Program 11: Evolutionary Cosmology

Even if we ignore for a moment the discovery of cosmic expansion, Hubble's use of various distance indicators to demonstrate the extreme remoteness of some galaxies has mind-boggling implications. In the first place, light travels at a finite speed (~10^{13} km in a year) so that the light, which we receive now from a galaxy a billion years away, had to leave there a billion years ago. We see the galaxy now by light emitted then, so we see it as it was a billion years ago. The finite speed of light simply means that looking out in space is looking back in time. Under everyday circumstances in our tiny world, light seems to travel without delay, instantaneously; but obviously the speed of light is an important issue when considering cosmological distances. The following diagram shows how we can represent motion in general whether particles or bursts of radiation moving through space. The dashed line describes the motion of a burst of radiation. In time t', it travels a distance D_{light}, which is the largest distance that can be traversed in that time since no particle with mass nor any signal (no form of information) can travel faster than light does in a vacuum. A particle traveling at $v = 0.5c$ is also shown. It travels at half the distance of the light signal in the same time, t'. This is a two-dimensional spacetime diagram so only one space dimension can be shown-suppose that dimension is chosen as "up" from the surface of the earth at the location from which the motion is being observed. "Distance" then corresponds to "altitude". The third trajectory may represent a rifle bullet shot vertically, reaching a maximum altitude, and finally falling back to its starting point at time t'. Clearly the slope of a trajectory shown on this diagram corresponds to the speed of motion: the steeper the slope the slower the speed since a smaller distance is covered in a fixed time increment. Also, if the line slopes from lower left to upper right, motion is away from the observer because distance is then seen to increase with time. Conversely, if the line slopes from lower right to upper left, the motion is toward the observer. No slope is shallower than that corresponding to the speed of light; so all trajectories that intersect the origin of the graph (t=0, distance = 0) must always lie above the dashed line. Note that the observer defines the point from which distance is measured; thus, by definition, he "stands still" in the diagram. He moves only (and inexorably) along the time axis, a vertical trajectory in the diagram.

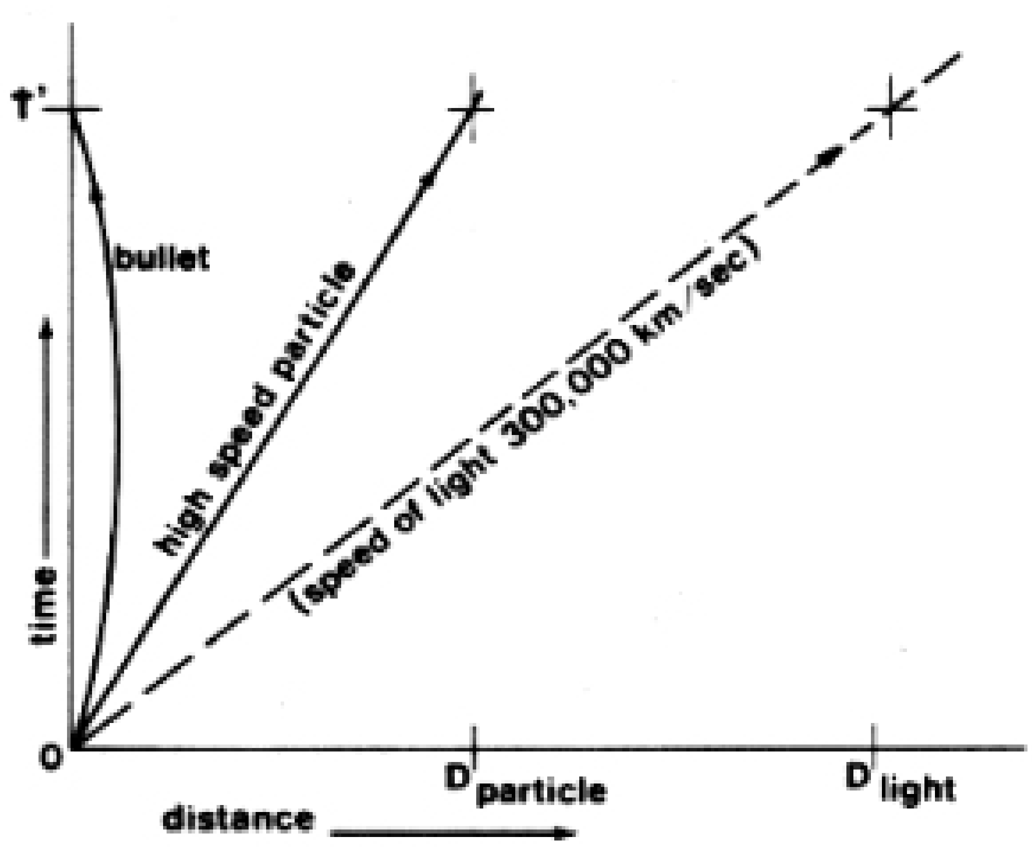

FIG. 11a

Using this kind of diagram, we can represent the history of motion of galaxies relative to us as observers, taking into account both the cosmic expansion and the finite speed of light. In this schematic representation only two galaxies are shown, one at 100 Mpc receding at 5000 km/sec. The other is twice as far away moving twice as fast. If we see these galaxies at the present moment they must lie along that single line sloping to the upper left which corresponds to the path of any light that reaches us "now". One may also construct the lines that give the past trajectories of the galaxies in their outward motion. These lines slope to the upper right, the slower twice as steep since it moves half as fast (if the light lines were realistically portrayed on the same scale in this diagram, they would be almost indistinguishable from horizontal lines). From simple geometry, since their distances are in a ratio of two and their speeds in a ratio of ½, their past trajectories converge at the position of the observer in the remote past as shown. In fact, the Hubble law implies that any galaxy considered would be found at our position back at a time which has been labeled t = 0 in the diagram.

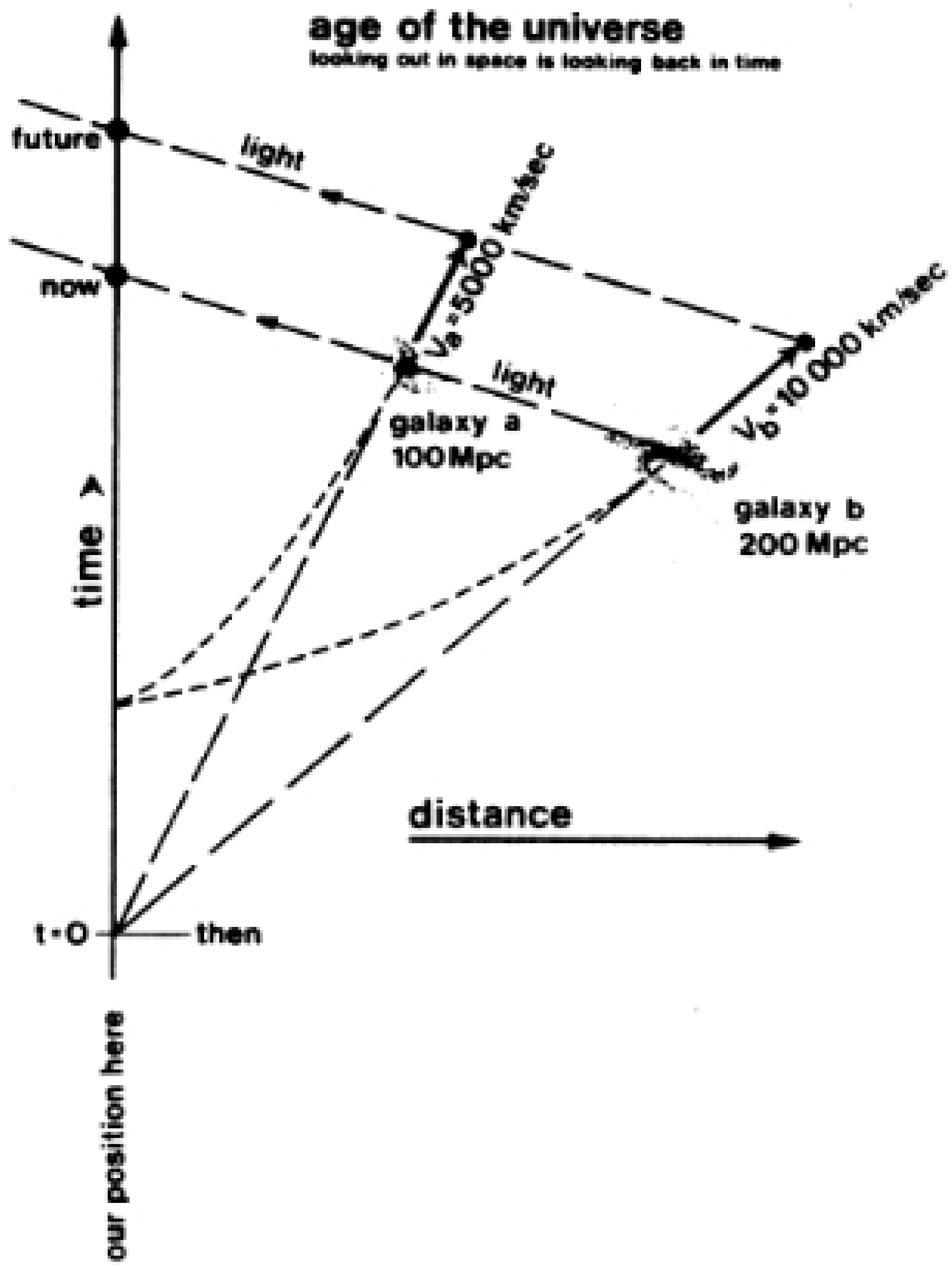

FIG. 11b

Perhaps there is a simpler, less formal way to visualize this phenomenon. Suppose you are watching a movie of cosmological expansion in which galaxies and clusters of galaxies are seen to be retreating according to the Hubble Law. The projectionist suddenly decides to reverse the machine and we see the universe closing in on us (galaxies appear blueshifted now). The longer we view, the closer those once remote galaxies approach us. Obviously this claustrophobic situation culminates in a singular state. Galaxies eventually merge and the density of matter becomes arbitrarily large as we approach the "initial" moment, t = 0. Clearly a universe so constructed is quite different from the static eternal cosmos of Newton and the 19th Century. An expanding universe seems inescapably to embody the concept of age. It is a universe that "begins" at some point in time. One might say it is semi-eternal in the sense that it never ceases to be, but it appears necessary to discard the notion that it has always existed (at least in a form we can presently understand).

The obvious question then is: How old is the Universe? This question seems to have a simple answer. From a tall building we watch a distant segment of a straight freeway leading from our position to the next city. We can judge the distance to a receding car by its apparent size (we know its true size) and we might use a Doppler radar system to measure its speed (a beefed up version of the kind used by the police). In any case, suppose we determine that the distance is 5 miles, and increasing at the rate of 50 miles per hours. Assuming the car has maintained this speed, we would have found it at our location about:

$$\frac{5\text{ miles}}{50\text{ miles / hour}} = 0.1\text{hours ago}$$

From the distance and recession speed, one may easily estimate the elapsed travel time from here to a remote position. In the same way, since we know the distance and recession speed of remote galaxies, we may estimate the age of the Universe. By the Hubble law, if the distance is D, the recession speed is the Hubble constant, H, times D. Thus if D is 10 megaparsecs (10Mpc):

$$\text{Age} = \frac{\text{Distance}}{\text{Speed}} = \frac{10\text{ Mpc}}{(10 \cdot 50)\text{ km / sec}} \cong 0.02\left(\frac{\text{Mpc}}{\text{km}}\right)\text{sec}$$

One megaparsec is about 3 x 10^19 kilometers, so:

$$\text{Age} \cong 0.02 \cdot 3 \cdot 10^{19}\text{ sec} = 6 \cdot 10^{17}\text{ sec}$$

There are about 3 x 10^7 seconds in a year, thus:

$$\text{Age} \cong 20 \cdot 10^{9}\text{ years (20 billion years).}$$

Of course this estimate assumes the recession speed of a given galaxy has always been the same. This necessarily means the Hubble "constant" is not constant, that distant galaxies were moving at the same high speed, even when closer. If we account for the fact that the gravitational attraction between distant masses has gradually decelerated that motion, then the speeds were greater in the past and the age estimate must be correspondingly smaller. This possibility is shown in the spacetime diagram as the curved trajectories for the galaxies that indicate a higher speed (shallower slope) in the past and the consequent reduction in the time interval between their intersection and our current sighting of them. This age does not disagree with other estimates based on the ages of the oldest stars, and on radioactive decay measurements.