OBSERVATIONS OF LENS SYSTEMS WITH KECK I

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Abstract. The extreme difficulty of many essential optical and infrared observations of lens systems has impeded progress and contributed to the popular but erroneous view that lensing is a curiosity rather than an important astrophysical tool. Keck I, with its unprecedented sensitivity for spectroscopy and infrared imaging, will have a major impact on lensing observations.

1. Introduction

The Caltech lensing consortium—R. Blandford, J. Cohen, G. Djorgovski, D. Hogg, J. Larkin, C. Lawrence, K. Matthews, G. Neugebauer, and I. Smail—was organized with both the possibilities and inevitable problems of the early days of a new telescope and instruments in mind. Comprising members the Near Infrared Camera (NIRC) and Low Resolution Imaging Spectrometer (LRIS) teams as well as the Caltech lensing "regulars", the consortium developed prioritized but rather inclusive lists of targets for both imaging and spectroscopy that could be adapted on short notice to available observing time and capabilities. Our goal was to demonstrate the value of Keck by making difficult but important lens observations. Some early highlights are given below.

2. Observations

NIRC (Matthews & Soifer 1994) has a 256×256 InSb array with $0\farcs15$ pixels, giving a $38\farcs4 \times 38\farcs4$ field. Standard filters are available in the 1–5 μm range, as well as low-resolution spectroscopic capability.

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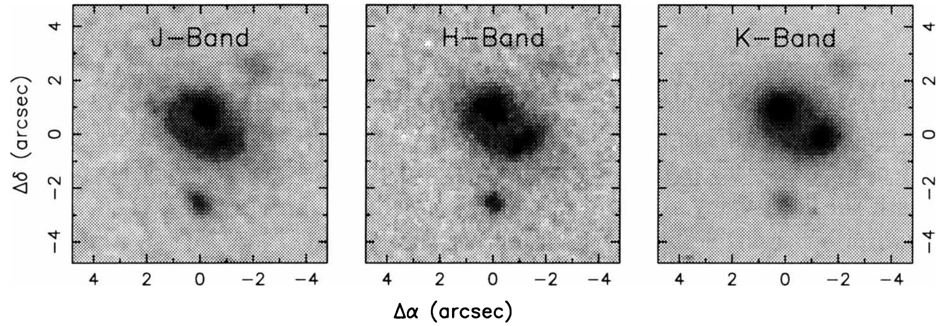

Figure 1. NIRC images of MG 1131+0456 taken on 4 March 1994 (UT). Integration times were 360, 900, and 720 seconds for the J (1.1–1.4 μm), H (1.5–1.8 μm), and K (2.0–2.4 μm) images, respectively. The two quasar images dominate the K image, although the centroid of the one to the east is affected by the nearby galaxy core. The quasar images can still be seen faintly in the H image, but are not detected in the J image. The lensing geometry requires a massive galaxy, but the J image suggests an interacting or merging galaxy rather than a normal, smooth elliptical.

LRIS (Oke et al. 1995; Cohen et al. 1993) has a 2048 × 2048 thinned Tektronix CCD with a peak quantum efficiency of 80% at 6500 Å. Single slits 3′ long, available in several widths, illuminate a 2048 × 800 region on the chip. Various gratings give $800 \lesssim R \lesssim 4300$. The maximum throughput is a high 42%.

MG 1131+0456 was observed at 1.2 and 2.2 μm during the first NIRC engineering run in 1993 March to test our suspicion that the two peaks seen by Annis (1992) at 2.2 μm were the heavily reddened counterparts of the radio core. The images immediately gave strong support to this suspicion, and led us to conclude that $A_V > 4$ mag along two paths through the lens separated by almost 10 kpc (Larkin et al. 1994). Figure 1 shows images taken in 1994 March in better seeing.

MG 0414+0534 (Hewitt et al. 1992) has a unique optical spectrum that is well-fit from 4300–9400 Å by $F_\nu \propto \nu^{-8.8}$. There is a strong absorption feature near 8650 Å. Infrared spectra reveal emission lines, including a strong H α line, that give $z = 2.639$ (Lawrence et al. 1995a). The remarkable overall shape of the spectrum is reproduced very well by a ν^0 continuum, Fe II pseudo-continuum, and standard quasar lines all reddened by $A_V = 5.5$ mag of dust at $z = 0.5$, the theoretically "most likely" lens redshift (Kochanek 1992).

The absorption feature corresponds to ~ 2380 Å at $z = 2.639$. Although Fe II lines near this wavelength are often seen, their equivalent width is usually much smaller. It seemed likely that the absorption feature came

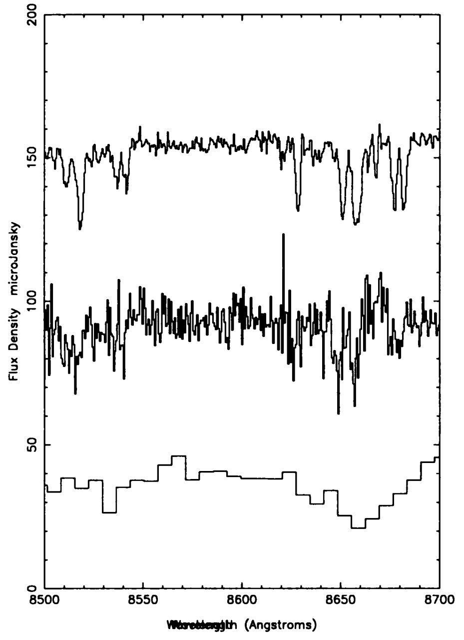

Figure 2. Spectra of absorption in MG 0414+0534. From bottom to top: 4-Shooter spectrum at 27 Å resolution (Hewitt et al. 1992); LRIS spectrum at 2 Å resolution from 1993 October with high readout noise (preprint, never to be published!); and LRIS spectrum from 1994 November (Lawrence et al. 1995b). The top spectrum is fitted beautifully by four Fe II triplets (λ =2343.495, 2373.737, and 2382.039) at z = 2.63172, 2.63487, 2.64268, and 2.64474. The iron is unusually but not unprecedentedly strong.

instead from the lens, and that an unambiguous identification of the feature would give the lens redshift. The strongest absorption lines are from the Na D doublet at $z = 0.47$ and the Mg II doublet at $z = 2.10$, which could be easily distinguished by their separations of 9 and 22,Å, respectively, in a high resolution spectrum.

Accordingly, MG 0414+0534 was observed at 2.0 Å resolution during an early LRIS engineering run in 1993 October. Despite readout-noise problems, a clear doublet was seen at 8650 Å with exactly the separation of Na D at $z = 0.47$. We were sufficiently confident of the identification to submit a paper entitled *The Redshift of the Lens in MG 0414+0534* and to distribute preprints, but sufficiently concerned to reobserve in 1994 November after the readout problems were corrected. Figure 3 shows the original 4-Shooter spectrum along with the two Keck spectra. The answer is unambiguous. The absorption is due entirely to Fe II, and the redshift of the lens remains unknown (Lawrence et al. 1995b).

Lawrence et al. (1995a) and Larkin et al. (1994) discuss three explanations for the extremely red colors of MG 0414+0534 and MG 1131+0456: dust in the lens; dust near the quasar; and intrinsically red quasars. None is free of improbabilities, nor are the three mutually exclusive. The following reasons summarize why on balance we prefer the dust-in-the-lens explanation.

1. The spectrum of MG 0414+0534 is fitted very well by standard quasar "components" reddened by dust at $z \sim 0.5$, significantly less well by dust at $z = 2.64$ with ultraviolet extinction as observed in the Small Magellanic Cloud (i.e., no 2200 Å feature), and hopelessly badly by dust at $z = 2.64$ with standard Galactic ultraviolet extinction.

2. The systematic variation of flux ratios with wavelength but not with time (but see Vanderriest et al. this volume for a possible temporal change) is explained easily by differential extinction along paths through the lens separated by up to 10 kpc, and not easily by microlensing.

3. MG 0414+0534 and MG 1131+0456 are the reddest quasars known to us in complete radio samples. It *might* be just coincidental that both lie behind galaxies. It is much more likely that the quasars are red *because* they lie behind galaxies.

2016+112 was observed with LRIS during the summer of 1994. The primary goal was to measure the redshift of the second lens, which Lawrence et al. (1993) estimated at 2 from colors. We do not yet have a redshift for the galaxy, but we got nice spectra of the three images, including for the first time C′, shown in Figure 4. The mean flux density of C′ from 5500–7000 Å is only 1.0 μJy!

1422+231 was observed at 2.2 μm with NIRC in 1993 March. 1422+231 itself was saturated because of a bug in the acquisition software, but the image confirmed Hogg & Blandford's (1994) prediction of additional mass to the southeast with the detection of two faint galaxies.

1413+117 was observed at 2.2 μm with NIRC in 1995 June, with the goal of detecting the lens (Figure 5). Neither inspection nor preliminary PSF subtraction reveals the lens, but the 0″.3 FWHM of the images (!!) shows Keck I's outstanding optical performance.

0218+357 was observed with LRIS in the summer of 1994 to determine the redshift of the blazar (Figure 5). Hints of an emission line near 5500 Å had been reported (Browne 1993). An emission line is confirmed near 5500 Å, with an associated absorption doublet. The most likely identification is Mg II $\lambda\lambda$2795.528,2802.705 at a redshift of 0.96. Spectra extending further to the red (to cover H β and the [O III] doublet) or to the blue (to cover [O II]λ3727) should confirm this result.

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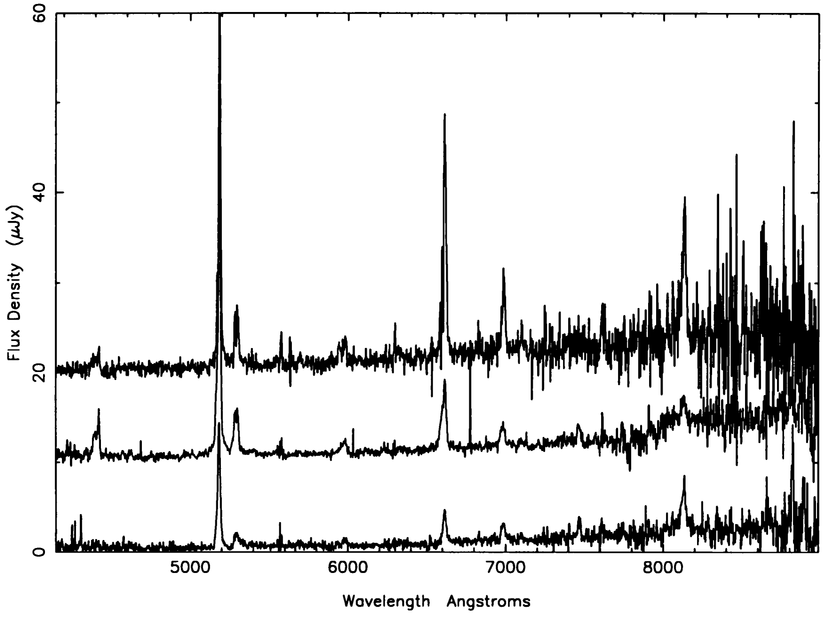

Figure 3. Spectra of 2016+112 A (top), B (middle), and C′. A and B are offset by 20 and 10 μJy, respectively, for clarity. The slit covered galaxy D and C′. Total integration time was 15,000 s, but telescope tracking glitches meant that C′ was not always in the slit and A and B sometimes were. Light from galaxy D appears in B redward of ~ 8000 Å.

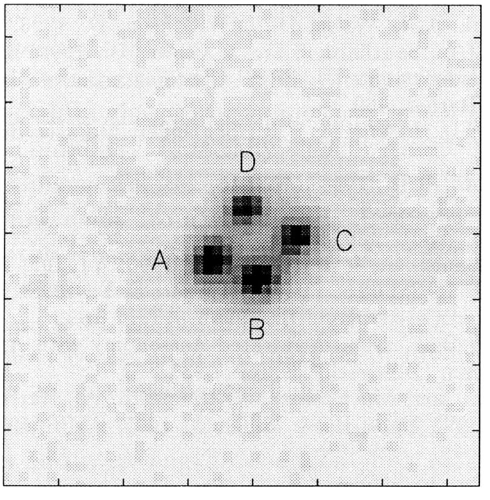

Figure 4. Image of 1413+117 obtained with NIRC in 1995 June. The total integration time was 2220 s. Tick marks are 1″ apart.

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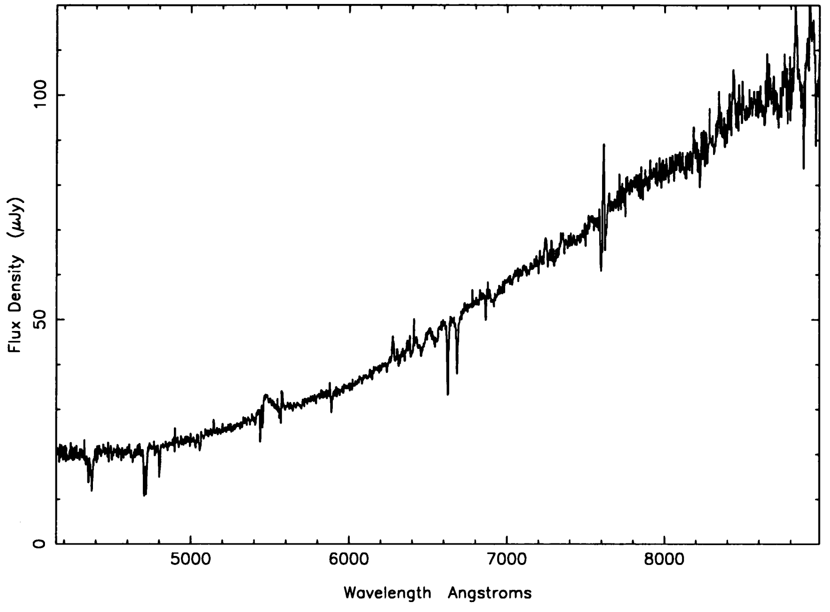

Figure 5. Spectrum of 0218+357, showing an unambiguous emission line near 5560 Å with associated absorption doublet.

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