Lecture 3. Velocities in the Universe

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3.1. Peculiar velocities

Each object in the Universe moves with some peculiar velocity associated with the different scales of structure. This is the name given to the motion of a galaxy due to its rotation and motion as influenced by the gravitational pull of nearby clusters. For example, the Earth's equatorial rotation speed is 0.3 km/s, the escape speed from the Earth is 10 km/s, the speed of the Earth around the Sun is 30 kms/s, the speed of the Sun around the centre of the Galaxy is 250 km/s, disc stars also have random motions (i.e. a velocity dispersion) of around 20 km/s superposed on this general rotation and in elliptical galaxies the stellar velocities are of order 100 km/s but most of this is in random motion since there is little rotation.

Our Galaxy itself has a peculiar velocity of around 100 km/s relative to the Local Group; one can understand this as arising from the net gravitational pull of all the other members of the group. Within rich clusters galaxies may have velocity dispersions as high as 1000 km/s. The large-scale redshift surveys show that clusters and superclusters themselves have peculiar motions. For example, the Local Group and possibly the entire Virgo supercluster has a peculiar velocity of 600 km/s relative to the cosmic microwave background radiation which was mentioned in previous lectures and will be discussed in more detail in the next lecture.

In any gravitationally bound system the characteristic velocity V associated with a system of size R, mass M and average density $\rho \sim M/R^3$ in order of magnitude is determined from

$$V \sim a_{grav} \times \tau, \tag{1}$$

where the gravitational acceleration

$$a_{grav} \sim \frac{GM}{R^2}, \tag{2}$$

and τ is time scale

$$\tau \sim \frac{R}{V}, \tag{3}$$

hence

$$V \sim \frac{GM}{R^2} \times \frac{R}{V}, \text{ and } V \sim \sqrt{\frac{GM}{R}} \sim (G\rho R^2)^{1/2}. \tag{4}$$

These are only order-of-magnitude relations but they can be specified more precisely in any particular context. The quantities V and R can usually be measured observationally and a dark matter problem arises whenever the value of M or ρ exceeds the mass or density in visible form.

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If an object is not a member of a gravitationally bound system the previous arguments for estimating the peculiar velocity should be slightly modified: instead of time scale τ we should take the age of the Universe, t_{univ}: mass M at distance R induces acceleration, a_{grav}, but during the whole life of the Universe the gain of velocity after time equal to the age of the Universe is

$$v = \frac{GM}{R^2} t_{univ}. \tag{5}$$

This order of magnitude estimate neglects the expansion of the Universe (we assume that the distance R is nearly the same during time t_{univ}), however this is a good estimate, since the expansion reduces v only by small factor.

3.2. Hubble velocities

At the beginning of 20^{th} the idea that the universe was expanding was thought to be absurd. However, in 1929, Edwin Hubble announced that his observations of galaxies outside our own Milky Way showed that they were systematically moving away from us with a speed that was proportional to their distance from us (see Fig. 3.1.)

The more distant the galaxy, the faster it was receding from us. The universe was expanding! Hubble observed that the light from a given galaxy was shifted further toward the red end of the light spectrum the further that galaxy was from our galaxy (see Fig. 3.2.)

The specific form of Hubble's expansion law is important: the speed of recession is proportional to distance. This suggests a homogeneous, isotropic, and expanding universe.

Edwin Hubble was observing a group of objects known as spiral nebulae (spiral galaxies). These objects contain a very important class of stars known as Cepheid Variables. Because the Cepheids have a characteristic variation in brightness, Hubble could recognize these stars at great distances and then compare their observed luminosity to their known luminosity. This allowed him to compute the distance to the stars, since luminosity is inversely proportional to the square of the distance. The intrinsic, or absolute, luminosity is calculated from simple models that have been commensurate with observations of near Cepheids. When Hubble compared the distance of the Cepheids to their velocities (computed by the redshift of their spectrum) he found a simple linear relationship:

$$\vec{v} = H\vec{r}, \tag{6}$$

where $\vec{v}$ is the velocity of the galaxy, H is the so-called Hubble constant. It is clear that time scale of expansion, i.e. the age of the Universe is of order

$$t_{age} \sim \frac{|\vec{r}|}{|\vec{v}|} = H^{-1}. \tag{7}$$

We will see later that the Hubble constant is not actually a constant, but can be a function of time depending on the chosen model. The standard notation is to adopt H_0 as the 'current' observed Hubble parameter, whereas H = H(t) is referred to as the Hubble constant. At the begining the value of the Hubble parameter, obtained from the original Hubble's observation was to large and the age of the Universe was too short (shorter than the age of the Earth). As we now understand, this was related to some mistakes in determination of distances (see Fig. 3.3.)
The current accepted value of the Hubble parameter is

$$H_0 = 100 km s^{-1} Mpc^{-1} h_0, \tag{8}$$

where

$$h_0 \approx 0.7. \tag{9}$$

One factor which must be considered in calculation of the Hubble velocity field is the concept of peculiar velocity. The motion of any object in the Universe is a superposition of peculiar velocity and the velocity which is related to the expansion of the Universe.

$$V_{tot} = H_0 D + V_{pec}. \tag{10}$$

Peculiar velocities don't exceed 500 km s-1, and can be neglected at far distances where the Hubble velocity proportional to the distance

$$H_0 D >> 500 \text{ kms}^{-1}. \tag{11}$$

The Hubble velocity will only dominate on scales exceeding

$$D \approx V_{pec}/H_0 \approx 20 \div 40 \text{ Mpc}. \tag{12}$$