

EARLY UNIVERSE

Lyman-alpha comes of age

Fifty-one years after Lyman-alpha lines were predicted (and 20 years after this author got involved in searching for Lyman-alpha galaxies), it was a pleasure to see so much progress in this field in the Spring Cosmic Lyman-Alpha Workshop at Tokyo University.

The Lyman-alpha ($\text{Ly}\alpha$) line is the strongest recombination line of hydrogen, which constitutes the dominant share of normal matter in the Universe. Fifty-one years ago, it was predicted that $\text{Ly}\alpha$ emission should appear prominently in the spectra of young primordial galaxies¹. For the next 30 years, this prediction was tested by many surveys, but none found the predicted galaxies at the predicted luminosities. The blame for these non-detections was squarely cast on the resonant nature of the $\text{Ly}\alpha$ line, which requires $\text{Ly}\alpha$ photons to scatter off many hydrogen atoms before escaping from a galaxy. This can hugely increase the path that they traverse, and consequently also the probability that they will be absorbed by dust. This remained the dominant explanation of the missing high-redshift lines for decades, despite some dissenting opinions about the effect of dust². The spectra of nearby galaxies from the International Ultraviolet Explorer are inconclusive about what allows galaxies to be $\text{Ly}\alpha$ emitters³. The 'missing' lines were finally detected 20 years ago⁴, at flux levels much below the original predictions — a difference that we understand to be predominantly due to the hierarchical growth of galaxies, such that star-forming objects at high redshift are much less massive than anticipated in the original prediction¹.

The discovery and study of $\text{Ly}\alpha$ galaxies has blossomed into an invaluable method for understanding the youngest stages of galaxy formation, the circumgalactic medium, and ultimately the epoch of reionization. The high equivalent widths of $\text{Ly}\alpha$ galaxies from the earliest high-redshift surveys show that they are low-mass galaxies dominated by young stellar populations⁵. The [Sakura CLAW workshop](#) (which used the Twitter hashtag #SakuraCLAW) gathered more than 110 participants (Fig. 1) who showcased progress that pushed the frontiers of $\text{Ly}\alpha$ galaxy science in sample size, sensitivity, redshifts and physical understanding.

Surveys

This year we saw results from several large surveys of $\text{Ly}\alpha$ emitters (LAEs). The narrowband survey SILVERRUSH,



Fig. 1 | Participants in the Sakura Cosmic Lyman-Alpha Workshop held in Tokyo, Japan, between 26 and 30 March 2018. Credit: Masami Ouchi, ICRR, University of Tokyo

using the Hyper Suprime Cam on Subaru, obtained 2,000 LAEs at redshifts of 5.7 and 6.5. Integral field spectroscopic surveys using MUSE on the European Very Large Telescope (VLT) have given us the deepest observations of $\text{Ly}\alpha$ emission so far, resulting in the most complete surveys both in terms of flux and surface brightness. MUSE has also been used to find 171 lensed $\text{Ly}\alpha$ sources. We were also treated to the earliest result from the HETDEX integral field survey on the Hobby–Eberly Telescope. HETDEX ultimately expects to find around 10^5 LAEs at redshifts $1.9 < z < 3.5$. Multiple speakers (Stark; Pentericci; Rhoads) showed spectra of LAEs at some of the highest redshifts and earliest epochs yet ($z > 7$).

Why Lyman-alpha?

Ciardullo asked what seems to be an age-old question: “What makes a $\text{Ly}\alpha$ galaxy a $\text{Ly}\alpha$ galaxy?” Multiple studies of strong $\text{Ly}\alpha$ galaxies, both at high redshifts and nearby ($z < 0.3$), show that $\text{Ly}\alpha$ is stronger in galaxies with low metallicities and high ionization (Erb; Yang; Trainor). Rivera-Thorsen showed a lensed $\text{Ly}\alpha$ source with an unusual triple-peaked $\text{Ly}\alpha$ profile, whose middle peak is at the systemic velocity, implying the $\text{Ly}\alpha$ can escape through a low-column-density channel in the neutral gas distribution.

Ionized ‘holes’ in the interstellar medium and circumgalactic medium play a large role in the escape of both $\text{Ly}\alpha$ and Lyman continuum radiation. Empirically, Kerutt showed that $\text{Ly}\alpha$ galaxies are also big Lyman continuum leakers. Verhamme described

theoretical modelling of $\text{Ly}\alpha$ and Lyman continuum escape. Galaxies with high ionization parameter (as indicated by the $[\text{O III}]/[\text{O II}]$ ratio), high $\text{Ly}\alpha$ escape, and small separation of the blue and red $\text{Ly}\alpha$ line peaks tend to have comparatively large escape fractions of Lyman continuum radiation.

Ostlin discussed the Lyman Alpha Reference Sample (LARS) of nearby galaxies, which has played an important role in our understanding of $\text{Ly}\alpha$ escape. Hayes discussed a search for empirical predictors of $\text{Ly}\alpha$ escape based on other properties of the LARS galaxies, such as star-formation rates, H I, ionization parameter, dust, metallicity or stellar mass. Using multiple parameters, they are able to generalize the two-parameter $\text{Ly}\alpha$ escape predictions by Yang et al.⁶ (although the parameters in ref. ⁶ include velocity offset of the $\text{Ly}\alpha$ line).

Gronke reported that $\text{Ly}\alpha$ profiles of nearby galaxies often defy simple explanations. Successful modelling can constrain much about feedback mechanisms and structure of the circumgalactic medium. Another way to study the circumgalactic medium and the ionized state of the intergalactic medium is to study $\text{Ly}\alpha$ absorbers and $\text{Ly}\alpha$ halos around galaxies. Both Momose and Kusakabe studied the properties of faint $\text{Ly}\alpha$ halos around $\text{Ly}\alpha$ galaxies. Their observations are consistent with $\text{Ly}\alpha$ scattering in halos, but disfavour cold streams.

Lee detected a three-dimensional network of $\text{Ly}\alpha$ absorbers by spectroscopy of Lyman-break galaxies, with a large void at $z = 1$. Bosman and Chardin, examining $\text{Ly}\alpha$

opacity in 62 quasi-stellar objects at $z > 5.7$, found a large spread in Ly α opacities, which can best be explained if the ionizing sources responsible for reionization are rare and powerful. The Keck Cosmic Web Imager is imaging the circumgalactic medium and finding supporting data for multi-filament inflow models.

Reionization

And that brings us to the most hotly debated topic in Ly α studies: reionization. Ly α photons are resonantly scattered, which might be a curse for interpreting Ly α emission from galaxies but can be used as a diagnostic to measure the neutrality of the intergalactic medium around Ly α galaxies. Treu showed that the fraction of Lyman-break galaxies with Ly α emission decreases at $z > 6$, as predicted if reionization happened around that time. Pentericci found this trend to be less significant with larger samples of spectroscopic data from the VLT.

Using Ly α selected samples, Zheng showed that the shape of the luminosity function changes at $z = 6.9$. This is consistent with fainter Ly α being scattered by neutral intergalactic medium, whereas the bright ones can ionize their

surroundings and thus be visible. Rhoads reported on instances of enhanced Ly α clustering at $z > 7$, whereas Barger discussed whether the line profiles of the most luminous LAEs show evidence for these ionized bubbles. Itoh reported a luminosity function that differs from Zheng's results at the same redshift. More data will hopefully settle this discrepancy. Jiang showed the results of a large spectroscopic survey of $z = 5.7$ LAEs, indicating a lower luminosity function than claimed in imaging surveys.

Mesinger presented simulations showing that Ly α galaxies will be more clustered in inhomogeneously ionized intergalactic medium, giving a more robust test of ionization. And looking to the future, Rhoads described the potential for NASA's Wide Field Infrared Survey Telescope to survey large regions for Ly α at $z > 7$, where they can be compared with future 21-cm studies.

The various approaches to surveys and understanding Ly α galaxies with multiple instruments in space and telescopes large and small on the Earth hold great promise for exciting future discoveries. Widefield imaging with the Dark Energy Camera (DECam) and the Subaru telescope is

giving us large samples of high-redshift Ly α emitters; and we expect that spectroscopy from the James Webb Space Telescope will let us measure other lines for high- z Ly α near the epoch of reionization. Follow-up of $z > 7$ galaxies by the Atacama Large Millimeter/submillimeter Array is already yielding clues to the physics of the gas in these galaxies (as shown by Hashimoto's results at this meeting). But the most promising sign for the future of Ly α research is the bright young people joining this field. $\square$

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Published online: 1 August 2018

<https://doi.org/10.1038/s41550-018-0539-4>

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