An Optical and Ultraviolet Cosmological Mapper

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Why Mapping the Largest Scale of the Universe?

Astronomical observations have become a vital tool for studying fundamental physics, and advances in fundamental physics are now essential for addressing the key problems in astronomy and cosmology. The past 15 years have been a period of tremendous progress in cosmology: we now have a simple cosmological model that fits a host of observations. One of the strangest *features* of our current cosmological model is the observation that the expansion rate of the universe is accelerating. This late-time acceleration implies either the existence of dark energy (DE), a substance whose equation of state is bizarre or the break down of Einstein's gravitation theory (GR) on cosmological scales. Understanding the cause of cosmic acceleration is one of the great challenges of physics. Another great *unknown* is the origin of primordial perturbations that grew to form the large scale structures (LSS) that we observe today, i.e. what physics is describing the universe when it was 10^{-30} second old and its temperature was about 10^{16} GeV.

Observations of large-scale structure have played an important role in developing our standard cosmological model and will likely play an essential role in our investigations of the origin of cosmic acceleration and cosmic origins. *Novel use of optical and UV observations potentially offer very potent avenues to address this issue in a definite manner.*

Working in the "intensity mapping regime" – large scale, low spatial resolution, moderate spectral resolution – optical and UV surveys offer a potentially very powerful, yet economical, avenue to map cosmological scales. The idea consists in mapping the aggregated line emission of many galaxies in a given frequency/redshift range rather than the emission of individual galaxies. To not aim at resolving individual galaxies naturally allows the use of a smaller telescope and also increases the signal strength, thus decreasing sensitivity requirements.

The matching between frequency and redshift requires that the line being mapped is well identified. Observing at radio frequencies and focusing on the bright 21 cm HI line, this idea lead to a flurry of experimental development and already pioneering measurements (Chang *et al.* 2010, Masui *et al.* 2012). These developments aim either at mapping the epoch of reionization or at mapping large scales at lower redshift to characterizing DE (Peterson *et al.* 2009). Recently, the use of other lines such as CO or CII emission states has received some interest as a probe of reionization and is also motivating several observational efforts (Lidz *et al.* 2011, Gong *et al.* 2011, Visbal *et al.* 2010, Gong *et al.* 2012).

An obvious candidate line to extend this technique to the optical and UV window is the hydrogen Lyman-α line (Lyα). Indeed, to map this 121.6 nm emission line over the full optical and ultraviolet window would allow us to map continuously a redshift range up to z$\sim$ 6. To extend it to slightly larger wavelengths would lead to an interesting probe of the epoch of reionization up to $z \sim 12$ (Silva *et al.* 2012, Pullen *et al.* 2012). The observational set-up required to perform this large scale mapping is quite modest.

Some Modest Observational Requirements

To briefly illustrate what such an experiment would take, we will set as a simple requirement that we want to map comoving scales up to 1 (10) Mpc/h up to $z = 6$. This naturally sets the required angular resolution since spatial resolution perpendicular to the line of L in Mpc/h indeed requires an angular resolution given by $\Delta\theta = L/D_A(z = 6)$ where D_A is the comoving angular diameter distance up to $z = 6$. Assuming a standard cosmology, it is about 0.6 (6.) arcmin. for L= 1 (10) Mpc/h. A telescope with a diameter of a few tens of cm would achieve this while providing a large collecting area. Our target redshift window requires a frequency coverage from 121.6 nm up to 850 nm. Targeting an identical spatial resolution along the line of sight leads to a frequency resolution, $R = 2\pi c(1 + z)/H(z)/L$, of 2200 (220). As such, it is clear that such a survey would have rather modest needs as compared to more contemporary surveys.

Our estimates lead to a line flux for the Lyα line varying from 5×10^{-19} to 2×10^{-16} erg.s^{-1}.cm^{-2}. arcsec^{-2} when the source moves from $z = 6$ to 1. Such measurements are likely to be sky background limited. The very dark near and far UV sky background is dominated by scattering of starlight by interstellar dust at a continuum level of order 400-600 photons.cm^{-2}.(s.sr.A)$^{-1}$ at the galactic poles, and increases toward the galactic equator (Murthy *et al.* 2010). The sensitivity of an instrument designed to measure the diffuse Lyα emission from large scale structures depends on the aperture, spectral resolution, throughput, sky background, detector background and other factors. Although it is premature to offer a detailed description of the instrument configuration and resulting exposure time, preliminary calculations indicate that high signal to noise ratio can be achieved in relatively short exposures with a modest aperture, assuming high instrument throughput and sky background limited observations. Note that the access to space would be critical to access the large scales of interest, provide good flat-fielding and avoid atmospheric fluctuations.

The Need for Spectral Deconvolution

For the sake of illustration, we so far made the simplifying assumption that we can directly match a frequency to a given redshift. It is obviously true only in the limit where one line dominates, as is the case for the 21cm radio line. In the frequency coverage of interest to us, an abundance of emission lines will contribute and requires an extra-step to separate the measured emission at all frequencies into redshift slices. We need to perform a spectral deconvolution (Holder & Doré 2012).

The intensity as a function of wavelength is generally a superposition of many sources along the line of sight at a variety of cosmological redshifts:

$$I(\nu) = \int dz f(z) j(\nu, z) \ , \qquad (1)$$

where $f(z)$ indicates the flux per unit redshift and j is the redshifted spectrum. In the simple case of a non-evolving rest-frame spectrum j_{rest}, this can be written as

$$I(ln\nu) = \int dz f[ln(1+z)] j_{rest}[ln\nu + ln(1+z))] \ . \qquad (2)$$

This is a pure convolution, where the rest frame SED has been convolved with the redshift distribution, both of which are unknown quantities of interest. Different positions on the sky, however, will have different $f(z)$ (from fluctuations in large scale structure) but similar j_{rest}, allowing a separation of these two quantities. This is a cosmological analog of the Fourier quotient method of stellar kinematics (Sargent et al. 1977), with the added feature of using multiple lines of sight to disentangle the rest spectrum and that the dominant line ratios are very perfectly known.

Cosmological evolution of the SED will complicate this simple picture, but evolution with redshift should be modest over the scales of interest; a parameterized redshift evolution that is subsequently marginalized over should be sufficient to minimize this source of confusion. Ultimately, we expect to be able to separate deconvolution in angular, redshift and $\ln\nu$ space from which we will be able to extract the 3D matter power spectrum as a function of scales. This last stage will require the determination of an effective luminosity weighted bias as function of redshift. This will be possible using the measurement of redshift space distortion on very large scales using techniques developped for spectroscopic galaxy survey (Hamilton 1997, Kaiser 1987, White *et al.* 2008).

Cosmological Implications

We propose a modest experimental set-up that allow to map in the optical and UV the full sky as a function of redshift up to $z \sim 6$. While it is clear that such a survey would have rather modest needs as compared to contemporary cosmological surveys, its fundamental physics or astrophysics impact could nevertheless be paramount.

We could basically produce a three-dimensional map of the matter distribution throughout our universe. Our three dimensional resolution is enough to probe all the modes in the quasi-linear regime which are typically used for doing cosmology. As such, to compare the cosmological information content of our survey, it is fair to compare its volume (directly proportional to the number of modes) to other current and future surveys. Roughly speaking, mapping 8,000 square degrees up to $z \simeq 0.7$, the SDSS-I survey has mapped around 5 $[\mathrm{Gpc}/h]^3$, the current BOSS survey will map 8,000 square degrees up to $z \simeq 0.9$, that is about 9 $[\mathrm{Gpc}/h]^3$. The ESA/NASA Euclid is set to cover 15,000 square degree up to $z \simeq 2$, that is about 80 $[\mathrm{Gpc}/h]^3$. The mapper we are proposing, mapping the full sky up to $z \sim 6$ would cover about 800 $[\mathrm{Gpc}/h]^3$.

This mapping would thus turn into orders of magnitude improvements in the constraints on cosmological parameters expected from the experience mentioned above. To access large (linear) scales in redshift space would enable the joint determination of the expansion history and the growth rate of structures. The former stems from the measure of the baryonic acoustic oscillations scale (Eisenstein *et al.* 2005), the characteristic scale imprinted by the sound waves within the primordial plasma in the Early Universe, and use this cosmic ruler to determine the hubble constant as a function of redshift. The latter results from the impact of cosmic velocity on the measured redshift, which depends upon the growth rate of structures (Kaiser 1987). To be able to probe both the acceleration and the growth is critical: if cosmic acceleration is caused by DE, then there is a simple relation between the two. Deviations would imply the breakdown of GR, a nearly century-old pillar of modern physics (Weinberg *et al.* 2012).

This mapping would also provide exquisite constraints on the nature of the initial conditions and in particular the primordial non-Gaussianity. The sensitivity of such an experiment would be such that the primordial non-Gaussianity would be easily measured, independently of the Inflation model considered, a feat achieved by no other cosmological planned experiment. The combination of small and large scale power would provide a precision tests of inflation, since it would extend the lever arm for constraining the spectral index and its running for the power spectrum of inflationary seed fluctuations. It would also provide an ideal test-bench to test general relativity on cosmological scales. Finally, the exquisite shape measurement of of the power spectrum and its redshift evolution would allow to constrain neutrino mass to a tenth of an eV.

Such a survey would certainly contributes towards NASA's strategic goal 3.4 "*Discover the origin, structure, evolution, and destiny of the universe*" (NASA Science plan, p.161).

We'll directly address the suggested "Decadal Outcomes" outlined in NASA's science plan to "*1. Progress in understanding the origin and destiny of the universe ... and the nature of gravity*" and "*2. Progress in understanding how the first stars and galaxies formed, and how they changed over time into the objects we recognize in the present universe.*" (NASA Science Plan page 161). This proposal also addresses six of the key questions identified in the Atro2010 report "New Worlds, New Horizons in Astronomy and Astrophysics (NAS Decadal Survey): *Why is the universe accelerating?*, *What is the fossil record of galaxy assembly from the first stars to present?*, *What are the connections between dark and luminous matter? How do cosmic structures form and evolve?* and *"How did the universe begin?"*.

We would be definitely be interested in participating and presenting our science objectives and investigations at a workshop, if invited.

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