ABSTRACT

The redshifts of the gravitational lens galaxies in MG 1131 +0456 and B1938 +666 are 0.844 and 0.881, respectively. Both are early-type galaxies lying at the redshifts predicted by assuming that they are early-type galaxies with old stellar populations lying on the fundamental plane. We also find evidence for a foreground group of galaxies at $z = 0.343$ near MG 1131 +0456. The source redshifts are predicted to be $\geq 1.8$ in both systems, but they are so red that infrared spectra will be required to determine their redshifts.

Key words: distance scale — gravitational lensing

1. INTRODUCTION

There are now over 50 multiple-image gravitational lens systems. The lens sample is a unique and powerful tool for studying cosmology, galactic structure, and galactic evolution. For studying galaxy structure and evolution, (1) it is the only sample of galaxies selected based on mass rather than luminosity; (2) it is one of the largest samples of galaxies with precisely measured masses; and (3) it is comparable in size to the largest kinematic samples outside the local universe. The lenses are one of the more promising alternatives to measuring $H_0$ other than using the local distance ladder (see Koopmans & Fassnacht 1999), and their incidence and redshift distributions can be used to measure the underlying geometry ($\Omega_0$, $\Lambda_0$; see Falco, Kochanek, & Munoz 1998). Lenses can also be used to study the hosts of high-redshift active galactic nuclei (AGNs) and quasars (Rix et al. 2000) and the dust (Falco et al. 2000) and interstellar medium (e.g., Menten, Carilli, & Reid 2000) of the lens galaxy. Surveys to find new lenses are now very productive (e.g., Browne et al. 2000), and Hubble Space Telescope (HST) imaging surveys are providing detailed surface photometry for most of the lens galaxies (Falco et al. 1999). Thus, the remaining barrier to exploiting the astrophysical potential of gravitational lenses is the high fraction of unmeasured lens and source redshifts. In this paper we determine the lens galaxy redshifts of MG 1131 +0456 and B1938 +666.

MG 1131 +0456 (Hewitt et al. 1988) is a radio-selected lens, and it was the first Einstein ring to be discovered. The radio map (Chen & Hewitt 1993) shows two images of the radio core, an elliptical ring image formed from the jet, an unlensed radio lobe, and a central, unresolved image at the position of the lens. Ground-based optical (Hammer et al. 1991) and infrared (Annis 1992; Larkin et al. 1994) observations established that the system was very red, but HST imaging was required to understand its morphology (Kochanek et al. 2000b). At optical wavelengths, the emission is dominated by a red, early-type lens galaxy with a photometric redshift of $0.84 < z_l < 1.01$ (Kochanek et al. 2000a). There is a faint, incomplete optical ring image of the host galaxy of the radio AGN. In the infrared, the $H$-band image is dominated by a bright, complete Einstein ring image of the AGN host galaxy ($H \approx 17.4$ mag). The AGN host appears to be a very dusty galaxy, which would be classified as an extremely red object (ERO; e.g., Thompson et al. 1999), while the lens galaxy is a normal, transparent early-type galaxy. Hammer et al. (1991) proposed a redshift of 0.85 for the lens galaxy.

B1938 +666 (King et al. 1997) was also radio-selected. The radio map shows a partial Einstein ring formed from four images of the radio jet and two offset images of the radio core. Like MG 1131 +0456, ground-based optical and infrared imaging found that the system was very red (Malhotra, Rhoads, & Turner 1997). The lens galaxy again appears to be a red, early-type galaxy with a photometric redshift of $0.81 < z_l < 1.04$, with no sign of any optical images of the source (Kochanek et al. 2000a). In the infrared, roughly equal amounts of flux come from the lens galaxy and an almost perfectly circular Einstein ring image of the AGN host galaxy (King et al. 1998).

By modern standards, neither lens galaxy is faint ($I = 20.8$ and 21.5 mag respectively). Measurement is difficult only because the spectral features of early-type galaxies at $z \geq 0.7$ are buried in the Meinel OH bands. The source redshifts, however, are almost certainly unmeasurable in the optical; the emission is very faint and dominated by the host galaxy rather than an AGN. In § 2 we report measurements of the lens redshift in MG 1131 +0456 and B1938 +666. We discuss the consequences of the measurements in § 3.

2. OBSERVATIONS AND REDUCTIONS

MG 1131 +0456 was observed on 1999 May 11 and 12 using the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) at the Keck 2 Telescope on Mauna Kea. Both nights were clear and the seeing was variable, but extremely good ($<0.5$) on the night of May 11. We used a 1′′ slit combined with the 400 line mm$^{-1}$ grating blazed at 8500 Å to obtain spectral coverage from 6250 to 10050 Å.
with a spectral resolution of $\approx 5$ Å FWHM and a scale along the slit of 0:211 pixel$^{-1}$. The MG 1131+0456 observation totaled 3900 s on the lens, and serendipitously caught three other galaxies, G1, G2, and G3, at the same time. The slit was oriented at a position angle of 63$^\circ$, as illustrated in Figure 1.

B1938+666 was observed on 1997 October 26 and 27, and again on 1998 July 23. The October nights had light

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**Fig. 1.**—Slit positions and galaxy identifications for MG 1131+0456 and B1938+666. North is up and east is to the left, and a 10$^\prime$ scale is given.
circular and ~ 1" seeing; July was clear and had excellent seeing of about 0.7. In 1997 October the grating was rotated to provide coverage from 3800 to 8700 Å, with a spectral resolution of ≈ 7.9 Å FWHM; in 1998 July the 400 lines mm⁻¹ grating was used over the range 5250–9050 Å, with a spectral resolution of ≈ 5 Å FWHM. The much improved seeing in July resulted in much more signal for the lensing galaxy, so the analysis of the lens galaxy is based only on those data. Figure 1 shows the two slit positions that were used. At P.A. 96° (1997 October) the slit caught galaxy G2, which showed [O II] emission, and at P.A. 133° (1998 July) the slit also caught galaxy G1.

The observing program was similar in all respects to that of Tonry (1998), and the same template stars were used for the redshift determinations reported here. A log of the observations is presented in Table 1.

The spectra were reduced using software described in detail by Tonry (1984). The basic steps are to flatten the images, remove cosmic rays, derive a wavelength solution as a function of both row and column using sky lines (wavelengths tabulated by Osterbrock et al. 1996), derive a slit-position solution as a function of both row and column using the positions of the template star images in the slit, rebin the entire image to coordinates of log wavelength and slit position, add images, and then sky-subtract. A linear fit to patches of sky on either side of the object (including a patch in between for the galaxy pair observations) did a very good job of removing the sky lines from the spectra. In each case, the spectrum was extracted and cross-correlated with the template spectrum according to Tonry & Davis (1979), as well as being analyzed by the Fourier quotient method of Sargent et al. (1977). The cross-correlation is more robust in the case of low signal-to-noise ratio, but at the signal levels here the two results are statistically the same, and are simply averaged. The redshift and error were calculated for each spectrum. Table 2 lists the redshifts, errors, and cross-correlation significance r values for each spectrum or emission lines used for redshift determination.

2.1. MG 1131 + 0456

The spectrum of the lens galaxy in MG 1131 is typical of an early-type galaxy at a redshift of z_l = 0.8440 ± 0.0005. With a cross-correlation r-value of 7.6, the redshift is determined to a high degree of confidence, and it is confirmed by the H and K lines visible at 7300 Å and the weak [O II] emission. The spectrum is illustrated in Figure 2. No hint of source galaxy features could be discerned in the spectrum.

The other three galaxies caught in the slit, G1, G2, and G3, are part of a group or cluster at redshift 0.343. G1 is an early-type galaxy, whereas the spectra of G2 and G3 are dominated by very strong emission lines. The velocity dispersion of the cluster inferred from these three galaxies is only 233 km s⁻¹, but it seems likely that this is quite a rich group, given that the slit happened to pick up three at once. This is in addition to the group or cluster that seems to be associated with the lens galaxy (see Kochanek et al. 2000).

2.2. B19381 + 666

The poor seeing in the 1997 observing run precluded determination of a redshift for the B1938 lensing galaxy,

| Observation | Object | UT Date | UT | sec z | P.A. | Exposure (s) | Grating |
|-------------|--------|---------|----|-------|------|-------------|--------|
| 1           | B1938  | 1999 Oct 26 | 04:59 | 1.18  | 96   | 1500        | 300/5000 |
| 2           | B1938  | 1999 Oct 26 | 05:25 | 1.44  | 96   | 1500        | 300/5000 |
| 3           | B1938  | 1997 Oct 27 | 04:47 | 1.08  | 133  | 1500        | 300/5000 |
| 4           | B1938  | 1997 Oct 27 | 05:15 | 1.38  | 133  | 1500        | 300/5000 |
| 5           | B1938  | 1998 Jul 23 | 06:04 | 1.97  | 133  | 1500        | 400/8500 |
| 6           | B1938  | 1998 Jul 23 | 06:33 | 1.83  | 133  | 1500        | 400/8500 |
| 7           | B1938  | 1998 Jul 23 | 07:01 | 1.73  | 133  | 1500        | 400/8500 |
| 8           | B1938  | 1998 Jul 23 | 07:31 | 1.63  | 133  | 1500        | 400/8500 |
| 9           | MG 1131 | 1999 May 11 | 06:50 | 1.03  | 63   | 1200        | 400/8500 |
| 10          | MG 1131 | 1999 May 11 | 07:11 | 1.04  | 63   | 1200        | 400/8500 |
| 11          | MG 1131 | 1999 May 11 | 06:29 | 1.03  | 63   | 1200        | 400/8500 |

Note.—P.A. is east from north.

| Galaxy       | Slit Position y (arcsec) | z          | r/Emission* |
|--------------|--------------------------|------------|-------------|
| MG 1131 GL... | 0.0                      | 0.8440 ± 0.0005 | 7.6 [O II] |
| MG 1131 G1... | 15.6                     | 0.3438 ± 0.0002 | 5.0        |
| MG 1131 G2... | 31.0                     | 0.3437 ± 0.0002 | [O II]*, Hβ, [O III], Hα, [N II], [S II] |
| MG 1131 G3... | 75.3                     | 0.3420 ± 0.0002 | [O II]*, Hβ, [O III], Hα, [N II], [S II] |
| B1938 GL...   | 0.0                      | 0.8809 ± 0.0005 | 5.9 [O II] |
| B1938 G1...   | 4.4                      | 0.9247 ± 0.001 | 3.9        |
| B1938 G2...   | 9.5                      | 0.8784 ± 0.0005 | [O II]     |

* Cross-correlation r-value or emission lines (asterisk [*] indicates second-order).

2 In the labeling scheme used by Kochanek et al. (2000), our galaxy G1 is their galaxy G2, and our galaxies G2 and G3 lie outside the field of view of their HST images.
although features that might be construed to be H and K were found at $z = 0.88$. The galaxy G2, which was placed in the slit at P.A. 96°, has a single strong emission line that is almost certainly [O ii] at a redshift of 0.8784, judging from its width and isolation. Revisiting the lensing galaxy in 1998 under conditions of good seeing soon provided a spectrum that shows that it has a redshift of $z_L = 0.881 \pm 0.0005$. These spectra are plotted in Figure 3. Again, no hint of source-galaxy features could be spotted.

In Table 2 we list a tentative redshift of 0.924 for galaxy G1, which lay in the P.A. 133° slit, but the $r$-value of only 3.9 makes it very possible that this redshift is not correct.

3. DISCUSSION

The MG 1131+0456 and B1938+666 lens galaxies are normal, passively evolving early-type galaxies at $z_r = 0.844$ and 0.881, respectively. We see this directly in their spectra. The spectroscopic redshifts agree very well with the photometric redshift estimates of Kochanek et al. (2000a), based on the fundamental plane of lens galaxies and the agreement of the broadband colors with passively evolving models of stellar populations.

With the lens redshift known, we can use the fundamental plane to estimate the source redshift. The limits will be imprecise, because the position of the lens galaxy relative to the fundamental plane depends on the source redshift only through the effects of the weakly varying distance ratio, $D_{LS}/D_{OS}$, on the inferred velocity dispersion of the lens galaxy (see Kochanek et al. 2000a). The estimated velocity dispersion, $\sigma^2 \propto D_{OS}/D_{LS}$, is divergent at the lens redshift and monotonically declines with increasing source redshift. Thus, we obtain firm lower bounds of $z_s > 1.9$ and $z_s > 1.7$ for the source redshifts of MG 1131+0456 and B1938+666, respectively. There is no firm upper bound for the redshift of either source over the range we considered ($1 < z_s < 5$). For MG 1131+0456, there is no statistically significant estimate for a best source redshift, while for B1938 we estimate that $z_s = 2.8$. In both systems, the optical counterparts of the source are too faint for redshift measurements, but both should be measurable with the new generation of infrared spectrographs. MG 1131+0456 is very bright in the infrared, and the counterparts of the radio cores become steadily brighter at longer wavelengths (see Larkin et al. 1994) as the dust in the host galaxy becomes increasingly transparent. B1938+666 is more challenging, because it is fainter and lacks obvious counterparts to the radio cores. Both hosts are examples of extremely red galaxies that probably would be missed in surveys based on the “UV dropout” method.

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