Radiative Processes in the Circumgalactic Medium: Lyα and He II

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ABSTRACT

Understanding the circumgalactic medium (CGM) is key for understanding how high-redshift galaxies evolved into the ellipticals and spirals they are today. Simulations show that clumpy, pristine, cool gas is accreted from the CGM onto these galaxies, but observations have been limited. Through improved sensitivity and resolution of wide-field integral field spectrographs (IFS) it is possible to observe the CGM in direct emission through fluorescence around high-redshift quasi-stellar objects (QSOs). This paper focuses on understanding the emission observed around z$\sim$2 QSOs, at which the most prominent spectral lines measured in the optical are Lyα, C IV λ1549, and He II λ1640. Of these, Lyα is the brightest by over an order of magnitude, but is limited by complicated radiative transfer effects. He II, although fainter, is more suitable for studying gas accretion as it is optically thin and not contaminated by recombination lines from star-forming galaxies. The ionization mechanisms in high redshift QSO host galaxies are also poorly understood. This paper aims to describe the radiative transfer effects of Lyα and He II in the CGM to gain a better understanding of the evolution of young galaxies.

1. INTRODUCTION

The universe is composed of a cosmic web that connects galaxies and clusters through pristine, cool gas filaments. Studying this large scale structure is a daunting task for optical astronomy. After the first observations through absorption in the Lyman alpha forest, few thought it would be possible to study in emission. Ideas were proposed such as observing intergalactic gas through cosmic ultraviolet background fluorescence, but with modern technology, no observatory is capable of making those observations. Recently, an idea was put forth to observe the circumgalactic medium (CGM) around high redshift QSOs through QSO fluorescence emission. At first this was done with narrowband imaging which showed extended nebulosity around the QSOs.[2] It wasn't until studies were done with integral field spectrographs such as MUSE on VLT and KCWI on Keck that the true extent of these nebulae (up to 1 arcmin) was fully revealed.[1]

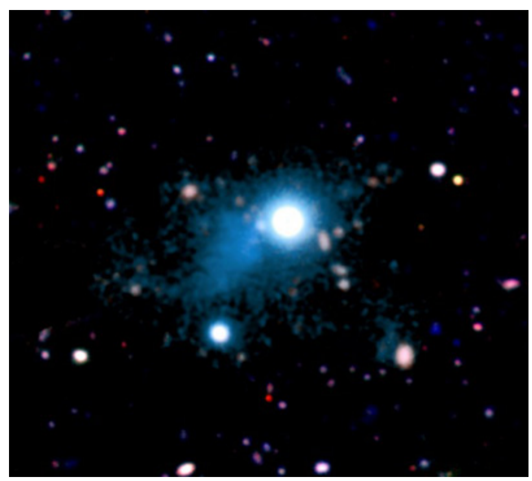

Figure 1. Color image of the Slug Lyα Nebula. This image spans over 2 Mly and shows part of the IGM in emission. Image taken from Cantalupo et. al. 2014[1]

In 2014, the Slug Lyα nebula was discovered and published in Nature in the paper "A cosmic web filament revealed in Lyman-α emission around a luminous high-redshift QSO".[1] This paper showed the largest at the time image of the CGM in direct emission (Figure 1). The nebula spans over 500 kpc with a Lyα surface brightness (SB) reaching over 10^{-16} erg/s/cm^2/arcsec^2 and He II SB reaching 8×10^{-18} ergs/s/cm^2/arcsec^2. This observation showed Lyα nebulae were significantly more extended than previously thought.

Observations of the CGM are important for constraining galaxy evolution models. Simulations require more and more precise measurements to constrain their predictions of the CGM gas kinematics and ionization mechanisms. Most studies of the CGM have been done in absorption, but since the discovery of the Slug and other

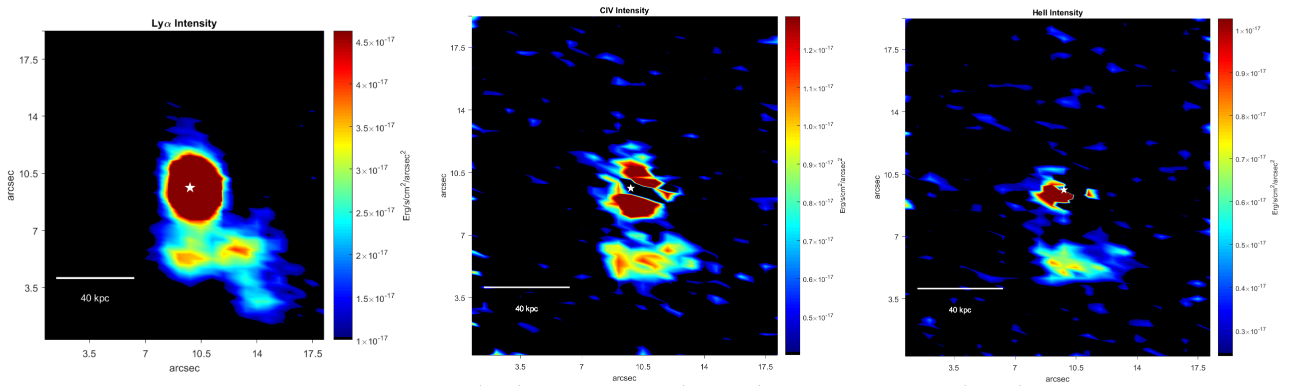

Figure 2. Integrated intensity maps of Lyα (left), C IV λ 1549 (middle) and He II λ 1640 (right) of the CGM around QSO 4C05.84. Lyα extends about 80 kpc around the QSO while the C IV and He II emission is mostly in a cloud separated from the QSO by about 30 kpc. The star marks the location of the QSO.

large Lyα nebulae, many more have been discovered in emission. Multiple ideas were put forth as to what was causing the ionization and luminosities observed in these Lyα nebulae. Some believed it to be scattered or fluorescent light from the central galaxies.[3] Starburst driven superwinds or photoionization by bright stars is another possibility.[4] Understanding these mechanisms is key for understanding the kinematics in the CGM.

High SNR observations of the CGM around the QSO 4C05.84 at z$\sim$2.32 were taken, covering the lines Lyα, C IV λ 1549, and He II λ 1640. While He II is much fainter than Lyα and requires longer integration time, it is not subject to as complicated radiative transfer as Lyα making it more suitable for studying the CGM. The main mechanism leading to the flux observed is QSO fluorescence emission. It is important to understand Lyα absorption, scattering, and other processes in order to use Lyα and He II to better constrain galaxy evolution models.

2. OBSERVATIONS

9 hours of integration time of the CGM around the QSO 4C05.84 were taken with the integral field spectrograph (IFS) KCWI on the Keck II Observatory in the BLM configuration. This covers Lyα, C IV λ 1549, and He II λ 1640 at a redshift of z$\sim$2.32 with a spectral resolution of R$\sim$1800 and a spatial scale of 0.7”.[5] For every 20 minutes of on object time, a 10 minute pure sky frame was taken. This was necessary to perform scaled sky subtraction to maximize the SNR of the He II. PSF subtraction was also performed to fully bring out the CGM around the QSO.

Figure 2 shows integrated line intensity maps of Lyα, C IV, and He II of the CGM around 4C05.84. The Lyα emission extends up to 10” or 80 kpc from the QSO. The He II emission is associated with a cloud about 30 kpc to the south of the QSO. In this cloud, the Lyα SB reaches up to 4×10^{-17} Ergs/s/cm^2/arcsec^2 and He II reaches 8×10^{-18} Ergs/s/cm^2/arcsec^2.

Figure 3 shows the He II to Lyα line ratio of the southern cloud. Observationally, this is defined as:

$$\frac{\langle F_{HeII} \rangle}{\langle F_{Ly\alpha} \rangle} = \frac{h\nu_{HeII}}{h\nu_{Ly\alpha}} \frac{\alpha^{eff}_{HeII}(T)}{\alpha^{eff(T)}_{Ly\alpha}} \frac{\langle n_e n_{HeIII} \rangle}{\langle n_e n_p \rangle}$$

where α is the temperature dependant effective recombination coefficient.[6] The fluxes and line ratio maps support the emission being from QSO fluorescence, as is discussed in the next section.

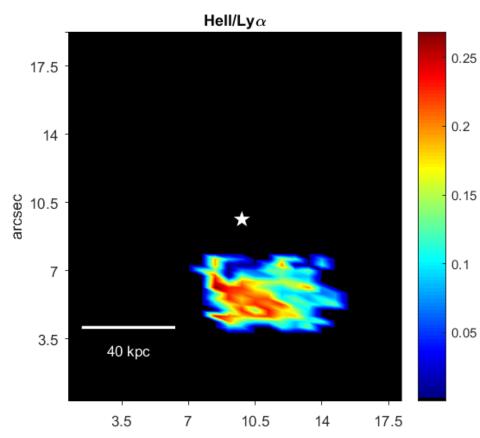

Figure 3. He II to Lyα line ratio map of the southern cloud. The maximum value is $\frac{1}{4}$. The star marks the location of the QSO.

1D spectra collapsed over different apertures and Velocity dispersion maps show a broad and complex shape of the Lyα line and a simple shape of the He II λ 1640 line. Lyα has many absorbers, and is significantly broader than He II. The next section delves into emission mechanisms for Lyα and He II and some of the complicated radiative processes of Lyα.

3. RADIATIVE PROCESSES

Lyα is the brightest spectral line in these observations but presents an issue when trying to use it to understand gas kinematics and ionization mechanisms. Lyα is generally optically thick and subject to complicated radiative transfer. The He II line is much fainter and requires much more expensive on sky time to achieve necessary SNR, but is generally optically thin and not subject to as complicated radiative transfer as Lyα. Many studies are done to try to disentangle the Lyα line, but studies of He II may prove more fruitful.

The main process causing Lyα and He II emission observed around 4C05.84 is QSO fluorescence. There are also contributions from gravitational cooling radiation. These both are examined in the paper "Probing Galaxy Formation with He II Cooling Lines" by Y. Yang et. al. 2005[4] where simulations of cooling radiation are made and show that the flux observed around 4C05.84 could not be due to cooling radiation alone. Many more processes affect the Lyα line such as absorption and scattering. These are explored in the paper "A new model framework for circumgalactic Lyα radiative transfer constrained by galaxy-Lyα forest clustering" by K. Kakiichi et. al. 2018.[3] In this paper, many radiative transfer processes are touched upon, but there is more focus on background QSO absorption and Lyα scattering in halos around central sources in the "single scattering approximation".

3.1 QSO Fluorescence

The main radiative process in my observations is QSO fluorescence. A QSO pointing in the right direction can shine on part of the CGM, illuminating it like a flashlight. The ultraviolet radiation emitted from the QSO is absorbed and ionizes the gas, which emits recombination radiation. This process causes both the Lyα and He II emission and accurately describes their fluxes as seen in my observations. A simple model of photoionization by AGN is given in Yang et. al. 2006.[4]

In this model, the strength of the emission due to QSO fluorescence is proportional to the number of ionizing photons emitted by the AGN. The equation for the luminosity of the emitting region is given by:

$$L_{line} = c_{line} Q = c_{line} \int_{V_{LL}}^{\infty} \frac{L_0}{h\nu} (\frac{\nu}{\nu_0})$$

where Q is the number of ionizing photons emitted per unit time, and c_{line} is the line emission coefficient in ergs which is the energy of the line photon emitted for each H I or He II ionizing photon.

For case B recombination with an electron temperature of $T = 30000$ K and $n_e = 100$ cm^{-3}, Yang calculates $C_{1216} = 1.04 \times 10^{-11}$ and $c_{1640} = 5.67 \times 10^{-12}$ ergs. It is found that to power a Lyα blob with luminosity $L_{Ly\alpha} = 10^{43}$ ergs s^{-1}, an AGN must have $L_{\chi} \gtrapprox 10^{41.8}$ ergs s^{-1} which would generate a He II blob with $L_{HeII} \gtrapprox 10^{41.7}$ ergs s^{-1}. These luminosities are similar to those observed in 4C05.84.

To separate QSO fluorescence from gravitational cooling, it is necessary to investigate Lyα blobs spectroscopically. QSO spectra can be characterized by a strong C IV λ 1549 doublet line while this line is much fainter in a pure gravitational cooling case.[4] This line is present and very bright in the 4C05.84 observations.

3.2 Lyα Absorption

Most studies performed of the CGM are done in absorption, but this presents limitations such as most information being one-dimensional. A recent observational method is to look for QSO pairs, which is to use a QSO as a background light source to study the CGM of another intermediary QSO in absorption. The Lyα absorption arises from residual neutral gas in the photoionized IGM and self-shielded gas. The absorbance features in QSO spectra is a consequence of the cosmic web.[3]

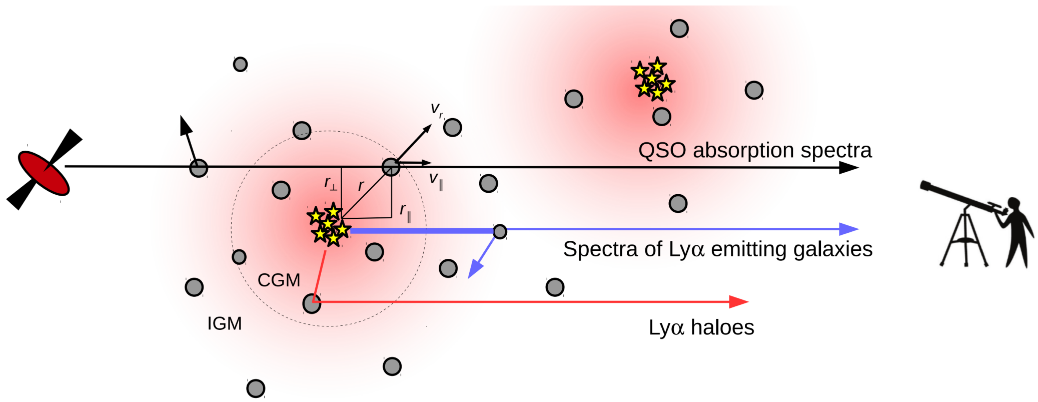

Figure 4. Illustration of a survey of Lyα emitting galaxies in QSO fields. Galaxies are represented by groups of stars. Cool gas is represented by the gray clumps. The dashed circle represents the virial radius. Lyα halos are represented by fuzzy red spheres. Image taken from K. Kakiichi and M Dijkstra 2018.[3]

One aspect making Lyα more complicated than He II radiative transfer is that Lyα is generally optically thick while He II is not. In K. Kakiichi 2018, the equation for the optical depth of Lyα is given by:

$$\tau_a(\nu_e) = \sigma_\alpha N_{HI} \varphi_\nu [T, \nu_e(1 - \frac{\mu||}{c})]$$

where $\sigma_\alpha = (\pi e^2/m_e c) f_{12} = 0.011 \text{ cm}^2$ is the Lyα cross section and $\varphi_\nu(T, \nu)$ is the Voigt profile at gas temperature T and frequency ν. $f_{12} = 0.4164$ is the oscillator strength of the $2P \to 1S$ transition and $\mu_{||}$ is the total line-of-sight velocity of an absorber relative to the associated galaxy.

The mean equivalent width of the Lyα line around galaxies is given by:

$$\langle EW_{r_\perp} \rangle = \lambda_\alpha \int \frac{d\nu_e}{d\nu_\alpha} [1 - \frac{F(\nu_e, r_\perp)}{\tilde{F}(z)}]$$

where $\tilde{F}(z) = e^{-\tilde{\tau}_{eff}(z)}$ is the mean effective optical depth. Observations of Lyα in absorption further constrain these models and our knowledge of the cosmic web in the ΛCDM cosmology. Although to further constrain galaxy evolution models, it is also necessary to observe the CGM in emission.

3.3 Lyα Scattering

One proposed cause of extended Lyα emission is the scattering of light originating from the ISM within a galaxy.[3] This light escapes the ISM into the CGM around it before being absorbed and re-emitted. In the "single scattering approximation", this light is re-emitted exactly once. Kakiichi gives the attenuated luminosity of light escaping the ISM into the CGM as:

$$\langle L_\nu(\nu_e) \rangle = e^{-\tau_{eff}^{Ly\alpha}(\nu_e)} \langle f_{esc,ISM}^{Ly\alpha} \rangle \langle L_\alpha^{intr} \rangle \langle \phi_\alpha^{ISM}(\nu_e) \rangle$$

where $\langle L_\alpha^{intr} \rangle$ is the average Lyα luminosity due to nebular recombination in star forming regions, $\langle \phi_\alpha^{ISM}(\nu_e) \rangle$ is the intrinsic Lyα profile, $\langle f_{esc,ISM}^{Ly\alpha} \rangle$ is the Lyα escape fraction, and $\tau_{eff}^{Ly\alpha}$ is the effective optical depth.[3] The attenuation is caused by the same neutral gas giving rise to absorption in the background QSO spectra.

For Lyα halos around galaxies in the single scattering approximation, the luminosity is given by:[3]

$$L_\alpha(r, \nu_r, N_{HI}) = \int [1 - e^{-\tau_\alpha(\nu_{inj,N_{HI}})}] L_\nu(\nu_e) d\nu_e$$

Simulations of this effect produce fainter luminosites than those observed around the QSO 4C05.84, but is still important as it acts to broaden the Lyα line.

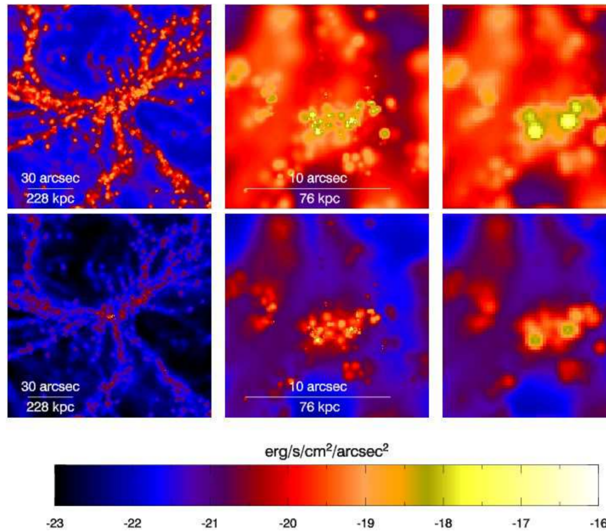

Figure 5. (top) Lyα and (bottom) He II cooling radiation maps at z=3. The middle panel is a zoom in of the left panel, and the right panel is a simulation of an observation with current observational capabilities. Image taken from Yang et. al. 2005[4]

3.4 Gravitational Cooling

There are only two possible ways of producing astronomical Lyα and He II λ 1640 radiation. (1) Ionization followed by the recombination cascades of a captured electron from a hydrogen or ionized helium atom, and (2) collisional excitation followed by radiative decay.[4] In Yang 2005, gravitational cooling radiation simulations were ran at z$\sim$3 showing H I and He II cooling maps (Figure 5).

In these simulations, pristine, cool gas is pulled towards a galaxy, becomes collisionally excited and emits gravitational cooling radiation. The simulated SBs were a bit fainter than those observed around 4C05.84 at a maximum Lyα SB of $\sim 10^{-18}$ ergs/s/cm^2/arcsec^2 and a maximum He II SB of $\sim 10^{-19}$ erg/s/cm^2/arcsec^2 compared to Lyα of $\sim 4 \times 10^{-17}$ and He II of $\sim 8 \times 10^{-18}$. The observed He II to Lyα line ratio map is also higher than the simulated one supporting the idea that QSO fluorescence is the main mechanism behind the emission around 4C05.84.

Gravitational cooling for He II and Lyα is important to observe as the line cooling rates for each peak at different temperatures. This means measurements of both lines could constrain the physical conditions of the emitting gas. Measurements of both Lyα and He II also help to distinguish cooling radiation from other mechanisms that fuel Lyα blobs[4]

4. SUMMARY

Galaxies are connected through pristine, cool gas filaments called the cosmic web. Most studies of the CGM are done in absorption, but information derived from such studies is limited. To gain a full three-dimensional image, we must view the CGM in emission. For optical astronomy this is a difficult task, but by looking near QSOs we can view the CGM through QSO fluorescence emission.

Deep observations of the CGM around the QSO 4C05.84 show extended Lyα, C IV, and He II emission. Complicated data reduction was performed to maximize the SNR and PSF subtraction was performed to bring out the CGM around the QSO. Lyα is the brightest line in these observations, but is subject to complicated radiative transfer. For this reason, high SNR in He II is strived for to accompany the Lyα line.

Multiple mechanisms were investigated to show that QSO fluorescence was indeed the driving force behind the 4C05.84 nebula. It was shown that QSO fluorescence could produce the observed SBs and line ratios around 4C05.84. Lyα scattering and gravitational cooling radiation produce too faint luminosities to explain the emission seen. Simulations of these also fail to reproduce the observed line ratios. It is still important to understand these effects as they affect the shape of the Lyα line.

To further constrain the gas kinematics and ionization mechanisms in the CGM, it is necessary to fully unwrap the complicated radiative transfer of the Lyα line or to gain the ability to easily observe He II. Improved observations of both would further constrain simulations of the physical conditions in the CGM, and are necessary to further constrain galaxy evolution models.

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