the exact age of the Universe depends on the exact nature of the spacetime.

The Distribution of Galaxies

Once the Hubble relation is established, we can use the Hubble constant to find distances. In other words, the redshift can be translated into distance – the larger the redshift, the larger

the distance, although the exact relation between distance and redshift depends on the spacetime curvature of the Universe.

In the nearby Universe, galaxies are seen to distribute in clusters. At large distances, galaxies and cluster of galaxies are mapped out to ~ 200 Mpc. Filaments, sheets, and voids are seen in these maps.

The Hubble Space Telescope took deep images of a field 2.5 minute of arc across. 1500 galaxies are detected in this field. These galaxies span a large range of redshift, with the farthest galaxies at 1-3 billion pc away. By examining galaxies at different z , it is possible to study the evolution of galaxies.

Quasars

In the 1950s and 1960s, radio surveys of the sky found many bright radio sources that appear to be blue stars with strange spectra. One of these “blue stars”, 3C273, shows a short streak of light next to the stellar image. In 1963, Maarten Schmidt recognized the regularly spaced hydrogen Blamer series in the spectrum of 3C273. A redshift of $z = 0.16$ was measured. Similarly large z was measured for other objects. It is then recognized that these radio-loud “blue stars” with large redshifts belong to a new class of objects – *quasars*, for “quasi-stellar radio sources”.

Optical surveys found many “blue stars” with large redshifts. These are the radio-quiet versions of quasars. Both radio-loud and radio-quiet cases have been included in a class called *QSOs*, for Quasi-Stellar Objects.

QSOs show light variations over 10 days, indicating that their sizes are ~ 10 light days, or no larger than the solar system. If their redshifts imply cosmological distances, then their luminosities could be as large as 10^4 times that of the Galaxy. It is curious how such a high luminosity can be generated in such a small volume.

The cosmological distances to QSOs are firmly established by the detection of Lyman α absorption. The hydrogen Ly α line of quasars usually show absorption components with smaller z , indicating absorption by intervening gas clouds (associated with galaxies). The quasar must be farther away than the absorbing gas clouds; thus, quasars must be at cosmological distances.

QSOs have been found in fuzzy patches of light that show spectra similar to those of galaxies, indicating that QSOs are extremely active nuclei of galaxies. QSOs are probably similar to active galaxies and contain a massive black hole in the center. The accretion of gas converts gravitational energy into other forms of energy, including radiation.

Gravitational Lenses

The light of a distant quasar may be bent by the gravitational field of a galaxy along the line of sight. The galaxy is called a *gravitational lens*. Clusters of galaxies can also act as gravitational lenses, providing a powerful tool to probe the distribution of matter in the Universe.