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Precision cosmology

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Abstract

The good agreement between large-scale observations and the predictions of the now-standard ΛCDM theory gives us hope that this will become a lasting foundation for cosmology. After briefly reviewing the current status of the key cosmological parameters, I summarize several of the main areas of possible disagreement between theory and observation: big bang nucleosynthesis, galaxy centers, dark matter substructure, and angular momentum, updating my earlier reviews [Primack, J.R., 2004. In: Ryder et al., S.D. (Eds.), IAU Symposium 220 Dark Matter in Galaxies (Astron. Soc. Pacific), p. 53 and p. 467, and other articles in that volume. Primack, J.R., 2003. Status of Cold Dark Matter Cosmology. In: Cline, D. (Ed.), Proceedings of 5th International UCLA Symposium on Sources and Detection of Dark Matter, February 2002. Nucl. Phys. B, Proc. Suppl., 124, 3 (astro-ph/0205391)]. The issues in all of these are sufficiently complicated that it is not yet clear how serious they are, but there is at least some reason to think that the problems will be resolved through a deeper understanding of the complicated astrophysics involved in such processes as gas cooling, star formation, and feedback from supernovae and AGN. Meanwhile, searches for dark matter are dramatically improving in sensitivity, and gamma rays from dark matter annihilation at the galactic center may have been detected by H.E.S.S.

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1. Introduction

Modern cosmology – the study of the universe as a whole – is undergoing a scientific revolution. New ground- and space-based telescopes can now observe every bright galaxy in the universe. We can see back in time to the cosmic dark ages before galaxies formed and read the history of the early universe in the ripples of heat radiation still arriving from the Big Bang. We now know that everything that we can see makes up only about half a percent of the cosmic density, and that most of the universe is made of invisible stuff called "dark matter" and "dark energy." The cold dark matter (CDM) theory based on this (ΛCDM)

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appears to be able to account for many features of the observable universe, including the heat radiation and the large scale distribution of galaxies, although there are possible problems understanding some details of the structure of galaxies. Modern cosmology is developing humanity's first story of the origin and nature of the universe that might actually be *true* – in the sense that it will still be true in a thousand years. Although this talk is entitled "Precision Cosmology," I think we should be even more impressed that modern cosmology is true than that it is precise.

Building on the work of Copernicus, Brahe, Kepler, and Galileo, Newton established the basis of what we now call classical physics. Although there have been many scientific revolutions in physics since the Newtonian synthesis, none of them have overthrown Newtonian physics the way that the Copernican–Newtonian scientific revolution overthrew earlier Aristotelian and Ptolemaic ideas. Ptolemy was never afterward taught as science, only as history, but Newtonian physics will always be taught. The subsequent revolutions in physics – wave optics, field theory, thermodynamics, relativity, and quantum mechanics – encompassed Newtonian physics rather than overthrowing it (Weinberg, 2001).

Once a well-confirmed basis for further progress is established, such as that provided by Newtonian physics, a scientific field can expand its range of successful applicability without any further overthrowing revolutions, and in this sense it can be said to be progressive. I think it is likely that the modern revolution in cosmology has now established such a basis for progress. Even though there is so much that we still do not know – in particular, the nature of the dark matter and dark energy, and the origin of the initial conditions – what we do know is now so well confirmed by diverse data that it is likely to be true.

Ever since Einstein's general relativity provided the essential language for cosmology, the field has progressed in the normal scientific style, with predictions followed by confirmations. Friedmann and Lemaitre predicted the expansion of the universe, which was subsequently confirmed by Hubble in 1929. Gamow, Alpher, and Hermann in 1948 predicted the existence of the cosmic background radiation (CBR) which was found by Penzias and Wilson in 1965, with its thermal spectrum confirmed by the FIRAS instrument on the COBE satellite in 1989. The cold dark matter theory (Blumenthal et al., 1984) predicted the amplitude of the CBR fluctuations, which were discovered by the DMR instrument on COBE in 1992 and found to have the predicted amplitude. By early 1992, it was clear that the only viable simple versions of CDM were ΛCDM with $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$, and Cold + Hot DM (CHDM) with $\Omega_m = 1$ and $\Omega_\nu = 0.2$–0.3. A few years later CHDM and all other $\Omega_m = 1$ cosmologies were ruled out by the discovery of abundant high redshift galaxies and by the discovery of strong evidence for Λ using high-redshift supernovae in 1998. The combination of CDM and cosmic inflation predicted the acoustic peak in the CBR angular power spectrum, which was discovered by the BOOMERANG and MAXIMA balloon experiments and the DASI instrument at the South Pole in 2000–2002. Now WMAP has confirmed and extended the CBR observations of ground- and balloon-based instruments, and both the CBR angular power spectrum and the galaxy power spectrum look exactly like the predictions of ΛCDM (Spergel, 2003).

Our modern cosmological synthesis is based on several assumptions of simplicity, in particular the "cosmological principle" (we do not live at a special place in the universe) and the assumption that the same laws of physics that describe phenomena in our laboratories on earth and nearby are valid at all times and places throughout the universe. These assumptions are being checked against observations. For example, comparison of the details of atomic spectra in the laboratory and from galaxies at various redshifts suggested that there might be variations in the fine structure constant $\alpha = e^2/(\hbar c)$ of $\Delta\alpha/\alpha = -0.574 \pm 0.102 \times 10^{-5}$ (Webb, 2001; Murphy, 2003), but the latest results from another group and telescope do not see that effect, finding $\Delta\alpha/\alpha = 0.06 \pm 0.06 \times 10^{-5}$ (Srianand, 2004; Chand, 2004; Cowie and Songaila, 2004). This seems to me good news, since such a variation might be inconsistent with the entire framework of relativistic quantum field theory (Banks et al., 2002; Dine, 2003; Mota and Barrow, 2004). But of course it will be necessary to test this new result,