Transactions IAU, Volume XXVIIIA
Reports on Astronomy 2009–2012
Ian Corbett, ed.

doi:10.1017/S1743921312002943

COMMISSION 47 COSMOLOGY

COSMOLOGIE

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TRIENNIAL REPORT 2009-2011

1. Introduction

The period 2009-2011 has seen a consolidation of our theoretical understanding around the Flat-Λ CDM Universe model, with experiments on several fronts providing observations consistent with this model, and leading to improved constraints on the values of H_0, Ω_B, Ω_M, and Ω_Λ. The recently launched Planck Satellite has started to provide a wealth of new observations of the Cosmic Microwave Background (CMB) and should lead to substantial progress in the physics of the CMB over the coming years. There has also be a steady progress in mapping the formation of structure and galaxies to higher and higher redshifts. Observations of objects at the highest redshifts are suggestive that the reionization of the Universe might not be complete at these epochs. This epoch will be probed in the near future with low-frequency radio surveys. This report, prepared from the inputs received from the committee members, concentrates on these areas.

2. Developments within the past triennium

2.1. *Progress in Understanding The Cosmological Model*

After the discovery in 1998 that the Universe is currently undergoing accelerated expansion, the field of cosmology witnessed a series of cosmological experiments which could probe this unexpected result. All these observations are consistent with a spatially flat Universe dominated (73%) by a Cosmological Constant, and pressureless matter (27%), split between baryonic material (4.5%) and an unknown form of cold, non-interacting matter usually described as Cold Dark Matter (22.5%).

This Flat-Λ CDM model is not theoretically motived, but rather is the simplest model which adequately describes observations of the Universe. In addition to the complexity of three cosmologically relevant species of matter, it would appear we live in a special time of the Universe, where the Cosmological Constant and the pressureless matter components have roughly the same density - a state that persists for only a short period in the cosmological history. A significant amount of theoretical effort has been put into describing alternative theories that might provide insights into why the Universe is either constructed as the Flat-Λ CDM model suggests, or how a different physical paradigm might mimic this model. Some of the major areas of theoretical investigation have included looking at modifications of General Relativity, the assumption of homogeneity in the cosmological model, and a range of scalar field alternatives for the Cosmological constant. It is probably fair to say that cosmological constant remains the simplest description of dark energy consistent with all observations. Observational cosmology has marched on, undertaking a series of new and/or refined measures to test the predictions of the Flat-Λ CDM model.

Type Ia supernovae still provide one of the most precise probes of the Concordance Model through relatively local measurements ($0 < z < 1.5$) of cosmological expansion. A huge dataset useful for cosmology has now been assembled by several teams. Additions since 2009 include nearby SN Ia ($z < 0.1$) from the CfA (Hicken *et al.* 2009), Berkeley (Ganeshalingam, *et al.* 2010), and Carnegie groups (Folatelli, *et al.* 2010), moderate redshift ($0.1 < z < 0.4$) from the SDSS-II consortium (Kessler *et al.* 2009), high-redshift ($z > 0.3$) from the Supernova Legacy Search (Guy *et al.* 2010) and *HST* program of Amanullah *et al.* (2010). These programs show the increasing difficultly of eliminating systematic biases in the samples, including the effects of dust, supernova intrinsic color, and environmental effects, but in total, the experiments appear consistent with the Flat-Λ CDM model's prediction of luminosity distance evolution over the entire redshift range to a level of a few percent.

The technique of measuring the baryon acoustic oscillations (BAO), which trace the anisotropies seen in the CMB as imprinted in large scale structure, was first undertaken through the SDSS and 2dF redshift surveys. More targeted experiments are now completed (WiggleZ) or well underway (BOSS; www.sdss-3.org), with the combination of all measurements able to directly measure the acceleration of the Universe (Blake *et al.* 2011a), which have yielded similar results to the supernova experiments. These surveys have also enabled the measurement of the growth of structure to $z > 0.6$ (Blake *et al.* 2011b), finding a result in accord with the Flat-Λ CDM model. The *BOSS* project will provide a substantial improvement in precision of the BAO scale in the redshift range $0.3 < z < 0.7$ over the next few years. In addition, *BOSS* and the innovative *HETDEX* (http://hetdex.org/) project will probe the BAO scale at $z > 2$

Measurements of the anisotropies in the cosmic microwave background (CMB) have reached a new level of refinement through the release of the *WMAP* 7-year maps (Komatsu *et al.* 2011). Coupled with a better measurement of the Hubble constant from the geometrically derived radio maser distance to NGC4258, *HST* Cepheid variable stars, and optical observations of SN Ia (Riess *et al.* 2011), *WMAP* provides remarkably tight constraints on the curvature of the Universe, and additional useful constraints which, when combined with other methods such as baryon acoustic oscillations and supernovae, can simultaneously constrain curvature, matter density, dark energy density, and the equation of state of the dark energy (Komatsu *et al.* 2011, Sullivan *et al.* 2011, Blake *et al.* 2011a). These comparisons find that the Flat-Λ CDM model continue to withstand this intense scrutiny.

As to be expected, future experiments are becoming more ambitious in scale and in budget. BigBoss (http://bigboss.lbl.gov) aims to equip the Mayall 4-m telescope with a huge purpose-built spectrograph, and undertake a 20 million galaxy BAO survey. BAOs are also targets of the proposed *EUCLID* (http://sci.esa.int/euclid) and *WFIRST* (http:// wfirst.gsfc.nasa.gov) satellites. These satellites also aim to use weak gravitational lensing to measure the properties of dark energy. The Large Synoptic Survey Telescope (http://www.lsst.org), aims to also exploit gravitational lensing through a deep map of the entire southern sky. These future experiments will push the current tests of the Concordance Model an order of magnitude higher than currently available, and will hopefully help us to understand two of cosmology's greatest mysteries - nature of the dark matter and dark energy.

2.2. *Progress in Cosmic Microwave Background Observations*

A key event for cosmology in this period was the dual launch on 14th May 2009 of the *Planck* satellite and the *Herschel Space Observatory.* This successful launch ushered in a new era of precision mapping of the cosmic microwave background (CMB), as well as opening up the far-infrared and submillimeter wavebands for a wide range of studies, including cosmological ones.

Planck (Tauber *et al.* 2010) is the third generation CMB satellite, following on from *COBE* and *WMAP*. Its two instruments image the entire sky over frequencies from 30 GHz to 857 GHz, with improved sensitivity and angular resolution. Press releases in 2010 demonstrated that *Planck* worked according to design, and in January 2011 a series of 25 papers was submitted. These focused mainly on 'foreground' science, but included studies of the first all-sky sample of clusters found using the Sunyaev-Zeldovich effect (Planck Collaboration VII 2011), as well as an investigation of clustering in the cosmic infrared background (Planck Collaboration XVIII 2011). The release of the first primary CMB cosmology results is planned for January 2013.

Herschel has been carrying out a number of surveys which are important for the study of galaxy formation and evolution, particularly (in order of shallow and wide to deep and narrow) H-ATLAS (Eales *et al.* 2010), HerMES (Oliver *et al.* 2010) and H-GOODS (Elbaz *et al.* 2011), using the SPIRE and PACS instruments. Results have included counts of galaxies at wavelengths from 70 to 500 μm, constraints on the evolution of the bolometric luminosity function, studies of correlations in the submillimeter background, investigation of the relationship between *Herschel*-detected galaxies and a wide range of other wavelengths, and the discovery of strongly lensed systems at high redshift.

WMAP has continued to release updates of results for the years 5 (Komatsu *et al.* 2009) and 7 (Komatsu *et al.* 2011) of the satellite's data-set. These have firmed up the values of cosmological parameters, and provided a range of tests of the Flat-Λ CDM paradigm.

On smaller angular scales, the Atacama Cosmology Telescope (Swetz *et al.* 2011) and the South Pole Telescope (Carlstrom *et al.* 2011) have provided exquisite new measurements of the CMB anisotropy power spectrum, showing several additional acoustic peaks. These experiments have also demonstrated the ability to find galaxy clusters, as well as to measure the effects of gravitational lensing on the CMB anisotropies.

2.3. *Progress in understanding the Formation and Evolution of galaxies from large deep surveys*

Deep imaging and spectroscopic surveys constitute a workhorse resource to test galaxy formation and evolution. During this period, multi-wavelength surveys with large visible and near-IR arrays have developed towards greater depth and larger areas. One noticeable evolution has been the broader wavelength coverage including the near-IR (JHK) of the most recent surveys, offering a better constraint onto the spectral energy distributions (SEDs) and the morphological properties. One can note the important impact of the mid-IR space observatory Spitzer, and the far-IR space observatory Herschel at the end of the period, further extending the multi-wavelength data to include the radiation of cold components.

Existing and new large imaging cameras (the largest have about 0.5° on a side) have produced large quantities of data, mostly in the visible and near-IR domains. Deep galaxy imaging surveys in the visible domain ($ugriz$) now reach several hundreds of square

https://doi.org/10.1017/S1743921312002943 Published online by Cambridge University Press

degrees (CFHTLS), very faint magnitudes AB $\sim 28-30$ at visible wavelengths (CFHTLS, COSMOS, GOODS), $AB \sim 25$ at near infrared (UKIDSS, Lawrence *et al.*, 2007; Ultra-Vista, on going), or $AB \sim 23$ at mid/far infrared (Sanders *et al.*, 2007). The *HST-ACS*, followed by WFC3 have opened the way to extremely deep surveys under high spatial resolution, like the COSMOS 2deg^2 survey (Scoville *et al.*, 2007) or the CANDELS survey (Grogin *et al.*, 2011).

Narrow-band imaging surveys are now deep enough to identify relatively large samples of emission line objects, particularly focusing on the Ly-α 1215 Å Hydrogen line used to track the highest redshift objects. Atmospheric windows are exploited in narrow transmission ranges at redshifts $z \sim 5.7, 6.5, 7.7$, (Ouchi *et al.*, 2008); but attempts at $z = 8.8$ have been unsuccessful up to now (e.g. Cuby *et al.*, 2007).

Using the large multi-wavelength datasets, the technique of photometric redshifts determined from template fitting to the SED has considerably matured. The best surveys now reach a redshift accuracy of $\sim 0.03(1+z)$ with catastrophic failures less than 2% (e.g. Ilbert *et al.*, 2006). As this applies to all sources measured on images, this opens up statistically robust analysis from very large samples reaching close to one million galaxies (COSMOS, Ilbert *et al.*, 2009).

As deep photometry has been gaining in area and depth, so have the large spectroscopic surveys. Large and efficient multi-object spectrographs on 8–10 m telescopes have continued to deliver large quantities of data. The exploitation of the DEEP2 (Faber *et al.*, 2007) and VIMOS VLT Deep Survey (Garilli *et al.*, 2008), with about 50,000 spectroscopic redshifts each in $0.5 < z < 1.4$ and $0 < z < 5$ respectively, has continued, and new surveys like zCOSMOS bring a new insight with 20,000 redshifts in the COSMOS field with $0 < z < 1.2$ (Lilly *et al.*, 2009). The larger volumes sampled to $z \sim 1$ have opened-up the possibility to study the properties of galaxies in relation to different types of environment.

An important development has been the demonstration of the evolution of galaxy type vs. local density relation, well known locally. At $z \sim 1$ this relation is almost flat with galaxies of different types no longer segregated in relation to environment (Cucciati *et al.*, 2006; Cooper *et al.*, 2006; Tasca *et al.*, 2009). The picture of galaxy evolution connected to hierarchical growth of the dark matter halos has received support from the evidence of the major role of mergers since $z \sim 1$ (Lotz *et al.*, 2008; de Ravel *et al.*, 2009), with a strong dependency of the merger rate on the mass.

The star formation rate density evolution and the stellar mass density, two major statistical indicators of evolution have received considerable attention, with new measurements available out to early epochs. The star formation rate density has evolved in several steps, with a strong increase from redshift 7 to 4 (to be confirmed from larger samples, Bouwens *et al.* 2007), a constant high rate from $z \sim 3$ to $z \sim 1$ (Tresse *et al.*, 2007; Cucciati *et al.*, 2011), and a strong decrease by about one order of magnitude from $z \sim 1$ to the present, as observed by earlier surveys like CFRS. The stellar mass density evolution has been traced robustly out to $z \sim 2$ (Arnouts *et al.*, 2007; Ilbert *et al.*, 2010). It is found that between $z \sim 2$ and $z \sim 1$ there is a strong build-up of mass in early-type galaxies by almost a factor of 10, pointing to this epoch as an important phase in early-type galaxy evolution.

The question of the way that mass has assembled into galaxies is still hotly debated. While major mergers are readily demonstrated to contribute 25% to 40% of the mass growth in galaxies since $z \sim 1$ (de Ravel *et al.*, 2009), cold accretion along the filaments of the cosmic web has been claimed to be mostly responsible for the mass accretion onto galaxies at $z \sim 2$ (Genzel *et al.*, 2008; Dekel *et al.*, 2009). This is challenged by the observation of a large fraction of about (1/3) of galaxies in close pairs at $z \sim 1.5 - 2$

(Forster-Schreiber *et al.*, 2009; Epinat *et al.*, 2009). This issue should become clarified once larger samples are available.

The question of the complete census of galaxies, necessary to properly account for all star formation and mass content, is still open. To help find the needle in the haystack, various a priori selection criteria have been used to detect the highest redshift populations based on photometry, like Lyman Break Galaxy or BzK ($z \sim 2$) selection. However, these techniques may miss out a fraction of the population, as the counts of galaxies from these seem to be significantly lower than from direct flux selected samples (Cucciati *et al.*, 2011). Compounded with the difficulty of constraining the faint end (low mass) slope of the luminosity (mass) function beyond redshift $z \sim 2$, this uncertainty in counts results in significant uncertainties on the star formation or mass density (among other things) at $z > 2$. New surveys are addressing this issue using near-IR flux selection (van Dokkum *et al.*, 2006), or a combination of criteria to minimize the possible biases.

Despite this enormous progress, it is clear that deep surveys will need to expand further towards the classical avenues of wider, deeper, and redder observations. The next years will see a consolidation of the results from Herschel, and the start of operations of ALMA to look at high redshift galaxies from their cold components, to estimate the total gas and dust content and obtain a complete star formation census. New generation facilities will start operations or be developed in the next few years to enable these new generation surveys, including new near-IR multi-object spectrographs. All-sky surveys at $z \sim 1-2$ are now within reach of technical capabilities, and facilities are being proposed to observe several millions or tens of millions of distant galaxy spectra (ESA-*Euclid*, *BigBoss*, *Subaru-PFS*). On the extremely distant front, *JWST* and the *ELT*s will follow-up the candidates identified in large surveys with imaging cameras, hopefully before the end of this decade. One major goal will be to track the reionization epoch, finding first light.

2.4. *Progress in Understanding the Epoch of Reionization*

The epoch of reionization (EoR) sets a fundamental benchmark in cosmic structure formation, corresponding to the birth of the first luminous objects that act to ionize the neutral intergalactic medium (IGM). The H-ionizing photons emitted by such sources in fact produce HII bubbles in the surrounding medium on a range of size scales. With the passage of time, the bubbles finally punch through the walls separating each other, to leave behind an almost fully ionized IGM, which remains such to the present. Despite the agreement reached by the scientific community on the general characteristics of the EoR (for example it is thought to be a gradual process mainly driven by stellar-type sources), its details are still being debated.

The progress made in the development of the sophisticated numerical techniques necessary to model the EoR has recently made possible a more accurate treatment of the physical processes involved, by considering e.g. a larger mass range, the contribution of x-ray photons from sources more energetic than stars and the impact of He physics on H reionization, among others (e.g. Baek *et al.* 2010; Iliev *et al.* 2011; Ciardi *et al.* 2011). But our persisting ignorance in particular of the efficiency of star formation, the escape fraction of ionizing photons and the stellar properties of high-z galaxies makes it difficult to improve substantially such modeling until more stringent observational constraints become available.

In fact, present observations offer information on the final stages of reionization and on the global amount of electrons produced during the process, but a crucial observational insight on the evolution of the EoR and the properties of its sources is still lacking. The latest release from the WMAP satellite (Larson *et al.* 2011) gives a Thomson scattering optical depth of $\tau_e = 0.088 \pm 0.015$, which provides an estimate of the global amount of electrons produced during the reionization process. On the other hand, this does not provide any constraint on the evolution of the electron number density, i.e. on the reionization history. If reionization were an instantaneous process, the above value would correspond to a reionization redshift of $z_{reion} = 10.5 \pm 1.2$. But it is very likely that the process is gradual and hence is expected to start at higher redshift.

Information on the latest stages of reionization has been gathered through the years from observations at near-IR wavelengths of absorption by the IGM in the spectra of the highest redshift quasars (e.g. Becker *et al.* 2001; Fan *et al.* 2006), suggesting that the IGM is mostly ionized by $z \sim 6$. Recently though, a quasar at $z = 7.09$ has been detected (Mortlock *et al.* 2011) with a highly ionized near zone which is smaller than those around quasars of similar luminosity at $z \sim 6$, indicating that the volume averaged HI fraction is larger than 0.1 (Bolton *et al.* 2011), i.e. the IGM is still significantly neutral. This might be compatible with the possibility that reionization was yet to fully complete by $z \sim 6$ (Mesinger 2010). The possibility of a significant neutral fraction in the IGM surrounding such a quasar makes it an excellent target for studies of the IGM ionization state using the redshifted 21-cm transition.

Indeed, it has long been known (e.g. Field 1959) that neutral hydrogen in the IGM and gravitationally collapsed systems may be directly detectable in emission or absorption against the CMB at the frequency corresponding to the redshifted HI 21 cm line. In general, 21-cm spectral features will display angular structure as well as structure in redshift space, due to inhomogeneities in the gas density field, hydrogen ionized fraction, and spin temperature. Several different signatures have been investigated in the recent literature (see the review by Morales & Wyithe 2010): (i) fluctuations in the 21-cm line emission induced by the 'cosmic web', by the neutral hydrogen surviving reionization and by minihalos; (ii) a global feature ('reionization step') in the continuum spectrum of the radio sky that may mark the abrupt overlapping phase of individual intergalactic HII regions; (iii) and the 21-cm narrow lines generated in absorption against very high-redshift radio sources by the neutral IGM and by intervening minihalos and protogalactic disks.

A number of radio observational facilities are presently being built (e.g. LOFAR, MWA, PAPER) and planned (SKA) with the aim of providing critical insight into the EoR. Among these, LOFAR has started its commissioning phase in early 2011 and, together with the other radio interferometers, will hopefully, in the next 5–10 years, provide more stringent constraints on the reionization history.

3. Closing remarks

As part of the lead up to the 2012 IAU General Assembly, Commission 47 will create a strategic plan for the next 3 years. This plan will be developed by the organising committee with inputs from commission membership. The Vice-President, Brian Schmidt, will take the lead in preparing and finalising it for adoption at the General Assembly in Beijing.

Thanu Padmanabhan
President of the Commission

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