DISTANT GALAXIES AND COSMOLOGICAL MODELS

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Model V - With a Cosmological Constant

Can there be a model with less than critical mass density and yet flat space? When Albert Einstein was first developing his equations of general relativity and applying them to these cosmological questions he found that his model universe would be either expanding or contracting. He did not like this result as he felt the universe should be static and eternal. In order to cancel out the effects of gravity on galaxy motions, he introduced into his equations a repulsive force by adding an arbitrary constant called the cosmological constant. This can be thought of as representing the energy density of space itself. This produced a model with unstable equilibrium however, the least movement away from a stationary universe would cause the universe to continue to contract or to expand. When Hubble and others made measurements of the recession velocity of galaxies and developed the picture of an expanding universe, starting in the big bang, the idea of a static universe fell into disfavor. Einstein felt that the cosmological constant was inappropriate and he dropped it.

For some years the cosmological constant has not been used much or has been set equal to zero in most models and has been set equal to zero in the discussion thus far. Recently, however, there has been great renewed interest in a non-zero cosmological constant. If we use it in a model, and still start with the big bang and choose a certain range of values for the cosmological constant, we will get a universe which expands very rapidly at first, then slows down like our Model III but stops decelerating at some point and then begins to **accelerate** for ever after. Space can be flat in such a universe.

Our final model, Model V, is an example of such a universe which is now in the accelerating mode. It is illustrated in **Figure VI**.

The cosmological constant represents the energy density of empty space and provides a repulsive force opposing gravitational attraction. It can be seen that the path of a galaxy in this Figure has a slight s-curve shape as it first slows down and then speeds up. Some recent observations, discussed below, seem to support this model. In such a model, the gravitational force is very strong when the universe is young and dense and it overcomes the repulsive force of the cosmological constant. As the universe expands, however, the gravitational force weakens as the universe becomes less dense, and finally the repulsive force wins out and galaxies accelerate. Using the results of the recent papers suggesting an accelerating universe, the curves of Model V assume that the accelerating phase started some 7 billion years ago and the present rate of expansion is some 18% greater than the rate at the beginning of acceleration and that space is also flat. A good discussion of the cosmological constant and dark energy and alternative concepts is in *Science News* for *May 22, 2004. (15)*

For this model, the concepts of curvature and extent and open or closed discussed above do not apply directly, the situation is more complicated. While space is flat in this model and the universe is unbounded (unless it is multiply connected), the expansion does not slow down to a standstill after an infinite time as in Model III, the universe continues to speed up and eventually expands exponentially.

For a model such as this in which space is flat and the cosmological constant is greater than zero, there is a different meaning to density. The density of **matter** divided by the critical density of $3H(t)^2/8\pi G$ is called Ω_m and the cosmological constant divided by $3H(t)^2$ is called Ω_λ . For this model, Ω_m plus Ω_λ equals 1 (when the universe is old enough that the contribution by radiation density is unimportant) indicating flat space. Model V assumes that the **present** value of Ω_m, called Ω_{m0}, is 0.3 and of Ω_λ, $\Omega_{\lambda 0}$, is 0.7. In the very early universe, Ω_m was nearly 1 and Ω_λ was nearly 0. As time goes on, Ω_m will decrease toward 0 and Ω_λ will increase toward 1. An Ω_λ of 1 indicates an exponentially expanding universe forever.

The behavior of Ω_m is shown in **Figure VI**. There will be considerable discussion of the values of Ω_m and Ω_λ in times to come as more data flood in. Appendix III describes the equations which give the behavior of these quantities and of the scale factor as functions of time.

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