Cosmology with large-area radio and optical surveys

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Outline

- Introduction
- All-sky radio surveys
- Cosmology with continuum
- Cross-correlations
- Summary
1. Introduction
Tracing structure

- Universe filled with density fluctuations
- Structure only visible through galaxies (distribution) and photons (weak lensing)
- Galaxies and photons here are functioning as test particles - tracing out the gravitational field
- Most low-redshift surveys have not measured spectrum of density fluctuations
  - Much more sensitive to transfer functions
- Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)
Most major results have come from CMB (continuous density field, high-redshift) and optical galaxy surveys (discrete density field, low-redshift)
  - Best cosmology experiment existing is still Planck, which is cosmic-variance limited at largest scales

Radio (discrete and continuous density field, low- to medium-redshift) has lacked the number density to be a contender
  - Only 2 million extra-galactic radio sources currently known

Radio has less of a problem with dust obscuration than optical, and observations can be faster
  - Access to very large-scale information, e.g. cosmic dipole, primordial non-Gaussianity

Next generation of radio telescopes will provide large-scale structure data that will be independent and complimentary to optical and CMB experiments
Radio Surveys

- HI galaxy
  - Measures RA, Dec and redshift - Functions like an optical galaxy redshift survey
  - Can also measured peculiar velocities through Tully-Fisher relation
- Continuum galaxy
  - Measures RA, Dec, but not redshifts - Angular clustering survey
  - Cross-correlate with CMB and low-z sample for ISW and cosmic magnification
- HI intensity mapping
  - Measures RA, Dec, z, but no galaxies - delocalised in angular space
  - Can still use it like a spectroscopic survey (BAO & RSD) - competitive with Euclid
- Weak lensing shear
  - Shapes of continuum galaxies, need intensity mapping or similar for redshifts
H1R4: DESI x Tianlai simulations

- N-body simulation
- Halo catalogue
- HI halos
- HI brightness T
- DEC
- RA
- ELG halos
- ELG density
- DEC
- RA

Asorey et al. (2018)

Distribution of hydrogen masses following Eq. 1 using the parameters shown in table 1 which are based on Padmanabhan & Refregier (2017) fit to data.

We assign masses to dark matter halos by following the halo model parameters shown in table 1. We can define the bias of neutral hydrogen, $b_\text{HI}$, as a multiplicative constant that corresponds to the amount of HI hosted in a dark matter halo of mass $M$. In Barnes & Haehnelt (2015); Padmanabhan et al. (2016); Padmanabhan & Refregier (2017), HI foreground will be difficult. Wolz et al. (2014) proposed removing the foregrounds using independent component analysis in frequency space (FastICA).

We used the Horizon Run 4 (Kim et al. 2015) simulations as the initial framework for the neutral hydrogen development. The radial components of the BAO give a direct probe of the Hubble parameter at redshift zero of the this wavelength range has made the optical sources most accessible. However, these will soon reach a natural limit, as the expansion of the Universe will redshift the spectra of these objects out of the observable range, leading to a 'redshift desert' above this wavelength band. However, since the spontaneous hydrogen spin-temperature can be overwhelmed by foreground radio emission at the same optical wavelength band. Therefore, since the spontaneous hydrogen spin-temperature can be overwhelmed by foreground radio emission, we have used the 21cm emission of neutral atomic hydrogen (HI) as the alternative, the 21cm emission of neutral atomic hydrogen (HI). This is an N-body simulation run on a box of $10^5$ Mpc$^3$ while the neutral hydrogen density parameter is:

$$\Omega_{\text{HI}} = 0.16 - 0.63 \times 10^{-3} \Omega_{\Lambda}$$

Distribution of halo masses for halos selected in the expected redshift range for Tianlai.

Table 1.

<table>
<thead>
<tr>
<th>$M_{\text{min}}$</th>
<th>$M_{\text{max}}$</th>
<th>$N(M_{\text{halo}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{12}$ M$_\odot$</td>
<td>$10^{15}$ M$_\odot$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

Kim J., Park C., L'Huillier B., Hong S. E. 2015
Precursors

- **Australian Square Kilometre Array Pathfinder (ASKAP) - SKA Survey**
  - 36 12-metre antennas spread over a region 6 km in diameter
  - frequency band of 700–1800 MHz, with an instantaneous bandwidth of 300 MHz
  - FoV ~ 30deg$^2$, pointing accuracy > 30 arcsec
  - Angular resolution ~ 10 arcsec

- **Murchison Widefield Array (MWA) - SKA low**
  - Tiles of 4x4 dipole antenna (150 MHz)
  - Core area has 50 antenna tiles uniformly distributed over a 100m diameter core, surrounded by 62 tiles, distributed over a 1.5 km diameter circle.
  - Drift-scan, FoV ~30 deg$^2$
  - Angular resolution ~ 2-3 arcmin

- **MeerKAT (Karoo Array Telescope) - SKA mid**
  - 64 13.5m dishes, with 48 concentrated in a 1km core
  - 580 MHz up to 1.65 GHz
  - Field of view ~ 1 deg$^2$
SKA

• SKA-low built in Australia (MWA site)
  • 100 stations, each containing 90 arrays of dipole antenna. Freq: 50-350 MHz

• SKA-mid built in South Africa (Karoo site)
  • 200 dishes, 13.5m diameter. Freq: 350 MHz to 1.76 GHz

• No SKA-survey as part of SKA-1
2. Cosmology in the continuum
Continuum surveys

- Continuum surveys measure intensity of total radio emission, across waveband
- Emission dominated by synchrotron, so spectrum (almost) featureless
- Measure RA and Dec of sources, but need other information for redshift

Chen and Schwarz (2016)
Cosmological Observables

1. Angular correlation function of radio galaxies
2. Cosmic Magnification of high-z radio galaxies by low-z optical foreground galaxies
3. Cosmic Magnification of CMB by radio galaxies
   - Cross-correlation between radio density and CMB on small scales
4. Integrated Sachs-Wolfe effect
   - Cross-correlation between radio density and CMB on large scales

Image credit: Tamara Davis
Correlation functions

- All observables measured through correlations of objects
  - Angular power spectra = correlations of objects in the same bin
  - Magnification = correlations of objects in different bins, or objects with CMB
  - ISW = correlations of objects with CMB

\[ C_{ij}^\ell = \frac{2}{\pi} \int W_i^\ell (K) W_j^\ell (k) P(k) k^2 dk \]

- Need to understand the window function \( W_l(k) \) of different populations

\[ W_l(k) = \int j_l(kr)b(z) \frac{dN(z)}{dz} dr \]

- CMB Window function easy – localised at \( z_{rec} \).
- Galaxy window function more difficult – signal can be confused with number or bias evolution
3. All-sky continuum surveys
EMU (Evolutionary Map of the Universe) is an all-sky radio survey using ASKAP:
- 75% of the sky to declination +30°
- Frequency range: 1100-1400 MHz
  - Same as WALLABY, but EMU is continuum imaging, not 21cm spectroscopy
- 40 x deeper than NVSS
  - 10 μJy rms across the sky
- 5 x better angular resolution than NVSS (10 arcsec)
- Will detect and image ~70 million galaxies
  - All data to be processed in pipeline
  - Images, catalogues, cross-IDs, to be placed in public domain
- Survey starts end 2018
  - Early science has already started
- Total integration time: ~1.5 years
• Early Science Data from ASKAP-12, from 10 pointings
• Covers area inside Dark Energy Survey region
• Cross-identification using likelihood ratio between optical and radio sources (Sevilla-Noarbe, Seymour, Asorey and Parkinson, in progress)
EMU Early Cosmology - Island

![Graph: EMU Early cosmology island: jackknife](image)
EMU Early Cosmology - Component
Histograms

Continuum Component Catalogue

- Poisson prediction

Number of pixels

Number of galaxies

2 4 6 8 10

Continuum Island Catalogue

- Poisson prediction

Number of pixels

Number of galaxies

2 4 6 8 10
Estimators

- “Generally it is assumed that the variance of these estimators is the Poisson error of the bin counts” (Peebles 1980, Landy and Szalay 1993)
  - This is not true if there are double sources, as the bin counts will not be Poisson
- Landy-Szalay or similar is optimal estimator for Poissonian distribution - if not Poisson then not optimal
- Variance and bias of estimator may be underestimated if points are not true tracers, but part of multi-component sources
EMU pilot data

- New pilot data, over 10 fields (rough 270 sq. degs)
- Covers SPT deep field and part of DES
- ~250,000 sources
- Able to cross-correlate with DES and SPT lensing maps
4. Magnification
Cosmic Magnification

- The trajectories of photons are perturbed by the local gravitational potential
- This is gravitational lensing
- **Shear**: the ellipticities of galaxy shapes become correlated with the matter density, integrated over the whole photon trajectory
- **Magnification**: the brightness/surface density of distant galaxies becomes correlated with the matter density integrated over the whole photon trajectory
Magnification and Density

- Measured density field has correction due to gravitational lensing magnification
  \[ \delta_n = \delta_g + \delta_\mu \]
- Effect takes the form of some ‘magnification bias’
  \[ \delta_\mu(\theta, z_0) = (5s(z_0) - 2) \times \int_0^\infty dz \frac{c}{H(z)} g(z, z_0) \nabla^2 \phi(\chi(z)\theta, z_0) \]

Image credit: Song Chen
We consider the EMU survey will a number of different photometric redshift bins

- Two bins and five bins

We compute auto- and cross-angular power spectra, and measure cosmology

How biased is our result if we do not include magnification in cross-correlation?
In the two bin case not including magnification can introduce an offset (higher amplitude, lower hubble rate) compared to the input cosmology, to match the missing boost created by magnification.

This can be reduced by introducing an evolving bias, which matches the data through the nuisance parameter.

The five bin case works in reverse, as an evolving bias can mimic magnification in the high redshift bins, which leads to a predicted power deficit at low redshift.
Modified Gravity

![Graphs showing Modified Gravity parameters](image-url)
5. Cross-correlations
Cross-correlations

- Almost all LSS probes are systematic limited
- Combinations can remove systematics, as well as providing new cosmological tests
- Multi-tracer: Cross-correlating galaxy populations with different bias allows some quantities to be measured without cosmic variance
- Cross-correlating continuum/IM with large-area optical/IR (e.g. LSST) can improve measurement of primordial nonGaussianity/GR effects

Ferramacho et al. (2014)
Raccanelli et al. (2015)
EMU-early & DES

- Improves the cosmology we can do
  - Cosmic magnification require cross-correlation between bins (i.e. two radio bins, high-z radio with low-z optical, high-z CMB with ‘low redshift’ radio sources)
- ISW requires CMB information
- Improves our redshift estimates
  - Clustering redshifts, and photo-z information from optical/NIR counterparts
  - DES will provide photo-z information, to split the EMU sample into redshift bins
Magnification
Summary

• The next generation of radio surveys will make deep surveys over a wide area, approaching their confusion limit
  • Number of detected extra-galactic radio sources will increase to $> 10^8$

• The large volume will allow us to access the matter power spectrum of density fluctuations on the largest possible scales, detecting:
  • the imprint from the initial conditions of the Big Bang (non-Gaussianity)
  • the effect on the propagation of light over large-distances (magnification and ISW)

• This will deliver complementary and independent constraints on the cosmological parameters

• Cross-correlation, with optical/IR data, will increase the detection and utility of the continuum map

• This is a good time to be involved in large radio projects!