EXCLAIM - Novel Line Intensity Mapping on a Balloon Borne Telescope

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Abstract

Line intensity mapping (LIM) is a new and cost-efficient technique to study different astrophysical processes within our universe. LIM measures the collective emission from all sources in a region of the sky at a particular frequency. Distinguishing the line emission from different emission lines and redshifts is important for studying different astrophysical processes, such as star formation. The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) will be a balloon borne experiment that aims to study star formation by mapping the intensity of singly ionized carbon [CII], and carbon monoxide CO transition lines. Building high fidelity simulations is required to develop the analysis pipeline when data is available.

1 Introduction

1.1 Line Intensity Mapping

Line intensity mapping (LIM) is a novel technique that detects the sum of all sources emitting at a particular spectral line in a given pixel. These are 3-dimensional maps that probe emissions at different redshift slices simultaneously (see Fig.1). Instead of resolving individual galaxies, LIM collects all the photons emitted, including those emitted by sources that are too dim to detect individually. By measuring the spectral fluctuations in these emissions, LIM can be used to understand galaxy formation and evolution, star-formation history, metal/dust build-up in galaxies, identify background light sources, and to study different cosmological models in hopes of uncovering new physics (Switzer et al., 2021). LIM is a very cost effective approach for large area surveys compared to direct detection of individual galaxies (Switzer et al., 2021).

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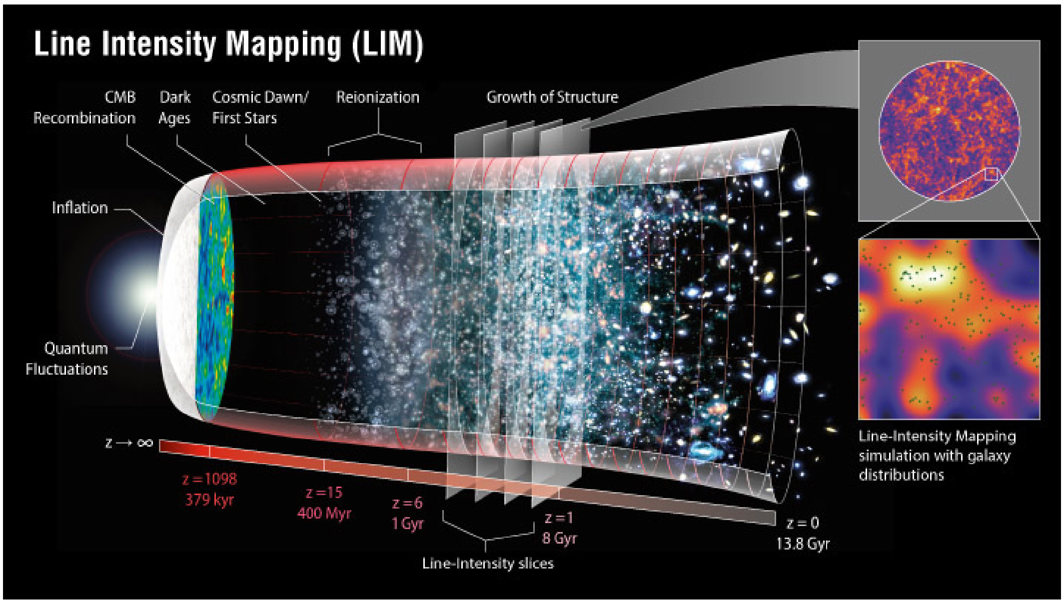


Figure 1: Diagram showing spectral line intensity mapping at different redshift values and highlighting the growth of large-scale structure in the universe (credit: NASA / LAMBDA archive team) (Aeronautics and Administration)

The spectral line of singly ionized carbon ([CII] emission at rest wavelength 158 m) is a good line of LIM studies. [CII] is one of the brightest emission lines in star forming galaxies and appears in the mm-IR regime near $z \approx 2$ where galaxies are most actively forming stars (cosmic noon) (Pullen et al., 2022).

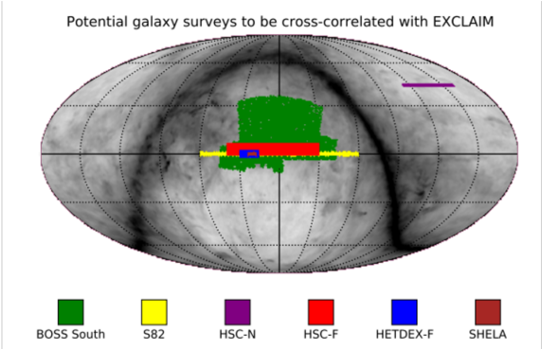
1.2 EXperiment for Cryogenic Large-Aperture Intensity Mapping

The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) is a balloon-borne cryogenic telescope that will perform line intensity mapping surveys on diffuse emissions from the Milky Way and the cosmic-web to study star formation and galaxy evolution. The main emission lines interest are the singly ionized carbon line transition, [CII] (also known as C+) over redshift $z = 2.5 - 3.5$ and carbon monoxide CO transitions over $z \leq 1$ to model foreground contamination (Pullen et al., 2022). EXCLAIM is sensitive over the $420 - 540$ GHz frequency range, and the telescope will map 100 deg^2 in the galactic plane and 320 deg^2 outside the galactic plane coinciding with Stripe-82 (Pullen et al., 2022). The balloon-borne design was chosen as opposed to a ground-based experiment in order to avoid atmospheric foregrounds that would otherwise dominate the spectrum (see Fig.2).

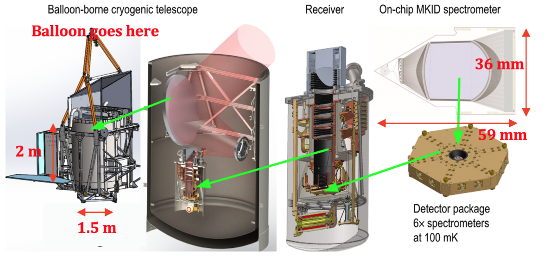
2 Materials and Methods

2.1 Limlam Mocker: A package for line intensity mocks

Limlam mocker, written by George Stein with numerous additions by Dongwoo Chung and publicly available on Github (`https://github.com/georgestein/limlam_mocker`), is code that is used to create mock line intensity maps with galaxy halo catalogues as



(a) A celestial map of galaxy surveys that coincide in observing region with the EXCLAIM Stripe-82 band.(Pullen et al., 2022)



(b) Diagram of the EXCLAIM telescope consisting of the balloon platform, gondola containing the optics and electronics, and the liquid He bucket dewar.(Switzer et al., 2021)

Figure 2: EXCLAIM survey plan and telescope design.

input that uses only the NumPy and SciPy libraries (Stein and Chung). The halo catalogues contain information about the halo's mass in $M_{\odot}$, positions in comoving Mpc, velocities in km/s, observed and formation redshifts, and the cosmological information used to generate the catalogues. Limlam mocker takes the individual halo information in the catalogues and computes the halo luminosity using user defined luminosity functions. For this project, the [CII] luminosities were computed using the Padmanabhan 2019 model in (Padmanabhan, 2019), and the CO transition luminosities with the Li/Keating model (Li et al., 2016)(Keating et al., 2020). The luminosity is then used to create 3-dimensional intensity maps with frequencies along the z-direction.

2.2 mass-Peak Patch simulated halo catalogues

The simulated halo catalogues were provided by the Canadian Institute of Theoretical Astrophysics (CITA) using the mass-Peak Patch method to create mock halo distributions (originally used for the COMAP experiment) (Stein et al., 2018). We are collaborating with CITA to produce simulations of halo catalogues that fall within the EXCLAIM band. We currently have access to 192 CO cubes spanning $0.1 \leq z \leq 1.0$, and 160 [CII] cubes spanning $2.5 \leq z \leq 3.6$, which we are using to develop our analysis pipeline.

In order to make realistic simulations of the data that EXCLAIM would collect, we need to account for various other emitting sources and instrumental effects that can contaminate our underlying [CII] signal.

2.3 Instrument beam

Given the finite angular resolution of the EXCLAIM beam due to diffraction effects, we need to convolve our intensity maps with a Gaussian beam with a beam width of 3.5 arcmin, which corresponds to the beam width for EXCLAIM. The beam samples in pixels 1/3 in FWHM in the scan and drift directions (Pullen et al., 2022). The Gaussian takes the following form:

$$\text{Gaussian} = \exp(-0.5 * (\frac{R}{\sigma_{beam}})^2)$$

$$\sigma_{beam} = \frac{\text{FWHM}_{beam}}{\sqrt{8 \ln 2}}$$

where $R = \sqrt{X^2 + Y^2}$, X and Y are the angular pixel positions along the x and y directions in the 2x2 deg^2 region in the maps that we are simulating (McMahon and Hlozek). Here, $\text{FWHM}_{beam} = 3.5$ arcmin.

2.4 CO interloping lines

Since line intensity mapping collects all photons at a particular frequency, our signals will have contaminants from spectral lines other than [CII] with the same redshifted frequency. The CO(J=7-6), CO(J=6-5) and CO(J=5-4) with redshift $z \leq 1$ coincide in frequency with the EXCLAIM frequency band. We need to add simulated intensity maps of these CO interloper lines with the simulated [CII] maps. We expect the signal from these CO interloper lines to be much smaller than that of [CII] at these frequencies. The CO luminosities in limlam mocker are calculated using the Li/Keating model (Li et al., 2016)(Keating et al., 2020).

2.5 Milky Way foregrounds

Another major contaminant are Galactic foregrounds. For our mock intensity maps, will include thermal dust as a single-component modified black body to simulate the foregrounds in the EXCLAIM frequency band and add them to the [CII] maps. We use PySM to generate the full-sky simulations of galactic foregrounds. The code is publicly available on Github: `https://github.com/bthorne93/PySM_public` and developed by B. Thorne et. al (Thorne et al., 2017). A full-sky Mollweide projection of the thermal dust galactic foregrounds as modeled with PySM is shown in (Fig.3) in celestial coordinates.

2.6 Instrumental noise

One other source of contamination comes from instrumental noise and is the long-timescale drift in gain of the telescope in response to receiving intensity signals. Different processes contribute to this drift including temperature fluctuations and changes in behavior of external noise sources, etc. These processes are grouped together and called 1/f noise. We hope to use Crawford 2007 (Crawford, 2007) in helping us develop a frequency dependent noise model for EXCLAIM that will account for 1/f noise in our simulations.

2.7 Analysis tools

Here we will review some of the current analysis tools used in line intensity mapping experiments, such as the 3D power spectrum. We will also introduce a new tool to study intensity maps called the voxel intensity distribution (VID) that is a complementary tool to the power spectrum (Breysse, 2022).

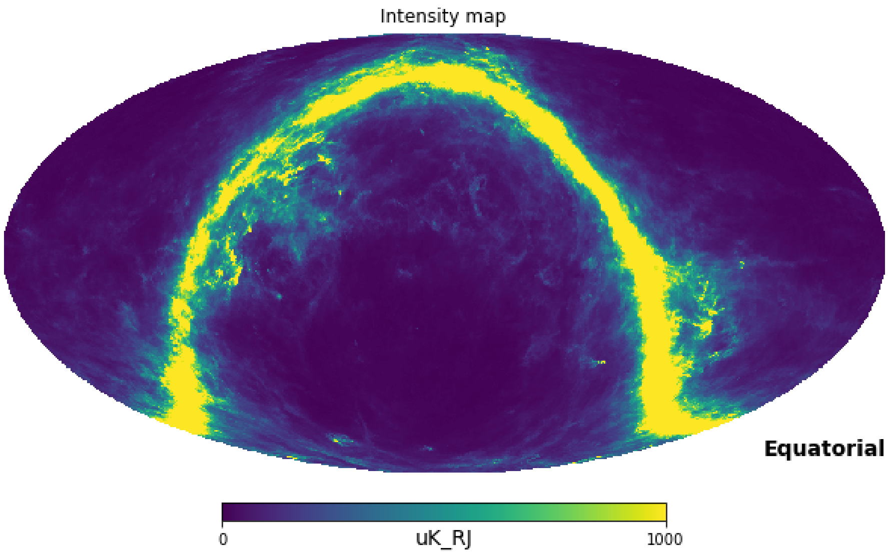


Figure 3: Galactic thermal dust foregrounds in Mollweide projection generated with PySM in a celestial coordinate system. The intensity values have been scaled from the original [353 - 7.25e+04]μK_{RJ} to [0 - 1e+03]μK_{RJ} on the color bar scale to allow ease of visibility of the structures.

2.7.1 *Power spectrum*

The power spectrum of an intensity map provides the total power present in different Fourier modes of the line fluctuations:

$$P(k) = \bar{T}^2 \bar{b}^2 P_m(k) + P_{shot}$$

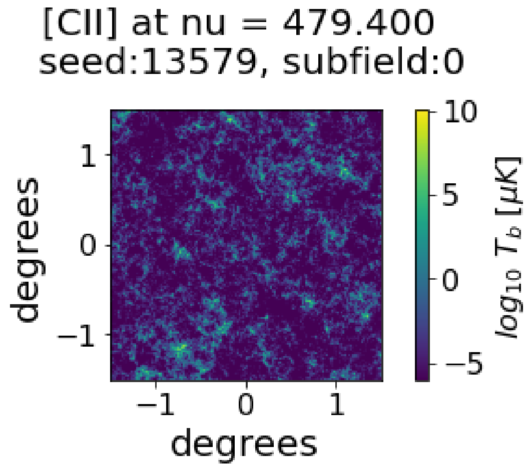
where $P_m(k)$ is the underlying matter power spectrum, $\bar{T}$ is the mean intensity of the target spectral line, $\bar{b}$ is the luminosity weighted bias of the emitting galaxies, and P_{shot} is the scale independent shot noise due to the discreteness of the emitting sources (Breysse, 2022). By assuming a spectral luminosity function, $L(M)$ and measurements of luminosities of emitting sources through LIM, we can find $P_m(k)$. The details of how to infer $P_m(k)$ from $L(M)$ and halo luminosities is explained in (Breysse and Alexandroff, 2019).

2.7.2 *Motivating voxel intensity distributions (VID)*

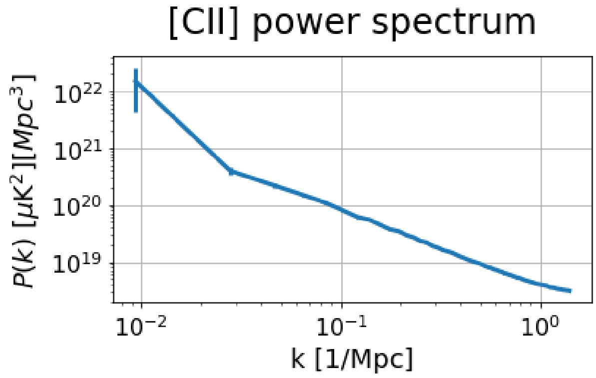
There is a key limitation when it comes to using power spectra to study intensity maps, and it is that the mean line intensity $\bar{T}$ is degenerate with the bias term $\bar{b}$. It is usually impossible to measure $\bar{T}$ by itself from an intensity map without first inferring a model for the bias (Breysse, 2022). The voxel intensity distribution (VID), which is a one-point analysis, is a complementary method to the power spectrum that allows for the breaking of this degeneracy and will serve as another possible analysis tool. The details of how to derive and use the VID are highlighted in (Breysse, 2022).

3 Key Results

Using the halo catalogues and the limlam mocker code, we produce different realizations of [CII] data cubes that fall within the EXCLAIM frequency band (see Fig.4).



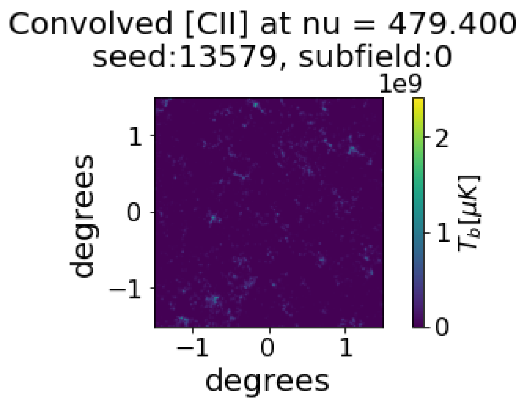
(a) Central slice of [CII] line intensities for one halo catalogue realization. Intensities plotted on the log scale to help with visualization.



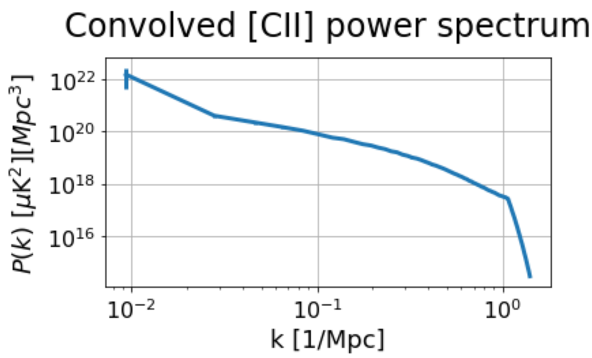
(b) 3D power spectrum of the [CII] intensities of the full data cube shown on the left.

Figure 4: [CII] line intensity map of central frequency slice in the EXCLAIM band and its corresponding 3D power spectrum.

Once we made intensity maps of [CII] we convolved the map with a Guassian beam of beam width 3.5 arcmin where the beam samples in 1/3 of FWHM in scan and drift directions (see Fig.5). Convolving the beam eliminates some of the higher k-modes from the original power spectrum.



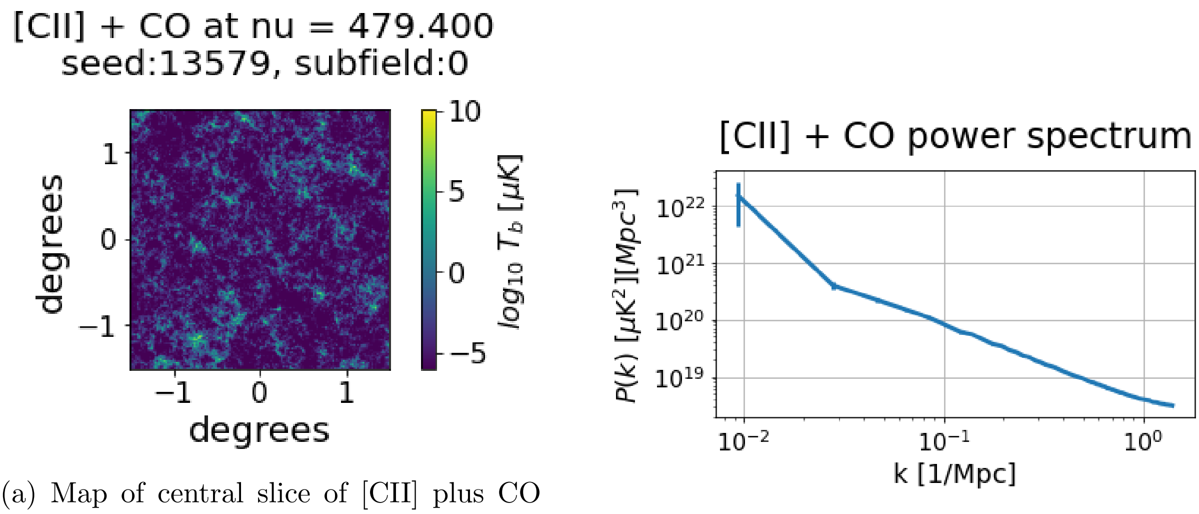
(a) Central slice of [CII] map convolved with a Guassian beam for one of the halo catalogue realizations.



(b) Corresponding power spectrum of the [CII] convolved map shown on the left.

Figure 5: The Gaussian beam convolved intensity map and corresponding power spectrum.

Next we add the mock intensity maps of the interloper CO transition lines that overlap in frequency with the [CII] maps (see Fig.6). The CO signals do not affect the map and power spectrum by very much. This is expected since the CO signal is expected to be much weaker than the [CII] signal at the EXCLAIM frequencies.

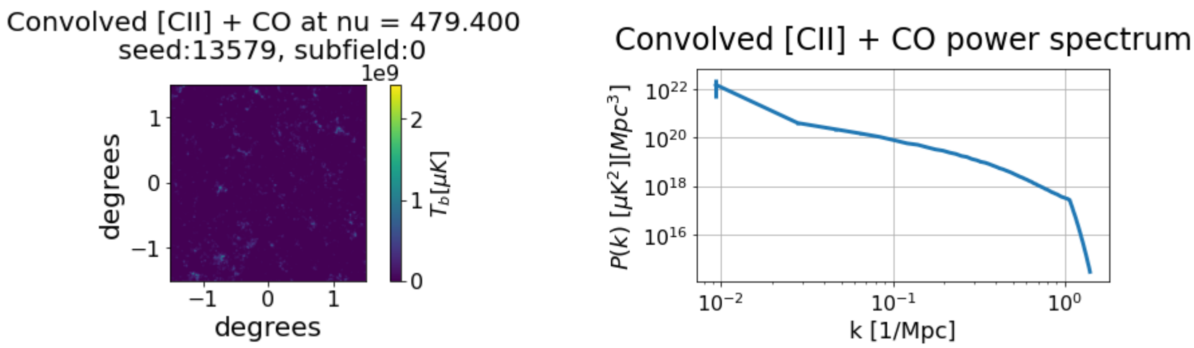


(a) Map of central slice of [CII] plus CO interlopers 3D intensity map. Plotted on a log10 scale to help with visualization.

(b) 3D power spectrum of the [CII] plus CO interloper intensity map shown on the left.

Figure 6: Intensity map and corresponding 3D power spectrum of [CII] plus CO interlopers for a single realization.

We convolve the [CII] plus CO interloper map with a Gaussian beam of the same characteristics as before and compute its power spectra (see Fig.7). The higher k-modes again drop off.



(a) Map of central slice of [CII] plus CO interlopers 3D intensity map convolved with a Gaussian beam.

(b) 3D power spectrum of the [CII] plus CO interlopers intensity map convolved with a Gaussian beam shown on the left.

Figure 7: Intensity map and corresponding 3D power spectrum of [CII] plus CO interlopers for a single realization convolved with a Gaussian beam.

4 Discussion

Line intensity mapping is a new and growing field in cosmology that studies the collective spectral line emission at a particular frequency, or range of frequencies in a given pixel in the sky. By studying the fluctuations in these emissions, we can learn a lot about different processes in our universe (Switzer et al., 2021). One novel line intensity mapping experiment is the EXperiment for Cryogenic large-aperture intensity mapping experiment (EXCLAIM) which will map the singly ionized carbon line transition, [CII] over $z = 2.5 - 3.5$, and several carbon monoxide transition lines: CO(J=7-6), CO(J=6-5) and CO(J=5-4) over $z \leq 1$. EXCLAIM will be sensitive in the 420 - 540 GHz frequency range and will map 100 deg^2 in the galactic plane, and 320 deg^2 outside the galactic plane along Stripe-82 (Pullen et al., 2022).

We are developing the analysis pipeline in preparation for first flight by creating mock simulations of intensity maps. The mass-peak patch method is used to create the halo catalogues for the mock line intensity maps of [CII], and the maps are generated with Limlam mocker. So far we have added the CO interloper lines, and have convolved the maps with a Gaussian beam of beam width 3.5 arcmin, and sampling rate in pixels 1/3 in FWHM in the scan and drift directions. From these maps, we again used Limlam mocker to make plots of the 3D power spectrum. In the future, we hope to incorporate galactic foregrounds generated with PySM and add in instrumental noise to our mock intensity maps. We also plan to incorporate the VID into our analysis pipeline and see how it compares to the 3D power spectrum.

Despite its enormous potential, LIM has not yet been demonstrated to work except in cross-correlation with existing galaxy redshift surveys. EXCLAIM will serve as a pathfinder in establishing the potential of LIM to be a new tool in observational cosmology. My simulations analyzed with the flight data will help to establish LIM as a future observational tool in cosmology studies.

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