Peering towards Cosmic Dawn
Proceedings IAU Symposium No. 333, 2018
V. Jelić & T. van der Hulst, eds.

doi:10.1017/S1743921317011085

Line Intensity Mapping during the Epoch of Reionization

Marta B. Silva[1] **and Saleem Zaroubi**[1,2]

[1]Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747AD Groningen, the Netherlands
[2]Department of Natural Sciences, The Open University of Israel, 1 University Road, P.O. Box 808, Ra'anana 4353701, Israel

Abstract. Characterizing the properties and the evolution of the first stars and galaxies is a challenging task for traditional galaxy surveys since they are sensitivity limited and can only detect the brightest light sources. Three-dimensional intensity mapping (IM) of transition lines can be a valuable alternative to study the high redshift Universe given that this technique avoids sensitivity limitation problems by measuring the overall emission of a line, with a low resolution, without resolving its sources. While 21cm line IM surveys probe neutral hydrogen gas and can, therefore, be used to probe the state of the IGM and the evolution of the ionization field during the Epoch of Reionization (EoR). IM surveys of other lines, such as CO, CII, Ly-alpha or H-alpha, can be used to probe the galaxies which emitted most of the ionizing radiation responsible for the EoR. These lines will trace the different ISM gas phases, the excitation state of this gas, its metallicity, etc. This study addresses IM of multiple transition lines and how it can be used to probe the EoR and to constrain the redshift evolution of galaxy properties.

Keywords. galaxies: high-redshift, Galaxy: evolution, (ISM:) dust, extinction, (cosmology:) large-scale structure of universe

1. Introduction

In recent years, a new method for probing gas in the Universe, called Intensity Mapping, has been proposed (Madau *et al.* 1997). The method consists in observing the intensity of a specific line emission, e.g. HI 21 cm radiation (Madau *et al.* 1997, Chang *et al.* 2010), and map it at every point in space and redshift, down to the resolution and sensitivity of the telescope.

Intensity mapping survey data consists of three-dimensional intensity maps, where each observational voxel is set by a certain angular resolution and covers a wide range of frequency. Given the large volume covered by each observed voxel, it will contain emission from several unresolved sources. Instead of resolving galaxies, IM surveys aim at detecting the overall emission from both bright and faint sources, as well as extended emission sources. Since this method probes a certain spectral line, the redshift of the observed gas parcel is automatically obtained. Therefore, the 3D mapping made available by this method contains an enormous amount of information about the integrated galaxy and IGM emission from each voxel.

This new technique is expected to provide a wealth of information that is not yet available to current probes. Given its simplicity and many advantages, IM has been extended to several other atomic and molecular emission lines, such as CO, CII, and Lyα, used to probe the Epoch of Reionization (EOR) (Visbal *et al.* 2010, Lidz *et al.* 2011, Gong *et al.* 2012, Silva *et al.* 2013, Silva *et al.* 2015). Moreover, IM has also been proposed as a probe of the medium to low redshift Universe in several lines (Pullen et a. 2014, Uzgil *et al.* 2014, Silva *et al.* 2016, Fonseca *et al.* 2017, Silva *et al.* 2017).

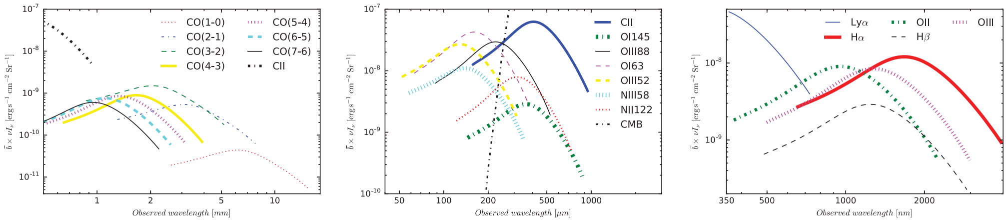

Figure 1. Estimates of the product $b \times \nu I_\nu$ of several lines as a function of the observed wavelength. All plotted lines are for the redshift interval $z = 0 - 5$. Left, center and right plot correspond respectively to radio, Far infrared and UV/optical lines. This figure was taken from Fonseca *et al.* 2017.

The IM technique can be used to probe constrain the Universe from the cosmic dawn to the present day. At very early times ($z \gtrsim 10$) X-ray emission from the first stars heated the IGM. This period can be probed with the IM of the HI 21cm line, which is expected to be seen in absorption against the CMB. However, at lower redshift ($z \lesssim 10$) galaxy formation was already well underway and so the overall emission from several hydrogen or metal lines from galaxies is strong enough to be detected by IM surveys.

During the EoR ($10 \lesssim z \lesssim 6$), IM of HI 21cm line emission probes the thermal and ionization state of the IGM while IM of galaxy lines probes the main sources of the ionizing radiation.

In the study of the post-EoR Universe, IM missions can be used to complete and to confirm observations by other surveys, such as traditional galaxy surveys, extragalactic background light surveys, etc. As an example, using IM surveys in combination with galaxy surveys will link the distribution of galaxies with IGM overdensities. Moreover, there has been an increasing interest in using low-z IM of galaxy lines as cosmological probes. As an example, IM of Lyα with the HETDEX - Hobby Eberly Telescope Dark Energy eXperiment (Hill *et al.* 2008) will have enough statistics to resolve the wiggles from the Baryonic Acoustic Oscillations at $z \sim 2$ (Fonseca *et al.* 2017). Furthermore, in the post-EoR, IM surveys can be combined with galaxy surveys to establish relations between global astrophysical quantities.

The potential of the IM technique as a cosmological probe is relatively well accepted by the scientific community. On the other hand, the potential of Line IM to probe galaxy properties is still in debate. This technique is criticised by not being able to differentiate between emission powered by star forming galaxies or by AGN. Moreover, the intensity of an emission line depends on several parameters and so on its own, cannot be used to put strong constraints on an individual astrophysical parameter such as the star formation rate (SFR). The first point is unavoidable, however, it can also be seen as an advantage, given that as a result of not resolving emission sources, the IM technique is not biased towards the signal from bright galaxies and can be effectively be used to track the evolution of the overall intensity in an emission line. The second issue can be solved or at least decreased by combining the signal detected by several IM surveys probing the same sky area.

2. CO, CII, Hα and Lyα Intensity Mapping

The main target lines for IM missions are the CO, CII, Hα and Lyα lines. As shown in Figure 1, these are strong emission lines and will often dominate the signal detected by an IM survey over a given frequency range.

https://doi.org/10.1017/S1743921317011085 Published online by Cambridge University Press

CO Intensity Mapping: The CO(1-0) line is the target line for the mmIME, COPSS, AIM-CO and COMAP missions to probe molecular gas in the $1 \lesssim z \lesssim 5$ redshift range. At higher redshifts, the CO(1-0) line fluctuations are too faint to be detected against CMB emission. However, molecular gas during the EoR can be probed with the CO(2-1) line. This will therefore be the target line of the COMAP mission in the $5.8 \lesssim z \lesssim 7.8$ redshift range. CO rotational transition lines trace molecular gas which is the fuel for star formation. However, the conversion factor between CO emission and IR luminosity or star formation is still poorly constrained given that it will changes considerably depending on the type of galaxy and should evolve with redshift. Moreover, the relation between molecular gas and CO(1-0) emission is much tighter than the relation between molecular gas and higher order CO transitions. This is due to the luminosity of high order CO transitions depending on the excitation state of the gas which depends on the hardness of the ionizing radiation in the galaxy. This key problem can be solved by combining data from galaxies surveys with data from IM surveys. As an example, data from the ALMA galaxy survey can be combined with data from the COMAP - CO Mapping Array Pathfinder (Li *et al.* 2016) in order to probe the connection between IR emission, star formation rate and molecular gas in high redshift galaxies ($2.4 \lesssim z \lesssim 3.4$).

CII Intensity Mapping: The single ionized carbon CII($158\mu m$ rest frame) line is considered a good tracer of star formation and of stellar mass. This line is mainly emitted from photodissociation regions (PDRs) and from ionized circumgalactic gas. This line is also one a major cooling mechanism for galaxies ISM. The TIME Crites *et al.* 2014, the CONCERTO (Lagache in prep.) and the CCAT-prime are competing missions that aim at using the CII line to probe star forming galaxies during the EoR. The main problem with intensity maps of CII emission is that they will be contaminated by several other strong lines, namely several CO rotational lines. The IM missions targeting CII emission from the EoR will, therefore, often attempt to also produce maps of CO emission at lower z. These CO maps will be used to probe the contamination in the CII maps. Moreover, cross-correlations between two CII intensity maps, contaminated by two different CO lines originated from the redshift, can be used to estimate the product of the two CO lines (Silva *et al.* 2015). Moreover, this method can be used to determine the degree of CO emission left in the CII maps after the voxels contaminated by the strong CO emission are masked, see right panel of Figure 2.

Hα and Lyα Intensity Mapping: The intrinsic intensities of the Hα and the Lyα lines scale with the instantaneous star formation. Both these lines are sensitive to dust extinction in the ISM. However, towards high redshift the dust extinction is expected to be lower than that observed in the post-EoR Universe. The CDIM mission, although still in the proposal phase, plans on detecting emission from the EoR using both these lines. The Lyα emission, from the EoR, will often be scattered by the neutral hydrogen in the CGM and in the IGM and so its observed magnitude should not be much stronger than that of Hα emission (Silva *et al.* 2017).

As can be observed in the middle panel of Figure 2 the SFRD traced by Hα emitters is poorly constrained. Note that the error bars in the observational points at $z > 3$ do not account for the uncertainty related to the poorly constrained extinction by dust in the interstellar medium. The extrapolation towards higher redshift assumes a model based in simulations and normalized to the SFRD probed by Hα emitters at low redshift. The CDIM mission proposes to probe the instantaneous SFRD using emission in the Hα line.

This mission also aims to map Lyα line emission up to $z \sim 10$ and to cross-correlate this signal with HI 21 cm as detected by the SKA-low survey. As shown in the right panel of Figure 2, the shape of the cross-correlation of these two lines can be used to trace the characteristic size of ionized regions. This is due the HI signal being originated outside

https://doi.org/10.1017/S1743921317011085 Published online by Cambridge University Press

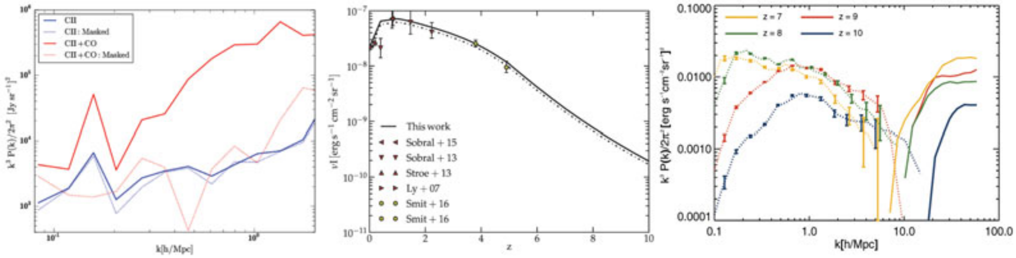

Figure 2. Left panel: Cross-correlation power spectra between observational intensity maps at frequencies 288.2 GHz and 216.1 GHz, which correspond to CII emission from redshift 7.8 and 5.6, taken from Silva *et al.*(2015). Middle panel: SFRD evolution as probed by Hα emitters extrapolated into the EoR using the model from (Silva *et al.* 2017). Right panel: The Lyα cross-power spectra with HI 21cm emission at z = (7, 8, 9, 10), taken from Silva *et al.* 2013.

of HII regions emission and galaxies being usually located inside HII regions and so the emission from these lines is anti-correlated at scales smaller than the average ionezed regions.

3. Discussion

The intrinsic fluxes, of hydrogen lines, scale mainly with the intensity of the ionizing radiation, which is one of the galaxy properties more easily accessible to observations. On the other hand, the fluxes of metal lines also depend strongly on additional galaxy properties, such as gas clumping, metallicity, and hardness of the ionizing spectrum. The redshift evolution of these additional galaxy properties is not easy to infer from observations. Nevertheless, a combination of several IM probes is essential to break degeneracies between the many astrophysical parameters that contribute to the intensity of a line. Overall, there will be a large number of IM surveys targeting emission lines characteristic of different gas phases. As a result, at high-z, Line IM should be seen as an important tool to probe the high-z Universe and its data should be combined with that of traditional galaxy surveys.

References

Chang T.-C., Pen U.-L., Bandura K., & Peterson J. B., 2010, *Nature*, 466, 463

Cooray A., Bock J., Burgarella D., Chary R., Chang T.-C., Doré O., Fazio G., Ferrara A., Gong Y., Santos M., Silva M., & Zemcov M., 2016, arXiv:1602.05178

A. T. Crites, J. Bock, C. M. Bradford, T. C. Chang, A. R. Cooray *et al.*, 2014., *Proc. SPIE*, 9153:9153,9,doi: 10.1117/12.2057207

Fonseca J., Silva M. B., Santos M. G., & Cooray A., 2017, *MNRAS*, 464, 1948

Gong Y., Cooray A., Silva M., Santos M. G., Bock J., Bradford C. M., & Zemcov M., 2012, *ApJ*, 745, 49

Hill, G. J., Gebhardt, K., Komatsu, E., Drory, N., *et al.*, 2008, *ASPC*, 399, 115 H

Li, T. Y., Wechsler, R. H., Devaraj, K., Church, S. E., *et al.*, 2016, *ApJ*, 817, 169

Lidz A., Furlanetto S. R., Oh S. P., Aguirre J., *et al.*, 2011, *ApJ*, 741, 70

Madau P., Meiksin A., & Rees M. J., 1997, *ApJ*, 475, 429

Pullen A. R. & Doré O., Bock J., 2014, *ApJ*, 786, 111

Silva M. B., Santos M. G., Gong Y., Cooray A., & Bock J., 2013, *ApJ*, 763, 132

Silva M., Santos M. G., Cooray A., & Gong Y., 2015, *ApJ*, 806, 209

Silva, M. B., Zaroubi, S., Kooistra, R., & Cooray, A. 2017, ArXiv: 1711.09902

Uzgil B. D., Aguirre J. E., Bradford C. M., & Lidz A., 2014, *ApJ*, 793, 116

Visbal E. & Loeb A., 2010, *JCAP*, 1011, 016