I. Observational Basis of the Standard Model

The Standard Big Bang Model: Key Observations

1. The night sky is dark.
2. General relativity accurately describes gravity on solar system scales.
3. The universe is expanding: $\mathbf{v}$=$\mathbf{Hr}$ (Hubble's law). (NB: Isn't perfect – peculiar velocities. Breaks down when $v \sim c$.)
4. The observed universe is isotropic on very large scales.
5. The inferred ages of globular clusters are $\sim 1/H_0$, to within a factor of two.
6. We observe a nearly isotropic background of microwave radiation with a *blackbody* spectrum, $T \sim 2.7$K.
7. The helium abundance in the lowest metallicity stars is $\approx 25\%$ (by mass).
8. Abundances of other light elements are $\sim 10^{-5}$ (D, ^{3}He), $\sim 5 \times 10^{-10}$ (^{7}Li), to within a factor of 20.

Implications and connections

(1) rules out a static, infinite universe.

Combination of (4) with the "Copernican Principle" (nothing special about us) implies the "Cosmological Principle": the universe is homogeneous and isotropic. First introduced by Einstein as an unsupported assumption. Now good evidence that it is true on large scales.

Combination of the cosmological principle, the validity of GR, and some plausible assumptions about the material content of the universe (non-exotic equation of state) implies that the universe has expanded from a very dense, very hot state. According to classical GR, this initial state was a singularity.

Note: the "plausible assumption" of a non-exotic equation of state does not appear to hold true today.

Definition of the Big Bang Theory: The universe has expanded from a very dense, very hot state that existed at some finite time in the past.

The BBT predicts (3), which is the only expansion law consistent with the cosmological principle. $\mathbf{v}_1 = H\mathbf{r}_1$, $\mathbf{v}_2 = H\mathbf{r}_2 \Longrightarrow \mathbf{v}_2 - \mathbf{v}_1 = H(\mathbf{r}_2 - \mathbf{r}_1)$.

The BBT also predicts (5), since the expansion age of the universe is $\sim 1/H_0$ (precise value depends on matter and energy content of the universe).

The BBT also predicts (6), though it does not predict the value of the temperature itself.

Given $T = 2.7$K and a mean baryon density consistent with observations, the BBT predicts (7) and (8).

The “ΛCDM” Model: Key Observations

9. The present day universe is structured: galaxies, clusters, superclusters, etc.
10. Dynamical studies imply that most of the mass in the universe is dark. The dark matter around galaxies is much more extended than the luminous components.
11. Dynamical estimates of the average density of dark matter imply that (a) it is $\sim 30\%$ of the “critical density” required to make space flat, (b) it is more than the average baryon density allowed by the observed light element abundances and the theory of big bang nucleosynthesis.
12. Star-forming galaxies and quasars are observed out to redshifts $z \sim 6$ and beyond.
13. The cosmic microwave background (CMB) has fluctuations, $\left(\frac{\Delta T}{T}\right)_{\rm rms} \sim 10^{-5}$.
14. Best estimates of the Hubble constant are $H_0 \sim 70\text{km s}^{-1}\ \text{Mpc}^{-1}$, with $1/H_0 \sim 14$ Gyr. Inferred ages of oldest globular clusters are $\sim 1/H_0$, significantly older than $2/(3H_0)$.
15. Studies of redshifts of distant supernovae, assumed to be “standard candles” as they are in the local universe, imply that the cosmic expansion has accelerated over the last ~ 5 Gyr.
16. The power spectrum of CMB anisotropies is approximately flat at large angle, and shows a series of alternating peaks and troughs at smaller angles. The first of these peaks is at multipole $l \sim 200$, angle $\theta \sim 0.5$ degrees. CMB fluctuations are Gaussian to high precision.
17. The amplitude of matter fluctuations at lower redshifts over a wide range of scales, inferred from galaxy clustering, weak gravitational lensing, and the Lyα forest, is consistent with ΛCDM predictions (normalized to the CMB) at the $\sim 50\%$ level.

Implications and connections

(9) implies that the homogeneous model of the standard big bang theory is only an approximation that holds on large scales.

(10)-(12) imply the existence of non-baryonic, non-dissipative dark matter that had a low velocity dispersion in the early universe, a.k.a. “cold dark matter (CDM).”

The leading idea for CDM is some kind of not-yet-discovered, stable fundamental particle, such as the lightest supersymmetric partner or the axion.

(13) Shows that the fluctuations that seeded the growth of galaxies and present-day structure were present at recombination, $z \sim 1100$. Structure formed by gravitational instability.

(15) implies that the present energy budget of the universe is dominated by some component with an exotic equation of state that produces (in GR) repulsive gravity.

This component could be a “cosmological constant” (denoted Λ), whose energy density is constant in space and time, or it could be something else.

The angular scale ($l \sim 200$) in (16) implies that space is approximately flat, and thus that the total energy density is close to the critical density.

Combination with (11) implies that there is an additional component to the energy budget beyond baryonic matter and dark matter.

Combination with (14) implies that this additional component has an exotic equation of state (repulsive gravity), since otherwise the age of the universe would be $\lesssim 2/(3H_0)$.

Given parameters $\rho_{\rm CDM} \sim 0.3\rho_{\rm crit}$, $\rho_{\rm bar} \sim 0.04\rho_{\rm crit}$, and $\rho_\Lambda \sim 0.7\rho_{\rm crit}$, the detailed statistical properties of CMB anisotropies and other measurements of structure (16, 17) are consistent with the predictions of *inflation*, which posits that the primordial fluctuations originated as quantum fluctuations during a period of rapid accelerated expansion in the very early universe.

Thus, ΛCDM is shorthand for "inflationary cosmology with cold dark matter and a cosmological constant."

It is possible that the evidence for cosmic acceleration reflects a breakdown of GR on cosmological scales rather than a new constituent of the universe. The predictions of a modified gravity model must be fairly similar to those of ΛCDM. However, given the absence of good candidates for the exotic component, and the limited observational constraints on cosmic expansion, this kind of solution to the "dark energy problem" seems plausible.

In a similar vein, it is possible that the evidence for "dark matter' is really evidence for a breakdown of GR on galactic and larger scales. Again, the predictions of a modified gravity model must be fairly similar to those of ΛCDM. Given the presence of several plausible candidates for dark matter and the rich phenomenology of structure formation that any alternative model must reproduce, this kind of solution to the "dark matter problem" seems unlikely.