[CII] 158 µm line intensity mapping in the Epoch of Reionization (Redshifts 6-8)

Background: Intensity mapping is a technique that measures the spatial fluctuations of signals due to large-scale structure at low spatial resolution. The perhaps best-known example of this application are the temperature and polarization fluctuation maps of the cosmic microwave background (CMB) as measured by COBE, WMAP, and Planck. While CMB maps are integrated along the line of sight, and thus, do not contain three-dimensional information without other assumptions, intensity mapping studies in spectral lines can recover redshift structure (and therefore, measure signals at early epochs as a function of cosmic time).

Compared to other techniques probing the epoch of Reionization (EoR), spectral line intensity mapping thus has the advantage of providing three-dimensional spatial information of the sources of emission (or absorption) that can be used to further understand the processes of structure formation. Intensity maps can also be used as cosmological probes, since the fluctuations in the intensity of emission/absorption lines are correlated with the underlying dark matter density fluctuations.

21cm HI epoch of reionization (EoR) mapping has been proposed as such a pathway a long time ago, but these experiments are very challenging, and contaminated by strong foregrounds. Also, it takes an SKA-like, multi-billion-dollar facility to reach proper mapping capabilities, which will not be ready in the near-term future. There however are proposed complementary and alternative methods to probe the EoR: CO and [CII] intensity mapping. The clear advantage of these methods is that it takes only a single small telescope with a big array of (low spectral resolution) spectrometers to map the signal on few arcmin^2 scales, since the expected signals are much stronger than HI 21cm. One concern for CO is that the observable CO luminosity per unit H_2 mass is strongly affected by metallicity, which is expected to steeply drop in the EoR. Thus, [CII] is perhaps the most promising pathway towards obtaining a tomographic map of the EoR in the near-term future. Compared to the 21cm HI signal, which is primarily sensitive to the intergalactic medium (IGM), [CII] has the advantage that it enables direct mapping of the sources of reionization. Since the goal of this study is to measure the spatially-integrated signal on clustering scales at z~6-8 (few arcmin^2), rather than individual galaxies, this science is carried out more efficiently with small telescopes. Thus, it is a stronger science case for CCAT-p than full CCAT, which will measure the evolution of galaxies by measuring [CII] line emission in individual sources.

Proposed science: CCAT-p will be an ideal telescope to map [CII] fluctuations at z~6-8 (requirement; goal: z~5-9) as a complement to 21cm tomographic mapping of the EoR. The clear advantage of this measurement relative to HI 21cm is that the signal will be much brighter if there are any metals out to z~8. Also, these observations will not be hampered by radio frequency interference (RFI), a major concern for SKA HI surveys. In contrast to other bright diagnostics available at optical wavelengths (e.g., Ly-α, Hα), the [CII] signal will not be subject to absorption due to the increasingly neutral IGM when probing deeper into the EoR, or due to dust extinction in galaxies and along the line of sight. Thus, with CCAT-p, it will become possible to map out the structure of the EoR through the clustering signal from star-forming galaxies and [CII], and thus, to map the distribution and properties of the sources of reionization. Such measurements are currently not possible in other diagnostics, and may even stay out of reach for the James Webb Space Telescope (JWST), since the main sources of reionization are very numerous, but intrinsically extremely faint (e.g., Robertson et al. 2013, 768, 71). However, since intensity mapping detects the aggregate signal from these faint sources, the sensitivity requirements are much less demanding, such that detection of a signal is expected to be possible (see model predictions by, e.g., Gong et al. 2012, ApJ, 745, 49).

Requirements: The goal is to detect the aggregate clustering signal of faint galaxies in the EoR in the [CII] line at rest-frame 158 µm. Since it is not required to detect individual lines from individual galaxies, moderate spectral resolution (R~300-500) will be sufficient. The goal is to detect this signal at z~6-8, which requires coverage of approximately the 210-275 GHz range, with a goal of 190-315 GHz (z~5-9). This spectral range is free of strong atmospheric absorption lines, but given the nature of the signal, atmospheric stability is a key criterion – as readily available at the CCAT-p site. Complete coverage of this bandwidth is critical to reject foreground contamination, most prominently due to CO lines at intermediate redshifts (which are spaced by 115.2712 GHz/(1+z) – and thus, can be rejected by anti-correlation of the corresponding frequencies of neighboring CO lines), and to a lesser degree, other, typically much fainter fine structure lines. The goal is to measure the signal on clustering scales at z~6-8, which corresponds to a few arcmin scales on the sky. Thus, an ideal instrument has of order ~1 arcmin resolution. A 6-m telescope is a great match to this requirement at the low frequency end.

Instrumentation: There are at least three possible approaches to detecting this signal with a telescope like CCAT-p: (1) a Fourier Transform Spectrometer (FTS) mounted on a large camera; (2) a Fabry-Perot on a large camera, or (3) a wide-band, direct detection spectrometer (e.g., SuperSpec technology), with tens of spatial resolution elements on the sky. Table 1 below provides predictions for example surveys carried out with a 6 m telescope and other possible telescopes of three different aperture sizes for reference. With a large enough instrument, detection of the signal could be possible in hundreds of hours, but surveys of significant cosmological volumes to match the SKA HI surveys will require a significant, multi-year effort even in an optimistic part of the parameter space.

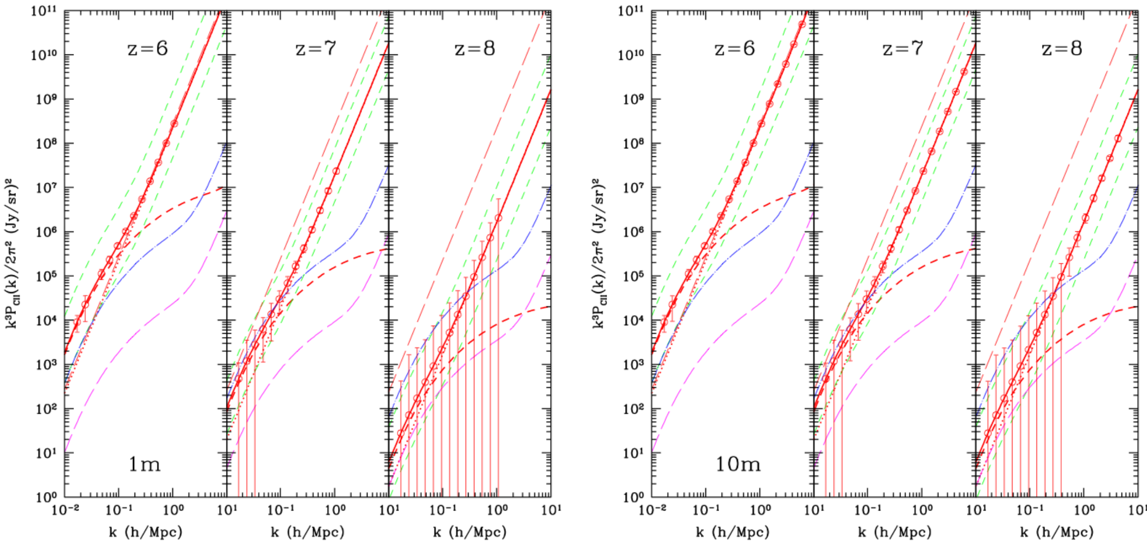

Figure 1: Model predictions for clustering, shot-noise, and total power spectrum of the [CII] emission line at z = 6, z = 7, and z = 8, adopted from Gong et al. (2012). The red solid, dashed, and dotted lines denote the [CII] total, clustering, and shot-noise power spectrum, respectively. The green dashed lines are the 1σ error of the [CII] power spectrum. The error bars and noise power spectrum (red long-dashed line) in the top left and top right panels are estimated assuming telescopes of 1 m and 10 m aperture, respectively. The magenta long dashed line is derived from the [CII] luminosity estimated by Visbal & Loeb (2010), JCAP, 11, 016. The blue dash-dotted line is estimated by assuming $L_{CII}/L_{CO(1-0)} \simeq 10^4$.

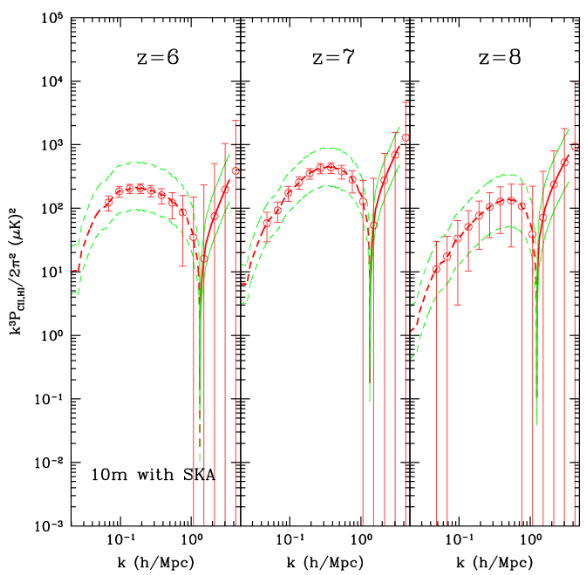

Figure 2: Model predictions for the cross power spectrum of the [CII] and HI 21 cm emission lines at z = 6, z = 7, and z = 8, adopted from Gong et al. (2012). Red dashed lines denote negative correlations, and red solid lines show positive correlations. The 1σ errors are shown as thin red lines. The error bars in the left panel are estimated using a (sub-) millimeter survey with a 10 m aperture telescope for the [CII] line and SKA for HI 21 cm.

Table 1: Predictions for different instrumental parameters, based on the predictions by Gong et al. (2012). A 6 m telescope would be an ideal basis for this experiment.

Experimental Parameters for a Possible C II Mapping Instrument

			CCAT-p	
Aperture Diameter (m)	1	3	6	10
Survey Area (A_S; deg^2) *e.g., deep HyperSC fields: COSMOS, UDS*	16	16		16
Total integration time (hours)	4000 ~1.5yr *(8-10hr/day)*	4000		4000
Free spectral range (B_ν; GHz)	185–310	185–310		185–310
Freq. resolution (δ_ν; GHz)	0.4	0.4		0.4
Number of bolometers	20,000	20,000	(same)	20,000
Number of spectral channels	312	312		312
Number of spatial pixels	64	64		64
Beam size[a] ($\theta_{\rm beam}$; FWHM, arcmin)	4.4	1.5	0.75	0.4
Beams per survey area[a]	2.6×10^3	2.3×10^4	9.4×10^4	2.6×10^5
$\sigma_{\rm pix}$: Noise per detector sensitivity[a] (Jy$\sqrt{\rm s}$/sr)	2.5×10^6	2.5×10^6	2.5×10^6	2.5×10^6
$t_{\rm pix}^{\rm obs}$: Integration time per beam[a] (hours)	100	11	3	1.0
$z = 6$ $V_{\rm pix}$ (Mpc h^{-1})^3	217.1	24.1	7.5	2.2
$z = 7$ $V_{\rm pix}$ (Mpc h^{-1})^3	332.9	37.0	9.2	3.3
$z = 8$ $V_{\rm pix}$ (Mpc h^{-1})^3	481.3	53.5	13.4	4.8
$z = 6$ $P_N^{\rm C\,II}$ (Jy sr^{-1})^2 (Mpc h^{-1})^3	5.4×10^9	5.4×10^9		5.3×10^9
$z = 7$ $P_N^{\rm C\,II}$ (Jy sr^{-1})^2 (Mpc h^{-1})^3	4.8×10^9	4.9×10^9	(same)	4.8×10^9
$z = 8$ $P_N^{\rm C\,II}$ (Jy sr^{-1})^2 (Mpc h^{-1})^3	4.4×10^9	4.4×10^9		4.3×10^9

Note. [a] Values computed at 238 GHz, corresponding to C II at $z = 7$.