JRF to SRF Upgradation : Progress Report

Field of Research: Circumgalactic, Intergalactic Medium and Artificial Intelligence

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Date: **9 June, 2025**

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1 Summary of Course work

Paper Code	Subject	Credit	Grade
PAS1001	Research Methodology	4	O
PAS1002	Research Publication & Ethics	2	O+
PAS1003	Indian Knowledge System	2	A+
TTR-622	Pedagogy of Teaching-Learning Process	2	A+
PAS1005	Advanced Computational Methods in Physics	4	O
PAS1013	Advanced Astronomy & Astrophysics	4	O+
	Total Credits Earned	18	

Table 1: Summary of PhD Coursework.

The table 1 shows the courses taken as PhD course work with their respective credits earned and the total number of credits earned from this course work are 18 credits.

2 Summary of Research Work

2.1 Circumgalactic medium of quasar host galaxies at $0.4 \leq z \leq 0.8$ probed by strong Mg II absorption

We investigated the properties of the circumgalactic medium (CGM) around quasar host galaxies in the redshift range $0.4 \leq z \leq 0.8$, using strong Mg II absorption as a tracer. The CGM, composed of diffuse metal-enriched gas, plays a critical role in regulating star formation and gas accretion in galaxies. It can be studied either through absorption lines in the spectra of background quasars or via diffuse emission.

A key question in this context is whether active galactic nuclei (AGN), particularly quasars, significantly influence the CGM of their host galaxies. Several earlier studies have reported an enhancement in the rest-frame equivalent width (W_{2796}) and covering fraction (f_c) of Mg II absorption around AGN host galaxies compared to inactive galaxies (e.g., Chen et al., 2023; Farina et al., 2014; Johnson et al., 2015).

To explore this further, We utilized a sample of 166 carefully selected, closely spaced quasar pairs to probe the CGM of quasar-hosting galaxies. This was compared against a control sample of normal galaxies, matched in redshift ($0.4 \leq z \leq 0.8$) and impact parameter (20–100 kpc). The control sample combines data from MAGICAT (Nielsen et al., 2013) and Huang et al. (2021), ensuring similarity in redshift and impact parameter distribution. Our analysis primarily focused on strong absorbers with $W_{2796} \geq 1$ Å, based on the typical SNR of SDSS spectra.

The main outcome of the study shows that both the W_{2796}–D and f_c–D distributions are statistically similar between quasar host galaxies and normal galaxies (See Figure 1 and 2. This suggests that low-luminosity quasars (typically $L_{bol} \leq 10^{45}$ erg s^{-1}) do not significantly alter the CGM properties. We verified that our results are not biased by differences in stellar mass or impact parameter distributions, as these were well-matched across the samples.

While some prior works (e.g., Chen et al., 2023; Johnson et al., 2015) reported enhanced CGM absorption near quasars, their samples included higher-luminosity quasars and covered broader redshift ranges. In our study, only a weak trend in f_c with bolometric luminosity was observed,

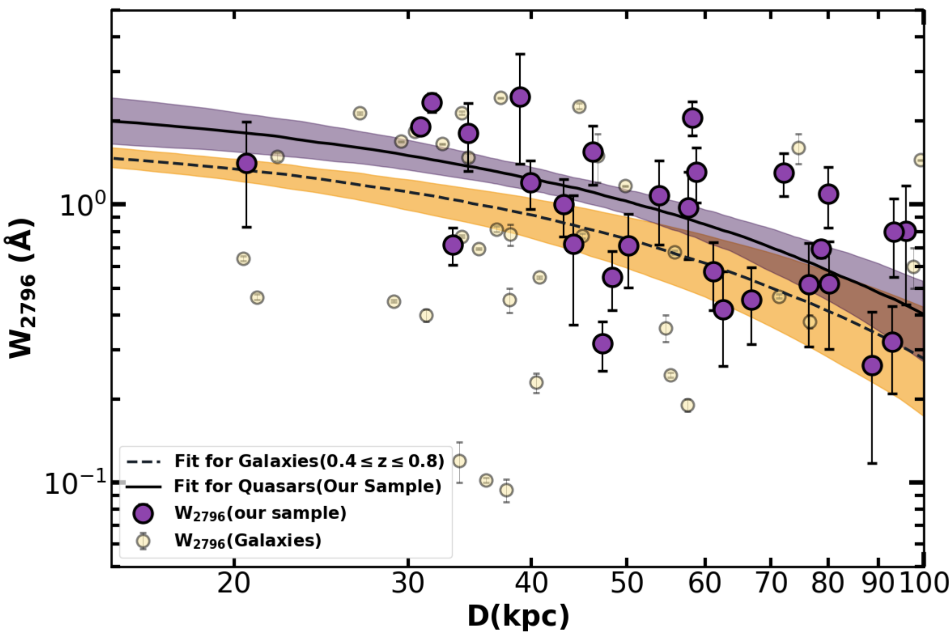

Figure 1: The relationship between W_{2796} and the impact parameter (D) for foreground quasars. Violet filled circles represent cases with detected MgII absorption. The faded yellow-filled circles are detections for galaxies. The solid black line and the violet shaded region around it indicate the fit for quasars, while the black dashed line and the yellow shaded region around it show the fit for the galaxy sample over the redshift range $0.4 \leq z \leq 0.8$.

and no clear correlation was found between luminosity and W_{2796}. This may be due to the limited luminosity range of quasars in our dataset. Additionally, we found no increase in the scatter of velocity offset between quasars and associated absorbers with increasing luminosity, contrary to previous findings.

Interestingly, we also confirmed that the probability of detecting Mg II absorption is lower along the line of sight to the quasar compared to the transverse direction, supporting earlier results by Chen et al. (2023). This anisotropy could be due to directional dependence in either radiation or matter distribution around quasars (e.g., Jalan et al., 2019). However, our sample lacks sufficient sightlines at impact parameters < 50 kpc to examine this effect in detail.

In summary, our results indicate that at intermediate redshifts and for low-luminosity quasars, the CGM properties are comparable to those of normal galaxies. This highlights the need for future studies involving high-SNR and high-resolution observations of more luminous quasars, especially probing smaller impact parameters and lower equivalent width absorbers, to better understand the role of AGN feedback in shaping the CGM. **This work has been submitted to Monthly Notices of the Royal Astronomical Society (MNRAS). The first revision has also been submitted following a positive reviewer's feedback.**

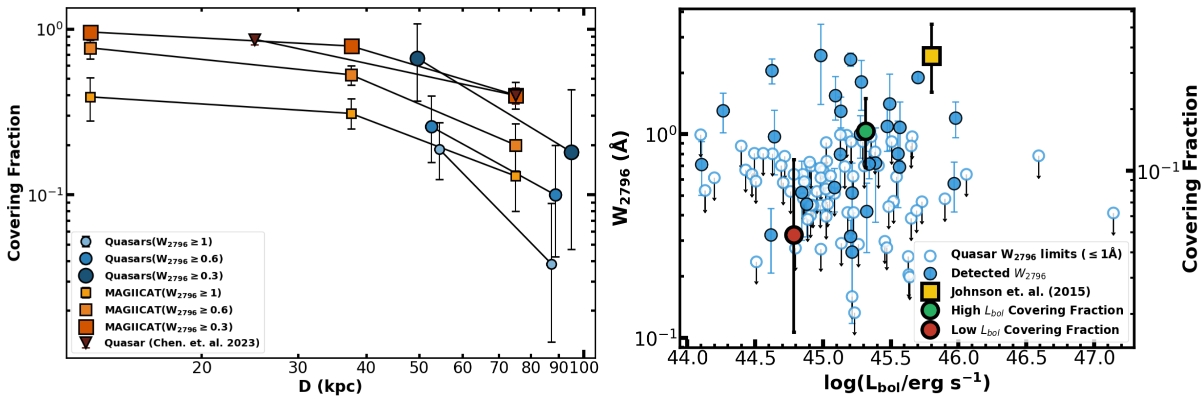

Figure 2: *Left panel*: Comparison for the covering fraction of the CGM of galaxies hosting quasar in our sample with that of (i) similar study (i.e., quasar hosting galaxies) by Chen et al. (2023) and (ii) the CGM study of normal galaxies in MAGICAT by Nielsen et al. (2013). *Right panel*: The figure illustrates the variation of W_{2796} with bolometric luminosity for the quasar sample. Overlaid in the right hand side ordinate are the covering fractions for two luminosity bins and $W_{2796} \geq 1$.

2.2 Investigating the Circumgalactic Medium through Mg II Absorption Coincidence

We investigate the properties of the circumgalactic medium (CGM) around galaxies by analyzing Mg II absorption in projected quasar pairs, using data from the SDSS-DR16Q quasar catalog (Lyke et al., 2020), which contains 750,414 quasars. To construct our sample, we identified 61,195 quasar pairs with angular separations smaller than $1.5'$ to balance sample size with the feasibility of visual inspection. Mg II absorption systems along these sightlines were obtained from the SDSS DR16 Mg II absorber catalog by Anand et al. (2021).

We restricted our analysis to systems where the Mg II absorber lies at a redshift lower than the foreground quasar and fully redward of the Lyman-α emission line of the background quasar. From this filtered dataset, we selected quasar pairs with Mg II absorption in both sightlines within a velocity offset of 1500 km s^{-1}, and those with absorption in only one sightline. Because of catalog incompleteness and potential false positives, we visually inspected all such systems. This led to the identification of 198 coincident absorption cases—where both sightlines show Mg II absorption with $\Delta v < 1500$ km s^{-1}—and 14,043 non-coincident cases.

To ensure that the absorption in single-absorber pairs did not fall in the Lyman-α forest of the other sightline, we imposed two criteria: (1) $z_{\rm abs} > z_f$ of the other quasar, and (2) $(1 + z_{\rm abs}) \times 2796 > (1 + z_f) \times 1216$. For all non-coincident cases, we computed the 3σ upper limits on the Mg II $\lambda 2796$ rest-frame equivalent width (W_{2796}) in the spectrum of the other quasar, within ± 2000 km s^{-1} of the absorber redshift, using the method described in Churchill et al. (2000).

We calculated the coincidence probability as a function of projected separation, defined as the ratio of coincident to non-coincident pairs within 100 kpc impact parameter bins. A pair is considered coincident if both sightlines show W_{2796} above a given threshold, and non-coincident if one sightline has W_{2796} above the threshold and the other has a non-detection with a 3σ upper limit below the detected W_{2796}.

To test whether the observed coincidence rate is due to random chance, we constructed a control sample. For each real quasar pair, we replaced one quasar with a randomly selected quasar from SDSS-DR16, matched in redshift ($\Delta z < 0.01$) and r-band magnitude ($\Delta r < 0.5$), and separated by more than 1°. This substitution was repeated three times per pair to build robust statistics. As visual inspection was not feasible for the large control sample, we relied entirely on the Anand et al. (2021) catalog to identify coincidences and non-coincidences and applied the same analysis.

Our results reveal a clear trend: the frequency of coincident Mg II absorption decreases with increasing projected separation. Approximately 12% of pairs show coincidence at separations near 50 kpc, dropping to around 2% at 500 kpc. This pattern suggests a higher covering fraction of cool, metal-enriched gas in the inner CGM and provides observational constraints on the spatial distribution of Mg II-absorbing gas (see Figure 3).

We are currently continuing this work, with the aim of constructing a statistical model to interpret the coincidence probability in terms of halo mass, redshift evolution, and absorber strength.

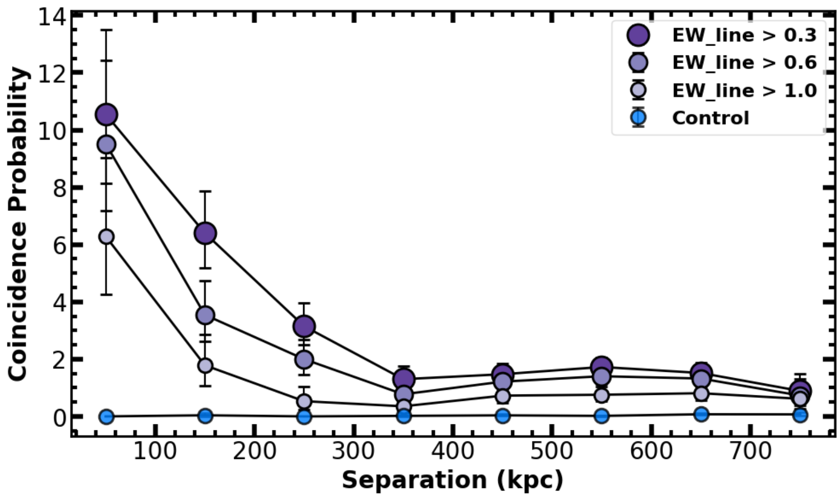

Figure 3: Coincident probability with projected pairs separation at z_{abs}.

2.3 Accelerating Absorption Line Modeling in Quasar Spectra using Convolutional Neural Networks

Absorption line modeling in quasar spectra is a powerful tool for probing the intergalactic medium (IGM), circumgalactic medium (CGM), and broader aspects of cosmological evolution. Traditionally, such analyses rely on Voigt profile fitting routines, such as VIPER (Voigt Profile Parameter Estimation Routine), which are capable of accurately retrieving physical parameters like column density, Doppler parameter, and redshift of absorbers. However, these methods are computationally expensive, especially when applied to large datasets. As astronomy transitions into the era of big data—with ongoing and upcoming surveys like DESI (Dark Energy Spectroscopic Instrument) producing millions of high-resolution quasar spectra—the demand for faster and scalable analysis tools is becoming increasingly critical. In this context, we explore the potential of deep learning techniques, specifically convolutional neural networks (CNNs), as a high-speed alternative to traditional profile-fitting codes.

In this ongoing project, we train CNN models using a combination of simulated and observed quasar spectra, including a wide range of Mg II and other common IGM absorption features. The training dataset includes synthetic spectra with known line parameters, generated under realistic noise and instrumental conditions. The CNN is designed to predict Voigt profile parameters directly from flux-normalized spectra, bypassing the need for iterative fitting. Preliminary results demonstrate that the CNN achieves parameter estimates that are consistent with those obtained from VIPER, while reducing computation time by orders of magnitude. This makes it feasible to analyze large volumes of spectral data efficiently, with minimal human intervention. Such capabilities are crucial for enabling large-scale statistical studies of the IGM and CGM. We are currently refining the architecture and expanding the training set to improve performance across a broader redshift range and absorber types. Future goals include extending the model to multi-component systems, uncertainty estimation via Bayesian CNNs, and application to real survey data from SDSS and DESI.

2.4 Contribution to Astronomy Education Survey

As part of a collaborative effort to assess the status of astronomy education in India, we contributed to a nation-wide baseline survey targeting secondary school students. This study, conducted in ten Indian languages and involving over 2,000 participants from diverse socio-economic backgrounds, explored students' understanding of basic astronomical concepts, access to educational resources, and interest in the subject. Although this work is not a part of our thesis, we actively participated in the implementation of the survey and are co-authors on the resulting publication. The findings revealed widespread gaps in fundamental astronomy knowledge, particularly among students from under-resourced regions, while also highlighting a strong interest in the subject across demographics. This work has important implications for curriculum development and teacher training in science education across India. **This work has been submitted to the Astronomy Education Journal. The first revision has also been submitted following a positive reviewer's feedback.**

3 Future Plan

We are focusing on the Mg II absorption coincidence project. Utilizing a large dataset of over 61,000 quasar pairs from SDSS DR16Q, we aim to characterize the spatial coherence of Mg II-absorbing gas in the circumgalactic medium (CGM). Preliminary results from a subset of 14,869 suitable pairs indicate that the coincidence probability of Mg II absorption in both sightlines decreases from about 12% at 50 kpc to 2% at 500 kpc. This trend reflects the typical spatial extent of cool gas in galaxy halos. We plan to model this behavior quantitatively using the two-point correlation function formalism and explore its dependence on absorber strength and redshift. In parallel, we are developing a deep learning-based tool for fast and scalable absorption line modeling in quasar spectra. Traditional routines like VIPER, though precise, are computationally intensive and not well-suited for large upcoming datasets. We are training a convolutional neural network (CNN) using both synthetic and real quasar spectra to predict Voigt profile parameters directly from observed data. Preliminary tests show promising accuracy with orders-of-magnitude improvements in speed, making this approach ideal for big-data cosmological applications.

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