A Close-Separation Double Quasar Lensed by a Gas-Rich Galaxy

Michael D. Gregg\(^2,3\), Lutz Wisotzki\(^4,5\), Robert H. Becker\(^2,3\), José Maza\(^6\), Paul L. Schechter\(^5,7\), Richard L. White\(^8\), Michael S. Brotherton\(^9\), and Joshua N. Winn\(^5,7\)

ABSTRACT

In the course of a Cycle 8 snapshot imaging survey with STIS, we have discovered that the z=1.565 quasar HE 0512−3329 is a double with image separation 0\,\prime\prime\,644, differing in brightness by only 0.4 magnitudes. This system is almost certainly gravitationally lensed. Although separate spectra for the two images have not yet been obtained, the possibility that either component is a Galactic star is ruled out by a high signal-to-noise composite ground-based spectrum and separate photometry for the two components: the spectrum shows no trace of any zero redshift stellar absorption features belonging to a star with the temperature indicated by the broad band photometry. The optical spectrum shows strong absorption features of Mg\(^{\text{II}}\), Mg\(^{\text{I}}\), Fe\(^{\text{II}}\), Fe\(^{\text{I}}\), and Ca\(^{\text{I}}\), all at an identical intervening redshift of z=0.9313, probably due to the lensing object. The strength of Mg\(^{\text{II}}\) and the presence of the other low-ionization absorption features is strong evidence for a damped Ly\(\alpha\) system, likely the disk of a spiral galaxy. Point spread function fitting to remove the two quasar components from the STIS image leads to a tentative detection of a third object which may be the nucleus of the lensing galaxy. The brighter component is significantly redder than the fainter, due to either differential extinction or microlensing.

Subject headings: gravitational lensing; quasars: individual

\(^1\)Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract No. NAS5-26555.
1. Introduction

The study of gravitationally lensed quasars has become a powerful tool for addressing a number of astrophysical questions. In particular, concentrating on studying the lensing objects themselves provides a sample of distant galaxies selected by mass rather than by light (Kochanek et al. 1999). Because the component separations scale with the square root of the mass of the lens, sampling the low end of the lens mass function becomes difficult from the ground, particularly in the optical/IR, for separations $\lesssim 1''$. This observational bias leads to a preponderance of massive spheroidal galaxies in the present sample of lenses and at least partly accounts for the relative lack of known close-separation lenses, which are predicted to exist by theoretical models of the lensing phenomenon (e.g. Maoz & Rix 1993; Rix et al. 1994; Jain et al. 1999). There are currently only seven systems with separations $\leq 0'.9$ out of 43 confirmed lensed quasars listed by Kochanek et al. (1998).

We are now well into a Cycle 8 snapshot survey of up to 300 targets, aimed specifically at finding close-separation lensed quasars using the imaging capabilities of STIS (Kimble et al. 1997; Woodgate et al. 1998) on board the Hubble Space Telescope. The probability that a quasar is lensed increases with redshift and apparent magnitude (Turner, Ostriker, & Gott 1984); the snapshot survey targets bright, high redshifts quasars selected using estimates for the probability of lensing by Kochanek (1998). The results of the full snapshot survey will appear in time (Gregg et al. 2000, in prep.); here we report the discovery of a close-separation gravitationally lensed quasar from among the first 80 snapshot targets.

2. Observations

2.1. Discovery

The quasar HE 0512$-$3329 was originally identified in the Hamburg/ESO survey for bright QSO’s (Wisotzki et al. 1996). With $B = 17.0$ and $z = 1.569$ (Reimers, Köhler, & Wisotzki 1996), HE 0512$-$3329 had an a priori probability of $\sim 1.3\%$ of being lensed, fairly typical for the targets in our snapshot survey. The STIS snapshot sequence, obtained on 1999 August 26, consists of $3 \times 40s$ CR-split exposures in the clear 50CCD (CL) aperture and one additional 80s CR-split exposure in the longpass F28$\times$50LP (LP) filter. The effective wavelength and full width half maximum of the CL band are 6167.6 Å and 4410Å and for the LP band are 7333Å and 2721Å. The STIS images reveal two point sources with a separation of $0'.644$. The difference in brightness between the two components A and B is $\Delta CL = 0.35$ and $\Delta LP = 0.49$; this small difference is characteristic of the more highly magnified lensed systems, which our selection technique is designed to favor.

The lensing hypothesis was strengthened by examining the discovery spectrum of HE 0512$-$3329 which shows a rather typical quasar energy distribution having emission lines of C IV 1549 and C III] 1909 (see Figure 1 of Reimers et al. 1996). If one of the two components were a garden variety Galactic star, the strongest stellar absorption lines would be easily identifiable (see below,
§2.3). A binary quasar is a possible alternative explanation (Kochanek, Falco, & Muñoz 1999), however, the discovery spectrum exhibits a strong absorption feature consistent with Mg II at an intervening redshift of 0.93, and a few weaker absorption lines of Fe II at the same redshift. These low-ionization absorption features suggested that the duplicity is due to a lensing object at this redshift.

2.2. Follow-up Spectroscopy at Keck Observatory

In early 2000 January, we obtained a 9Å resolution spectrum of HE 0512–3329 using the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) at Keck Observatory. The slit was oriented at the position angle of the two quasar images on the sky, 17°. The seeing was 1", insufficient to resolve the components. From this 300s exposure (Figure 1), we obtain a redshift of $z = 1.565 \pm 0.001$ based on Gaussian fits to the C IV and C III] emission peaks. The S/N of this new spectrum is 50 to 100 over most of its wavelength range and confirms the presence of the strong intervening absorption, clearly resolving the Mg II $2796.4, 2803.5$ doublet and detecting the associated Mg I 2853 line. Also seen is a rich absorption system of Fe II $2260.8, 2344.2, 2374.5, 2382.8, 2586.7, 2600.2$, and Ca I 4227.9 belonging to the same intervening system; Ca II 3933 and 3969 fall in the atmospheric A band. The mean of the absorption redshifts is $z = 0.9313 \pm 0.0005$. The profile of the Mg II emission line is asymmetric, which can be attributed to absorption by Fe I $3721.0$ or intervening Mg II local to the quasar. There is another weak intervening Mg II absorption feature at $z=1.1346$.

Component B is 70% the brightness of A. The lack of any discernible stellar absorption features in the Keck spectrum (Figure 1) argues strongly against component B being a foreground star. The RMS noise in the spectrum is at the level of 0.15Å equivalent width. The strongest features in late type stars have equivalent widths of a few Ångstroms and would be detected easily in the Keck spectrum; for comparison, the equivalent width of the intervening Mg I 2853Å feature is 1.4Å. The only possible stellar contaminant is a completely featureless O-type subdwarf or white dwarf and such stars are extremely rare. If this were the case, however, the spectrum of HE 0512–3329 would be much bluer, unless either the QSO or the putative star has a large amount of intrinsic reddening.

2.3. Photometry

We have done point-spread function (PSF) fitting photometry on the STIS images using IRAF/DAOPHOT. From observations of an unlensed quasar in our program, we obtain aperture corrections of $-0.222$ and $-0.303$ for the CL and LP bands, to go from the fitted 3 pixel radius to 0''5. To this we add an additional $-0.1$ magnitudes to correct to the “true” magnitude in an infinite aperture, as is standard practice with WFPC2 (Holtzman et al. 1996). The resulting calibrated STIS “STmagnitudes” and errors are listed in Table 1.
Fig. 1.— Keck LRIS 9Å resolution spectrum of HE 0512–3329 obtained in January, 2000. The upper abscissa scale is the rest frame of the quasar with a redshift of 1.565; prominent emission line features are marked above the spectrum. Lines associate with the intervening system at z=0.9313 are identified below the spectrum. The absorption lines are probably due to the lensing galaxy and are unresolved at the instrumental resolution. There is a second rather weak intervening Mg II 2800 absorption system at z=1.1346, marked in parenthesis. The small difference in brightness of the two components and the lack of any visible stellar absorption features (dotted lines) in this high S/N composite spectrum argues strongly against component B being a foreground star.
The \( LP \) bandpass is completely contained within the \( CL \). Because they are similar in shape, the \( LP \) flux can be scaled by the relative throughputs and subtracted from the \( CL \), producing an effective “shortpass” measurement (Gregg & Minniti 1997; Gardner et al. 2000) extending from 5500Å to 2000Å, with effective wavelength of 4424Å and FWHM of 2569Å. The \( SP – LP \) difference provides some wide-band color information (Table 1).

In 1999 December, we obtained VRI photometry of HE 0512–3329 using the Mosaic II CCD imager at the Blanco 4m telescope at Cerro Tololo Inter-American Observatory\(^{10}\). Although the seeing was \( \sim 0'8 – 0'9 \) and the two components are not cleanly resolved, point-spread function (PSF) fitting using IRAF/DAOPHOT successfully separated them, yielding positions in excellent agreement with the HST images and photometry consistent with the STIS results. The separations obtained in V, R, and I are 0'654, 0'646, and 0'643, respectively, compared to 0'644 obtained from the centroids of the components in the STIS CL images.

No photometric standards were taken at CTIO, so we have calibrated the CTIO photometry using zeropoints determined by convolving the Keck spectrophotometry with Cousins VRI passbands. This procedure is itself calibrated using a model for the spectrum of Vega (Kurucz 1992) for which we adopt \( B = V = R = I = 0.0 \). Slit losses limit the absolute accuracy, but, fortuitously, the spectroscopy was obtained when the position angle of HE 0512–3329 was only 23° from the parallactic angle. Because the effective slit width was somewhat greater than the atmospheric dispersion between the red and blue extremes of the spectrum (Filippenko 1982), the colors obtained from the composite spectrum are reasonably accurate and can be used to establish the relative zeropoints of the VRI photometry. Also, we have determined a zeropoint transformation between the effective STIS SP bandpass and Johnson B using the mean quasar spectrum (Brotherton et al. 2000) from the FIRST Bright Quasar Survey (FBQS; White et al. 2000), redshifted to \( z=1.565 \). The resulting colors of HE 0512–3329 are \( B – V = 0.68, V – R = 0.46, V – I = 0.82 \) for component A, and \( B – V = 0.32, V – R = 0.37, V – I = 0.69 \) for component B (Table 1). Schlegel, Finkbeiner, & Davis (1998) estimate a Galactic extinction of \( A_B = 0.104 \) for this line of sight; Burstein & Heiles (1982) give a much lower value of 0.010. The numbers in Table 1 have not been corrected for Galactic extinction.

The broad band colors of the two components clinch the case for HE 0512–3329 being a lensed quasar. By comparison with the Bruzual et al. stellar library, the \( B – V \) color of component B indicates a spectral type of F0, yet V-R and V-I are consistent with a much cooler object, about F9/G0. Our simulations show that any star in this spectral range with the relative brightness of component B would contribute easily detectable absorption features, at \( \sim 10\sigma \) level or greater, to the composite spectrum at the indicated locations in Figure 1; Ca II H and K and the Balmer lines would be particularly conspicuous. The broad band colors of component B are, in fact, more consistent with a slightly reddened quasar than a star.

\(^{10}\)Cerro Tololo Inter-American Observatory, NOAO, is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.
### Table 1. HE 0512−3329

| Object | R.A. (J2000) | Dec. (J2000) | CL | LP | SP | B  | V  | R  | I  |
|--------|--------------|--------------|-----|----|----|----|----|----|----|
| A      | 05 14 10.7833 | −33 26 22.504 | 17.94 | 18.53 | 19.47 | 18.36 | 17.68 | 17.22 | 16.86 |
| B      | 05 14 10.7687 | −33 26 23.121 | 18.28 | 19.03 | 19.46 | 18.35 | 18.03 | 17.66 | 17.34 |
| B−A    | −0.′183       | 0.′618       | 0.35  | 0.49  | -0.01 | -0.01 | 0.35  | 0.44  | 0.48  |
| errors | 0.′003        | 0.′003       | 0.02  | 0.02  | 0.02  | 0.04  | 0.02  | 0.02  | 0.02  |

Note. — Photometry is uncorrected for Galactic reddening; errors are statistical only.

### Table 2. Field Star Difference Photometry

| Object | R.A. (J2000) | Dec. (J2000) | $\Delta V$ | $\Delta R$ | $\Delta I$ |
|--------|--------------|--------------|-------------|-------------|-------------|
| Star 1 − A | 05 14 08.98 | −33 27 08.1 | -1.04       | -1.14       | -1.12       |
| Star 2 − A | 05 14 11.62 | −33 26 50.1 | 0.56        | 0.77        | 0.95        |
| Star 3 − A | 05 14 14.83 | −33 27 24.7 | 0.91        | 0.93        | 0.96        |
| Star 4 − A | 05 14 18.74 | −33 26 03.6 | -0.38       | -0.38       | -0.32       |
| Star 5 − A | 05 14 19.06 | −33 26 13.6 | 1.33        | 0.99        | 0.72        |
| Star 6 − A | 05 14 08.63 | −33 24 26.9 | -0.30       | -0.17       | -0.09       |
| Star 7 − A | 05 14 08.51 | −33 24 48.4 | 0.81        | 0.78        | 0.77        |
| Star 8 − A | 05 13 57.75 | −33 26 24.3 | 1.25        | 0.88        | 0.54        |
| Star 9 − A | 05 14 05.42 | −33 29 15.7 | -0.58       | -0.42       | -0.29       |

Note. — Numbers are instrumental magnitude differences $m_{\text{star}} − m_A$ in the Cousins system; no color terms have been applied.
For future reference for monitoring variability of the lens components, we list in Table 2 the instrumental magnitude differences, $m_i - m_A$, for nine field stars with $V \approx 16$ to 18 in the vicinity of HE 0512−3329. The astrometry has been derived from the digitized sky survey and has an offset of $\Delta R.A. = +0.55'$ and $\Delta Dec. = +0.77'$ relative to the STIS images, but these positions are sufficient to unambiguously identify the comparison stars.

3. The Nature of the Lensing Object

The presence of the strong intervening Mg II absorption and the many associated low ionization lines are evidence that the lensing object contains a damped Ly$\alpha$ absorption (DLA) system (Boisse et al. 1998). A DLA system at a redshift < 1 is most likely to be the hydrogen-rich disk of a spiral galaxy. Dust in the galaxy may produce differential reddening in the two components of HE 0512−3329.

3.1. Possible Detection of a Third Object

To explore for the lensing galaxy and possible additional quasar images, the STIS $CL$ images were combined using the DRIZZLE package (Fruchter & Hook 1998) in IRAF/STSDAS. A sampling rate of 0.5 times the original image scale and a PIXFRAC value of 0.6 were used. The subpixel image shifts were determined using the IRAF task XREGISTER. The final combined $CL$ image is shown in the left panel of Figure 2. The distance between centroids of the two images is $0.644'$; at the probable lens redshift of 0.9313, this separation is only $\sim 4$ kpc, adopting $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. The mass associated with an Einstein ring of this scale is $\sim 3 \times 10^{10} M_\odot$.

The PSF removal was done using the SCLEAN task in IRAF/STSDAS. For the PSF itself, we used the theoretical STIS PSF from the Tiny Tim package and also the STIS PSF generated by the Hubble Deep Field South project (Gardner et al. 2000). They yield very similar results. The residual image is shown in the right hand panel of Figure 2. There is an excess of counts just above and to the right of component A (white arrow in Figure 2). The RMS in the background-subtracted image is $\sim \pm 1.3$ counts while the peak in the excess region is 8.7. The total flux is $\sim 5.9$ magnitudes fainter than component A, giving it $CL = 23.8$. Its FWHM is roughly twice that of a point source, consistent with being nonstellar. We tentatively identify this object as the nucleus of the lensing galaxy. For our adopted cosmology, this object has $M_V \approx -19$, roughly the nucleus of a roughly $L^*$ galaxy with a bulge-to-disk ratio of $\sim 3$ and, for the above quoted Einstein ring mass, a M/L ratio of $\sim 20$. At the intervening redshift of 0.9313, the the two lines of sight to the quasar pass 1.6 (A) and 2.7 (B) kpc from the position of the third object.

There is excess light of lower surface brightness between the two quasar images and immediately below component A as well as to the right of component B in Figure 2. Although the third object
Fig. 2.—**Left:** STIS 50CCD (CL) image of HE 0512−3329. Component A is 0.35 magnitudes brighter than B in this passband. The separation is 0′′644. The orientation is given by the compass points; the North arrow is 0′′25 long.

**Right:** Residuals after PSF removal. The object immediately above and to the right of A, indicated by the white arrow, may be the nucleus of the lensing galaxy. There is also excess low surface brightness flux around each component.

is not detected with confidence in the LP image, the low surface brightness light distribution is qualitatively reproduced in the redder passband. No such excess light is seen when the same analysis is applied to an image of an unlensed quasar from our snapshot program. Deeper images are needed to confirm the reality of this low surface brightness fuzz and, if real, determine whether it is due to the lens, the host galaxy, or another object.

### 3.2. Reddening Analysis

The STIS and ground-based photometry are consistent in showing that component A is redder than B. Going from red to blue, the magnitude difference between the two images decreases, becoming equal within the errors in the concocted STIS SP and transformed B bands (Figure 3).
Fig. 3.— Trend of the broad band magnitudes of HE 0512−3329 for components A, B, and the composite A+B. The VRI photometry is from the ground-based CTIO imaging while the B magnitudes are derived from the difference between the STIS CL and LP bands; both have been zeropointed using the Keck spectrophotometry in Figure 1 (see text for details). The brightness of the two images converges from red to blue. This can be attributed to differential extinction or microlensing, possibly both. These data have been corrected from Table 1 for Galactic absorption of $A_B = 0.104$.

Observed in the ultraviolet, component B will be the brighter. This trend can be attributed to differential reddening, with extinction along the line of sight to component A being greater. Color differences between the quasar images can also be arise from microlensing by stars in the lensing galaxy, producing differential magnification of the quasar continuum (Wambsganss & Paczyński 1991) along the two lines of sight. This effect has been observed in at least one quasar, HE 1104–1805 (Wisotzki et al. 1993). The following reddening analysis is valid only if microlensing is negligible in HE 0512−3329.

To quantify the amount of differential reddening, we have fitted an extinction model to the photometry results, following the procedure of Falco et al. (1999). In this approach, it is assumed that the quasar is not variable, that the lensing magnification is not wavelength dependent, and that the extinction law does not vary with position in the lensing galaxy and is well-approximated by a typical Galactic extinction curve with $R_V = A_V/E(B−V) = 3.1$. Correcting a sign error in
equation 3 of Falco et al., we have
\[
\chi^2 = \sum_{j=1}^{N_\lambda} \sum_{i=1}^{N_c} \frac{\left\{ m_i(\lambda_j) - m_o(\lambda_j) + 2.5 \log(M_i) - E_i \, R[\lambda_j/(1+z)] \right\}^2}{\sigma_{ij}^2}
\]
(1)

where \( m_i \) are the observed magnitudes of each of the \( N_c \) components in the \( N_\lambda \) photometric bands with effective wavelength \( \lambda_j \), \( m_o \) is the unlensed magnitude of the quasar, \( M_i \) is magnification of each component, \( E_i \) is the extinction of each component, \( z \) is the redshift of the lens, and \( \sigma_{ij} \) are the photometric errors. The summations are over the 4 bandpasses, \( B, V, R, \) and \( I \), and two components, A and B.

Relative magnifications and extinctions can be found by minimizing \( \chi^2 \) while holding one magnification fixed at unity and one extinction at 0. As component B is bluer and fainter, we fix its parameters at these values. The extinction law has been parametrized using the equations of Cardelli, Clayton, & Mathis (1989). For this analysis, we first corrected the photometry listed in Table 1 for Galactic extinction of \( A_B = 0.104 \) from Schlegel et al. (1998).

The fit for the relative extinction results in the estimate of \( A_V = 0.34 \) for component A, in excess of the extinction at component B; the unextincted, wavelength independent relative magnification of A is 2.45 times that of B. The \( \chi^2 \) of this fit is 0.66. For comparison, a fit with both extinctions held to zero yields a relative magnification of 1.35, roughly consistent with the brightness difference between the two components in \( V \) or \( R \). The \( \chi^2 \) for this fit is 67, as might be expected given the varying magnitude difference between the two components as a function of wavelength, which renders an achromatic magnification model a poor explanation of the brightness variation with wavelength.

The separate extinctions to each component of HE 0512−3326 can be estimated by assuming that the unlensed quasar spectrum has typical colors. After correcting for Galactic reddening using the Schlegel et al. (1998) value, the difference in \( B - V \) between the composite spectrum of HE 0512−3326 (Figure 1) and the FBQS mean spectrum is 0.31. With \( R_V = 3.1 \), this is equivalent to \( A_V = 0.97 \). Knowing the \( V \) magnitudes and relative extinction, the separate extinctions can be computed as \( A_A^V = 1.10 \) and \( A_B^V = 0.76 \), excluding any grey component. Given the multitude of assumptions and the bootstrapping from the spectrophotometry, these numbers must be considered provisional, but they do suggest that the extinction to each component is comparable and that both lines of sight intercept the same or similar absorption systems. Spectroscopy of the two components separately would allow a detailed study of the extinction curve in the disk of the lensing galaxy and would also determine whether microlensing could be contributing to the pattern of color differences.

4. Conclusion

The presently available data leave little doubt that HE 0512−3329 is gravitationally lensed. The spectroscopic evidence strongly suggests that the lens is a spiral galaxy. Spatially resolved
spectroscopy of the two images of HE 0512−3329 is needed to confirm its nature; however, the presence of strong low-ionization lines in the composite spectrum indicates that at least one of the lines of sight is sure to pass through a damped Lyα system in the disk of the lens. Ultraviolet spectroscopy of the A and B components can further be used to derive the extinction curve in the disk of the lens as well as abundances of heavy elements. This lensed quasar has been found among the first 80 targets of an HST Cycle 8 snapshot program designed to search for such small separation systems. The program was renewed for up to 300 additional snapshots in Cycle 9. If close-separation targets are found with this frequency for the duration of the survey, the lensing statistics for small separation systems will be boosted by a significant factor.

Mark Lacy is thanked for helpful discussions. The referee is credited with constructive comments which improved this paper. We are grateful to Sune Toft for calling our attention to an error in our original calculation of the differential reddening. Support for this work was provided by NASA through grant number GO-8202 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. We also acknowledge support from NSF grant AST-98-02791. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. J.N.W. thanks the Fannie and John Hertz Foundation for financial support.

REFERENCES

Boisse, P., Le Brun, V., Bergeron, J., Deharveng, J.-M., 1998, A&A 333, 841
Brotherton, M. S., Tran, H. D., Laurent-Muehleisen, S. A., Becker, R. H., White, R. L., & Gregg, M. D. 2000, in preparation
Bruzual, A. G., Persson, S. E., Gunn, J. E., Stryker, L. L. 1996, Stellar Atlas, from the STScI database, ftp://ftp.stsci.edu/cdbs/cdbs2/grid/bpgs
Burstein, D. & Heiles, C. 1982, AJ, 87, 1165
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Falco, E. E., Impey, C. D., Kochanek, C. S., Lehár, J., McLeod, B. A., Rix, H.-W., Keeton, C. R., Muñoz, J. A., Peng, C. Y. 1999, ApJ, 523, 617
Filippenko, A. V. 1982, PASP, 94, 715
Fruchter, A. S. & Hook, R. N. 1998, astro-ph/9808087
Gardner, J. P., et al. 2000, astro-ph/9912167
Gregg, M. D. & Minniti, D. 1997, PASP, 109, 1062
Gregg, M. D., Wisotzki, L., Becker, R. H., Schecter, P. L., Maza, J. & White, R. L. 2000, in preparation
Holtzman, J. A., et al. 1995, PASP, 107, 156
Jain, D., Panchapakesan, N., Mahajan, S., & Bhatia, V. B. 1999, astro-ph/9911004
Kimble, R. A., et al. 1997, ApJL, 492, L83
Kochanek, C. 1998, private communication
Kochanek, C. S., Falco, E. E., Impey, C., Lehar, J., McLeod, B., Rix, H.-W. 2000, cfa-www.harvard.edu/castles
Kochanek, C. Falco, E. E., Impey, C. D., Lehar, J., McLeod, B. A., Rix, H.-W., Keeton, C. R., Muñoz, J. A., Peng, C. Y. 1999, astro-ph/9910165
Kochanek, C. S., Falco, E. E., & Muñoz, J. A. 1999 ApJ, 510, 590
Kurucz, R. L. 1992, private communication
Maoz, D. & Rix, H.-W. 1993, ApJ, 416, 425
Oke, J. B., Cohen, J. G., Carr, M., Cromer, J., Dingizian, A., Harris, F. H., Labrecque S., Lucinio, R., Schaal, W., Epps, H., & Miller, J. 1995, PASP, 107, 375
Reimers, D., Köhler, T. & Wisotzki, L. 1996 A&AS, 115, 235
Rix, H.-W., et al. 1994, ApJ, 435, 49
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Turner, E. L., Ostriker, J. P. & Gott III, J. R. 1984, ApJ, 284, 1
Wambsganss, J. & Paczyński, B. 1991 AJ, 102, 864
White, R. L., et al. 2000, ApJS, in press
Wisotzki, L., Köhler, T., Groote, D., & Reimers, D. 1996, A&AS, 115, 227
Wisotzki, L., Köhler, T., Kayser, R., & Reimers, D. 1993, A&A 278, L15
Woodgate, B. E., et al. 1998, PASP, 110, 1183