Transactions IAU, Volume XXXIA
Reports on Astronomy 2018-2021
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DOI: 00.0000/X000000000000000X

COMMISSION J2 INTERGALACTIC MEDIUM

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TRIENNIAL REPORT 2018–2021

1. Introduction

The IAU Commission J2 on the "Intergalactic Medium" was founded in 2015. It was proposed by Avery Meiksin (United Kingdom), along with Hsiao-Wen Chen (United States), Nissim Kanekar (India) and Joop Schaye (Netherlands). It is the first IAU commission focussing on the Intergalactic Medium. It is an inter-divisional commission, with parent division Division J, "Interstellar Matter and Local Universe," and is cross-listed with Division B, "Facilities, Technologies and Data Science" and Division H, "Interstellar Matter and Local Universe." In 2018, Valentina D'Odorico (Italy) became the new president, while James Bolton (UK), Benedetta Ciardi (Germany) and Céline Peroux (France) became member at large of the commission organizing committee.

The main observational probe of the Intergalactic Medium (IGM) is the Lyman-α forest, the absorption features visible in the spectra of high redshift Quasi-Stellar Objects (QSOs) due to the scattering of Lyman-α photons by intervening intergalactic neutral hydrogen. The Lyman-α forest traces the density fluctuations of the diffuse intergalactic gas. On the one hand, the properties of the observed absorption lines are linked to the physical state and chemistry of the gas, whilst on the other hand the gas fluctuations trace the underlying perturbations of the dark matter and have been used to constrain cosmological model parameters. In addition to the hydrogen component, the IGM contains diffuse helium gas and a wide range of metal ions. The observational campaign to map out the distribution of metal absorbers, their evolution and their affiliation with galaxies has continued to grow in intensity. Alongside the observations, numerical simulations of the IGM in a cosmological context have grown increasingly refined. A new chapter is opening in modelling the diffuse gas near galaxies, the Circumgalactic Medium (CGM), that is making new connections between the IGM and models of galaxy formation.

2. Scientific highlights

We chose a few recent scientific achievements that already had a positive impact on the studies of the IGM and CGM and that will likely expand in the future thanks to the advent of new observational and computational facilities.

- *The simulation of the CGM at high resolution.* The CGM is the low-density gas surrounding a galaxy and extending to its virial radius and beyond. The CGM is increasingly recognized for its significant role driving the evolution of galaxies, operating as both the reservoir of gas providing fuel to the galaxy, as well as the sink into which stars and active galactic nucleus (AGN) deposit energy, mass, and metals (Tumlinson et al. 2017). Observations suggest that the CGM is a complex, multiphase structure, with the presence of cool 10^4 K gas bearing neutral hydrogen and low ionization ions like Mg II and Si II, as well as warm-hot gas ($10^{5.5}$–10^6 K) traced by "high ions" in the form of NV, O VI, and Ne VIII. Furthermore, the H I clouds bearing the "low ions" most likely have sub-kpc sizes (e.g. Lehner et al. 2019; Rudie et al. 2019). "Classical" hydrodynamical simulations struggle to reproduce the properties of the CGM, in particular underproducing the column density of the "low ions". A possible explanation is that the absence of sufficient spatial resolution to resolve the natural gas cloud size, suppresses the multiphase gas structure. Recently, several groups have implemented different solutions to improve the resolution in the lower density CGM of hydrodynamical simulations (Van de Voort et al. 2019, Peebles et al. 2019; Suresh et al. 2019; Hummels et al. 2019). The general outcome of all these improved simulations is that while the bulk properties of the central galaxies are not affected, in the CGM the multiphase structure becomes more evident and there is an increase of its cool gas content and observed column densities of low ions (e.g., H I), together with a decrease of the size of the cool gas absorbers. For the next future, we expect that simulations will systematically include the physical treatment of fundamental mechanisms (e.g. magnetic fields, radiative transfer) to improve their predictive power and possibly overcome, at least in part, the computing time bottleneck with new approaches (e.g. Li et al. 2020; Van de Voort et al. 2020).

- *The detection of the IGM/CGM in emission.* The IGM is normally explored using absorption line spectroscopy, which provides a powerful way to trace the neutral hydrogen observed in Lyman-α absorption against bright background QSOs (e.g. Meiksin 2009). However, information is limited to one dimension along the line-of-sight to the background source, only in rare cases the use of multiple lines of sight allowed to obtain a 3-D picture of the gas distribution in the cosmic web (Lee et al. 2018). Imaging the cosmic web in emission would provide the missing 3-D information. The advent of powerful integral field spectrographs such as MUSE (Bacon et al. 2010) at the ESO VLT has allowed the detection in Lyman-α emission of the CGM around bright QSOs (e.g Borisova et al. 2016) but also normal galaxies (e.g. Wisotzki et al. 2018; Leclercq et al. 2020) mainly at $z \sim 2-3$. More recently, thanks to extremely deep observations of a few fields the signature of the cosmic web is starting to emerge traced by weaker Lyman-α emitters but also by diffuse Lyman-α emission (Lusso et al. 2019; Bacon et al. 2021) finally unveiling the connection between galaxies and the cosmic web. Using both MUSE and ALMA, the CGM is starting to be detected also in other line emissions at low ([OII], Hα, [OIII], Hβ, [NII], e.g. Epinat et al. 2018; Chen et al. 2019a) and high redshifts (CIV, [CII], e.g. Fujimoto et al. 2019; Travascio et al. 2020) allowing us to examine the physical condition of the gas based on comparisons of multiple transitions. An important topic of research and discussion for the next years will be how the information in emission can be combined with that in absorption to gain a more accurate picture of the CGM and its interface with the IGM (e.g. Chen et al. 2019b).

- *The significant increase in the number of QSOs discovered at $z \geqslant 6$.* The first 19 QSOs at $z \sim 6$ were discovered in the SDSS and allowed to put the first constraints on the final phases of the reionization epoch (Fan et al. 2006). The advent of wide-area photometric surveys has increased the number of known quasars at $z > 6$ to ~ 200 by today (e.g., Bañados et al. 2016; Wang et al. 2019). This has allowed the compilation of large samples of QSO spectra that has been used to characterize the ionization status and the metal enrichment of the IGM/CGM at the highest redshifts probed by those targets (e.g. Bosman et al. 2018; Becker et al. 2019; Zou et al. 2021). The continuous improvement in the size, quality and homogeneity of the spectroscopic QSO samples, will allow us to depict more and more details of the second half of the reionization process. A quantum leap in these kind of studies will be represented by the advent of the 30-40m class extremely large telescopes, that will allow to observe QSOs at the reionization epoch with the same resolution and signal-to-noise ratio that can be obtained today for QSOs at $z \sim 2 - 4$.

- *Fast radio bursts as probes of the missing baryons.* Fast Radio Bursts (FRB) are astronomical radio flashes of unknown physical nature with durations of milliseconds. They are mainly of extragalactic origin and for some of them it has been possible to identify the host galaxy (e.g. Chatterjee et al. 2017). Recently, Macquart and collaborators (2020) exploited the dispersion observed in a sample of localized FRBs to measure the electron column density and accounts for every ionised baryon along the line of sight (McQuinn 2014). This independent measurement of the baryon content of the Universe with a golden sample of 5 FRBs is consistent with Cosmic Microwave Background and Big Bang Nucleosynthesis values, substantially solving the missing baryon problem. The adopted model accounts for scatter in the electron column from foreground structures, which is largely caused by random variation in the number of halos a given sight-line intersects. Cosmological simulations show that this variation is sensitive to the extent by which galactic feedback redistributes baryons around galactic halos. In the near future, when a moderately large sample of localized FRBs will be available it will be possible to differentiate between viable feedback scenarios, suggesting that FRBs have not only revealed that all the baryons are present but will constrain where they lie.

3. Meetings

A variety of meetings were held that focussed on IGM science. Note that starting from spring 2020 all meetings were held online due to the COVID-19 pandemic. However, this situation fostered the organization of smaller more focussed workshops that happened more frequently during the last year.

- August 2018, *XXXth General Assembly of the International Astronomical Union*, Vienna, Austria
- September 2018, *IGM2018: Revealing Cosmology and Reionization History with the IGM*, Kavli IPMU, Kashiwa, Japan
- April 2019 *SKA General Science Meeting and Key Science Workshop 2019*, Jodrell Bank, England, UK
- June 2019, *Zoom-In and Out: From the Interstellar Medium to the Large Scale Structure of the Universe*, NORDITA, Stockholm, Sweden
- June 2019, *The Turbulent Life of Cosmic Baryons*, Aspen, Colorado, USA
- June 2019 *What matter(s) between galaxies*, Tenuta di Spineto, Sarteano (Siena), Italy
- July 2019 *SESTO 2019: Tracing Cosmic Evolution with C lusters of Galaxies* Sesto (Sexten), Italy
- September 2019, *Views on the Interstellar Medium in galaxies in the ALMA era*, Bologna (Italy)
- January 2020, *The interstellar medium of high-redshift galaxies*, Sexten (Italy)
- June 2020, *The circumgalactic medium*, Symposium at EAS 2020, online
- July 2020, *Summer All Zoom Epoch of Reionization Astronomy conference (SAZERAC)*, online

- October 2020, *The rise of metals and dust in galaxies through cosmic time*, Marseille, France (online)
- January-March 2020, *Fundamentals of gaseous halos*, Programme held at Kavli Institute for theoretical Physics, UC Santa Barbara, USA (online)

4. Databases

- First release of the UVES Spectra Quasar Absorption Database (SQUAD), Murphy et al. 2019
- Mg II absorbers catalogue from SDSS DR16, Anand et al. 2021

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