Lensing Groups in PG 1115+080 and B 1422+231[1]

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ABSTRACT

In a number of multiply imaged quasar systems, a significant contribution to the lensing potential is provided by groups and clusters of galaxies associated with the primary lens. As part of an ongoing effort to gather observational data on these systems, we present spectroscopy of galaxies in quadruple lens systems PG 1115+080 and B 1422+231. In both of these systems, the primary lens is a member of a compact group of galaxies with the median projected separation of 35 h^{-1} kpc. The velocity dispersion of the four-member PG 1115+080 group is 270 ± 70 km s^{-1}, implying a virial mass of $5 \times 10^{12} M_{\odot}$. The corresponding values for the six-member B 1422+231 group are 550 km s^{-1} and $1.4 \times 10^{13} h^{-1} M_{\odot}$. The groups in these two systems are crucial for the lensing models as they provide the source of shear required to produce the observed image configurations. A deep spectroscopic survey in fields of other lens systems would be highly desirable to investigate the importance of external sources of shear for models of gravitational lenses.

1. Introduction

One of the most exciting astrophysical applications of gravitational lensing is the determination of the cosmological distance scale. The technique of measuring the Hubble

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constant in multiply imaged variable sources was developed by Refsdal (1964), who realized that the time delay between variations of the individual images is inversely proportional to H_0. So far, two accurate time delays have been reported in the literature, one in the double quasar Q 0957+561 (Kundić et al. 1996) and the other in the quadruple quasar PG 1115+080 (Schechter et al. 1997), yielding consistent values of the Hubble constant. However, before Refsdal's method is universally accepted as a competitor to the traditional distance ladder approach, it has to be applied to a statistically significant sample of systems with different image morphologies and source and lens redshifts to verify the validity of the lensing models (Blandford & Kundić 1997).

Even with an accurately measured time delay, the value of H_0 derived in a gravitational lens system is only as good as the models of the system. While most lenses can be adequately represented by simple elliptical potentials, the resulting χ^2 is often unacceptably large and the inferred ellipticity quite different from the measured axis ratio of the lens. These problems can be alleviated if an additional, independent shear axis is added to the models (Blandford & Kundić 1996; Keeton, Kochanek & Seljak 1996, hereafter KKS96). The source of this additional shear can be the extended dark halo of the primary lens, groups and clusters of galaxies associated with the primary lens or individual galaxies and large-scale structure along the line of sight to the source.

A direct way to observationally investigate the presence of the perturbers is to conduct a deep spectroscopic survey in the field surrounding the lens. Here we present first Keck observations in the fields of two quads: PG 1115+080 and B 1422+231.

2. PG 1115+080

PG 1115+080 consists of four images of a $z_s = 1.722$ quasar (Weymann et al. 1980) lensed by a foreground group of galaxies at $z_d \sim 0.3$ (Henry & Heasley 1986; Angonin-Willaime, Hammer, & Rigaut 1993). HST imaging of PG 1115+080 established the relative positions of the four quasar images with an uncertainty of 5 mas and the centroid of the lensing galaxy with an uncertainty of 50 mas (Kristian et al. 1993). A schematic diagram of the system is shown in Fig. 1 of Keeton & Kochanek (1996, hereafter KK96). The differential time delays have been measured in this system (Schechter et al. 1997, Barkana 1997), making it an important target for detailed observations aimed at constraining the suite of the lens models.

Optical spectra of PG 1115+080 were obtained on two nights, 1997 February 7 and 1997 March 2, with the Low Resolution Imaging Spectrometer (Oke et al. 1995) at the

Keck II 10-m telescope. The first two exposures were taken with the 300 line/mm grating and the $0.7''$ slit, and the other three with the 600 line/mm grating and the $1.0''$ slit. The resulting spectral resolution, as measured from unresolved sky lines, was approximately 7 Å in the low-resolution spectra and 4.5 Å in the high-resolution spectra. The seeing was $\sim 0.7''$ in exposures 1 and 2, and $\sim 1.2''$ in exposures 3–5.

Approximate redshifts of the lensing galaxies were first estimated from strong absorption features in the spectra, particularly the Ca II H and K lines and the G band. These features, along with the Balmer series lines and the MG Ib triplet, are marked with dotted lines in Fig. 1. Accurate redshifts were then determined by cross-correlating the galaxy spectra with stellar templates of Jones (1996) available on the AAS CD-ROM 7 (Leitherer et al. 1997). Only G and K giants were used, since they provide the closest match to the spectral characteristics of the early type galaxies in the lensing group. The results of the cross-correlation analysis are summarized in Table 1. The errors listed in the table were calculated from the width of the cross-correlation peak (Tonry & Davis 1979) and an estimate of the systematic error in wavelength calibration. Our results are consistent with the previous measurement of the G1 and G2 redshifts by Henry & Heasley (1986), and marginally consistent (at 3σ) with the G redshift reported by Angonin-Willaime et al. (1993).

The spectra of G, G1, G2, and G3 clearly show that they belong to a single group of galaxies at the redshift of $z_d = 0.311$ (Fig. 1). The rest frame line-of-sight velocity dispersion of this group is $\sigma_v = c\sigma_z/(1+z) = 270 \pm 70$ km s^{-1}, where the formal error includes only the uncertainty in the individual galaxy redshifts. Because of the small number of galaxies used to derive σ_v, the velocity dispersion of the mass associated with the lensing group could be substantially larger (Ramella et al. 1994).

Properties of the lensing group in PG 1115+080 are very similar to those of Hickson's compact groups (HCGs) of galaxies (Hickson 1982, Hickson et al. 1992). The median projected separation of galaxies in the lensing group is 35 h^{-1} kpc (for $\Omega = 1$), as compared to 40^{+20}_{-10} h^{-1} kpc for HCGs (we quote the median with upper and lower quartiles). The one-dimensional velocity dispersion of 270 km s^{-1} is also within the range of 200^{+100}_{-80} km s^{-1} characteristic of HCGs. The absolute magnitudes of the lensing galaxies are less certain, but if we adopt $M_B = -19.1$ for the primary lens (KK96), the range of magnitudes in the lensing group, $-20 \lesssim M_B \lesssim -19$, is compatible with $M_B(\mathrm{HCG}) = -19.5^{+0.8}_{-0.7}$.

3. B 1422+231

The gravitational lens system B 1422+231 ($V = 16.5$, $z = 3.62$) was discovered by Patnaik et al. (1992) as part of the JVAS radio survey. VLA and MERLIN maps of the system exhibited four-image structure with three bright unresolved images (A, B and C) opposite a much fainter image D. The brighter components were shown to have similar polarization properties and spectral indices, strongly suggesting that they are lensed images of the same source. Infrared observations of the system (Lawrence et al. 1992) confirmed the relative positions and relative fluxes of the four images. The only disagreement between the radio and the optical data is in the flux ratio of images A and B. This is discussed in more detail in Kundić et al. (1997b). Optical imaging of the system revealed the primary lens (Yee & Ellingson 1994) and five nearby galaxies (Remy et al. 1993, Bechtold & Yee 1995). A tentative redshift of the lensing galaxy was obtained by Hammer et al. (1995). Astrometry of the system with the Faint Object Camera on the Hubble Space Telescope (Impey et al. 1996) confirmed the radio positions of Patnaik et al. with $0.01''$ accuracy. FOS spectra of the four images were shown to be strikingly similar, providing additional evidence for the lensing origin of the system.

LRIS spectra of B 1422+231 were taken on 1995 July 30–31, 1997 March 2, and 1997 June 2. On the first observing run (July 1995), a 300 line mm^{-1} grating was used which provides spectral resolution of 2.47 Å/pixel. The second and third set of spectra (March and June 1997) were taken with a higher-resolution 600 line/mm grating yielding 1.25 Å/pixel. A $1.0''$ slit was used throughout the observing program. The resulting FWHM of isolated sky lines was 10–15 Å in the low-resolution spectra and 4–5 Å in the high-resolution spectra.

The primary lensing galaxy G1 is within one arcsecond of the four quasar images and almost 6 magnitudes fainter than their combined flux (Impey et al. 1996, Yee & Ellingson 1994). To remove the quasar light, it was thus necessary to subtract a scaled quasar spectrum from the spectrum of G1 and interpolate over the remaining residuals of two strong quasar emission lines (Ly α at 5600 Å and C IV at 7200 Å). The resulting galaxy spectrum is shown in the top panel of Fig. 2. We are unable to confirm the detection of weak [OII] and [OIII] emission lines in the spectrum of G1 that lead Hammer et al. (1995) to the conclusion that the lensing galaxy redshift is 0.647. Instead, we find a break in the continuum at 5300 Å and two absorption lines blueward of the break that are well fitted by Ca H and K lines at $z = 0.3374$. Detection of the Na D line at 7882 Å (top panel of Fig. 2) provides further confirmation of this redshift.

Accurate redshifts for galaxies G2–G6 were determined by cross-correlating their spectra with the templates of G and K giants published by Jones (1996) on the AAS

CD-ROM 7 (Leitherer et al. 1997). The results of the cross-correlation analysis are summarized in Table 2. The errors listed in the table were calculated from the width of the cross-correlation peak (Tonry & Davis 1979) and an estimate of the systematic error in wavelength calibration. The spectra of five lensing galaxies are shown in Fig. 2. Major absorption features are marked in these spectra with vertical dotted lines. A closer inspection of the figure reveals a significant redshift difference ($\Delta z = 0.005$) between G3, the brightest group galaxy, and the rest of the lensing group. Galaxy G3 is thus a large contributor to the high velocity dispersion of the group (see Table 3).

4. A Comparison Between the PG 1115+080 and the B 1422+231 Lensing Groups

The close proximity of galaxies G1–G6 in redshift and angular coordinates on the sky strongly suggests that they are members of a gravitationally bound compact group of galaxies. The rest-frame line-of-sight velocity dispersion of this group, estimated with $\sigma_v = c\sigma_z/(1+z)$, is 550 ± 50 km s^{-1}. The median projected separation of group galaxies is 35 h^{-1} kpc, assuming $\Omega = 1$.

There are at least three other QSO gravitational lens systems where the primary lens is surrounded by a group or a cluster: the double quasar Q 0957+561 (Walsh, Carswell, & Weymann 1979), the quadruple quasar PG 1115+080 (Weymann et al. 1980), and the recently discovered radio quad MG 0751+2716 (Lehár et al. 1997). In the largest-separation confirmed lens system, Q 0957+561, the primary lens is positioned near the center of a medium-rich cluster with the velocity dispersion of 715 ± 130 km s^{-1} (Angonin-Willaime, Soucail, & Vanderriest 1994). Both PG 1115+080 (Kundić et al. 1997a) and MG 0751+2716 are lensed by compact groups of galaxies, although the redshifts of the MG 0751+2716 group galaxies are not yet available.

In Table 3 we compare properties of the two lensing groups that have been spectroscopically investigated at Keck: PG 1115+080 and B 1422+231. Both systems are similarly compact, but the velocity dispersion is much higher in B 1422+231 as a result of the large velocity difference between G3 and the rest of the group. Assuming that these lensing groups are self-gravitating, their masses can be estimated using the virial theorem (e.g. Heisler, Tremaine, & Bahcall 1985):

$$M = \frac{3\pi N}{2G} \frac{\sum_i v_i^2}{\sum_{i<j} 1/R_{\perp,ij}} \quad , \tag{1}$$

where v_i is the line-of-sight velocity of the ith galaxy relative to the centroid of the group, and $R_{\perp,ij}$ is the projected separation of galaxies i and j. The virial estimates, as well as the light-weighted group centroids, are listed in Table 3. These values should be treated with caution, because of the small number of galaxies used to derive them. The assumptions inherent in the virial mass estimate (Eq. 1) and its accuracy in reproducing the masses of simulated groups are discussed by Heisler et al. (1985). These authors find that 75% of mass estimates lie within $10^{0.25}$ of the correct value for groups with 5 members.

Frequent occurrence of groups and clusters near the primary lens is an important clue for statistical studies of gravitational lensing. KKS96 have convincingly shown that external shear is a more fundamental parameter for the lensing models than the radial distribution of mass in the primary lens. External sources of shear thus warrant careful observational scrutiny.

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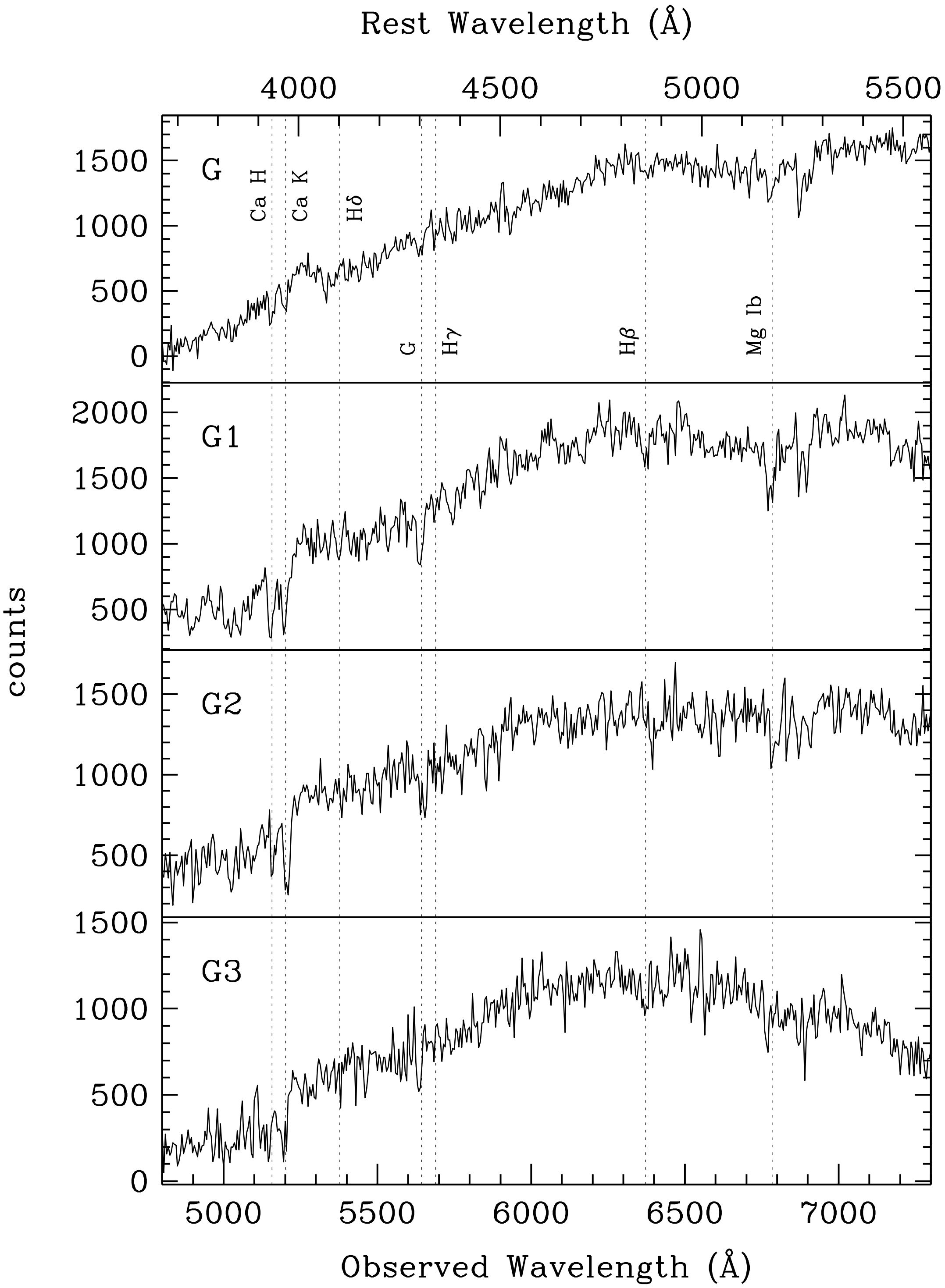

Fig. 1.— **PG1115+080:** The spectra of the primary lens G and group galaxies G1, G2, and G3 (*top to bottom*) binned to 5 Å resolution. Strong spectral features are identified with dotted lines assuming the group redshift of $z_d = 0.311$. The same redshift is used for the rest wavelength scale on the top of the figure. The redshift difference between G2 and the other three galaxies is noticeable.

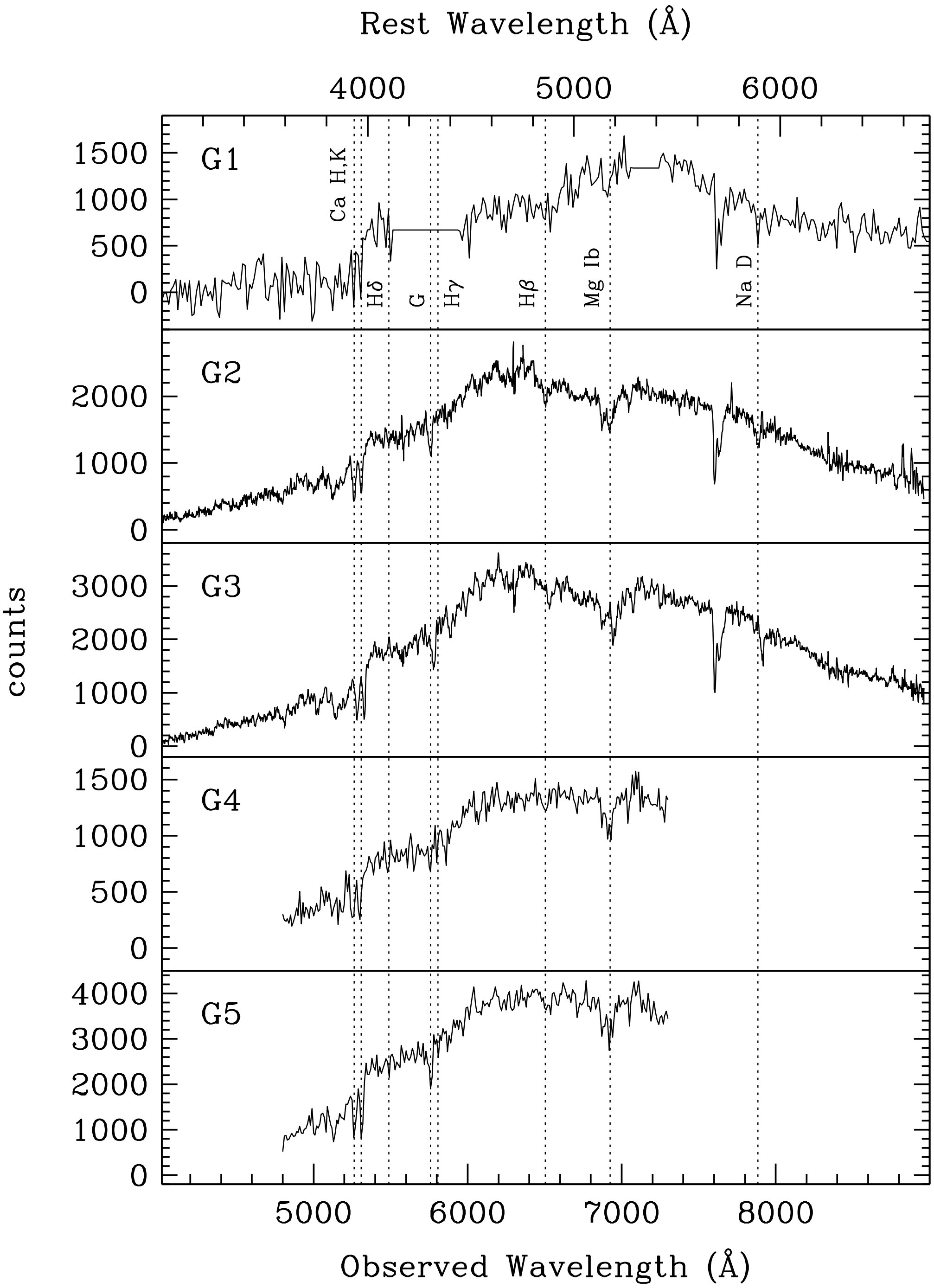

Fig. 2.— **B1422+231:** The spectra of the primary lens G1 and group galaxies G2, G3, G4 and G5 (*top to bottom*). In order to suppress noise, G1 spectrum is binned to 15Å resolution, while G4 and G5 spectra are binned to 10Å resolution. High signal-to-noise G2 and G3 spectra are shown at instrumental resolution. Strong spectral features are identified with dotted lines assuming the group redshift of $z = 0.338$. The same redshift is used for the rest wavelength scale on the top of the figure. Note the redshift difference between G3 (the brightest group member) and the other four galaxies.

Table 1. PG 1115+080: Lensing Galaxy Redshifts

Galaxy	$-\Delta\alpha$ ($''$)	$\Delta\delta$ ($''$)	Magnitude	Redshift
G	-0.4	-1.3	$R = 20.2$	0.3100 ± 0.0005
G1	20.1	-12.3	$r = 19.0$	0.3099 ± 0.0005
G2	11.5	-2.1	$r = 20.0$	0.3120 ± 0.0005
G3	13.8	-13.5	$r = 20.5$	0.3093 ± 0.0005

Note. — Galaxy positions are given relative to image C, based on the data from Young et al. (1991) and Kristian et al. (1993). The magnitude of G is taken from Christian, Crabtree, & Waddell (1987), while the other three magnitudes are adopted from Young et al. (1991).

Table 2. B 1422+231: Lensing Galaxy Properties

Galaxy	$-\Delta\alpha$ ($''$)	$\Delta\delta$ ($''$)	V^1	R	i^1	J	H	Ks	Redshift
G1	-0.7	-0.6	21.5^2	$r = 21.8^3$	···	···	···	···	0.3374 ± 0.0005
G2	-9.4	-4.9	20.4	19.9	19.1	17.1	17.9	16.4	0.3379 ± 0.0005
G3	-3.9	-7.2	20.0	19.6	18.8	16.7	17.5	16.0	0.3427 ± 0.0005
G4	-7.5	-10.4	21.6	21.0	20.5	18.4	19.0	17.6	0.3366 ± 0.0005
G5	-17.4	-28.8	20.3	20.0	19.4	···	···	···	0.3384 ± 0.0005
G6	4.4	-7.4	···	22.2	···	20.2	20.3	19.9	0.3357 ± 0.0005
G7	16.7	-12.0	···	23.0	···	18.9	···	18.4	···
G8	-2.1	12.9	···	22.4	···	20.2	20.7	20.0	0.2355 ± 0.0005
G9	25.5	35.0	···	21.7	···	···	···	···	0.4650 ± 0.0005
G10	16.6	-41.5	···	22.2	···	···	···	···	0.4055 ± 0.0005
S1	6.9	-15.9	18.1	17.4	17.1	15.7	···	15.6	···

Note. — (1) V and i magnitudes are taken from Remy et al. (1993); (2) V magnitude of G1 is taken from Impey et al. (1996); (3) Gunn r magnitude of G1 is adopted from Yee & Ellingson (1994).

Table 3. Lensing Group Properties: PG 1115+080 and B 1422+231

Gravitational Lens System	PG 1115+080	B 1422+231
Number of Galaxies	4	6
Group Redshift	0.311	0.338
Velocity Dispersion (km s^{-1})	270 ± 70	550 ± 50
Median Projected Galaxy Separation (h^{-1} kpc)	35	35
Virial Mass ($h^{-1}\, M_{\odot}$)	4.6×10^{12}	1.4×10^{13}
Group Centroid (d, θ)[1]	($17''$, $-121°$)	($14''$, $146°$)

Note. — (1) The luminosity-weighted center of the group is specified relative to image C in PG 1115+080 and relative to image B in B 1422+231. The distance of the centroid is quoted in arcseconds and its position angle is measured north through east.