THE HUBBLE SPHERE HYDROGEN SURVEY: A 3D HI MAPPING TO STUDY DARK ENERGY

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The expansion of the Universe appears to be accelerating and the origin of the agent of this acceleration, dark energy, is still unknown. Baryon acoustic oscillations can be used to study dark energy with direct measurements of redshifts of individual galaxies, by observing the 21cm line or by detecting optical emission. This proceeding describes the Hubble Sphere Hydrogen Survey (HSHS), an alternative approach, based on the 21 cm brightness which would allow mapping of most of the observable universe while avoiding the effort of creating a redshift catalog of galaxies.

Introduction

In the late 1990's, observations of Type Ia supernovae suggested that the Universe is undergoing an accelerated expansion. This fact seems to be corroborated by other independent sources: observations of the cosmic microwave background anisotropies and large scale structure studies. It is still not known whether Einstein's theory of gravity is incomplete, whether the acceleration is caused by a cosmological constant or by a completely new form of energy which was given the name of dark energy. This new form of energy appears to be the dominant component of the physical Universe. Yet there is no persuasive theoretical explanation for its existence or magnitude. To address the nature of dark energy we study its equation of state defined as the ratio of the pressure over density $w = p/\rho$ and the evolution of w as a function of the redshift z, $w = w_0 + w_a \times z/(1+z)$. If one finds that w is either redshift dependent or not exactly equal to -1.0, it would mean that the component is not the cosmological constant found in the Einstein field equations.

Several methods can be used to study dark energy: supernovae, galaxy clusters, gravitational lensing and large scale structure of the Universe through the measurement of baryonic acoustic oscillations (BAO). All these methods provide complementary information with different systematic errors and with different correlation coefficients between the cosmological parameters. The BAO approach appears to have the smallest systematic error while preserving a good statistical precision (see the Dark Energy Task Force report [1]). It is based on the fact that in the early Universe the temperature was so high that photons and baryons were strongly interacting. They formed a plasma that operated as a fluid exhibiting acoustic oscillations. These oscillations ceased when electrons "recombined" with nuclei to form atoms when the Universe was a few hundred thousand years old. The imprint of the oscillations has been observed as small modulations in the Cosmic Microwave Background temperature. They are also imprinted

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in the spectrum of galaxies where they produce an excess correlation between pairs of galaxies separated by 150Mpc, the distance travelled by a sound wave between the big bang and recombination. This excess correlation defines a "standard ruler" on the sky which can be used to determine distances. The apparent angular size of the ruler depends on the distance to the ruler and it is this distance that is determined by the characteristics of the dark energy. The 150Mpc correlation caused by BAO was detected by two optical galaxy surveys, 2dFGRS and SDSS in 2005[2]. The latter survey outlines the existence of these oscillations at a redshift $z \simeq 0.35$. This study combined with the observation of BAO in the cosmic microwave background ($z = 1100$) provides important constraints on the geometry of the Universe. While these measurements use mostly the transverse size of the ruler on the sky; the oscillations also appear in the radial direction. Observation of this would give a direct measurement of the expansion rate H(z) and would significantly improve the constraints on the dark energy equation of state.

A similar approach is pursued in the very wide radio surveys such as SKA or SKA pathfinders[3] : The galaxies are individually detected by using the neutral hydrogen 21cm spectral line corresponding to a $\nu_0 = 1.42$GHz frequency. Their redshift z is measured through the translation of the 21cm hydrogen transition which is the dominant spectral line at frequencies less then 1.42GHz and which is an isolated transition. However, this method requires a very good angular resolution (a few arcsec) and a long time of integration per pixel to achieve a signal/noise rejection at the order of a few sigmas. An alternative approach, proposed in the Hubble Sphere Hydrogen Survey (HSHS) project[4,5], would allow mapping of most of the observable universe while avoiding the effort of creating a redshift catalog of galaxies.

1 Three dimensional mapping of the Universe

In the HSHS approach, galaxies will not be fully resolved and a 3-dimensional map will be measured of the 21cm line intensity as a function of the position in the sky and redshift in the third dimension. The sky pixel resolution could be about $20' \times 20'$ and the spectral resolution about 10MHz (or $\simeq 10^{-3}$ in redshift unit) which is enough to observe the 150Mpc patterns imprinted in the Universe by BAO for redshift up to 1.5. This $20'$ angular resolution requires a minimal size for the interferometer around 100m. At $z = 1.5$, using HIPASS[6] measurements of $\Omega_{\rm HI} \simeq 3.5 \times 10^{-4}$, in such a pixel volume, the number of galaxies with a mass greater than $m^\star = 6 \cdot 10^9 M_\odot$ is around two hundred and the neutral hydrogen mass is about $10^{12} M_\odot$. Finally, the collective emission of few hundreds galaxies contained in one "wide" pixel should be significantly easier to detect than the emission of one individual.

The average sky HI brightness temperature is:

$$\bar{T}_{\rm HI} = 47\mu{\rm K}\ (1+z)^2 f(z)/[\Omega_\Lambda + (1+z)^3\Omega_m]^{1/2}\Omega_{\rm HI}/(3.5\times10^{-4}) \qquad (1)$$

where $f(z) = \Omega_{\rm HI}(z)/\Omega_{\rm HI}(z=0)$ described the evolution of HI mass in galaxies, fixed at z=0 by HIPASS. In contrast with optical or 21cm flux of individual galaxies, the HI brightness temperature increases with redshift. Following Eq. 1, $\bar{T}_{\rm HI}$ goes from 47μK for $z = 0$ up to 340μK for $z = 1.5$, assuming that $f(1.5) = 2.5$ which is consistent with Ly-α absorption studies[7]. Therefore, 3-D intensity mapping should extend more readily to high redshift than galaxy redshift survey techniques.

Neglecting the foregrounds and the background radio sources, the observed power spectrum for HI brightness temperature can be written as the sum of HI signal term and noise term related to T_{sys}, the system temperature of the radio-telescope:

$$\begin{aligned} P(k) = P(k)_{\rm HI} + P(k)_{\rm noise} &= P(k)_{\rm HI} + \left(\frac{T_{sys}}{\bar{T}_{\rm HI}}\right)^2 \frac{\Omega_{pix}}{\nu_0 t_{pix}} \frac{(c/H_0)\cdot(1+z)^2\cdot d_T(z)^2}{[\Omega_\Lambda + (1+z)^3\Omega_m]^{1/2}}, \qquad (2) \\ \text{with } d_T(z) &= \int_0^z \frac{(c/H_0)dt}{[\Omega_\Lambda + (1+t)^3\Omega_m]^{1/2}} \end{aligned}$$

where t_{pix} is the observation time for each pixel and Ω_{pix} is the pixel solid angle ($\Omega_{pix} \sim \lambda^2 A$, for a filled aperture telescope of area A). The observation time can be optimized in such a way that the two terms of Eq. 2 are equal at the first BAO peak, i.e. for $k = 0.075\, hMpc^{-1}$. Extrapolating the power spectrum $P_{\rm LSS}(k = 0.075) \sim 10^4\, (h^{-1}Mpc)^3$ measured at $z = 0$ by SDSS [8] to z=1.5, the HI brightness power spectrum is $P_{\rm HI}(k = 0.075) \sim 2500\, (h^{-1}Mpc)^3$, this leads to a minimal observation time per pixel, $t_{pix} \sim 1.5 \times 10^4 s$.

2 HSHS Concept

In a possible design, the radio-interferometer will consist of a packed array of ∼10-20 cylinders, each 100m long and 5-10m wide. They are aligned North-South allowing the telescope to instantaneously sample the entire meridian. This geometry allows all-sky coverage each 24-hour period in a telescope with no moving parts. The line-focus of the cylinder can then be outfitted with a set of evenly spaced feed antennas (∼ a few hundreds per cylinder) that collect the radiation from the sky. The analog signal coming out of an antenna is amplified, pass-band filtered, frequency shifted down to the 0-250MHz range and then converted to a digital signal using a 500MHz sampling frequency. The digitization of the signal is done very early in the electronics chain in order to perform a digital correlation: a Fast Fourier Transform (FFT) of the antennas signals gives the correlation in the North-South direction (in elevation) reducing the cost compared to usual correlator techniques.

With a cylinder width, $D_{cyl} \sim 5 - 10$m, this packed array layout allows accumulation of 10 minutes of integration time per day. In practice, only one month of observation would be required to achieve the minimal integration time per pixel, $t_{pix} \sim 1.5 \times 10^4 s$. Moreover, with such a configuration, this interferometer can measure the power spectrum $P(k)_{\rm HI}$ from $k_{min} = 2\pi D_{cyl} \nu_0 (1 + z)/(c d_T(z))$ up to k_{max} above the third BAO peak with a flat acceptance in k. However, for $z \sim 0.5$, k_{min} is equal to $0.089 (D_{cyl}/10\text{m})\, hMpc^{-1}$. Therefore, to be sensitive to the first BAO peak, it would be more appropriate to use narrower cylinder ($D_{cyl} \sim 5$m).

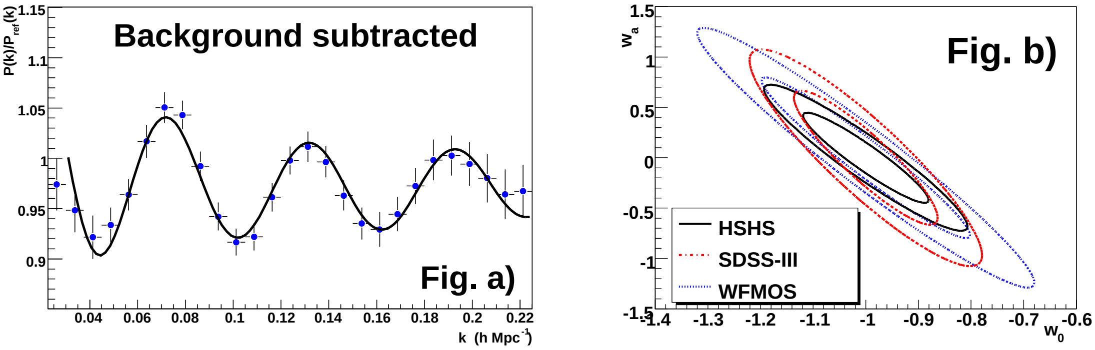

Figure 1: Fig. a), HI power spectra reconstructed and averaged over 100 realizations. The errors and the dots are the RMS and the mean of the 100 distributions for each k bin. Fig. b), 1σ and 2σ confidence level contours for HSHS and for future optical BAO surveys (SDSS-III and WFMOS) in the parameters plane (w_0, w_a).

We have simulated several configurations of HI survey to estimate the sensitivity on the measurements of cosmological parameters that we can achieve with HSHS. In all our simulations, we have assumed, a system temperature Tsys=50K, a half-sky coverage, a redshift depth, $\Delta z = 0.2$ for $0 < z < 1.6$. For each z, we have simulated 100 realizations. Then, for each realization, we have reconstructed the HI power spectrum and we have fitted the wavelength of the baryonic oscillation (see Fig.1-a)). The RMS of the fitted wavelength distribution gives an estimate of the precision expected on the measurement of the BAO wavelength. This precision allows one to measure the parameters describing the dark energy equation of state, w_0 and w_a respectively at 5% and 15% . The confidence contours on the two cosmological parameters (w_0, w_a) are shown on Fig.1-b).

As the HSHS project is a very new concept, validation studies are required both to demonstrate its feasibility and to provide a realistic estimate of the project cost: a prototype has been built in Pittsburgh by HSHS collaborator J.B. Peterson (Carnegie Mellon University). It consists of 2 cylinders with a size (25m × 10m) close to that needed for HSHS project. The collecting surface of $\sim 500\mathrm{m}^2$ and the angular $\sim 1^\circ$ should allow the observation of local HI from the Galaxy and nearby galaxies.

In addition of technical validations of the cylinder reflectors, physicists of CEA-Irfu/SPP and CNRS-IN2P3/LAL have developed a prototype for the full electronics chain. We want to test the different elements of the final electronics: analog signal shaper and frequency shifter, clock distribution system, 500MHz signal digitization and high speed data transmission board, PCI-Express data reception board. The first stage of the electronics chain, the analog boards, associated with a MATACQ board for the digitization[9], was successfully tested with the Nançay radio-telescope (NRT) in December 2007. Next summer, extensive tests with the full electronics chain will be carried out on the NRT. Once the electronics is qualified we will equipped the Pittsburgh prototype. The final goal will be to reconstruct multi-lobes with this prototype.

Conclusions

The HSHS project is an alternative approach to study Dark Energy with BAO, based on the 21 cm brightness which would allow mapping of most of the observable universe while avoiding the effort of creating a redshift catalog of galaxies. The expected sensitivity on the parameters describing the dark energy equation of state, w_0 and w_a respectively at 5% and 15% .

Acknowledgments

The author is most grateful to U.-L. Pen and J.B. Peterson who proposed the HSHS concept. He wishes to thank R. Ansari, J.-M. Le Goff, Ch. Magneville, M. Moniez, N. Palanque-Delabrouille, J. Rich V. Ruhlmann-Kleider for their contributions to the French R&D of HSHS which is financially supported by French scientific programs: PNC and P2I.

References

1. Dark Energy Task Force, E. Kolb et al. (2006), astro-ph/0609591.
2. S. Cole *et al.*, (the 2dFGRS Team), *Mon. Not. Roy. Astron. Soc.* **362**, 505 (2005); D. J. Eisenstein *et al.*, (the SDSS Collaboration), *Ap. J.* **633**, 560 (2005).
3. F. B. Abdalla, S. Rawlings, *Mon. Not. Roy. Astron. Soc.* **360**, 27 (2005).
4. J.B. Peterson, K. Bandura and U.-L. Pen, astro-ph/0606104, Rencontres de Moriond, Contents and Structures of the Universe, (2006).
5. T.Chang, U.-L. Pen, J.B. Peterson and P. McDonald, *Phys. Rev. Lett.* **100**, 091303 (2008).
6. M.A. Zwaan *et al.*, *Mon. Not. Roy. Astron. Soc.* **359**, L30 (2005).
7. A. Wolfe *et al.*, *Anni. Rev. Astron. Astrophy.* **43**, 861 (2005).
8. W. J. Percival *et al.*, (the SDSS Collaboration), *Ap. J.* **657**, 645 (2007).
9. D. Breton and E. Delagnes, Proceedings of IEEE NSS, San Diego, USA (2006).