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COMMISSION J2 **INTERGALACTIC MEDIUM**

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1. Introduction

The new 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."

The main observational probe of the Intergalactic Medium (IGM) is the Lyα forest, the absorption features visible in the spectra of high redshift Quasi-Stellar Objects (QSOs) due to the scattering of Lyα photons by intervening intergalactic neutral hydrogen. The Lyα 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. The diffuse Intergalactic Medium

A primary statistic for comparing observations with theoretical predictions is the one-dimensional flux power spectrum. The flux power spectrum traces the measured fluctuations in the forest as observed in QSO spectra. Recent samples have been used to measure the flux power spectrum, ranging from several tens of high-resolution, high signal-to-noise ratio QSO spectra (e.g. Walther et al. 2018) with sparse redshift sampling, to large datasets from the Sloan Digital Sky Survey and the Baryon Oscillation Spectroscopic

Survey. A sample of 100 QSO spectra at intermediate resolution with $3 < z < 4.2$ (XQ-100 sample, Lopez et al. 2016) bridged the scales covered by the previous two samples and allowed the small scale power of the IGM to be probed at high redshift (Irsic et al. 2017a). The small scale power was used to infer the nature of dark matter (Irsic et al. 2017b), and the power spectrum in general was used to place constraints on a variety of cosmological parameters, e.g. the mass of neutrinos (Palanque-Delabrouille et al. 2015; Yèche et al. 2017; Baur et al. 2017). QSOs from the Sloan Digital Sky Survey were used to make the first detection of Baryon Acoustic Oscillations in the IGM (Bautista et al. 2017). Combined with previous other measurements, the detection has made it possible to make an accurate determination of the cosmological parameters independent of Cosmic Microwave Background measurements. The results confirm a ΛCDM cosmology.

The physical state of intergalactic gas and its evolution, in terms of its temperature and effective equation of state, remain uncertain. New attempts to measure the thermal state were made. One is based on novel Bayesian approaches to the distributions of fitted column densities and Doppler parameters of Lyα absorption features (Rorai et al. 2018). A second uses a new method based on a comparison of the flux curvatures in the Lyα and Lyβ forests (Boera et al. 2016). A novel method for measuring the coherence length of intergalactic gas yielded results confirming the standard reionization scenarios (Rorai et al. 2017).

Whilst the metallicity and chemical abundances of the CGM has been widely investigated in recent years at both high and low redshifts, the distribution of heavy chemical elements far away from galaxies is still an open subject both observationally and theoretically. Recently, a new attempt to establish metallicity patterns was made using the highest signal-to-noise ratio quasar spectra ever obtained at high resolution. The volume filling factor of the IGM gas (down to the mean density) enriched to a metallicity $\log_{10} Z/Z_\odot \sim -3$ at $z \sim 3$ was estimated to be of the order of $10-13$ per cent (D'Odorico et al. 2016). This result is in agreement with predictions by theoretical studies in which the IGM was enriched at high redshift by low mass galaxies.

The XQ-100 survey provided new insight in the metal content of damped Lyα absorbers, including environmental effects such as proximity to QSOs (Berg et al. 2016). The Keck HIRES continues to provide high precision measurements of the Lyα forest, including the detection of the most metal-poor damped Lyα absorber known (Cooke, Pettini & Steidel 2017). The first and second data releases of the Keck Observatory Database of Ionized Absorption toward Quasars (KODIAQ) surveys were made public (O'Meara et al. 2015, 2017). H I and metal abundances of the low redshift IGM ($z < 1$) have achieved unprecedented levels of precision from the large absorption system survey using the Cosmic Origins Spectrograph (COS) on *HST*; about 30 percent of the baryons are accounted for by the Lyα forest and Warm-Hot IGM (Danforth et al. 2016). Nearby galaxies ($z \sim 0$) exhibit a very high covering fraction of cool hydrogen (Bordoloi et al. 2017).

IGM simulations continue to become increasingly sophisticated. In the Illustris Project galaxy formation simulation suite (Vogelsberger et al. 2014), using a new moving-mesh fluid scheme, the IGM and CGM components are an organic part of the simulation, as also in the EAGLE project fluid particle-based simulation suite (Schaye et al. 2015). A new grid-based code, `Nyx`, was introduced for performing cosmological simulations of the intergalactic medium (Lukić et al. 2015). The Sherwood IGM fluid particle-based simulation suite, the largest of its kind in terms of combined volume and mass resolution (Bolton et al. 2017), is currently being used for comparisons with a variety of observations.

3. The Circumgalactic Medium

Our understanding of the complex multiphase circumgalactic medium has been rapidly advancing in the past few years. A particularly exciting new development is the ability to probe the complex halo gas at multiple locations in a single halo. Recent observations show a strong coherence both in chemical enrichment and in gas kinematics in individual galactic halos (e.g., Zahedy et al. 2016; Rubin et al. 2017). These studies expand upon previous efforts of probing the intergalactic medium using multiply-lensed QSOs by targeting halos of known galaxies to establish a direct connection between galaxies and their surrounding halo gas.

Observations continue to find a lack of heavy ions (such as Si II, Si III, C IV, and O VI) beyond the nominal virial radii of low-mass galaxies with stellar mass ranging from $3 \times 10^9 \, M_\odot$ to less than $10^8 \, M_\odot$ (e.g., Burchett et al. 2016; Johnson et al. 2017). A tight correlation between quasar luminosity and the incidence of chemically-enriched cool ($T \sim 10^4$ K) gas in quasar host halos has been discovered (e.g., Johnson et al. 2015). The lack of heavy ions at large distances from low-mass galaxies may indicate that galactic winds from dwarf galaxies are not effective in polluting the CGM/IGM with heavy elements. The tight correlation between quasar luminosity and their CGM content implies a causal link between the physics of accretion onto the central super massive black holes on scales of 0.01 pc, and gas in the circumgalactic medium on scales of 100 kpc.

The Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) optical integral field spectrograph on the VLT has opened a new window onto the circumgalactic medium.

MUSE has enabled the detection of Lyα emission around individual, low-mass ($10^8 - 10^9 \, M_\odot$) galaxies at redshifts $3-6$ (Wisotzki et al. 2016). The emission is detected out to ~ 10 kpc and is substantially more extended than the UV continuum. Much larger Lyα haloes of $> 10^2$ kpc are detected around each of 17 bright, radio-quiet quasars (Borisova et al. 2016). While the physical origin of the emission is still debated, it is clear that the spatially and spectrally resolved Lyα nebulae are powerful new probes of the neutral circumgalactic gas that was previously only accessible in absorption.

MUSE allows the efficient detection and characterization of galaxy counterparts to intergalactic absorbers over its 1×1 arcmin field of view (e.g. Schroetter et al. 2016; Peroux et al. 2017; Fumagalli et al. 2017b). Extended background sources, such as gravitationally lensed arcs, can be used instead of quasars to study the spatial extent and velocity profile of the absorbing gas (Lopez et al. 2018).

At low redshift MUSE has been used to detect fluorescent Hα emission from the neutral gas in the outskirts of a spiral galaxy (Fumagalli et al. 2017a). Assuming that the emission is not powered by local sources of ionizing radiation, this provides a measurement of the intensity of the extragalactic ultraviolet background radiation, which is a crucial parameter for ionization models of intergalactic gas.

In clusters of galaxies MUSE has revealed and characterized tens of kiloparsec long tails of gas that have been stripped from infalling galaxies (e.g. Consolandi et al. 2017). Interestingly, Poggianti et al. (2017) found that six out of seven galaxies with MUSE detected gas "tentacles" harbour active nucleii, suggesting that the ram pressure provided by the intracluster medium triggers black hole growth.

Cosmological simulations are converging on the properties of the CGM. The Illustris, EAGLE, Sherwood and `Nyx`-based simulations well reproduce the rise in H I optical depth near Lyman Break Galaxies at $2 < z < 3$ and their H I covering fractions, allowing for galactic feedback that scales with the halo mass, although only some models recover the highest optical depths within the virial radii of galaxies (Meiksin et al. 2017, Sorini et al. 2017, Turner et al. 2017). Observed C IV optical depths around galaxies are also well matched at $z \sim 2$ by the EAGLE simulations (Turner et al. 2017). There is less success on matching the measured H I optical depths around QSOs. Simulation results suggest an alternative feedback mechanism to supernovae-driven winds is acting, with feedback by an Active Galactic Nucleus the preferred model. At high redshifts ($z \sim 6$), matching high ionization (eg C IV and Mg II) absorption statistics remains a challenge (Keating et al. 2016, Rahmati et al. 2016).

4. Local Group intergalactic gas

The Australian Square Kilometre Array Pathfinder has constructed a detailed map of the Small Magellanic Cloud revealing a level of complexity previously unknown. The structure suggests, in addition to the impact of supernovae, the galaxy interacts with the Large Magellanic Cloud and the Milky Way.

The Wisconsin Hα survey has shown that material in winds expelled by the Large Magellanic Cloud is captured by the Milky Way, possibly replenishing its reservoir of gas for star formation (Ciampa et al. 2017).

Following the discovery of evidence for a massive, extended CGM around the Andromeda Galaxy (M31) (Lehner, Howk & Wakker 2015), COS observations have shown the CGM has a complex, multiphase structure (Richter et al. 2017, Zheng et al. 2017).

5. Radio measurements of the Intergalactic Medium

Significant progress has taken place over the last few years in redshifted H I 21 cm absorption studies, driven mainly by the installation of new wide-band receivers on the upgraded Giant Metrewave Radio Telescope and first light on the new Australian Square Kilometre Array Pathfinder (ASKAP). The new GMRT receivers resulted in three new detections of redshifted H I 21 cm absorption at $z \sim 2$, increasing the number of H I 21 cm absorption detections at $z >\sim 2 - 10$ (Kanekar 2014). The GMRT receivers also enabled a large survey for H I 21 cm absorption in high-redshift ($z > 1.8$) damped Lyα systems: the large number of non-detections implied high spin temperatures in normal galaxies at high redshifts, and that cold gas in normal galaxies only builds up by $z < 1.5$. A pilot ASKAP H I 21 cm absorption survey resulted in the detection of a new H I 21 cm absorption system, at $z \sim 0.44$ (Allison et al. 2015). The GMRT was also used to carry out a large survey for redshifted H I 21 cm absorption from gas in the environments of compact active galactic nuclei (AGN), yielding 3 new detections at $z \sim 1.3$ (e.g. Aditya & Kanekar 2018). The preponderance of non-detections in high-z AGN indicates that the gas near high-z AGN is either warm or mostly ionized, due to either redshift evolution or a higher AGN luminosity.

In studies of fundamental constant evolution, it is now clear that present optical echelle spectrographs are affected by serious wavelength calibration issues, yielding systematic errors in the wavelength scale. As such, much effort has been invested in super-calibration techniques. Recent Very Large Telescope (VLT) UVES spectroscopy of a single absorber at $z \sim 1.1508$ towards the bright quasar HE0515-4414, calibrated with HARPS spectra of the same absorber, yielded strong constraints on fractional changes in the fine structure constant, α, ruling out fractional changes in α greater than ~ 3 parts per million (Kotus, Murphy & Carswell 2017). Spectroscopy with the Keck telescope and the VLT was also used to obtain constraints on changes in α at slightly higher redshifts, from the Zn II and Cr II lines in 12 absorbers, ruling out (at 3σ significance) fractional changes in α larger than ~ 5 parts per million at redshifts $1.0 - 2.4$ (Murphy, Malec & Prochaska 2016). At radio wavelengths, two deep studies yielded strong constraints on changes in the proton-electron mass ratio, μ, and α: Kanekar et al. (2015) used methanol lines detected at $z = 0.886$ with the Very Large Array to constrain fractional changes in μ to be less than a few parts in ten million. Kanekar, Ghosh & Chengalur (2018) used a deep Arecibo telescope integration on the conjugate satellite hydroxyl lines of a $z = 0.247$ AGN to constrain fractional changes in a combination of α and μ to be less than a few parts per million, with strong constraints on unaccounted systematic effects.

6. Meetings

A variety of meetings over four continents were held that focussed on IGM science:

- Galaxies in Absorption Conference, Pittsburgh, USA, April 2015
- The Metal Enrichment of Diffuse Gas in the Universe, Sesto, Italy, July 2015
- IGM16: From Wall to Web, Berlin, Germany, July 2016
- What matter(s) around galaxies, Durham, UK, June 2017
- The Circle of Life: Connecting Intergalactic, Circumgalactic, and Interstellar Media, Kruger Park, South Africa, August 2017
- Galaxies in Absorption, Pune, India, December 2017
- Intergalactic Interconnections, Marseille, France, July 2018

7. Databases

- First Data Release of the KODIAQ Survey (O'Meara et al. 2015)
- Second Data Release of the KODIAQ Survey (O'Meara et al. 2017)

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