Exploring Protogalaxies through Extended Ly-α Emission around High-Redshift QSOs

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QSOs and "Protogalaxies"

QSOs difficult to interpret as probes of galaxy evolution

Well-established now that QSOs hosted by galaxies

Evolution of QSO and galaxy populations expected to be linked, but exhibit different behaviour (Madau diagrams)

Quasar phase may be a natural (but brief) evolutionary phase in life of all massive galaxies

Expect spatially-extended cold gas (10,000K - radiative cooling time shorter than dynamical)

What is the physical effect of a QSO turning on within an assembling galaxy?
SPH simulations, distribution of neutral gas at z~3 (from Katz et al. and Rauch, Haehnelt & Steinmetz). Left box is 22Mpc comoving, 15arcmin; right zoomed x10
Effect of QSO on host

Ionizing photons from QSO → recombination line emission from optically-thick neutral hydrogen clouds

Get low surface-brightness Ly-α "fuzz" anyway from line cooling of gas in halo potential, and external photoionization by UV background - QSO enhances this

Haiman & Rees (2001 ApJ 556, 87) - Ly-α halo significant fraction of virial radius (10-100Kpc), ≈3"
& surface brightness 10^{-17}erg/s/cm^2/arcsec^2
(accessible to large telescopes with spectroscopy/NB)

BUT Alam & Miralda-Escudé (astro-ph/0106424) claim 100 times fainter surface brightness and v. small (0.4")
Characteristic Surface Brightness

Ly-α halo surface brightness $10^{-17}\text{erg/s/cm}^2/\text{arcsec}^2$

Seen in radio galaxies, radio-loud QSOs (e.g. Bremer et al. 1992 - related to outflows)

Yet to be seen for quasars which are not radio loud (Hu & Cowie 1987 - search inconclusive)

QSOs only turn on when gas has settled into thin disk or formed stars?

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Haiman & Rees
Spatially Extended Ly-α Emission

$z_{em} = 4.487$

5"
We have been undertaking an extensive study of the quasar PC0953+4749 at $z=4.46$ which has 3 damped Lyman-alpha systems (DLAs) at $z>3$, including Keck/LRIS and HST/WFPC2.
Extended Ly-α Emission

The long-slit spectroscopy was obtained using Keck/LRIS (Oke et al. 1995).

Inspection of the 2D spectrum reveals Ly-α at the QSO redshift but extended spatially beyond the continuum of the QSO.

This line emission extends over ~5” beyond the QSO PSF. Emission is asymmetric - gas is clumpy? Radiation beamed anisotropically?

First time this phenomenon has been seen at z>4 in a QSO which is not radio-loud.
Narrow Extended Ly-α

Central QSO (solid line)

Extended Ly-α (dashed line)
Ly-α Spectral Properties

The extended line emission (dotted line) covers a spectral extent of ≈1000 km/s $FWHM$ (resonantly broadened).

Much narrower than Ly-α from the $QSO$ (solid line).

No evidence of continuum is seen for the extended emission line region.

Recombination line probably powered by reprocessed QSO UV flux rather than by local star formation.

The HI cloud of the host galaxy is $\sim 35 \text{kpc}/h_\odot$ ($\Omega = 0.3$).
Summary

Moderate resolution (R~1500) Keck/LRIS spectra of a high redshift QSO (z~4.5)

Discovered extended Lyman-α emission around QSO

Narrow in velocity spread and slightly offset in redshift from the broad line emission of the QSO

The QSO illuminates surrounding cold gas of host, ionizing photons producing Lyman-α fluorescence

"Fuzz" around a distant quasar places strong constraints on galaxy formation and the extended distribution of cold, infalling (?) gas (Haiman & Rees 2001)