KECK SPECTROSCOPY OF 4 QSO HOST GALAXIES

J. S. MILLER 1 AND A. I. SHEINIS 1

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ABSTRACT

We present optical spectroscopy of the host galaxies of 4 QSO’s: PG 1444+407, PKS 2349-147, 3C 323.1, and 4C 31.63 having a redshift range 0.1 \leq z \leq 0.3. The spectra were obtained at the Keck Observatory with the LRIS instrument offset 2-4 arcseconds from the nucleus at several position angles in each galaxy. The objects close to 3C 323.1 and PKS 2349-147 have the same redshifts of their nearby QSOs and appear to be the nuclei of galaxies in the final states of merging with the host galaxies. The spectra of the hosts show some variety: PKS 2349-147 and 3C 323.1 show strong off-nuclear emission lines plus stellar absorption features, while the other two show only stellar absorption. PKS 2349-147 and PG 1444+407 have a mixture of old and moderately young stars, while 4C 31.63 has the spectrum of a normal giant elliptical, which is very rare in our larger sample. The spectrum of the host of 3C 323.1 appears to dominated by older stars, though our data for it are of lower quality. The redshifts of the off-nuclear emission lines and stellar components are very close to those of the associated QSOs.

Subject headings: galaxies: active—(galaxies:) quasars: general—techniques: spectroscopic—(galaxies:) quasars: individual (PG 1444+407, PKS 2349-147, 3C 323.1, and 4C 31.63)

1. INTRODUCTION

A long history of imaging studies of QSO hosts dates back to early 60’s and 70’s (Sandage & Miller (1966), Kristian (1973)). More recently there have been several infrared (Taylor et al. (1996)) and HST based imaging studies (Bahcall et al. (1997), McLure et al. (1999)). These studies have yielded colors, morphologies and constraints on galaxy magnitudes.

Spectroscopic observations are necessary for direct information on the nature and kinematics of these nebulosities. Several groups have performed spectroscopic observations, dating back to the early 80’s. The most extensive early investigations were those of Boroson & Oke (1984) and Boroson et al. (1985), who obtained off-nuclear spectra of 24 objects with the Palomar 200” using a 2-arcsecond slit. They determined continuum colors for most objects and showed that a number of them had an extended emission-line component, but, with the exception of 3C48, no stellar absorption lines were detected in any of the objects. More recently several groups (Hickson & Hutchings (1987), Hutchings & Crampton (1990), Hughes et al. (2000) and Nolan et al. (2001)) have made extensive observations with 4 meter class telescopes. With the advent of the Keck 10 meter telescope one group has been able to compare detailed absorption spectra with population synthesis models for these objects (Canalizo & Stockton (2000), Canalizo & Stockton (2001)).

Conclusions about the nature of low-z QSO host galaxies differ. One group of collaborators, (McLure et al. (1999), Hughes et al. (2000) and Nolan et al. (2001)) believes these objects to be predominantly normal massive ellipticals, while Miller (1981), in the first spectroscopic investigation of a sample of these objects, concluded that they are not normal luminous ellipticals, a result which was later confirmed with better data from the Keck telescope in Miller et al. (1996). Moreover, other groups (Canalizo & Stockton (2000), Canalizo & Stockton (2001) and Sheinis (2001)) have seen post-starburst spectra in a substantial fraction of these objects.

In this Letter we present data from 4 of the 20 objects studied by us with the Keck 10 meter telescope; a subsequent, more lengthy paper on the entire sample is in preparation (Sheinis & Miller (2003)). The objects discussed here- PG 1444+407, PKS 2349-147, 3C 323.1 and 4C 31.63- exhibit a redshift of 0.1 \leq z \leq 0.3. Data acquisition and reduction techniques are discussed in Section II, and Section III presents a discussion of the results.

2. DATA ACQUISITION AND REDUCTION

The data were taken using the Low Resolution Imaging Spectrograph (LRIS) (Oke et al. (1994)) on the Keck 10 meter telescope, and the observations are summarized in table 1. In general, a short observation of the QSO (120 sec) was followed by several longer exposures of the off-nucleus regions, typically two to four exposures of 1800 sec at each position. In most cases the slit location and orientation was determined using published HST images (Bahcall et al. 1997) to identify regions of high surface brightness. These slit locations were mostly between 2 and 4 arcseconds from the nucleus. The data were reduced with the VISTA data reduction package Stover (1988), and final spectra were extracted by standard techniques. Typically 3 to 4 arcseconds along the slit centered on the closest approach of the slit to the QSO were used for the host, and since the slit was approximately 7 arcminutes projected on the sky, it was straightforward to identify suitable regions along the slit free of any host contamination for sky subtraction. The last step was correction for scattered QSO light, which is described in the next section.

[Table 1 about here.]

3. SCATTERED LIGHT SUBTRACTION

The light from the QSOs in this study is 2-5 magnitudes brighter than the entire host galaxy, which complicates the data reduction. The regions of the host galaxies observed in our study were typically 5 to 8 magnitudes fainter than the QSO. As a result of the blurring produced by the earth’s atmosphere plus a small contribution from the intrinsic optical point-spread function and diffraction produced by the telescope, some light from the QSO entered the spectrograph in the off-nucleus observations. To make an approximate correction for the scattered
light, the following process was adopted; it is very similar to that used by Boroson & Oke (1984). With the assumption that any broad Balmer lines that are visible in the off-nucleus spectrum arise from scattered QSO light, it is possible to estimate the fraction of scattered QSO light present at the wavelengths of each of the broad lines. The scattering fractions are fit by a polynomial, and the spectrum of the QSO is scaled by this scattering-efficiency polynomial and subtracted from the off-nuclear spectra. The result is a spectrum with the broad lines and other QSO spectral features removed. The correction becomes uncertain at wavelengths beyond the range covered by the Balmer lines. The correction is especially uncertain toward the blue end of the spectrum, well beyond any detectable broad lines.

As a result of this uncertainty in the blue end of our spectra, we had to adopt a more complex technique for the scatter subtraction for the very bluest object, 3C 323.1. In this approach we simultaneously derive a model for the scattered QSO fraction and stellar and gas components, assuming that the observed light can be represented entirely by these three components. The model contains: (1) A two-age-component stellar population synthesis model (Bruzual & Charlot (1993)); (2) A model spectrum for the narrow Balmer emission-line gas and (3) A scattered light model which is the QSO spectrum multiplied by a polynomial, and the spectrum of the QSO is scaled by this polynomial, and the spectrum of the QSO is scaled by this polynomial. This spectrum is very similar to that derived for the Balmer lines. The correction is especially uncertain toward the blue end of the spectrum, well beyond any detectable broad lines.

4. DESCRIPCTIONS OF INDIVIDUAL OBJECTS

4.1. PKS 2349-014

Bahcall et al. (1995) and Bahcall et al. (1997) present images of this object that show obvious morphological signs of gravitational interaction, such as large tidal arms and an extensive (50 kpc) diffuse, off-center nebulosity. The QSO has a typical spectrum with strong broad permitted lines and much narrower forbidden lines with a modest amount of Fe II emission. They identify several distinct regions for which we have obtained spectra. Figure 1a was taken 3 arcseconds south of the nucleus in the region of the off-center diffuse nebulosity and illustrates the method of scattered light subtraction used for all the spectra. Spectrum A includes the galactic light and the scattered QSO light. Spectrum C is the QSO spectrum modeled and scaled to represent the estimate of the scattered QSO component in Spectrum A, and Spectrum B is the difference of A and C. In Spectrum B, the absorption features show a strong resemblance to those of an elliptical galaxy with superposed narrow emission lines. Figure 1b is the spectrum of the so-called "north wisps", taken at 4 arcseconds north of the nucleus. Comparison of these spectra with model spectra created from a two-component population synthesis model (Bruzual & Charlot (1993)) suggests post-starburst spectra consisting of roughly 1/3 light from young stars and 2/3 light from old (age \(\geq 10 \text{ Gyr}\)) stars. While these comparisons with the population synthesis models show approximately the same contribution to the light from young stars for each observation, they suggest a somewhat younger population (age \(\leq 500 \text{ Myr}\)) for the observations to the south of the host as compared to those of the "north wisps" (age \(\simeq 1 \text{ Gyr}\)). Figure 1c shows the spectrum of the "north wisps" co-added with the other off-nuclear observation of the host galaxy from 3 arcseconds south. These two positions comprise all of the off-nuclear observations of this object that do not contain light from the companion object. They have been co-added to increase the signal-to-noise. Figure 1d shows the companion located 1.8 arcseconds from the QSO. (Bahcall et al. 1997) note that this object has a luminosity similar to that of the LMC if it is at the distance of the QSO and that it shows no sign of interaction in the HST imaging. This spectrum shows an old stellar population at the same redshift as the QSO, along with strong narrow permitted and forbidden emission lines. Examination of the spectral data as a function of position along the slit indicates that this emission is not directly associated with the companion object, but is distributed diffusely over the entire region. These data support the Bahcall et al. speculation that this object is the tidally-stripped nucleus of a galaxy about to be fully accreted by the host galaxy of PKS 2349-014.

4.2. 4C 31.63

Fig 2a shows the combined spectra for several observations to the east of the nucleus of 4C 31.63, all of which appear identical to within the accuracy of the data. These observations are listed in Table 1. This radio-loud object has the spectrum of a typical strong-Fe II QSO, with strong Fe II emission along with the usual broad Balmer lines and very weak or non-detectable forbidden lines. The off-nucleus spectrum shows no detectable emission lines, but clearly shows the absorption features of an old stellar population, i.e., the 4000 break along with the Ca II H and K, G band, and MgIb absorption features. The spectrum bears a strong resemblance to that of a normal giant elliptical at the same redshift as the QSO. Comparison of this spectrum to population synthesis models suggest all of the light is from an old stellar population (age \(\geq 10 \text{ Gyr}\)).

4.3. PG 1444+407

Fig 2b shows the combined spectra for all observations listed in Table 1 of PG 1444+414 with the scattered light subtracted. The spectrum of this radio-quiet QSO is similar to that of 4C 31.63, showing strong Fe II emission, broad Balmer lines and no detectable forbidden emission lines. Again as with 4C 31.63, no emission lines are detected in the off-nucleus spectrum. In fact, in our entire sample of 20 QSOs, the only ones that do not show off-nucleus emission are the strong Fe II objects. Clearly seen are stellar absorption features, but the absorption spectrum is different from that of the galaxy associated with 4C 31.63. While some features produced by cool stars are again apparent, such as Ca II H and K and a weak G band, compared to the 4C 31.63 galaxy the \(\lambda = 4000 \text{ break}\) is relatively weak, and the spectrum longward of 4000 is not as red; in addition some weak higher-order Balmer lines are visible. This is clearly not the spectrum of a normal giant elliptical, as it looks like the combination of a substantial fraction of relatively younger stars mixed in with the older population. Comparison of this spectrum to population synthesis models suggest this spectrum is composed of equal luminosity components of very young stars (age \(\leq 50 \text{ Myr}\)) and old stars (age \(\geq 10 \text{ Gyr}\)), indicative of very recent, or ongoing star formation.

4.4. 3C 323.1

The radio-loud QSO 3C 323.1 has a spectrum very typical of that of many QSOs, with strong broad Balmer emission lines along with narrow forbidden lines of [OII],[OIII], [NeIII], etc. There is a companion object 2.1 arcsecond from the QSO, which is about 3.9 mag fainter than the QSO itself Bahcall et al. (1997). Figure 2c shows a spectrum of this companion.
companion has the same redshift as that of the QSO and a spectrum with absorption features of cool stars as indicated plus [O III] emission. The [O III] emission is extended along the slit in the original data and does not appear to be associated with the companion itself. Consistent with the conclusions of Canalizo & Stockton (1997), the absorption spectrum is not that of a normal giant elliptical, as the 4000 break is not as pronounced and the continuum is less inflected. The data are consistent with the companion being the remnant nucleus of a galaxy in the final stages of merging as suggested by Stockton (1982).

Figure 2d shows the spectrum of the nebulosity around 3C 323.1 with the scattered light removed. This spectrum was formed by combining observations taken at several different position angles as listed in table 1, positions that avoided the companion. The data from the various slit positions all appear very similar, and the combined spectrum was formed to increase the signal-to-noise ratio. This spectrum shows very weak Hβ in emission along with stronger narrow forbidden lines of [OIII]. There appears to be a hint of the 4000 break, but no other absorption features are clearly visible. The hint of the 4000 break and the overall spectral energy distribution suggests that cool stars may be the main contributor to the observed light, but higher quality data are needed for this faint galaxy component before anything definitive can be said.

5. DISCUSSION AND CONCLUSIONS

Boroson et al. (1985) found correlations between the spectra of nebuleities associated with QSOs and the spectra of the QSOs themselves, and similar correlations are seen in our data. Specifically, in our study the two objects showing strong FeII emission, PG 1444+414 and 4C 31.63, show no emission lines in the host galaxy and have narrower, smoother, more symmetric permitted lines in the QSO. One has a compact nuclear radio source, while the other is radio quiet. The other two objects, PG 2349-014 and 3C 323.1, show strong forbidden emission lines, broader bumpy permitted emission lines, weak [Fe II] emission in the QSO, and very extended emission regions in the hosts. These objects also exhibit extended, steep radio structure.

The four QSOs we present in this study show a range in properties for the host galaxies. Only one host, that of 4C 31.63, has the spectrum of a normal giant elliptical galaxy. Two objects have what appear to be the remnant nucleus of a merging galaxy in the final stages of the merger very close to nucleus of the host galaxy. While close nuclear companions are not that common, the other characteristics of the host galaxies in these four objects are representative of our larger sample of 20 QSOs. Spectra typical of normal giant elliptical galaxies, without strong extended emission line gas, are a distinct minority. Only the spectrum of one additional object in our larger sample is consistent with this type of galaxy. Most of the hosts do show strong extended emission such as that shown here in 3C 323.1 and PKS 2349-014.

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[Figure 1 about here.]
[Figure 2 about here.]
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1 Four spectra of PKS2349-014: top frame (a) shows the spectra of PKS2349-014 taken at 3 arcseconds south of the nucleus: top curve (A) is the extracted spectrum, middle curve (B) is the residual host galaxy spectrum all position angles co-added, with scattered light subtracted and the bottom curve (C) is the subtracted scatter model; second frame (b) is the residual host galaxy spectrum taken at 4 arcseconds north of the nucleus; third frame (c) is the co-added spectra from 3 arcseconds south and 4 arcseconds north; bottom frame (d) is the spectrum from the “LMC-like” companion to PKS2349-014. The increased noise at the red end is due to strong OH night-sky lines.

2 Spectra of 3 objects: top frame (a) shows the spectra of PG1444+407; second frame (b) is the residual host galaxy spectrum of 4C31.63; third frame (c) is the residual host galaxy spectrum of the companion to 3C323.1; bottom frame (d) is the residual host galaxy spectrum of 3C323.1. The increased noise at the red end is due to strong OH night-sky lines.
Fig. 1.— Four spectra of PKS2349-014: top frame (a) shows the spectra of PKS2349-014 taken at 3 arcseconds south of the nucleus: top curve (A) is the extracted spectrum, middle curve (B) is the residual host galaxy spectrum all position angles co-added, with scattered light subtracted and the bottom curve (C) is the subtracted scatter model; second frame (b) is the residual host galaxy spectrum taken at 4 arcseconds north of the nucleus; third frame (c) is the co-added spectra from 3 arcseconds south and 4 arcseconds north; bottom frame (d) is the spectrum from the “LMC-like” companion to PKS2349-014. The increased noise at the red end is due to strong OH night-sky lines.
FIG. 2.— Spectra of 3 objects: top frame (a) shows the spectra of PG1444+407; second frame (b) is the residual host galaxy spectrum of 4C31.63; third frame (c) is the residual host galaxy spectrum of the companion to 3C323.1; bottom frame (d) is the residual host galaxy spectrum of 3C323.1. The increased noise at the red end is due to strong OH night-sky lines.
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| Object     | z    | date | Exposure | Slit width | offset | P.A.    | comment         |
|------------|------|------|----------|------------|--------|---------|-----------------|
| PG1444+407 | 0.267| 8/96 | 2 × 1800 | 1.0        | 3.0    | South @90|
|            |      | 8/96 | 2 × 1800 | 1.0        | 2.8    | Northeast @135|
|            |      | 7/97 | 3 × 1800 | 1.0        | 3.0    | South @90 |
| PKS2349-147| 0.173| 8/96 | 2 × 1800 | 1.0        | 3.0    | South @90 |
|            |      | 8/96 | 2 × 1800 | 1.0        | 2.0    | Southeast @20 |
|            |      | 8/96 | 2 × 1800 | 1.0        | 4.0    | North @70 |
|            |      | 3C323.1 | 8/96 | 2 × 1800 | 1.0    | 2.0    | Southeast @35 |
|            |      | 8/96 | 2 × 1800 | 1.0        | 2.0    | Northwest @25 |
|            |      | 7/97 | 2 × 1800 | 1.0        | 2.8    | Southeast @35 |
|            |      | 7/97 | 1 × 1800 | 1.0        | 2.0    | Southeast @35 |
|            |      | 9/97 | 3 × 1800 | 1.0        | 3.0    | North @90 |
|            |      | 9/97 | 3 × 1800 | 1.0        | 3.5    | South @90 |
| 4C31.63    | 0.297| 8/96 | 2 × 1800 | 1.0        | 4.5    | Northeast @135|
|            |      | 8/96 | 4 × 1800 | 1.0        | 3.0    | East @0 |
|            |      | 7/97 | 3 × 1800 | 1.0        | 2.0    | North @270|
|            |      | 7/97 | 2 × 1800 | 1.0        | 2.5    | East @180|
|            |      | 9/97 | 2 × 1800 | 1.0        | 3.0    | South @90 |
|            |      | 9/97 | 3 × 1800 | 1.0        | 3.0    | South @90 |