HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE GRAVITATIONALLY LENSED CLOVERLEAF BROAD ABSORPTION LINE QSO H1413+1143: IMAGING POLARIMETRY AND EVIDENCE FOR MICROLENSING OF A SCATTERING REGION

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ABSTRACT

We report the results of Hubble Space Telescope Wide Field and Planetary Camera 2 broadband F555W and F702W photometric and F555W polarimetric observations of the “Cloverleaf” QSO H1413+1143. This is a four-component gravitationally-lensed broad absorption line (BAL) QSO. Observations were obtained at two epochs in 1999 March and 1999 June separated by ≈100 days. The observations were photometrically and polarimetrically calibrated using the standard “pipeline” calibration procedures implemented at the Space Telescope Science Institute. The goal of our program was to detect any relative changes among the components and between the two epochs. Over this time baseline we detected an ≈0.07 mag dimming in component D of the lensed image, which we interpret as evidence for microlensing. In 1999 March we find significant evidence for a difference in the relative linear polarization of component D in comparison to the other three components; in 1999 June the combined polarization of the Cloverleaf components was lower. In 1999 March the apparently microlensed component D has a rotated polarization position angle and a somewhat higher degree of polarization than the other three components. We suggest that this difference in polarization is due to microlensing magnification of part of a scatter-light (i.e., polarized) continuum-producing region. The results indicate that in the Cloverleaf the size scale of the polarized scattered-light region exceeds ≈10^{16} cm but lies interior to the region producing the broad emission lines (<10^{18} cm).

Subject headings: gravitational lensing — polarization — quasars: general — quasars: individual (H1413+1143, Cloverleaf) — techniques: polarimetric

1. INTRODUCTION

Broad absorption line (BAL) QSOs comprise ≈10% of the objects in optically selected QSO samples. Their defining characteristics are deep, high-velocity (usually <1000 km s^{-1}) absorption troughs blueward of high-ionization broad emission lines (BELs) in species such as Si iv, C iv, N v, and O vi (e.g., Turnshek 1988 and Weymann et al. 1991). They also have a distribution of linear polarizations that peaks at a significantly higher polarization in comparison to non-BAL radio-quiet QSOs (Schmidt & Hines 1999; Hutsemékers, Lamy, & Remy 1998; Goodrich 1997; Turnshek 1988); indeed the origin of much of the polarization in most non-BAL QSOs is probably the Galactic interstellar medium.

The observed polarization properties of BAL QSOs depend on, and therefore contain relevant astrophysical information on, the geometries and physical properties of the inner regions of these QSOs (i.e., the narrow emission-line region, the dusty torus, the BAL region, the BEL region, any scattering regions, the thermal accretion disk, and any region producing nonthermal emission). Recent studies on the polarization properties of BAL QSOs (Schmidt & Hines 1999; Hutsemékers et al. 1998; Ogle 1998; Goodrich 1997) have shown that: (1) their continuum polarizations are, on average, significantly higher than non-BAL radio-quiet QSOs, with the degree of polarization rising mildly toward shorter wavelengths; (2) the BALs are more highly polarized than the continuum, with position angle rotations observed in the BAL troughs; (3) BELs in some BAL QSO spectra are polarized, but the degree of polarization is lower than in the continuum and the polarization position angles are not necessarily similar; and (4) there is some evidence that the degree of polarization is positively correlated with the BAL QSO’s balnicity index (defined by Weymann et al. 1991) and the presence of low-ionization BALs, with objects having higher balnicity indexes and/or low-ionization BALs being more polarized on average.

While it is generally agreed that the scattered continuum is, in large part (if not totally), responsible for the observed net polarizations observed in BAL QSOs (e.g., Goodrich & Miller 1995; Ogle 1998; Schmidt & Hines 1999), the size scales and geometries of the regions containing scattering particles (i.e., electrons and/or dust particles) are not yet well constrained. However, the gravitationally-lensed Cloverleaf BAL QSO H1413+1143 (z em ≈ 2.55) is at present a unique laboratory for study of the polarization mechanism. Its four components are known to have a combined net continuum polarization that has varied between 1.5%–3.5% over a decade (Goodrich & Miller 1995), and one of the four components (component D) shows evidence for microlensing in the form of light variability (see Angonin et al. 1990; Arnold et al. 1993; Remy et al. 1996; Ostensen et al. 1997; and new evidence presented here) and differences in BEL and BAL profile characteristics (Chae & Turnshek 1999 and references therein).

We know that, in principle, microlensing could alter the net polarization of a single gravitationally-lensed component, since this process selectively produces additional
magnification of a small region of an Einstein ring radius on the source plane. The resulting polarization properties during microlensing would depend on the detailed geometry of the region where the polarized light originates (see Belle & Lewis 2000 for examples). Consequently, the observed component polarization properties during microlensing can be used to constrain the projected sizes of the scattering regions and their projected distances from any central black hole (i.e., the central region of the accretion disk).

In this paper, we report the results of Hubble Space Telescope (HST) Wide Field and Planetary Camera 2 (WFPC2) broadband F555W and F702W photometric and F555W polarimetric observations of the Cloverleaf. We find new evidence for microlensing of component D and show that component D has significantly different relative polarization properties than the other three components. In § 2 we describe our observations and data analysis; in § 3 we present the results; and in § 4 we discuss the implications for models of the production of polarized light in BAL QSOs. We note that this paper is the fifth in a series of HST results on the Cloverleaf by members of our group. Earlier results include constraints on the sizes and shapes of absorbing regions producing the BALs (Turnshek 1995), constraints on the component image locations and magnifications (Turnshek et al. 1997), constraints on the properties of the intervening absorbers seen in the component spectra (Monier, Turnshek, & Lupie 1998), and implications for gravitational-lens models of the Cloverleaf, including a constraint on BEL region size scales (Chae & Turnshek 1999).

2. OBSERVATIONS AND DATA ANALYSIS

For this study the Cloverleaf QSO was observed at two closely spaced epochs, 1999 March 15–16 and 1999 June 23–24. Broadband F555W filter observations were made with the Wide Field Camera 2 (WFPC2) with either no polarizer or one of four polarizers (POLQ, POLQN18, POLQN33, POLQP15). Also, F702W filter observations were made with the Planetary Camera 2 (PC2) and no polarizer. The observations are summarized in Table 1 and numbered as a referencing convenience. Each F555W observation consisted of taking two sets of four dithered images. The pixel position of component A in the second set was chosen to coincide with that of component D in the first set. In addition to the normal procedures for identifying cosmic ray contamination of WFPC2 images, all pipeline processed images were also individually examined. Cosmic rays present near the Cloverleaf components were removed interactively, and the data were replaced using interpolation. After sky subtraction, each set of images was combined via the variable-pixel linear reconstruction algorithm, or the “drizzling” algorithm (Fruchter & Hook 1998; Fruchter et al. 1997). Point-spread function (PSF) fitting photometry showed that the photometric results of the two sets for each observation were consistent with each other. Finally, all eight images in the two sets were drizzled to form one image. The procedure of taking dithered images and combining them via drizzling partially restores the PSF, thereby facilitating more accurate PSF-fitting photometry. Using the final drizzled image for each observation, an empirical PSF was constructed iteratively from the Cloverleaf components themselves, and then the Cloverleaf components were fitted simultaneously using this empirical PSF. For the above procedures, the Image Reduction and Analysis Facility (IRAF) packages DAOPHOT and STSDAS were used. The reliability of the above PSF-fitting photometry was tested by visually examining the PSF-subtracted region and computing pixel statistics within the subtracted region; the mean pixel data number ($DN$) value within the region was $|DN| < 0.1\sigma$ in all cases.

The observations were photometrically and polarimetrically calibrated using the standard “pipeline” calibration procedures implemented at the Space Telescope Science Institute. The goal of our program was not to make absolute measurements, but to detect any relative changes among the components and between the two epochs. Thus, the errors we quote based on our differencing procedures are statistical in nature. Our relative measurements and the resulting interpretation should not be affected by a small systematic error in the pipeline calibration.

The derived F555W photometric results without polarizers (i.e., observation numbers 1, 2, 3, and 11, 12, 13) were found to be highly consistent with one another. This served as an independent test, confirming the reliability of our method of photometry. The F702W photometric observations without polarizers (i.e., observation numbers 4, 5, 6 and 16, 17, 18) allowed us to fill up the remaining time available for exposures in a number of the orbits using a filter that had previously been used to observe the Cloverleaf, but without the goal of deriving photometry using drizzling. We found the statistical errors to be considerably reduced using the drizzling method.

In order to determine the Stokes parameters ($I$, $Q$, $U$), the F555W observations with polarizers were incorporated into the WFPC2 polarization calibration model (Biretta & McMaster 1997). The Stokes parameters are related to the degree of polarization ($p$) and the position angle (P.A.) via the relations $p = (u^2 + q^2)^{1/2}$ and $\text{P.A.} = (1/2)\tan^{-1}(u/q) + n\pi/2$, where $q = Q/I$, $u = U/I$, and $n = 0, 1, 2$ for $u \geq 0$ and $q \geq 0$, $u \geq 0$ and $q \leq 0$ (or $u < 0$ and $q < 0$), and $u \leq 0$ and $q \geq 0$, respectively. For the March epoch, six observations were incorporated simultaneously using a $\chi^2$ fitting technique to determine the Stokes parameters. The $\chi^2$ is defined by

$$\chi^2 = \sum_{i=1}^{I} \left[ \frac{C_{i}^{\text{obs}} - C_{i}^{\text{mod}}(I, Q, U)}{\sigma_i} \right]^2,$$

where $i = 7, 8, 9, 10, 11, 12$ are the March observation numbers, $C_{i}^{\text{obs}}$ and $C_{i}^{\text{mod}}$ are the observed and calibration model predicted counts, respectively, and $\sigma_i$ are the statistical errors in the observed counts. The minimum $\chi^2$ value was $\chi^2_{\text{min}} < 7$, with 3 degrees of freedom for all components, indicating that there is a reasonable match between the model and the data. The 1 $\sigma$ statistical errors for each Stokes parameter were estimated using $\Delta\chi^2 = \chi^2$.
3. RESULTS

Below we consider the results of our WFPC2 observations in two separate parts. First, we consider any evidence for photometric variations among the four lensed components of the Cloverleaf between the 1999 June and 1999 March epochs (§3.1, Tables 2 and 3). Second, we consider any evidence for differences in the linear polarization among the four lensed components (§3.2, Table 4).

3.1. Brightness Variation of Component D: Evidence for Microlensing

The photometric observations of the Cloverleaf without polarizers were used to search for and measure any brightness variations over the time baseline (≈100 days) which separated the two epochs of observation. As noted earlier, the individual F555W photometric results for each epoch were very consistent with one another; the average F555W photometric results for each epoch are reported in Tables 2 and 3. The average F702W photometric observations are also reported in Tables 2 and 3, but are less accurate. The photometric results are shown in Figure 1. They clearly

### Table 2

| Filter  | Epoch          | \(m_A\)  | \(m_B\)  | \(m_C\)  | \(m_D\)  |
|---------|----------------|----------|----------|----------|----------|
| F555W   | 1999 Mar 15–16 | 0.000 ± 0.003 | 0.193 ± 0.003 | 0.300 ± 0.004 | 0.292 ± 0.003 |
|         | 1999 Jun 23–24 | −0.025 ± 0.003 | 0.188 ± 0.003 | 0.281 ± 0.004 | 0.368 ± 0.003 |
| F702W   | 1999 Mar 15–16 | 0.000 ± 0.007 | 0.171 ± 0.007 | 0.320 ± 0.008 | 0.385 ± 0.008 |
|         | 1999 Jun 23–24 | −0.004 ± 0.008 | 0.163 ± 0.008 | 0.344 ± 0.009 | 0.446 ± 0.009 |

*The magnitude of component A is set to zero for the March epoch.*
indicate that component D decreased its brightness over the 
\( \approx 100 \) day time baseline, while the other three components 
either remained about the same brightness (i.e., components B and C) or slightly increased their brightness (i.e., component A). Assuming an insignificant wavelength dependence to the brightness variation over the F555W and F702W passbands, using variance-weighting we find 
\( \Delta m_D = 0.074 \pm 0.004 \) mag and \( \Delta m_A = -0.023 \pm 0.004 \) mag. Evidence for brightness variations in components B and C are at the 2 \( \sigma \) level of significance or less.

Recent detailed work on modeling the Cloverleaf lens and time delays (Chae & Turnshek 1999) suggests that in all reasonable models component C is the leading component and component D is the trailing component, with the maximum time delay being model-dependent and lying in the range \( \approx 7-41 \) days. However, the predicted time delays between components C and A or components C and B are always a significant fraction (at least \( \approx 30\% \)) of the predicted time delay between components C and D. Given these lens models and observations of brightness variations in other BAL QSOs (Sirola et al. 1998), we believe that these new photometric data on the Cloverleaf are not likely to be consistent with simply an intrinsic variation in the source BAL QSO’s brightness coupled with time delays among the four components. The most likely cause of the light variation of component D is microlensing, which is consistent with the findings of others who have studied brightness variations in the Cloverleaf (Angonin et al. 1990; Arnould et al. 1993; Remy et al. 1996; Ostensen et al. 1997).

### 3.2. Polarimetric Results

For the 1999 March and 1999 June epochs of observation, Table 4 gives the measured normalized Stokes parameters \( g \) and \( u \), the degree of linear polarization (\( p \)), the corrected degree of linear polarization (\( p_{\text{corr}} \)), which takes into account the bias toward measuring higher polarization in low signal-to-noise data (Wardle & Kronberg 1974), and the polarization position angle (P.A.). For the March observations the derived \( g \) and \( u \) Stokes parameters are shown in Figure 2, and it is seen that the polarizations of components A, B, and C differ from the polarization of component D.

The main points of the polarimetric results are as follows: (1) The polarizations of components A, B, and C in 1999 March have no appreciable differences. (2) As is clearly seen in Figure 2, in 1999 March component D has a significantly different relative polarization in comparison to the other three components. The relative normalized Stokes parameters between component D and the combination of the

| Parameter | A | B | C | \( \Delta B C \) |
|-----------|---|---|---|------------|
| \( g \) (%) | -1.35 ± 0.43 | -1.42 ± 0.46 | -1.42 ± 0.46 | -2.65 ± 0.47 | -1.39 ± 0.26 |
| \( u \) (%) | 0.78 ± 0.49 | 1.76 ± 0.52 | 1.10 ± 0.53 | -1.13 ± 0.53 | 1.19 ± 0.30 |
| \( p \) (%) | 1.56 ± 0.45 | 2.27 ± 0.50 | 1.79 ± 0.49 | 2.88 ± 0.48 | 1.83 ± 0.28 |
| \( p_{\text{corr}} \) (%) | 1.49 | 2.21 | 1.72 | 2.84 | 1.81 |
| P.A. (degrees) | 75.0 ± 8.8 | 64.5 ± 6.1 | 71.0 ± 8.0 | 101.5 ± 5.2 | 69.7 ± 4.4 |
| \( \Delta B_{\text{pol}} \) (%) | ... | ... | ... | -1.26 ± 0.54 | 0 |
| \( \Delta C_{\text{pol}} \) (%) | ... | ... | ... | -2.32 ± 0.61 | 0 |

### 3.2.1. 1999 Mar 15–16

### 3.2.2. 1999 Jun 23–24

\* Quoted errors are relative statistical errors.

\^ The combined result of components A, B, and C.

\& We use the formula of Wardle & Kronberg 1974 to correct the bias toward higher polarization degree in low S/N ratio data:

\[
    p_{\text{corr}} = p \left[ 1 - \left( \frac{\sigma_p}{p} \right)^2 \right]^{1/2}.
\]

Our derived errors in P.A. are in good agreement with their general prescription for estimating the P.A. errors under such conditions: \( \sigma_{\text{P.A.}} \approx 28.65 \sigma_p / p \) degrees.
other components in 1999 March is $\Delta q_D,ABC = -1.26\% \pm 0.54\%$ and $\Delta u_D,ABC = -2.32\% \pm 0.61\%$ (Table 4), which is a difference in polarization at a level of significance of 4.5 $\sigma$. (3) The pipeline calibrated data suggest that the net polarization of the Cloverleaf changed between the 1999 March and 1999 June epochs, with the polarization being smaller during the June epoch.

4. DISCUSSION

These results are the first observational ones that address resolved polarization measurements in a gravitationally lensed QSO and, owing to our interpretation ($\S$ 3.1 and below), the first to report evidence for microlensing of a polarized light region in a QSO.

Before we examine the implications of our interpretation, we should comment on some issues that can affect the interpretation. For example, polarization induced by any dust that is present along the sight line toward the Cloverleaf is unlikely to be responsible for the added component of polarization that appears to be present in component D. There are several reasons for this. First, multicolor (F336W, F702W, and F814W) *HST* WFPC2 observations have shown that differential dust reddening is, in fact, present across the Cloverleaf components. Component B is the most reddened and component C is the least reddened, with the F336W–F814W color index being $0.56 \pm 0.04$ mag between components B and C. The reddening of components A and D are intermediate (see Fig. 3 in Turnshek et al. 1997). The source of this differential reddening may be dust in the interstellar medium of the lensing galaxy. However, since interstellar polarization is normally proportional to the amount of reddening, we would not expect the change in polarization of component D to be related to the reddening. Second, if the source of the polarization was the lens, it would seem unlikely that the induced polarization would be different only for component D. Third, interstellar polarization would not be expected to be time-variable, but the observations indicate that the polarization changed between the 1999 March and 1999 June epochs. Fourth, Faraday rotation due to Galactic or cosmologically intervening plasma that may be present along the sight line to component D could not reasonably give rise to any rotation in the polarization position angle. The observed change in position angle for component D, $\Delta q = 32^\circ \pm 7^\circ$ at $\lambda = 5300$ Å (for the F555W filter), would require a medium with a rotation measure of $\text{RM} = (2.0 \pm 0.4) \times 10^{12}$ radians m$^{-2}$; however, for example, this is 8 orders of magnitude larger than one of the highest values ever measured for an extragalactic radio source (e.g., 3C 295; Perley & Taylor 1991).

Consequently, we have argued that the $\approx 0.07$ mag relative decrease in brightness of component D over the $\approx 100$ day interval between 1999 March and 1999 June (Fig. 1) is evidence for microlensing of component D. In this scenario, component D evidently faded due to the motion of a microlens, causing it to be less magnified in 1999 June. This is consistent with the earlier conclusions of Chae & Turnshek (1999, also § 3.2), who interpreted the lower equivalent widths of the BELs in component D (observed with *HST* FOS in both 1993 June and 1994 December) as evidence for microlens magnification of just the continuum of component D (not the BELs). Now, relying on the new results

7 Interstellar polarization within the Milky Way is not significant for the Cloverleaf (e.g., Hutsemékers et al. 1998).
presented here, we can refine some of the conclusions of Chae & Turnshek (1999) and place better qualitative constraints on the size scale of the polarized scattered-light region in relation to our understanding of the size scales of the BEL and continuum-producing regions in QSOs.

We should point out that in all published individual spectra of the Cloverleaf components, the equivalent widths of the BELs in component D are smaller than observed in the other components. The first of four sets of component spectra were obtained in the spring of 1989 (Angonin et al. 1990), and this trend continues up until at least the spring of 2000, when HST Space Telescope Imaging Spectrograph spectra taken by E. M. Monier (PI) and several of the authors continued to show component D to have BELs with lower equivalent widths. This suggests that some level of microlens magnification of the continuum-producing region (but not the BELs) of component D is common over a relatively long time baseline.

The Cloverleaf's macrolens by itself achromatically amplifies all light lying within $\approx 10^{19-20}$ cm of the central source into four pointlike image components (see Fig. 1 of Chae & Turnshek 1999). Observations indicate that the macrolensed region includes the BEL region. This is consistent with expectations since the size of the region producing BELs like C iv and Ly$\alpha$ is estimated to be $\approx 10^{18}L_{B,5}^{2.6}$ cm from the central photoionizing source (Murray & Chiang 1998; Kaspi et al. 2000), where $L_{B,46}$ is the lensed QSO luminosity in units of $10^{46}$ ergs $s^{-1}$. The source QSO luminosity in the Cloverleaf is not well constrained because observations only provide results on the relative component amplifications; however, the lens models suggest that the luminosity is likely to be of order $L_{B,46}$. Evidently the Cloverleaf is polarized because an asymmetric continuum scattering region also lies within the macrolensed region. The asymmetry is a requirement since the net polarization is nonzero. This region is not static; changes in parts of it must give rise to the variable continuum polarization which is seen. The fact that we have evidence for a variation in the net polarization over an $\approx 100$ day interval in the observed frame ($\approx 30$ day interval in proper time) suggests that the size scales involved which lead to changes in polarization are less than $10^{17}$ cm. However, each part of this asymmetric scattering region by itself would be expected to give rise to highly polarized continuum light ($p_{\text{scatt,cont}} > 10\%$), but when averaged over the entire asymmetric region there would be a much smaller net polarization.

For the purpose of illustration we note that if $\approx 80\%$ of the flux of component D was composed of the continuum plus BELs (as seen in the nearly identical spectra of components A, B, and C), and the remaining $\approx 20\%$ of the flux of component D was solely composed of microlensed scattered continuum (i.e., no BEL flux), then the polarization of the scattered continuum component would have to be $p_{\text{scatt,cont}} \approx 13\%$ at $P.A. \approx 117^\circ$ to match the observations. This degree of polarization is reasonable for scattering.

Owing to the fact that the BEL equivalent widths in component D are observed to be smaller in comparison to the other components, the observed microlensed scattered-light region evidently does not scatter appreciable BEL flux. This suggests that the size scale of the polarized scattered-light region ($R_{\text{scatt}}$) must be less than the size scale of the region producing BELs, i.e., $R_{\text{scatt}} < 10^{18}L_{B,46}^{2.5}$ cm. At the same time, in order to produce the observed change in the polarization of component D relative to the other three components, the polarized scattered-light region must lie beyond the inner continuum-producing region which it reflects, far enough so that the inner continuum-producing region is not microlensed. This is because, if the entire scattering region were to lie within the microlensed region, there would be a near constant magnification across the region during microlensing, the continuum light and scattered continuum light would be similarly amplified, and the polarization would remain unchanged among the four components during microlensing. Note that microlensing of an unpolarized central continuum-producing region (e.g., the continuum from the thermal accretion disk) is also not a possibility, since this would reduce the polarization in component D, which is not observed. These constraints are new; they were not addressed in the discussion of Chae & Turnshek (1999) because component polarization information was unavailable.

The size of the microlensed region on the source plane will be of the order the Einstein ring size. Following Chae & Turnshek (1999), the Einstein ring size on the source plane produced by a microlensing star is given by $\eta_0 \approx 2 \times 10^4 (M/M_\odot)^{0.5} h_7^{-0.5}$ cm, where $M$ is the mass of the microlens. This is $\approx 8$ lt-days for a solar mass star, which is larger than the expected size of the continuum emitting region from any accretion disk. We would expect the size of the microlensed polarized scattering region to lie beyond this region.

Taken together our results therefore suggest that the size scale of the polarized scattered-light region in the Cloverleaf is

$$2 \times 10^{16} (M/M_\odot)^{0.5} h_7^{-0.5} < R_{\text{scatt}} < 10^{18}L_{B,46}^{0.5} \text{ cm}.$$ (2)

From these results it is clear that a more rigorous future program dedicated to monitoring (photometric, spectroscopic, and polarimetric) the Cloverleaf would hold promise for providing valuable constraints on models of the inner regions of QSOs (i.e., the BAL region, the BEL region, and the scattered-light region producing the polarization).

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REFERENCES

Angonin, M.-C., Remy, M., Surdej, J., & Vanderriest, C. 1990, A&A, 233, L5
Arnould, P., et al. 1993, in Proc. 31st Liege International Astrophysical Colloq., Gravitational Lenses in the Universe, ed. J. Surdej et al. (Liege: Univ. Liège, Inst. d’Astrophys), 169
Belle, K. E., & Lewis, G. F. 2000, PASP, 112, 320
Biretta, J., & McMaster, M. 1997, in Instrument Science Report WFPC2 97-11 (Baltimore: STScI)
Chae, K.-H., & Turnshek, D. A. 1999, ApJ, 514, 587

Fruchter, A. S., & Hook, R. N. 1998, preprint (astro-ph/9808087)
Fruchter, A. S., Hook, R. N., Busko, I. C., & Mutchler, M. 1997, in 1997 HST Calibration Workshop, ed. S. Casertano et al. (Baltimore: STScI), 518
Goodrich, R. W. 1997, ApJ, 474, 606
Goodrich, R. W., & Miller, J. S. 1995, ApJ, 448, L73
Hutsemekers, D., Lamy, H., & Remy, M. 1998, A&A, 340, 371
Kaspi, S., et al. 2000, ApJ, 533, 631
Monier, E. M., Turnshek, D. A., & Lupie, O. L. 1998, ApJ, 496, 177
Murray, N., & Chiang, J. 1998, ApJ, 494, 125
Ogle, P. M. 1998, Ph.D. thesis, Caltech
Ostensen, R., et al. 1997, A&AS, 126, 393
Perley, R. A., & Taylor, G. B. 1991, AJ, 101, 1623
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in FORTRAN (Cambridge: Cambridge Univ. Press), 689
Remy, M., Gosset, E., Hutsemekers, D., Revenaz, B., & Surdej, J. 1996, in IAU Symp. 173, Astrophysical Applications of Gravitational Lensing, ed. C. Kochanek & J. Hewitt (Dordrecht: Kluwer), 261
Schmidt, G. D., & Hines, D. C. 1999, ApJ, 512, 125

Sirola, C. J., et al. 1998, ApJ, 495, 659
Turnshek, D. A. 1988, in QSO Absorption Lines: Probing the Universe, ed. J. C. Blades, D. Turnshek, & C. Norman (Cambridge: Cambridge Univ. Press), 17
———. 1995, in QSO Absorption Lines, ESO Workshop, ed. G. Meylan (Berlin: Springer), 317
Turnshek, D. A., Lupie, O. L., Rao, S. M., Espey, B. R., & Sirola, C. J. 1997, ApJ, 485, 100
Weymann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, ApJ, 373, 23

Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249