Sparse Aperture Arrays for Neutral Atomic Hydrogen Surveys

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Dedicated to foxes, dogs, jackdaws, sphinxes, and Lorem Ipsum. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Proin sed ante a massa dignissim elementum in non tellus. Mauris vel quam sit amet mi ultricies gravida scelerisque sit amet nunc. Nulla condimentum nunc porta purus rutrum at tristique erat tincidunt. Donec malesuada bibendum urna porttitor dignissim. Quisque nisl elit, eleifend eget accumsan et, luctus et turpis. Mauris at rhoncus massa. Mauris molestie convallis eros, a lacinia orci tincidunt nec. Nulla eu orci non libero ornare mollis sit amet cursus tellus. Etiam tellus risus, faucibus id sagittis eget, gravida et nunc. Nam ultrices pretium risus ut accumsan. Fusce tellus velit, vulputate non malesuada at, lacinia ac nunc.

In my life, whenever two roads have diverged in a yellow wood, I have always had someone to guide me...

Abstract

Here, we present the Opto-Acoustic Parametric Amplifier (OAPA), a novel device which couples optical and acoustic degrees of freedom...

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Chapter 1

Introduction

1.1 Introduction

1.1.1 Fourier Series

For a function $f(x)$ you can write the Fourier Series:

$$f(x) = \sum_{-\infty}^{\infty} c_n e^{inx},$$

where the coefficients $c_n$are given by

$$c_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(x) e^{inx} dx$$

1.1.2 Maxwell's Equations

There are four of the buggers, and I like them in terms of total charge and current:

$$\begin{array}{rr} \nabla.\mathbf{E} = \frac{\rho}{\varepsilon_0} & \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla.\mathbf{B} = 0 & \nabla \times \mathbf{B} = \mu_o \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \end{array}$$

Where $\mathbf{B}$ is the magnetic field, $\mathbf{E}$ is the electric field and $\mathbf{J}$ is the total current density. Also, ε_0 is the permittivity of free space (electric constant) and μ_0 is the permeability of free space (magnetic constant).

It's good to know what these mean in words and integral forms, so:

- *Gauss' Law:* Electric flux through any closed surface is proportional to the enclosed electric charge:

$$\Phi = \oint_S \mathbf{E}\, d\mathbf{A} = \frac{Q_{enc}}{\varepsilon_0}$$

- *Gauss' Magnetic Law:* Magnetic monopoles don't exist:

$$\oint_S \mathbf{B}\, d\mathbf{A} = 0$$

- *Faraday's Law of Induction:* The induced electromotive force in any closed circuit is equal to the rate of change of the magnetic flux through the circuit:

$$\epsilon = -\frac{d\Phi_B}{dt}$$

- *Ampere's Law:* The relation between integrated magnetic field and current flowing:

$$\oint_S \mathbf{B}\, d\ell = \mu_0 I_{enc}$$

That should be enough to get you started.

1.2 Thesis Overview

Chapter 2

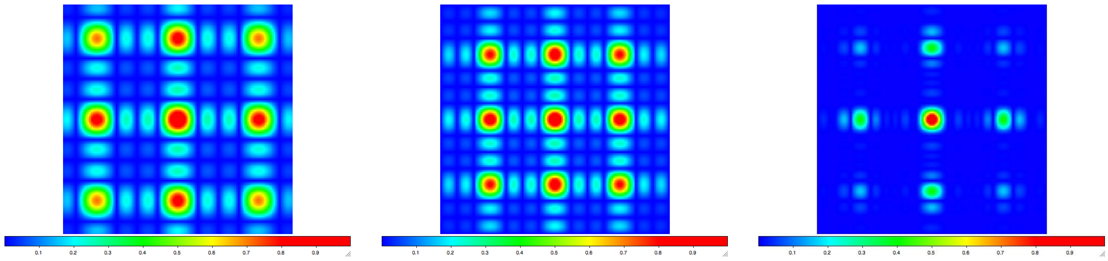
The Nature of Dark Energy

2.1 Baryon Acoustic Oscillations

Some example text: One of the most important issues in cosmology today is determining the properties of dark energy [1]. Over cosmological distances, dark energy acts as a repulsive force [6] which causes an acceleration in the rate of expansion of the universe, an observation first made using distant Type 1A supernovae [8, 7]. By measuring the rate of expansion, we can learn about the nature of dark energy which in turn can reveal a deeper understanding of the standard model of cosmology and the origin of the universe.

The rate of expansion of the universe can be determined from a measurement of its size at different epochs. A cosmological 'standard ruler' [2] is an object whose size relative to the universe remains fixed with the expansion of the universe. One such standard ruler is the typical length scale present in 'baryon acoustic oscillations' (BAO) [4]. These oscillations are the peaks and troughs in the spatial power distribution of baryonic matter which correspond to over- and under-densities of matter at specific length scales. The pressure resulting from over-densities present in the primordial plasma after the inflationary period created spherical acoustic waves which radiate outward from these over-densities at around half the speed of light.

As the Universe expanded and cooled, the electrons and protons eventually combined into neutral hydrogen atoms. At this point, referred to as recombination, the Universe became essentially transparent to photons, removing the outward pressure and effectively freezing the matter distribution. Over time, some of the dark matter at the centre of the original over-density was attracted to the location of the sound horizon [3]. Since the BAO are imprinted into the large-scale structure of the Universe they remain unchanged in relation to the size of the Universe. The BAO signal was first measured in the power spectrum of the cosmic microwave background (CMB)



(a) 2λ element spacing (b) $\frac{5\lambda}{2}$ element spacing (c) Product beam

Figure 2.1: An example of attenuation of grating lobes in the product beam of two arrays. In a) and b), we have the radiation power patterns at $300MHz$ for a 4×4 gridded array with spacing 2λ and $5\lambda/2$, respectively. Sub-figure c) shows the product beam, in which the grating lobe response is attenuated.

[5]. If one could measure the BAO signal at a different epoch this would constitute a standard ruler, which would provide a measure of the expansion rate of the universe.

References

[1] Filipe B Abdalla, Chris Blake, and Steve Rawlings. Forecasts for dark energy measurements with future hi surveys. *Monthly Notices of the Royal Astronomical Society*, **401**:743, Jan 2010.

[2] Chris Blake and Karl Glazebrook. Probing dark energy using baryonic oscillations in the galaxy power spectrum as a cosmological ruler. *The Astrophysical Journal*, **594**:665, Sep 2003.

[3] Daniel J Eisenstein, Hee-Jong Seo, and Martin White. On the robustness of the acoustic scale in the low-redshift clustering of matter. *The Astrophysical Journal*, **664**:660, Aug 2007.

[4] Daniel J Eisenstein, Idit Zehavi, David W Hogg, Roman Scoccimarro, Michael R Blanton, Robert C Nichol, Ryan Scranton, Hee-Jong Seo, Max Tegmark, Zheng Zheng, Scott F Anderson, Jim Annis, Neta Bahcall, Jon Brinkmann, Scott Burles, Francisco J Castander, Andrew Connolly, Istvan Csabai, Mamoru Doi, Masataka Fukugita, Joshua A Frieman, Karl Glazebrook, James E Gunn, John S Hendry, Gregory Hennessy, Zeljko Ivezić, Stephen Kent, Gillian R Knapp, Huan Lin, Yeong-Shang Loh, Robert H Lupton, Bruce Margon, Timothy A McKay, Avery Meiksin, Jeffery A Munn, Adrian Pope, Michael W Richmond, David Schlegel, Donald P Schneider, Kazuhiro Shimasaku, Christopher Stoughton, Michael A Strauss, Mark SubbaRao, Alexander S Szalay, István Szapudi, Douglas L Tucker, Brian Yanny, and Donald G York. Detection of the baryon acoustic peak in the large-scale correlation function of sdss luminous red galaxies. *The Astrophysical Journal*, **633**:560, Nov 2005.

[5] G Hinshaw, M. R Nolta, C. L Bennett, R Bean, O Doré, M. R Greason, M Halpern, R. S Hill, N Jarosik, A Kogut, E Komatsu, M Limon,

N Odegard, S. S Meyer, L Page, H. V Peiris, D. N Spergel, G. S Tucker, L Verde, J. L Weiland, E Wollack, and E. L Wright. Three-year wilkinson microwave anisotropy probe (wmap) observations: Temperature analysis. *The Astrophysical Journal Supplement Series*, **170**:288, Jun 2007.

[6] P. J Peebles and Bharat Ratra. The cosmological constant and dark energy. *Reviews of Modern Physics*, **75**:559, Apr 2003.

[7] S Perlmutter, G Goldhaber, H. J Marvin, R. A Muller, C. R Pennypacker, W. J Couch, and B. J Boyle. The program to measure qo using supernovae at cosmological distances. *Bulletin of the American Astronomical Society*, **22**:1332, Sep 1990.

[8] Adam G Riess, Alexei V Filippenko, Peter Challis, Alejandro Clocchiatti, Alan Diercks, Peter M Garnavich, Ron L Gilliland, Craig J Hogan, Saurabh Jha, Robert P Kirshner, B Leibundgut, M. M Phillips, David Reiss, Brian P Schmidt, Robert A Schommer, R. Chris Smith, J Spyromilio, Christopher Stubbs, Nicholas B Suntzeff, and John Tonry. Observational evidence from supernovae for an accelerating universe and a cosmological constant. *The Astronomical Journal*, **116**:1009, Sep 1998.

Appendix A

Appendix Name

Colourless green ideas sleep furiously.