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New instrument concepts for observational cosmology

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Abstract

A key goal of observational cosmology today is to understand what initiated the re-ionization epoch and how this spectacular phase unfolded over a period of a few hundred million years. Simulations show that this may ultimately require us to push observations to redshifts as high as $z \sim 25$. Here, I explore present and planned activities that will allow us to go beyond our current redshift limit ($z \sim 6.5$). We stand at the dawn of a new era where diffraction-limited observing will be possible on 8 m class telescopes at near infrared wavelengths. I describe some of the instrument concepts that lead naturally from the science cases, in particular an AO-assisted, OH-suppressed IFU spectrograph. The benchmark for these new concepts has been set by the James Webb Space Telescope (JWST). Can we expect the next instruments to live up to this goal? If we do succeed, a great deal of entirely new science will be possible long before the expected launch of JWST.

Keywords: Observational cosmology; Astronomical instrumentation; Photonics; Tunable filters

Contents

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1. Introduction

The structure of this meeting has emphasized the close bond of theory, experiment and observation. This has always been true for the frontier of observational cosmology which, more than any other astrophysical pursuit, has been the driving force for bigger telescopes and better machines over the past 50 years.

The microwave background experiments (COBE, Boomerang, WMAP, VSA) have shaped the observational frontier in two distinct ways. First, they have detected the signature of primordial structure and subsequently determined accurate measurements of the Standard Model parameters. This has allowed numerical simulators to concentrate on the more difficult gas physics rather than be left with cosmological uncertainties on the basic framework. Secondly, the WMAP polarization measurements suggest a possible reionization epoch as early as $z \sim 20$, although this value may well come down in subsequent reanalysis (cf. MacTavish et al., 2005). The most recent simulations suggest the first bound structures formed at $z = 26.0$, the first star at $z = 25.2$, with the first light and first HII regions at $z = 25.0$ and $z = 24.7$, respectively (Yoshida et al., 2004). We now talk in terms of First Light. This has provided the impetus to numerous experiments from gamma ray to radio wavelengths given that the Dark Ages might not be so dark after all.

At optical and infrared wavelengths, we do not need to await the James Webb Space Telescope (JWST) to make substantial progress in this arena. Existing 8 m telescopes can and will be used more effectively to pursue the Dark Ages, even before the launch of the JWST. Diffraction-limited performance is close at hand, and should come close to delivering D^4 performance (where D is the telescope diameter) for at least some of the planned instruments.

The focus of this meeting has been on 3D integral field spectroscopy. It is remarkable how far this technology has come since the first 3D spectrograph conference in Marseille (Bland-Hawthorn, 1995). This technology has matured considerably over the past decade and is widely employed on front line instruments. Here, we show that the combined impact of adaptive optics and new developments in photonics is expected to greatly enhance the sensitivity of near-infrared integral field spectrographs.

The structure of this paper is as follows. In Section 2, we summarise the key goals of First Light science. These lead directly into the technology goals listed in Section 3. In Section 4, we discuss the importance of tunable imaging filters. In Section 5, we explore sensitivity improvements in future integral field spectrographs through photonic OH suppression. In Section 6, we revisit the traditional meaning of wide-field (AΩ) advantage, and describe implications for high resolution work.

2. Science goals – the big questions

There are many things that we would like to know about the Dark Ages. What initiated the epoch of reionization and how did it develop? Did it happen in stages due to more than one type of source? Are the halo ultra metal poor stars we see today the byproduct of the First Stars and therefore reveal the metal products of this unique population? It is widely believed that the bulk of the galaxy spheroid population formed around $z \sim 3$ and the disks at $z \sim 1$, but unequivocal evidence for this scenario in the far field is still not secure. Can we demonstrate this more directly by establishing the progenitors of both systems? How did galaxies assemble before this time and where does the present day bulge – black hole mass relation come from (Magorrian et al., 1998)?

It is important to keep in mind that observational cosmology at these redshifts has the potential to provide insight on the nature of dark matter and dark energy, two of the great unknowns of contemporary astrophysics. Yoshida et al. (2003) illustrate how the evolution of structure in the early universe can indicate the presence of warm dark matter. At lower redshift, oscillations in the power spectra of future large-scale redshift surveys may shed light on the nature of dark energy (Seo and Eisenstein, 2003; Blake and Glazebrook, 2003).

3. Technology goals – key instrument parameters

For ground-based astronomy, there has been a great deal of technological progress in the past decade: 8 m telescopes, large format high efficiency CCDs and IR arrays, multi-object and integral field spectrographs (the subject of this meeting), high performance dispersers (e.g. tunable filters, volume phase holographic gratings) and differential techniques (e.g. iodine cells, nod & shuffle). When we look at the numerous scientific discoveries over the same period, we can identify four key factors which have made these possible: sensitivity, resolution, efficiency, and adaptability. These factors are fundamental to future scientific progress.

3.1. Sensitivity

During the so-called Dark Ages, several factors conspire to make objects darker: (i) distance and cosmological dimming, (ii) pervasive neutral medium scattering resonant emission lines, (iii) dust. In order to achieve the First Light science goals, ground-based telescopes will need to achieve much higher levels of sensitivity than have been possible before. Traditionally, this has meant pushing for higher instrument throughput and larger telescope apertures. Modern instruments often have total system efficiencies of 30% or higher; the only substantial instrument gains to be had are for niche applications (e.g. Baldry et al., 2004). Since the next telescope generation is a decade away, the greatest sensitivity gains in the short term must come from suppressing the night sky emission and diffraction-