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Rest-frame optical line emission from the high-redshift galaxy 1614 + 051A

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ABSTRACT

We report detections of [O III] and Hβ emission from the radio-quiet companion galaxy of the $z = 3.2$ quasar PKS 1614 + 051. The Lyα/Hβ ratio for the galaxy is $\sim 2 \pm 1$, showing evidence for strong absorption or scattering of the Lyα emission. The level of Hβ emission from the companion is too high for it to result from gas photoionized by only the quasar radiation, confirming that the gas in the galaxy is ionized by an embedded source and that the companion galaxy is mildly active. The [O III]/Hβ ratio in the object is lower than in nearby Seyfert 2 galaxies, which implies a low metallicity or a relatively low ionization state for the oxygen. If the latter is true, then carbon lines observed in the optical spectrum are at a higher ionization state than the oxygen lines, further supporting the case for an embedded source of ionization in the galaxy, with a spectrum harder than that of starlight.

Key words: galaxies: abundances – galaxies: active – galaxies: individual: 1614 + 051A – infrared: galaxies.

1 INTRODUCTION

Searching for Lyα emission from objects at the same redshift as high-redshift quasars is one possible way of finding high-redshift galaxies. The first object to be discovered using this technique was a companion galaxy, 6 arcsec away from the quasar PKS 1614 + 051 (Djorgovski et al. 1985). The quasar and companion galaxy (1614 + 051A) have a redshift of 3.214. Since then, a handful of other objects have been discovered in a similar manner (e.g. see Schneider et al. 1986, Hu et al. 1991 and Steidel, Sargent & Dickinson 1991; and the reviews by Pritchett 1994 and Djorgovski & Thompson 1992). Overall, the success rate of this method for finding high-redshift radio-quiet galaxies has not been good. As one of the main purposes of these searches was to find high-redshift protogalaxies, determining the amount of obscuration by dust at high redshift is important, as this may explain the low success rate. Modelling of the spectral evolution of young star-forming galaxies (Charlot & Fall 1993) supports the idea that, in general, high-redshift objects are dusty with little or no Lyα emission. Similarly, *IUE* spectra of low-redshift star-forming galaxies (e.g. Hartmann et al. 1988) often show Lyα emission to be absent, or the line to be in absorption. 1614 + 051A has strong Lyα emission; if the spectrum of this extreme object shows clear evidence for the effects of dust, then it will go some way towards explaining why no large population of sources with less extreme Lyα emission has yet been discovered.

Djorgovski et al. (1985, 1987) have claimed that the radio-quiet galaxy 1614 + 051A is not an ordinary primeval galaxy, but is mildly active, based on the compact optical structure of the object, the high equivalent width of Lyα and the presence of C IV and N V in the optical spectrum. The optical spectrum is not unlike the rest-frame UV spectra of nearby Seyfert 2 galaxies or LINERS (Ferland & Osterbrock 1986; Ferland & Netzer 1983, and references therein). An IR spectrum (equivalent to the rest-frame optical) allows comparison of the oxygen and Hβ emission lines with the rest-frame UV emission lines. We can derive a rough metallicity from the Lyα/Hβ ratio, using the anticorrelation of this value with metallicity in low-redshift star-forming galaxies (Hartmann et al. 1988). This ratio also determines the amount of dust absorption or scattering of Lyα and UV photons in the galaxy. By comparing the strengths of Hβ in the quasar and companion, we can determine whether the quasar appreciably photoionizes the galaxy. The limit on the [O III]/[O II] line ratio gives an indication of the ionization of the gas on kpc scales within the galaxy, and can be compared with the same ratio in low-redshift Seyferts, and also with the rest-frame UV spectrum. Any differences in the ionization states derived from UV and optical lines will be strong evidence for an active nucleus in the galaxy.

2 OBSERVATIONS

PKS 1614+051 was observed on the nights of 1993 July 17 and 18 using the CGS4 IR spectrograph on UKIRT (Mountain et al. 1990). The 150-mm focal-length camera and a 75 line mm^{-1} grating were used, resulting in a spatial pixel scale of 1.5 arcsec per pixel and a wavelength scale of 0.0033 μm per pixel. The spectral resolution corresponds to two pixels. The slit position used was 135°, such that light from both the quasar and the companion fell in the 3-arcsec-wide spectrograph slit. Light from a star 16 arcsec away from the quasar also fell in the slit. Two grating positions were used, resulting in central wavelengths of 1.571 μm (*H* band, the [O II] region of the spectrum) and 2.111 μm (*K* band for [O III] and Hβ). The standard procedure of nodding the telescope between exposures to form image pairs was used (e.g. see Eales & Rawlings 1993). A standard star (HD 161903) was observed, and arc and continuum lamp exposures were made once per hour.

The data frames were reduced in IRAF. Pairs of flat-fielded frames were combined, one frame subtracted from the other. The resulting frame, an 'image pair', contained both a positive and a negative spectrum of the quasar (and companion) separated by 25 arcsec on the array, as a result of the nodding of the telescope between exposures. The subtraction process also had the effect of a first-order sky subtraction. A second-order polynomial was fitted to the sky regions in each image pair to remove the residual sky.

The resulting image pairs were combined into an average exposure. This process also determined the uncertainty on each pixel, taken as the rms variation of the value of the pixel between the 'image pairs'. The residual background in the average image was subtracted using the IRAF task BACKGROUND.

The positive spectrum of the quasar and the negative spectrum were extracted from the average image. Previous optical work has shown that the companion is ~ 6–6.5 arcsec from the quasar, with most of the emission arising from a 1-arcsec region centred on this position. The rows corresponding to the positive and negative spectra of the companion were also extracted. The negative spectra were multiplied by −1. All spectra were then multiplied by the response of the spectrograph, normalized to unity at the central wavelength of the observation. The response curve was created by dividing the standard star observation by a 10 000-K blackbody spectrum. The resulting spectra were then added together, yielding one spectrum for each of the quasar and companion at each grating position.

Fluxes were determined by measuring the ratio of counts at a particular wavelength from the quasar (or companion) and standard star, allowing for the different integration times.

3 RESULTS

Continuum was detected from the quasar in both *H* and *K* spectra. [O III] λ5007 and Hβ were detected for both the quasar and the companion in the *K*-band spectrum. [O III] λ4959 was detected in the quasar, and barely detected in the companion. [O II] λ3727 was not detected from either object. The upper limit to the [O II] line flux is essentially the same in both objects, as the uncertainties in the spectra are dominated by residuals from the sky subtraction.

Table 1. Line fluxes and equivalent widths.

	Quasar	Companion
Flux Hβ	$2.5 \pm 0.5 \times 10^{-15}$	$5 \pm 2 \times 10^{-16}$
W_{rest} Hβ	30 Å	–
Flux [OIII]λ5007	$1.9 \pm 0.4 \times 10^{-15}$	$9 \pm 4 \times 10^{-16}$
W_{rest} [OIII]λ5007	25Å	–
Limit [OII]	$< 1.5 \times 10^{-15}$	$< 1.5 \times 10^{-15}$

Notes. Fluxes are in erg s^{-1} cm^{-2}. We did not attempt to determine equivalent widths for the companion galaxy, as the level of the continuum is consistent with zero. The velocity widths of the emission lines are poorly constrained, but are probably less than 1500 km s^{-1} in the companion object. The Hβ may be broader than the [O III] lines in the quasar spectrum, but again fits to the lines are poorly constrained in velocity. There is no evidence from published optical spectra that the companion galaxy has broad lines.

Details of the detections are given in Table 1, and the *K*-band spectra are shown in Fig. 1.

In the companion, the [O III]/Hβ ratio is 2 ± 1 and the limit on [O III]/[O II] is > 0.6. Different authors have given different values for the Lyα flux of the companion. Djorgovski et al. (1985) gave a value of about 3×10^{-15} erg s^{-1} cm^{-2}, whereas Hu & Cowie (1987), Hu et al. (1991) and Steidel et al. (1991) gave fluxes consistent to within 20 per cent of 1×10^{-15} erg s^{-1} cm^{-2}. This has been taken as weak evidence that the Lyα flux from the object is declining with time (Thompson, Djorgovski & Trauger 1995). We take a value of 1×10^{-15} erg s^{-1} cm^{-2} for the Lyα flux. Thus the Lyα/Hβ ratio is $\sim 2 \pm 1$. The Lyα flux of the quasar is 2.1×10^{-14} erg s^{-1} cm^{-2} (Steidel et al. 1991), leading to a Lyα/Hβ ratio of 9 ± 2 in the quasar.

4 DISCUSSION

The detection of [O III] and Hβ emission from 1614+051A allows comparison of the spectrum of the object with those of extragalactic objects, at both low and high redshifts. The presence of N V, C IV and C III] lines in the spectrum of the galaxy (Djorgovski et al. 1985; Steidel et al. 1991) implies a hard ionizing spectrum. This has prompted Djorgovski et al. (1985) to argue that the galaxy is mildly active, perhaps a high-redshift Seyfert 2 or LINER. Moreover, the large equivalent width of the Lyα line, 600 Å in the rest frame (see Steidel et al. 1991; Hu & Cowie 1987), is more than can be achieved from stellar photoionization alone (Charlot & Fall 1993), supporting the idea that the galaxy has an active nucleus. Alternatively, the hard photoionizing source may be the neighbouring quasar. The following discussion provides strong evidence that the galaxy is indeed active.

The strength of Hβ in the quasar relative to that in the companion galaxy clearly shows that photoionization by the quasar cannot be the dominant source of ionization for the gas in the companion. As the strength of Hβ scales directly with the ionizing photon flux (under case B conditions), the strength of Hβ in the companion is far too high for it to be photoionized by the quasar. Nevertheless, the complete (optical + IR) spectrum is still most likely a result of photoionization given the high ionization states, presumably

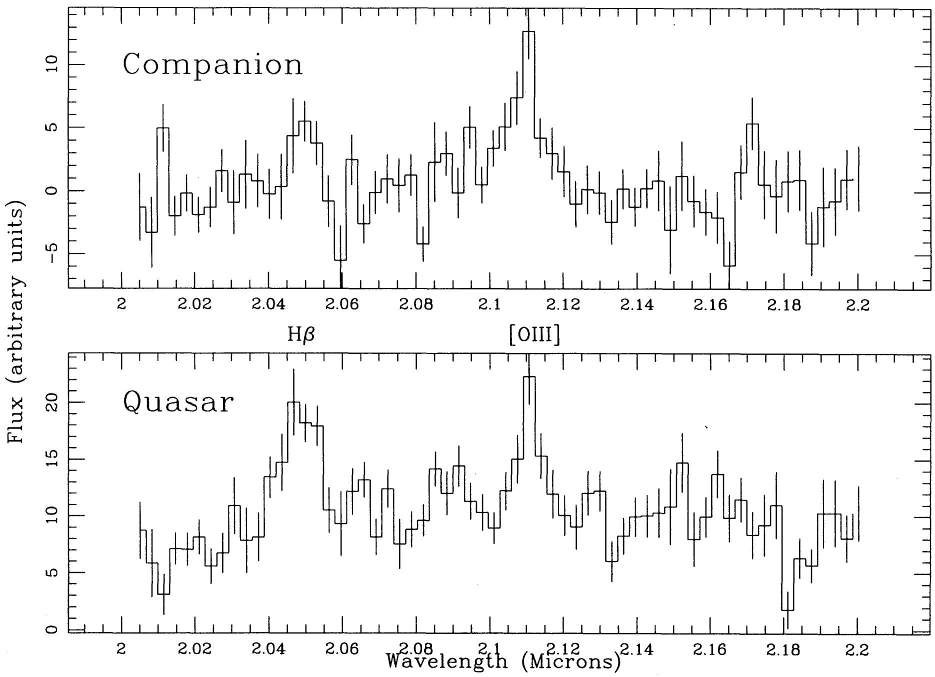

Figure 1. Extracted spectra of the companion galaxy and the quasar. The Hβ line is redshifted to 2.05 μm and the [O III] λ5007 line is at 2.11 μm. Error bars are 1σ, determined from the variation of the value in each pixel over all the summed short exposures.

caused by a source or sources within the galaxy itself. Only if the companion galaxy is exposed to a considerably higher ionizing luminosity than we observe (for example if the quasar is beamed towards the galaxy, or if the quasar is highly variable) can the quasar be the dominant source of ionization for the gas in the companion galaxy.

The difference in the Lyα/Hβ line ratio between the quasar and companion shows that the Lyα (and possibly the UV continuum) of the companion is either absorbed or scattered out of our line of sight by material related to the companion. A similar effect is seen in high-redshift radio galaxies (Eales & Rawlings 1993). These objects also show strong Lyα emission, along with Lyα/Hα and Lyα/Hβ ratios that imply absorption or scattering by dust.

The absorbing/scattering material is either intrinsic to the companion or along the line of sight to it, but not along that to the quasar. The Lyα/Hβ ratio for the companion galaxy is an order of magnitude less than the case B value of ~23 (Ferland & Osterbrock 1985). If the Lyα flux is declining (Thompson et al. 1995), then our derived ratio is an over-estimate and even further away from the case B value. The density of the line-emitting region is low enough for case B to be appropriate. A straightforward explanation for this depression of Lyα relative to Hβ is that dust associated with the galaxy absorbs the photons. If the dust were only in the emission-line clouds, then Lyα would be preferentially absorbed (Lyα photons undergo resonant scattering within clouds; the high path length increases the probability of dust absorption). This is unlikely to be occurring, as the already high equivalent width of the Lyα ($W_{\rm rest}$ ~ 600 Å: Steidel et al. 1991) implies that the line is not depressed relative to the neighbouring continuum. Alternatively, the dust may be distributed throughout the galaxy, reddening both lines and continuum. Calzetti & Kinney (1992) showed that the Lyα/Hβ ratio of low-redshift star-forming galaxies can be corrected to recover a (more or less) case B value by applying a dereddening law appropriate to the metallicity of the galaxy. Given the results of Calzetti & Kinney (see their table 2), it is likely that the ratio in 1614+015A can be corrected to within a factor of 2 of the case B value given an appropriate extinction law. This would also have the effect of making the intrinsic continuum up to 2–3 mag brighter in V than observed.

One other possibility is that the dust could be external to the galaxy. The optical spectrum of the quasar in Steidel et al. (1991) shows several strong Lyα absorption lines. If any of the systems giving rise to these are dusty, this could redden the galaxy. This would imply that the absorption-line system is at least 30 kpc in size (to cover both quasar and companion) and has a patchy dust distribution (to allow for different reddenings towards the two background objects).

Meier & Terlevich (1981) and Hartmann et al. (1988) show that the Lyα/Hβ anticorrelates with metallicity in low-redshift star-forming galaxies, presumably as dust influence increases with metallicity. There is considerable scatter in this relationship. Although the relationship has been determined for low-redshift star-forming galaxies and the characteristics of dust at high redshift may be different, a similar correlation will be valid for high-redshift narrow-line objects. Even if the lines originate from close to an active nucleus, the reddening effect of the surrounding galaxy might be expected to follow a similar law for metallicity. Given the ratio in 1614+051A, a tentative metallicity of 0.1 to 0.5 $Z_{\odot}$ for the galaxy is predicted, assuming that the reddening is not external to the galaxy. Clearly, more accurate determinations of the fluxes of several rest-frame optical emission lines are needed to constrain the metallicity better.

Although the spectrum of the object is similar to that seen in low-redshift Seyferts, the [O III]/Hβ ratio is low in comparison (see Ferland & Osterbrock 1986). This ratio plus that of [O III]/[O II] can be used to constrain the metallicity and ionization state of gas in AGN emission-line regions (e.g. see fig. 2 in Ferland & Netzer 1983). In the case of 1614+051A this is difficult, as we only have a limit on [O III]/[O II]. If the [O III]/[O II] ratio is similar to that in low-redshift Seyferts, then this implies a low metallicity for the emission-line gas ($\sim 0.1\ Z_\odot$), seemingly in contradiction with the strength of the metal lines in the optical spectrum. If, on the other hand, the ratio is low, then the metallicity is increased, but the oxygen lines are at a lower ionization state than the carbon lines. This is consistent with there being a central source of ionizing photons embedded in the galaxy. Clearly, it would be useful to determine the strength of the [O II] line, but this would probably require an integration of several hours on a larger telescope than UKIRT.

What does this observation tell us about the spectra of non-active galaxies at high redshift? If we imagine that the active nucleus in this object is switched off (assuming that it has one), then the ionizing photon density decreases. The Hβ line emission decreases in strength with the ionizing photon density, as does the [O III] emission. If the ionizing photon density decreased by an order of magnitude or more, these lines would be undetectable. Similarly, the Lyα and metal lines would be weaker (especially the high-ionization lines of C IV and N V). The maximum equivalent width of Lyα emission achievable from stellar photoionization is ~ 300 Å, and then only for dust-free systems (Charlot & Fall 1993). Consequently, without a hard source of ionizing photons, Lyα would either be weak in emission, or be in absorption. Only in the case of a starburst would the Hβ and [O III] emission recover somewhat.

5 CONCLUSIONS

We have detected [O III] and Hβ emission from the high-redshift radio-quiet galaxy 1614+051A. We also have a limit on the [O II] emission from this object. The Lyα/Hβ ratio implies that there is significant absorption or scattering of Lyα photons occurring within or along the line of sight to the galaxy. If this relative lack of Lyα emission is common in other high-redshift objects, it explains the low success rates in searches for high-redshift protogalaxies.

It has previously been claimed that 1614+051A is a mildly active object, possibly a high-redshift analogue of a Seyfert 2 galaxy. The [O III]/Hβ ratio is low if this is the case; the emission-line region may have a lower metallicity than the majority of the low-redshift Seyfert 2 galaxies. Alternatively, the oxygen lines are at a lower ionization state than the carbon lines seen in the optical spectrum. This argues for a range of ionization states within the galaxy, supporting the idea that the object has a central active nucleus.

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