Illuminating Protogalaxies? The Discovery of Extended Lyman-α Emission around a QSO at z = 4.5

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Abstract. We have discovered extended Lyman-α emission around a z = 4.5 QSO in a deep long-slit spectrum with Keck/LRIS at moderate spectral resolution (R ≈ 1000). The line emission extends 5 arcsec beyond the continuum of the QSO and is spatially asymmetric. This extended line emission has a spectral extent of 1000 km/s, much narrower in velocity spread than the broad Lyman-α from the QSO itself and slightly offset in redshift. No evidence of continuum is seen for the extended emission line region, suggesting that this recombination line is powered by reprocessed QSO Lyman continuum flux rather than by local star formation. This phenomenon is rare in QSOs which are not radio loud, and this is the first time it has been observed at z > 4. It seems likely that the QSO is illuminating the surrounding cold gas of the host galaxy, with the ionizing photons producing Lyman-α fluorescence. As suggested by Haiman & Rees (2001), this “fuzz” around a distant quasar may place strong constraints on galaxy formation and the extended distribution of cold, neutral gas.

Keywords: line: profiles, formation; techniques: spectroscopic; galaxies: formation, evolution; quasars: emission lines, high-redshift, individual - PC0953+4749

1. Introduction

Although it is by now well-established that QSOs are hosted by galaxies, QSOs themselves are difficult to interpret as probes of galaxy evolution. The evolution of the QSO and galaxy populations is expected to be linked, but in fact they exhibit very different behaviour: the extinction-corrected Madau-Lilly diagram of volume-averaged star formation is flat at redshifts beyond z = 1 (Hopkins, Connolly & Szalay 2000 AJ 120, 2843), yet the QSO luminosity function peaks sharply at z = 2 (Schmidt, Schneider & Gunn 1995 AJ, 110, 68).
A quasar phase may be a natural (but brief) evolutionary stage in the life of all massive galaxies, and theory predicts the proto-galaxy to be enveloped by spatially-extended cold gas of temperature $\sim 10,000$ K, with a radiative cooling time shorter than the dynamical time. Interesting questions include: What is the physical effect of a QSO turning on within an assembling galaxy? And is this observable?

Recent theoretical work predicts a Lyman-\(\alpha\) halo with a surface brightness of $\sim 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (Haiman & Rees 2001 ApJ 556, 87). Such haloes have been seen in radio galaxies and radio-loud QSOs (e.g., Bremer et al. 1992 MNRAS 258, 3) but in these cases it is probably related to outflows. Until now, this phenomenon has yet to be seen for quasars which are not radio loud (see Hu & Cowie 1987 ApJLett 317, 7). If no extended emission can be found, this may imply that QSOs only turn on when the gas has settled into a thin disk or the cold gas has already been consumed in star formation.

The ionizing photons from the QSO will generate recombination line emission from optically-thick neutral hydrogen clouds around the QSO. There will be low surface-brightness Lyman-\(\alpha\) “fuzz” anyway from line cooling of gas in the halo potential, and external photoionization by UV background (e.g., Bunker, Marleau & Graham 1998 AJ 116, 2086), but the presence of the QSO will greatly enhance this. Haiman & Rees (2001) predict a Lyman-\(\alpha\) halo extending out to a significant fraction of virial radius ($10 - 100$ kpc), corresponding to an angular size of $\sim 3''$. The predicted surface brightness of $\sim 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ is accessible to large telescopes with spectroscopy or deep narrow-band imaging. Another recent theory paper by Alam & Miralda-Escudé (2002 ApJ 568, 576) claims 100 times fainter surface brightness and very small extent for the extended Lyman-\(\alpha\) emission ($0.4''$). The large discrepancy in the predictions arises from different assumptions about the clumping factor of cold gas and central concentration of the line-emitting region.

2. Our Observations

We have been undertaking an extensive study of the radio-quiet quasar PC0953+4749 at $z = 4.46$ (Schneider, Schmidt & Gunn 1991 AJ 101, 2004) which has 3 damped Lyman-\(\alpha\) systems at $z > 3$ (Figure 1). The long-slit spectroscopy was obtained with Keck/LRIS (Oke et al. 1995 PASP 107, 375) for 1 hour at spectral resolution of 300km/s. Inspection of the 2D spectrum reveals Lyman-\(\alpha\) at the QSO redshift but extended spatially beyond the continuum of the QSO (Figure 2). This is the first time this phenomenon has been seen at $z > 4$ in a QSO which is not radio-loud.
Figure 1. Our Keck/LRIS spectrum of the radio-quiet QSO PC0953+4749 at $z = 4.46$. We confirm 3 damped Lyman-α systems at $z > 3$.

Figure 2. The upper panel shows the 2D longslit Keck/LRIS spectrum of the QSO PC0953+4749. Wavelength increases left-to-right, and the slit axis is vertical. The region around Lyman-α from the QSO at $z = 4.46$ is shown, and the damped Lyman-α absorption system at $z = 4.25$ can also be seen near the 6363 Å sky line. The spectrum of the QSO point source has been subtracted in the lower panel to reveal residual Lyman-α emission at 6670 Å ($z = 4.49$) extended over $\approx 5$ arcsec.
This line emission extends over $\sim 5''$ beyond the QSO point spread function. The emission is asymmetric, which implies either that gas is clumpy, or that the radiation is beamed anisotropically.

The extended line emission (the dashed line in Figure 3) covers a spectral extent of $\sim 1000$ km/s FWHM. This is not a good measure of the velocity dispersion of the gas, as this line is resonantly broadened. The spatially extended line emission is much narrower than Lyman-$\alpha$ from the QSO (solid line). No evidence of continuum is seen for the extended emission line region. This indicates that the recombination line is probably powered by reprocessed QSO UV flux rather than by local star formation.

The H$\text{I}$ cloud of this host galaxy is $> 35 h^{-1}_{70}$ kpc ($\Omega = 0.3$). The size and surface brightness agree more closely with the theoretical prediction of Haiman & Rees (2001) than with that of Alam & Miralda-Escudé (2002). However, we stress that this is only one example: other deep longslit spectra of high-redshift QSOs need to be studied to see if this extended emission is a generic feature of QSOs in young galaxies.

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