Dark Energy—Cosmic Acceleration

Just before the year 2000, cosmologists received a surprise. Gravity was assumed to be the predominant force on a large scale in the universe, and it was thought that the expansion of the universe ought to be slowing down in time because gravity acts as an attractive force between objects. But measurements on type Ia supernovae (SNIa, our best standard candles—see Section 33–3) unexpectedly showed that very distant (high z) SNIa's were dimmer than expected. That is, given their great distance d as determined from their low brightness, their speed v determined from the measured z was less than expected according to Hubble's law. This result suggests that nearer galaxies are moving away from us relatively faster than those very distant ones, meaning the expansion of the universe in more recent epochs has sped up. This **acceleration** in the expansion of the universe (in place of the expected deceleration due to gravitational attraction between masses) seems to have begun roughly 5 billion years ago (8 to 9 Gyr after the Big Bang).

Acceleration

What could be causing the universe to accelerate in its expansion, against the attractive force of gravity? Does our understanding of gravity need to be revised? We don't know the answers to these questions; many scientists say dark energy is the biggest mystery facing science today. There are several speculations. But somehow it seems to have a long-range *repulsive* effect on matter, causing objects to speed away from each other ever faster. Whatever it is, it has been given the name **dark energy**.

Dark energy

One idea is a sort of quantum field given the name "quintessence." Another possibility suggests an energy latent in space itself (vacuum energy) and relates to an aspect of General Relativity known as the **cosmological constant** (symbol Λ). When Einstein developed his equations, he found that they offered no solutions for a static universe. In those days (1917) it was thought the universe was static—unchanging and everlasting. Einstein added an arbitrary constant to his equations to provide solutions for a static universe. A decade later, when Hubble showed us an expanding universe, Einstein discarded his cosmological constant as no longer needed $(\Lambda = 0)$. But now it is being reconsidered: perhaps Λ is not zero. Theoretical attempts to calculate Λ have so far given unreal values.

Cosmological constant

There is increasing evidence that the effects of some form of dark energy are very real. The data from the WMAP survey and other recent experiments agree well with theories and computer models when they input dark energy as providing 73% of the mass–energy in the universe, and when the total mass–energy density equals the critical density ρ_c.

Today's best estimate of how the mass–energy in the universe is distributed is as follows:

73% dark energy

27% matter, subject to the known gravitational force.

Of this 27%:

23% is dark matter

4% is baryons (what atoms are made of) and only $\frac{1}{10}$ of this 4% is visible matter: stars, and galaxies (that is, 0.4% of the total).

Mass–energy types in the universe as % of total

It is remarkable that only 0.4% of all the mass–energy in the universe is visible as stars and galaxies.

The idea that the universe is dominated by a completely unknown form of energy seems bizarre. Nonetheless, the exquisite agreement between theory and the measured CMB anisotropy observations plus other experimental data (clustering of galaxies—see next Section) appears to be meaningful.