Onsala Proposal

Knudsen 0108.F-9312

[CII] intensity mapping survey of the reionization and post-reionization epoch with CONCERTO

Semester: may2021 **Science Cat.: Cosmology**

Abstract

We propose to conduct a major survey of 1.4 sq. deg. in the COSMOS field with CONCERTO to map the fluctuations of the [CII] line intensity, through the reionization epoch. Our survey will exploit the "intensity mapping" technique which probes cosmic structures by measuring the aggregate line emission from all galaxies across redshift. The [CII] line is a promising choice for its brightness and its role as a tracer of star-formation activity. Our survey will give the first constraints on the power spectrum of [CII]-emitting galaxies at z>5, allowing us to measure : (i) the star formation rate density, (ii) the number counts of [CII]-emitters, (iii) the typical halo mass scale and the average ISM conditions in high-z star-forming galaxies. Our survey also measures the CO and [CI] intensity fluctuations arising from z<2.5 galaxies, yielding the spatial distribution and abundance of molecular gas at cosmic noon. Cross-correlation with multi-wavelength data will be used for [CII] foreground removal and will provide information as on early metal enrichment and global reionization history.

Applicants

Name	Affiliation	Email	Country		Potential observer
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Applicants are continued on the last page

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		Remarks	Country: Sweden.

Is this a long term proposal: Yes

Large program with CONCERTO. Proposals are submitted to all partners with the ti
me distribution of 600h ESO, 300h Chile, 200h OSO, 100h Max Planck.
The request is for three semesters, so ~ 70 hours per semester.
The CONCERTO team will provide continuous support and will operate the instrumen
the long term specifics are continued on the last page

Overall scheduling requirements

the field is in the Sun Avoidance zone from July, the 25th to September, the 24th.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	Visitor instrument	70h (200h)		any	04-16	CONCERTO. Request for 200hours total, distributed over three semesters. The field is in the Sun Avoidance zone from July, the 25th to September, the 24th. Weather: up to 2.5mm!

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
COSMOS field	10:00:28.60	+02:12:21.0	J2000	0.0	4200	A	Survey 1.4 square degrees.

Scientific Rationale

The final frontier in piecing together a coherent picture of cosmic history relates to the period 300-900 million years after the Big Bang (redshifts $6 < z < 15$). During this period, the Universe underwent two major changes. Firstly, the earliest stars and galaxies began to shine, bathing the Universe in starlight. Secondly, the intergalactic medium transitioned from a neutral to a fully ionized gas, an epoch known as the reionization (EoR). Connecting these two changes is critical. Recent breakthroughs showed that reionization occurred at $6 < z < 10$ (Planck collaboration 2016) and that star-forming galaxies likely dominated the reionization process (e.g., Robertson+15). An other key result of the last decade has been the determination that the co-moving star formation rate (SFR) density at redshifts z∼1-4 is about an order of magnitude higher than present-day. Half of the energy produced was absorbed and reemitted by dust, at $\lambda \sim 100\mu$m-1mm (Dole et al. 2006), in dusty star-forming galaxies (DSFG). Today, only few DSFGs are known at $z > 5$ (e.g., Riechers+13, Strandet+17), and therefore the EoR is largely an uncharted territory for these studies. **What is the contribution of the dust-enshrouded star formation and metal enrichment at $z > 5$, and what is the role of star-forming galaxies in shaping cosmic reionization? These are fundamental questions our CONCERTO survey will address**.

The FIR-bright fine-structure [CII] emission line (157.7 μm) has been recently used as a workhorse for detecting the ISM at $z > 4$ (>150 detections to date at $z > 4.5$; see a compilation in Schaerer+20). [CII] is an excellent tracer of star formation and metal enrichment at all cosmic epochs, out to at least $z \sim 8$ (e.g. Vallini+15, Lagache+18a, Schaerer+20). However, most of the current [CII] detections at high z have been done in targets preselected in the rest-frame UV or IR (e.g. as in the ALPINE survey; Béthermin+20), thus missing the bulk population of galaxies in the early universe, and being biased by nature. The advent of ALMA spectroscopic surveys, such as the ASPECS (e.g. Walter+16; Aravena+16, +20) and ALCS (Fujimoto+21) large programs are yielding unique 3D surveys of the [CII] line emission in the early universe ($z = 6 - 8$). However, these are limited by the small covered areas (unlensed ∼4 arcmin^2 each), thus resulting in large uncertainties due to cosmic variance (Béthermin+21, Keenan+21, and see an illustration in Fig. 1). To understand the connection between the formation of large-scale structures and star formation in situ, unbiased surveys of the [CII] line emission over large cosmological volumes are essential.

We propose to conduct a major survey of about 1.4 square degrees to map in 3D the fluctuations of the [CII] line at $z > 5$ in the COSMOS field. The [CII] survey will start in P108 and will last 3 semesters. The time share between APEX partners and Chile will give a grand total of 1,200 hours of observation. The survey will provide a spatial-spectral data cube in which intensity is mapped as a function of sky position and redshift. The 3-D fluctuations will then be studied in Fourier space with the power spectrum. Some of our main objectives are:

- [CII] measurements and early star formation: We will provide the first constraints on the power spectrum of star-forming matter as traced by [CII] (Fig. 2). At large and intermediate scales, clustering dominates the power spectra, including the linear (clustering between galaxies in different dark-matter halos) and non-linear (clustering within a single dark-matter halo) term. We will model the clustering using empirical physical models or semi-analytical models, as those developed for the Cosmic Infrared Background (CIB) anisotropies analysis (e.g. Béthermin+17, Maniyar+21). With these models, we can uniquely constrain the star-formation rate density (SFRD) at $z > 5$, probe the cosmic metal evolution and provide in particular the typical halo mass scale of star-forming galaxies. These are essential ingredients for our understanding of galaxy evolution. Additionally, we will measure the luminosity function of [CII]-emitters as a function of redshift (Yue & Ferrara+19, Sun+21), which is poorly known (Yan+20, Loiacono+21) and the evolution of the mean [CII] line emissivities with redshift, which will be combined with multi-wavelength data to probe the properties of the reionizing population, the global history of reionization and the topology of the ionized regions. Our models that are describing the statistical properties of the [CII]-emitting galaxies will be physically driven by state-of-the-art hydrodynamic simulations developed by our collaborators (e.g. Pallottini+17, Behrens+18, Lupi+20).

- Gas content of galaxies at cosmic noon: The survey will also measure the CO and [CI] fluctuations at $z \leq 2.5$. This is a chance for investigating the star formation and gas content of galaxies (e.g., Riechers+19, Aravena+20). Cross-correlating 1) multiple CO transitions available in the CONCERTO bandpass and 2) lines emission with the spectroscopic samples of galaxies (with a total of 50,000 galaxies with z_{spec} <2.5 in the COSMOS field), we will measure the density and temperature of the gas in normal galaxies, the average relation between SFR and the molecular gas content, and detect potential large-scale reservoirs missed by interferometer measurements (Emonts+16). All these cross-correlations are straight forward and immediate results are guaranteed. We also illustrate on Fig. 3 how the contamination from these foreground lines will be mitigated for [CII].

Facilities Requested

We propose to use the CONCERTO instrument (CONCERTO+20) that has been successfully installed at APEX (starting on April, the 6th) and that is currently being commissioned. CONCERTO will be the first and only instrument in the world to perform intensity mapping of the [CII] line on a large field before the advent of the Fred Young Submm Telescope (FYST). The novel methodology targets an unexplored parameter space of observables on some of the fundamental processes in the early Universe. The project is extremely timely: with the kinetic inductance detectors and their very small time constants, a Martin-Puplett Interferometer operating faster than the atmospheric noise can now be used to get the spectra.

Observing Requirements

Sensitivities measured in lab have already been achieved on sky (among others: noise level, interferometric efficiency) and presented on May, the 6th to the APEX board. Accordingly, we used the computations detailed in CONCERTO+20 to determine the expected sensitivity of our survey. Our time request is fixed such as to detect the [CII] power spectrum at z=8 with SNR∼3. We consider 30% of overheads (focus, pointing, beam maps, calibration, tuning of the KIDS) and thus t_{survey}=840 hours for a total observation time equals to 1,200 hours. Table 1 summarises the survey characteristics. The [CII] survey is a large program shared between partners. Currently, the time distribution is 600h ESO, 300h Chile, 200h OSO, 100h Max Planck.
An ESO proposal of 600h has already been submitted in P104 when the APEX board requested the OPC to give a scientific judgement as to whether the science case warrants to proceed with the installation of CONCERTO at APEX. It was successful, with the following OPC comments: "This is a very strong proposal with clear and exciting scientific goals. CONCERTO will bring new life to APEX, particularly in the ALMA world. As such, this is a very interesting instrument and its installation should be supported."

References

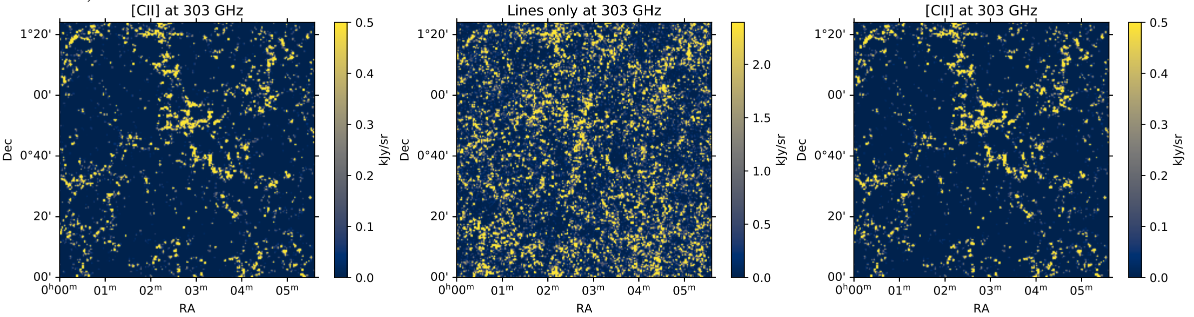
Aravena+16 ApJ 833, 71 • Aravena+20, ApJ, 901, 79 • Béthermin+17 A&A 607, 89 • Béthermin+20 A&A 634, 2 • Béthermin+21 to be submitted • Behrens+18 MNRAS 477, 552 • CONCERTO collaboration 2020, A&A 642, 60 • Chung+20 ApJ 892, 51 • Decarli+20 ApJ 902, 110 • Emonts+16 Sci 354, 1128 • Fujimoto+21, ApJ, 911, 99 • Keenan+21 ApJ 904, 127 • Laigle+16, ApJS 224, 24 • Lagache+18a A&A 609, 130 • Lagache+18b arXiv:1801.08054 • Loiacono+21 A&A 646, 76 • Lupi+20, MNRAS, 496, 5160 • Maniyar+21 A&A 645, 40 • Pallottini+17 MNRAS 471, 4128 • Perotto+20 A&A 637, 71 • Planck collaboration+16, A&A 596, 108 • Ponthieu+11, A&A 535, 90 • Riechers+13, Nat. 496, 329 • Riechers+19, ApJ 872, 7 • Robertson+15, ApJ 802, 19 • Schaerer+20, A&A 643, 3 • Strandet+17, ApJ 842, 15 • Sun+21 arXiv:2012.09160 • Vallini+15 ApJ 813, 36 • Yan+20 ApJ 905, 147 • Yue & Ferrara+19 MNRAS 490, 1928 • Walter+16 ApJ 833, 67

Table 1. CONCERTO [CII] survey characteristics. Signal to noise ratios (SNR) on the [CII] power spectrum are computed for Δz=0.6 and given for k=[0.1,1] h/Mpc and t_{survey}=840 hours (which corresponds to a total observation time of 1,200 hours taking into account the overheads). Numbers in brackets reflect a range of expected sensitivities (before on sky measurements), as given in Table 2 of CONCERTO+20.

Round FOV, Diameter [arcmin]	20
Spectral range [GHz]	130 - 310
Frequency resolution δ_ν [GHz]	1.5
Survey Area [deg^2]	1.4
Observation Time [hours]	1,200

Redshift	z=5.5	z=6.2	z=7	z=8
$\nu_{[CII]}$ [GHz]	292.5	264.0	237.6	211.2
Beam size [arcsec]	23.4	26.0	28.9	32.5
On sky sensitivity (MJy/sr)$\sqrt{sec}$	17.1 [11.4-22.8]	13.9 [9.3-18.6]	10.4 [7.1-14.1]	7.3 [5.1-10.2]
SNR $P^{[CII]}$ mean SFRD	23 [14-44]	12 [6.9-24]	5.7 [3.1-12]	2.0 [1.0-4.1]
SNR $P^{[CII]}$ low SFRD	4.5 [2.6-9.8]	1.9 [1.1-4.3]	0.78 [0.48-1.7]	0.23 [0.12-0.48]
SNR $P^{[CII]}$ high SFRD	79 [57-112]	55 [36-87]	34 [21-60]	16 [8.5-29]

Figure 1. SIDES simulation (1.4×1.4 deg^2) at 303 GHz (z=5.3 for the [CII] line). From *left* to *right*: continuum emission + lines (CO, [CI], [CII]), lines only, and [CII]. The SIDES simulation was initially designed to reproduce the continuum properties of galaxies from the far-IR to the millimetre (Béthermin+17). In order to obtain a realistic clustering, Béthermin+17 started from dark-matter simulations and populated them with galaxies using abundance matching and observed empirical relations. The new version (Béthermin+21) includes predictions for the [CII] lines, calibrated using the recent results from the ALPINE survey (Béthermin+20, Schaerer+20). The main foreground lines (CO and [CI]) are also included and their resulting luminosity functions are in good agreement with current constraints from ALMA (e.g., ASPECS: Decarli+20). SIDES simulations are also extended to a much larger area of 100 Sq. Deg. (private comm.).



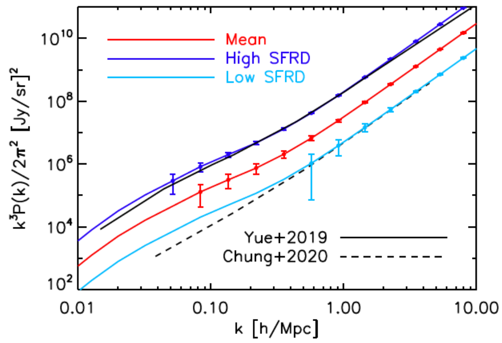


Figure 2. Predicted [CII] power spectrum at z=6. Three cases are shown, corresponding to three scenarios of SFRD at high z (Lagache+18b): high SFRD (dark blue), low SFRD (light blue), and the geometrical mean of the two (red). Only points with SNR>1 are shown. SNRs were computed considering an area of 1.4 square degrees and t_{survey}=840 hours. The [CII] power spectra were derived from the modelling of CIB power spectra (Serra+16), using a conversion from SFR to [CII] that conservatively underestimates the [CII] luminosity by a factor of 6 at z=5 compared to recent semi-analytical models (Lagache+18a) or ALMA ALPINE measurements (Schaerer+20). Our estimates of [CII] power spectra are thus likely to be underestimated. The predicted [CII] power spectra from Yue+19, using the local SFR-[CII] relation (black line) and Chung+20 (dashed black line) are also shown.

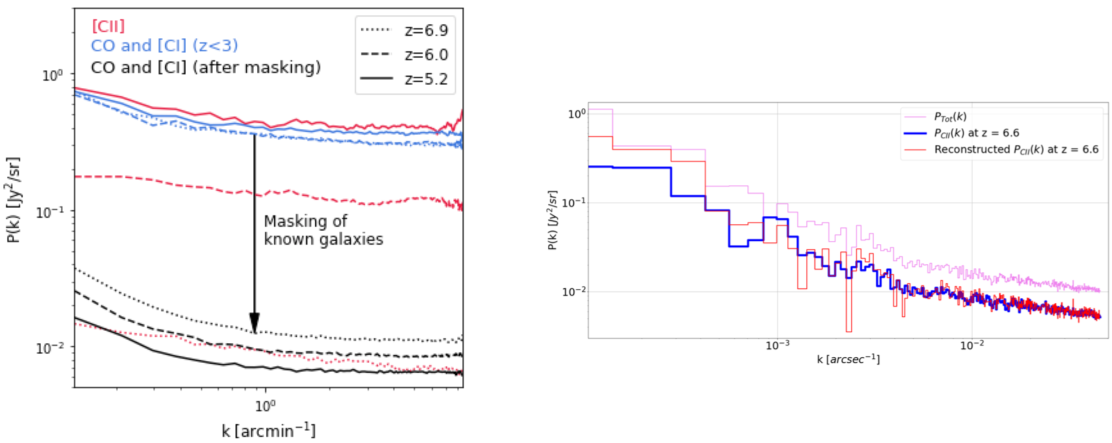


Figure 3. Illustration of foreground line emission removal for the [CII] survey using two methods: masking known galaxies (*left*) and internal cross-correlations (*right*).
Left: Power spectra of [CII] at z=5.2, 6.0 and 6.9 (continuous, dash, and dot red curves) and CO and [CI] interlopers at lower redshifts (at $z < 3$ at the frequency of the [CII] lines, blue curves). Also shown is the reduced CO+[CI] contamination (dark curves) obtained by masking known galaxies in the COSMOS field with stellar mass above the completeness threshold of Laigle+16 (that is varying with redshift). Note that the masked voxels represent a fraction of the map area at each frequency that is small enough (∼20%) to still allow to measure the power spectra (but using a dedicated algorithm as PoKER, Ponthieu+11).
Right: First attempt of removal of the CO contamination by using the cross-correlations of the different CO lines at a given redshift. The figure shows the original and reconstructed [CII] power spectrum at z=6.6 using this technique (blue and red curves, respectively). At a given [CII] redshift (and thus frequency), the CO contamination is measured from the cross-correlation of the CONCERTO maps at this frequency with the maps at frequencies of higher and lower rotational levels J.
These results have been obtained with the SIDES simulations (Béthermin+21) and contain a dispersion in the spectral line energy distributions as measured by high-z observations.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Mathilde Van Cuyck	Doctor	Yes	Prof Guilaine Lagache	Yes	2023/10	Yes
Athanasia Gkogkou	Doctor	Yes	Matthieu Bethermin	Yes	2023/11	Yes

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: Yes

Proposals are submitted to all partners with the time distribution of 600h ESO, 300h Chile, 200h OSO, 100h Max Planck. Total observing time with this combination is 1200h.

Relevant previous Allocations: No

Additional remarks

ESO=KKNUDSEN

ESO=glagache

Observing run info :

Applicants

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Large programme proposal specifics continued from page 2 :

t during the observations.