Moriond Conference Summary: The Cosmological Model(s)

Ofer Lahav
Institute of Astronomy, University of Cambridge, Madingley Road
Cambridge CB3 0HA, England; email:lahav@ast.cam.ac.uk

The XXXVIIth Rencontres de Moriond on "The Cosmological Model" is briefly summarized. Almost none of the current observations argues against the popular Cold Dark Matter + Λ concordance model. However, it remains to be tested how astrophysical uncertainties involved in the interpretation of the different data sets affect the derived cosmological parameters. Independent tests are still required to establish if the Cold Dark Matter and Dark Energy components are 'real', or just 'epicycles' that happen to fit the current data sets well.

1 Introduction

It is a challenging task in ‘data compression’ to summarize briefly a conference so rich in ideas and observational results, covered in over 100 oral presentations. On the observational side, we were fortunate to hear at this meeting for the first time the results from two CMB experiments: CBI and VSA, which largely confirmed earlier results for the CMB acoustic peaks. We also heard updates on redshift and cluster surveys at different wavelengths. On the theoretical side, we learnt about the most advanced numerical simulations, and on ideas which relate fundamental physics (e.g. ‘Brane World’) to cosmological models. The exponential growth of data has changed the character of the subject, in the sense that models can now be assessed quantitatively in great detail.

Below is a modest attempt to summarize the approaches of estimating the ‘best fit’ cosmological model. It is interesting that the title of meeting is “The Cosmological Model”, perhaps implying the good agreement within the community on the concordance Λ-Cold Dark Matter model. As this model has been so successful and popular, it is timely to ask ‘what can go wrong’, and if other models are still possible.
2 Basic Assumptions and Paradigms

As Jim Peebles emphasized in his Introduction talk, our study of the Universe is performed within the framework of General Relativity, and within that theory by assuming the Cosmological Principle, i.e. that on large scales the Universe is (roughly) homogeneous and isotropic. It is worth noting that the Cosmological Principle and the resulting FRW metric were formulated before observations could probe to significant redshifts, when the ‘dark matter’ problem was not well-established and the Cosmic Microwave Background (CMB) was still unknown. However, this ‘guess’ turned out to be successful. The COBE measurements of temperature fluctuations $\Delta T/T = 10^{-5}$ on scales of $10^\circ$ give, via the Sachs Wolfe effect, rms density fluctuations of $\delta\rho/\rho \sim 10^{-4}$ on $1000 h^{-1} \text{Mpc}$, i.e. the deviations from a smooth Universe are tiny. However, we note that on scales of $\sim 100 h^{-1} \text{Mpc}$ (probed e.g. by the recent redshift surveys 2dFGRS, SDSS) the rms fluctuations expected from conventional models are non-negligible, $\delta\rho/\rho \sim 0.1$. One also has to verify carefully that a sample properly represents a typical patch of the FRW Universe in order to yield reliable global cosmological parameters. It is also common to assume the Inflationary paradigm, but other Brane-inspired models have also gained popularity recently.

3 Cosmic Probes

The different cosmic probes discussed at the meeting determine different sets of cosmological parameters. Below we give the approximated dependence on the density parameters for matter (total) $\Omega_m$, baryons $\Omega_b$, and dark energy $\Omega_\Lambda$, the Hubble constant $H_0 \equiv 100h \text{ km/sec/Mpc}$, and the (linear theory) normalization $\sigma_8$ of the mass fluctuations in $8 h^{-1} \text{Mpc}$ spheres. Other important parameters include the primordial spectral index $n$, the age of the Universe $t_0$, the optical depth to reionization $\tau$, and the linear biasing parameter $b$ (which can be generalized to more complicated biasing schemes). While in the 1960’s Sandage’s goal was to ‘search for two numbers’ it is now appreciated that even the basic cosmological model requires a dozen or so parameters, which are linked in non-trivial ways:

- **Big Bang Nucleosynthesis**: $\Omega_b h^2$
- **The CMB**: $\Omega_\Lambda + \Omega_m$, $\Omega_m h^2$, $\Omega_b h^2$, $\sigma_8 e^{-\tau}$, $n$, $t_0$
- **SN Ia**: $3\Omega_\Lambda - 4\Omega_m$
- **Redshift surveys**: $\Omega_m^{0.6}/h$, $b\sigma_8$, $\Omega_m h$
- **Peculiar velocities**: $\sigma_8\Omega_m^{0.6}$, $\Omega_m h$
- **Cluster abundance**: $\sigma_8\Omega_m^{0.6}$
- **Weak lensing**: $\sigma_8\Omega_m^{0.6}$
- **Baryon fraction in clusters**: $\Omega_b, \Omega_m, h$
- **Cepheids, Sunyaev-Zeldovich clusters, time-delay**: $h$

An important point to note is that by using ‘orthogonal’ constraints one can significantly improve the estimation of cosmological parameters. The dependence on the factor of roughly $\Omega_m^{0.6}$ in different probes (peculiar velocities, cluster abundance and cosmic shear) is a coincidence, but having a number of different probes which are sensitive to the same combination of parameters provides an important cross check.
We also note that the choice of the model parameter space is somewhat arbitrary (e.g. by fixing some parameters given priors).

Some of these measurements are easy to interpret. For example the physics of the CMB is linear, so the acoustic peaks at redshift $z \sim 1000$ can probably be better understood than the weather conditions on the top of the Mont Blanc! The interpretation of other probes involves more complicated astrophysics, for example galaxy biasing, the mass-temperature relation in the cluster abundance, the evolution of SN Ia, and non-linear effects in weak gravitational lensing (shear). We also note that some of the methods (e.g. SN Ia and baryon fraction) are free of assumptions on the nature of the dark matter, while the interpretation of others (e.g. the CMB and redshift surveys) requires a specific power spectrum of fluctuations (e.g. CDM) to be assumed.

4 The Best-Fit Concordance Model: Ranking Our Belief

Although the Λ-CDM model with comparable amounts of Dark Matter and Dark Energy is rather esoteric, it is remarkable that different measurements converge to a ‘concordance model’. However, some parameters are more robust than others, and the list below is ordered (with a personal bias) from the more established to the less accurate parameters. We note that the meaning of the error bars below is non-trivial, as in some cases they are the result of marginalization over other free parameters. In other cases the error bars reflect the diversity of results derived by different methods. Refined values and error bars can be found in contributions by others in this volume and in numerous papers on astro-ph.

- The curvature of the Universe $\Omega_k = 1 - \Omega_m - \Omega_\Lambda = 0 \pm 10\%$ from the position of CMB acoustic peaks.
- The baryon density $\Omega_b h^2 = 0.02 \pm 10\%$ from BBN and the CMB.
- The Hubble constant $h = 0.7 \pm 10\%$ from the Cepheid-calibrated distances.
- The spectral index $n = 1 \pm 10\%$ from the CMB.
- The age of the Universe $t_0 \approx 14 \pm 10\%$ Gyr from the CMB alone (assuming $\Omega_k = 0$).
- The amplitude of fluctuations $\sigma_8 \approx 0.8 \pm 30\%$, where the large error reflects the spread in results derived from cluster abundance, the CMB+2dFGRS and cosmic shear.
- The mass density $\Omega_m \approx 0.3 \pm 50\%$, where again the derived values vary considerably (e.g. from mass-to-light vs. velocity fields).
- The neutrino mass density $0.001 < \Omega_\nu < 0.04$, where the lower limit is from the recent atmospheric and solar neutrino oscillations and the upper limit is from large scale structure (e.g. 2dFGRS).
- The cosmic equation of state $w = P/\rho$: the current data are consistent with $w = -1$ (i.e. a non-zero Cosmological Constant), but different forms of Quintessence $w(z)$ are still possible.

There is still room for tensor modes, non-adiabatic and non-Gaussian components in the CMB and for better estimation of the reionization parameter $\tau \sim 0.05$. There is also the possibility of time-dependent physical constants (e.g the fine-structure constant $\alpha$). Conceptually, it seems we have to learn to live in a multi-component complex Universe, which perhaps takes us away from an idealized model motivated by Occam’s razor.
5 Outlook

There is general acceptance (perhaps too strongly) of the ‘concordance’ model with the following ingredients: 4% baryons, 26 % Cold Dark Matter (possibly with a small contribution of massive neutrinos) and the remaining 70 % in the form of Dark Energy (the Cosmological Constant or ‘Quintessence’). While phenomenologically the Λ-CDM model has been successful in fitting a wide range of cosmological data, there are some open questions:

- Both components of the model, Λ and CDM, have not been directly measured. Are they ‘real’ entities or just ‘epicycles’? Historically epicycles were actually quite useful in forcing observers to improve their measurements and theoreticians to think about better models!

- ‘The Old Cosmological Constant problem’: Why is Ω_Λ at present so small relative to what is expected from Early Universe physics?

- ‘The New Cosmological Constant problem’: Why is Ω_m ∼ Ω_Λ at the present-epoch? Do we need to introduce a new physics or to invoke the Anthropic Principle to explain it?

- There are still open problems in Λ-CDM on the small scales e.g. galaxy profiles and satellites.

- The age of the Universe is uncomfortably close to some estimates for the age of the Globular Clusters, if their epoch of formation was late.

- Could other (yet unknown) models fit the data equally well?

- Where does the field go from here? Should the activity focus on refinement of the cosmological parameters within Λ-CDM, or on introducing entirely new paradigms?

These issues will no doubt be revisited soon with larger and more accurate data sets. We will soon be able to map the fluctuations with scale and epoch, and to analyze jointly redshift surveys (e.g. 2dF, SDSS, DEEP2) and CMB (e.g. MAP, Planck) data. These high quality data sets will allow us to study a wider range of models and parameters.

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