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ABSTRACT

We describe the first part of a survey for lensed quasars. The first sample includes 142 images of 121 quasars. All images are analyzed using empirical point spread functions and Monte Carlo simulations of the observations. We use Monte Carlo simulations to study the expected distribution of the properties of single stellar images, image pairs, symmetric image quads, known gravitational lenses, and statistical samples from the best fitting statistical lens models. The Monte Carlo simulations reproduce the essential features of the observational data. We accidentally rediscovered the lensed pair LBQS 1009-0252, and we found two strong lens candidates Q0010+023 and Q0011-002 that turned out to be low redshift galaxies, one weaker candidate Q0456+025 that is probably a false positive, one false positive Q0847+100, and we had two cosmic ray hits on the quasar image, Q1318-050 and Q1038+311. With our candidate selection criteria we expect to find three statistical false positives in our sample based on the Monte Carlo simulations. Other than these seven objects we found five images within 6"0 of the quasars, and we have identified two as stars and one as the lower-redshift quasar in LBQS 1009-0252. We found a total of 22 objects within 12"0 of the quasars, seven of which are brighter than the quasar. Of these 22, we have identified eight as stars, and one as a quasar. The spatial and magnitude distributions of these objects match the predicted distribution of stars and galaxies. Depending on the cosmological model and the mass normalization for E/S0 galaxies we expected to find between 0.8 and 2.5 lenses in this sample.

Subject headings: gravitational lenses – quasars

¹Observations reported here were obtained, in part, at MDM Observatory, a consortium of the University of Michigan, Dartmouth College and the Massachusetts Institute of Technology.

²This research made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration

³We have made use in part of finder chart(s) obtained using the Guide Stars Selection System Astrometric Support Program developed at the Space Telescope Science Institute (STScI is operated by the Association of Universities for Research in Astronomy, Inc., for NASA)

1 INTRODUCTION

Gravitational lenses are an important new method for examining the structure of galaxies, the background cosmological model, and the value of the Hubble constant. Studying the structure of galaxies and determining the value of the Hubble constant depends primarily on finding new lenses, while determining the cosmological model requires accurate estimates of the rate of gravitational lensing. For lensing by galaxies, radio surveys (Hewitt 1992, Patnaik 1994) have been the most successful means of finding lenses both in the total number of lenses and the intrinsic utility of the lenses as constraints on galaxies. Radio surveys have a typical yield of approximately one lens per five hundred sources examined. Optical surveys of quasars (Yee et al. 1993, Crampton et al. 1992, Maoz et al. 1993ab, Surdej et al. 1993, Jaunsen & Stabell 1994) have been less successful at finding lenses and they have examined fewer sources, but they are the only sample that allows accurate statistical calculations because of the wealth of information on the redshift and flux distributions of quasars. Bright quasar surveys yield approximately one lens per hundred quasars, although the incidence drops rapidly in fainter samples. Redshift surveys of nearby galaxies promise to find large numbers of lenses as the scale of redshift surveys grows (Kochanek 1992), but the incidence of lenses in such surveys is very low (about one in ten thousand redshifts).

The largest homogeneous survey for lensed quasars is the Snapshot Survey (Bahcall et al. 1992, Maoz et al. 1992, 1993ab) with 502 objects and five lenses (Q0142–100, Q0957+561, PG1115+080, Q1208+101 and Q1413+117). Other surveys are the Crampton et al. (1992) Survey with 100 objects, the Yee et al. (1993) Survey with 108 objects and one known lens (Q1413+117), the ESO/Liège Survey (Surdej et al. 1993) with 188 objects and four lenses (Q0142–100, PG1115+080, Q1208+101 and Q1413+117), and the NOT Survey (Jaunsen & Stabell 1994) with 168 objects. All these surveys independently selected high-redshift, high-luminosity quasars, and as a result there is considerable overlap between the samples. If we exclude the five lenses and the NOT Survey, there are 888 published observations of 648 distinct quasars between the remaining four surveys: 453 were observed by only one survey, 162 by two surveys, 22 by three surveys and 11 by all four surveys. The Snapshot Survey examined 54 Crampton et al. (1992) Survey objects, 52 Yee et al. (1993) Survey objects, and 111 ESO/Liège Survey objects leaving 322 unduplicated objects. The Crampton et al. (1992) Survey examined 34 Yee et al. (1993) Survey objects and 15 ESO/Liège Survey objects leaving 32 unduplicated objects. The Yee et al. (1993) Survey examined 28 ESO/Liège Survey objects leaving 35 unduplicated objects, and the ESO/Liège Survey has 64 unduplicated objects. Kochanek (1993a) gives an extensive discussion of the selection effects and reliability of these four surveys. The NOT Survey examined 31 quasars observed in the other four surveys, leaving 137 unduplicated.

Theoretical studies of gravitational lenses have focused on limiting the value of the cosmological constant (Turner 1990, Fukugita & Turner 1991, Kochanek 1993b, Maoz & Rix 1993) because the expected number of lenses is dramatically higher in cosmologies with $\Lambda \sim 1$. Distinguishing between normal cosmologies is harder, because an empty $\Omega = 0$ universe produces only twice as many lenses as an Einstein-deSitter $\Omega = 1$ universe (Turner, Ostriker & Gott 1984). We can only do accurate theoretical calculations of the expected

number of lenses for quasars, but the quasar lens sample has only five lenses and the statistical fluctuations in the number of lenses are comparable to the differences between the cosmological models. The only means of reducing the statistical uncertainties are to survey larger numbers of quasars or to do the spectroscopic surveys of the radio lens surveys to build up the information on redshifts and luminosities needed for the theoretical calculations. Since imaging is considerably simpler than spectroscopy, it is currently more efficient to increase the size of the quasar samples.

Eventually lens studies, like all other cosmological probes, will be dominated by systematic errors. The primary systematic uncertainty at the moment is the mass and structure of the lens galaxies. Fortunately the lens sample itself can be used to control this uncertainty (Kochanek 1993b, Maoz & Rix 1993) because the observed image separations provide an internal estimate of the lens masses with comparable accuracy to that of normal dynamical studies. Larger samples of lenses will further control this problem. Other issues we must eventually confront are galaxy evolution (Mao 1991, Mao & Kochanek 1994, Rix et al. 1994), reddening by lens galaxies (Kochanek 1991, Fukugita & Peebles 1994), the luminosity of the lens galaxy (Kochanek 1991), the accuracy of quasar and galaxy number counts, and the selection effects of the original survey that found the quasars (Kochanek 1991). Many of these issues can be examined by comparing the optical and radio samples, so eventually the spectroscopy of the radio sample must be pursued.

For the moment, however, we can make considerable progress by increasing the size of the sample of surveyed quasars. We want to achieve the most rapid increase in the constraints on the cosmological model that is practical, and we can do four things to that end: (1) minimize the overlap with existing surveys, (2) use a small telescope that is not excessively oversubscribed to maximize the available observing time, (3) avoid the major sources of background contamination, i.e., stars and galaxies, and (4) regard a major goal of the survey as producing short candidate lists that anyone may examine. All the existing lens surveys are strongly redundant, which is wasteful except as a cross check of possible biases of the different observational groups. The second and third goals overlap, because the background of stars and galaxies becomes a severe limitation only when the survey tries to find faint companions near the much brighter primary image of the quasar. Models of the statistics of lenses predict moderate flux differences between the multiple images, while the number counts of galactic stars show that 10% of quasars have a star within $6''0$ if we look for images 5 mag fainter than the quasar (Kochanek 1993a). The observed sample of lenses (both radio and optical) confirms the theoretical model, because all the known galaxy-scale lens systems contain an image pair with a magnitude difference smaller than 2.5 magnitudes even though the surveys could detect pairs with magnitude differences of 5 magnitudes. If we limit the survey to a magnitude difference of approximately 3 mag, then we both avoid being swamped by the stellar background and we can use a small telescope for which larger amounts of time are available. Obviously such a survey is more incomplete than one that looks for very faint image pairs, but in the statistical model we can compensate for the losses by using an appropriately defined selection function. We also catalog all detected objects within $12''0$ of the quasar so that once these objects are identified the survey will have more sensitivity to group and cluster mass scales than most earlier lens surveys.

In summary, the philosophy of the FKS lens survey is to obtain a quick look at a large number of quasars by sacrificing dynamic range. Thus, we suffer a moderate decrease in completeness, but enjoy a dramatic decrease in stellar contamination, and a dramatic increase in the survey rate. The design of the survey also makes objects easier to follow up by using larger telescopes, because the companions we do discover are brighter than those found in deeper surveys. We will present ranked lists of candidates as we proceed. Our goal is to survey 500 quasars over the next three years primarily using the SAO 48" telescope on Mt. Hopkins. Sample selection and data analysis are described in §2. All data are uniformly reduced using daophot (Stetson 1992) within IRAF to do PSF subtraction on the quasars. We estimate the statistical likelihood that the quasar images are isolated point sources from the daophot model of the quasar, the daophot models of stars of similar magnitude on the same CCD frame, and Monte Carlo simulations of the observations. Small separation candidates (less than $3''.0$) are discussed in §3, and larger separations (from $3''.0$ to $12''.0$) are discussed in §4. The systematic and statistical problems associated with finding objects, close pairs of objects, and other common lens geometries are examined in §5 using Monte Carlo simulations. The final section §6 summarizes the candidates and the data that need to be confirmed, and compares the observations to the theoretical predictions for the sample.

2 SAMPLE SELECTION, DATA COLLECTION AND ANALYSIS PROCEDURES

Since we are not conducting a survey for quasars, we select quasars from existing samples. We defined our sample by searching available quasar catalogs (Véron-Cetty & Véron 1991, Hewitt & Burbidge 1989, 1993 hereafter the HB catalog, Hewitt et al. 1994, Boyle et al. 1990) using NED (the NASA Extragalactic Database) and ADS (the Astrophysics Data System) for quasars visible from Mt. Hopkins, with $|b| > 20^\circ$, redshift $z > 1$ and magnitude $V < 19.5$ that have not been formally surveyed for gravitational lensing by Yee et al. (1993), Crampton et al. (1992), the ESO/Liège Survey (Surdej et al. 1993), the Snapshot Survey, or the NOT Survey (Nordic Optical Telescope, Jaunsen & Stabell 1994). The search yielded a list of nearly 700 quasars. Simply by avoiding overlaps with other surveys, we effectively double our efficiency compared to the earlier ground based surveys, all of which were significantly overlapping. Since the quasars are selected from published quasar catalogs, this survey is subject to the selection effects of the original quasar survey as discussed by Kochanek (1991).

The quasar list was ordered using the best-fit statistical model from Kochanek (1993b) to estimate the likelihood that each quasar is lensed based on its redshift and magnitude. To the extent scheduling allows, we observe the quasars with the highest likelihood of being lensed first. Such a ranking does not bias the resulting statistics (all other surveys were effectively selected on this basis), but it tries to falsify the best-fitting statistical model with the smallest number of observations. From a theoretical perspective, our sample is not as likely to contain gravitational lenses as the earlier surveys. It has a fainter average apparent magnitude because earlier lens surveys strongly emphasized examining bright quasars and recent surveys for quasars have emphasized finding fainter quasars. The average (and median) redshift of

FIG. 1.—The left panel shows the distribution in redshift and tabulated V magnitude of the 119 quasars surveyed in this paper. The right panel shows the tabulated and measured V magnitudes of the quasars. The shape of the point labels the color used for our observations. Color corrections of $V-R=0.1$ and $V-I=0.3$ were used for the R and I observations. The solid line shows where the two magnitudes are equal, and the dashed lines are offset by one magnitude.

the quasars in the observed sample is 2.0, comparable to the means of the five surveys we have mentioned, with 90% of the quasars between 1.1 and 3.1. Figure 1 shows the redshift and magnitude distribution of the sample we present in this paper.

Finding charts for the quasar sample are generated using the HST guide star catalog (GSC). The field of view of our standard images is 5.6 arcminutes, so most frames contain several GSC stars. A significant fraction of the frames do not contain any GSC stars (12 of 121) or only saturated GSC stars (19 of 142). These cases and any ambiguous finding charts were checked using the discovery finding charts. From the galactic star counts model of Bahcall & Soneira (1980) we estimate that almost every 1024^2 image will contain several unsaturated stars brighter than the quasar to estimate an empirical point spread function (PSF). Most of our observations were obtained under non-photometric conditions (66 out of 142 images). If the conditions were photometric, we obtained images of standard stars through airmasses similar to those of the quasar images as a cross-check of the calibration of the quasar brightnesses. In general, we estimate the magnitudes of the stars and quasars in each frame using the GSC stars in the frame. Using these stars gives magnitudes with uncertainties of approximately 0.20 mag (Lasker et al. 1988). While such estimates are hardly ideal, it is a considerable improvement over many of the tabulated magnitudes for the quasars. Figure 1 shows the differences between the tabulated V magnitudes of the survey quasars and our best photometric estimates.

At the Mt. Hopkins 48" telescope, we used a Loral 2048² CCD with a Johnson *B* or *V* filter or a Kron-Cousins *R* or *I* filter. The pixel scale of the CCD is 0".326, the nominal gain is 2.45 electrons/ADU, and the nominal read-out noise is 9.5 electrons per pixel. For

FIG. 2.—The left panel shows a histogram of the seeing FWHM for the observations on the 48" (light solid) and the MDM (heavy solid) telescopes. The right panel shows a histogram of the dynamic range of the observations between the quasar and the limiting magnitude of the observations estimated from Monte Carlo simulations (heavy solid) and the fifth from faintest star (light solid).

our first night of observations an electronics failure in the normal CCD forced us to use an alternative Loral 2048² CCD with pixel scale 0".326, gain 2.67 electrons/ADU, and read-out noise 19.3 electrons per pixel. The exposures are mainly taken in *R* with exposure times from 5 to 15 minutes for quasars with cataloged *V* magnitudes ranging from 16.5 to 19.5. Sources that appear interesting at the time of the observations are immediately reobserved in *V* (at times also in *B* or *I*). Because the exposure times are short, we generally read only the central 1024² of the CCD. In full 2048² mode, the time to read the chip becomes a significant fraction of the exposure time and reduces the survey efficiency. As we show in Figure 2, the best seeing obtained on the 48" is approximately 1".1 FWHM, but the median seeing in the observations reported here is 1".9, with 90% of the values in the range from 1".3 to 2".9.

On the Hiltner 2.4-m telescope at MDM, we used a Tektronix 1024² CCD, with gain 3.45 electrons/ADU, read-out noise 4.0 electrons per pixel, and pixel scale 0".275. All 2.4-m observations were made in the *I* band with exposure times between 3 and 5 minutes. The seeing at the 2.4-m varied between 0".8 and 1".3 (see Figure 2). The good seeing and relatively large pixels in the MDM images complicated the PSF subtraction procedures because the sampling of the better images is poor and stars are more easily saturated.

After flat fielding, the frames are reduced using daophot within IRAF (Stetson 1992) with fixed parameters aside from those that depend on the gain, read-out noise, seeing and sky brightness. A source detection threshold of 5 standard deviations above the sky is used to minimize the incidence of false positives. Daophot generates a catalog of objects with positions, magnitudes, a χ^2 statistic for the fit of a PSF to each luminous object, and the "sharpness," which estimates the difference between the width of the object and the PSF.

The χ^2 we quote throughout the paper is really the χ^2 per degree of freedom in the fitted model. Objects with large positive sharpness are more extended than stars and tend to be galaxies, while objects with large negative sharpness are less extended than stars and tend to be cosmic rays. Formally, the sharpness is related to the rate of decrease of residuals as the width of the PSF is increased. For each image we made two passes with daophot. On the first pass we find objects, determine and check the empirical PSF, and subtract the PSF from the cataloged objects. On the second pass we find objects on the residuals frame and then redo the subtraction with the updated catalog. The χ^2 and sharpness we quote for the quasar images are the values for fitting the quasar as a single PSF unless otherwise stated.

Each daophot catalog is contaminated by galaxies and cosmic rays, and some of the stars are unresolved doubles after only one pass. We developed a simple checking routine to help classify the objects in the daophot catalog. The first step of the check program is to estimate χ_{sky}^2 for modeling the residuals near each object as representing a uniform sky. If I is the original image, R is the residual image, S is the sky brightness we are fitting, and $N = (I\gamma + r^2)^{1/2}/\gamma$ is the noise estimated from the original image for gain γ and read-out noise r , then we optimize

$$\chi_{sky}^2 = \sum_{ij} (R_{ij} - S)^2 N_{ij}^{-2} \quad (1)$$

over a region of two FWHMs about each object. The statistic χ_{sky}^2 will diverge from one per degree of freedom only if the residuals from the subtraction are a statistically significant fraction of the original flux (n.b. we have not included the statistical noise in the empirical PSF, so χ_{sky}^2 will overestimate the importance of the residuals compared to the daophot χ^2).

The next step is to check for mistakenly included cosmic rays. In the daophot variables, cosmic rays generally have daophot magnitudes fainter than the detection threshold for real stars, a large χ^2 , and a large negative sharpness. We can explicitly model each detected object as a cosmic ray using a “two-hot-pixel” model in which we model the image as a uniform sky plus the two brightest pixels, with their brightnesses as free parameters. If χ_{CR}^2 is a better fit to the raw image than daophot’s PSF subtraction, the catalog entry is flagged as a cosmic ray and dropped from further study. Visual inspection confirms that this strategy is very good at eliminating cosmic rays from the catalog. Our cosmic ray model also eliminates most false detections associated with satellite/asteroid tracks and the diffraction spikes of bright stars.

The next step is to flag the catalog entries whose residuals are characteristic of galaxies and star pairs. A bright galaxy that is included in the daophot catalog has a particular signature in the residuals – a doughnut hole residual in which the peak of the galaxy is subtracted leaving the outer parts unaffected. We check each object’s residual pattern by convolving the residual with a kernel designed to detect doughnut holes but not flat sky:

$$K = \frac{1}{2\pi\sigma_1^2} \exp(-r^2/2\sigma_1^2) - \frac{1}{2\pi\sigma_0^2} \exp(-r^2/2\sigma_0^2) \quad (2)$$

where σ_0 is set to have the same FWHM as the PSF, and we choose $\sigma_1 = 2\sigma_0$. We then model the residuals as a flat sky plus a flux F times the kernel, $S + FK$, and compute χ_{gal}^2 by optimizing the fit with respect to S and F . An object is flagged as a galaxy if χ_{gal}^2 is

significantly less than χ_{sky}^2 and $F > 0$ (events with $F < 0$ are cosmic rays). The filter will flag galaxies, close star pairs, and gravitational lenses until we reach the magnitudes where star/galaxy separation fails. Because we are not attempting a full separation of stars from galaxies, we refer to the flagged objects as “galaxies.”

We developed the flagging procedures to sort through the catalog entries based on the residual patterns of galaxies, stars, and cosmic rays, so that we can compare the typical properties of star and galaxy images to the properties of the quasar images. We needed an automated procedure to sort through the enormous number of objects besides the quasar in the images. We also use the flagging procedures on the quasars, in particular whether the residuals from subtracting a PSF from the quasar image are star-like or galaxy-like. Although the details represent our biases, the results of applying these procedures to the quasar images were not prejudicial.

Our survey commenced in October 1993 and the 121 quasars discussed in this paper are the sample observed through June 1994. Table 1 presents the list of quasars in the present sample as well as their cataloged properties: columns 1 through 8 show, respectively, the name of each quasar, its right ascension, declination (epoch 1950.0), redshift, catalogued V magnitude, a discovery code (C=color, O=grism, R=radio, X=x-ray), galactic longitude ℓ^I and galactic latitude b^I . Table 2 presents a summary of each observation: columns 1 through 11 show, respectively, the name of each quasar, the date of observation in the format DDMMYY, the mode of observation (1 is the standard read-out of the inner 1024^2 pixels, 2 indicates read-out of the full 2048^2 pixels, and 3 indicates MDM data), the filter (B , V , R or I), the exposure time in minutes, the quality of the observation (C indicates clouds, P photometric conditions), the seeing (FWHM in arcsec), the background level and its rms in ADU, the instrumental magnitude of a calibration HST GSC star, and the GSC nominal V magnitude of the calibration star. Table 3 presents a summary of the results of our data analysis: columns 1 through 11 show, respectively, the name of each quasar, the location of the quasar image on the chip in pixels first along columns, then along rows, the fitted daophot value of χ^2 , the sharpness, the instrumental daophot magnitude of each quasar, the calibrated magnitude of each quasar for the filter used in the observation, the nominal daophot uncertainty in this magnitude, the distance to the nearest stellar neighbor fainter than the quasar in arcsec, and the calibrated magnitude of this neighbor. We have tried to include all of the information necessary to perform Monte Carlo simulations of our procedures by anyone attempting to interpret our results.

The quasars are given rough classifications at the telescope by visual inspection of each image. The classes are $Q = 0$ if there is no companion within $12''$, $Q = 1$ if there is a companion between $6''$ and $12''$, $Q = 2$ if there is a companion between $3''$ and $6''$, and $Q = 3$ if there is a companion within $3''$. Of the 121 quasars, only seven were flagged as peculiar and are discussed in §3, and 20 had objects within $3''.0$ to $12''.0$ of the quasar and are discussed in §4.

To get an internal estimate of the average quasar colors and the differences between our measured magnitudes and the tabulated magnitudes we first determined the mean and the dispersion of the magnitude differences. Then we iterated on the values twice by rejecting

outlying points more than two standard deviations from the mean and recalculating the mean and the dispersion. With this procedure, we find $\langle V - V_{tab} \rangle = -0.01 \pm 0.54$, $\langle V_{tab} - R \rangle = 0.21 \pm 0.50$, and $\langle V_{tab} - I \rangle = 0.37 \pm 0.49$. The 0.5 magnitudes of scatter are not surprising given the concentration of the tabulated magnitudes at 0.5 magnitude intervals (see Figure 1). For the limited numbers of objects where we measured the color of the quasars we find $\langle V - R \rangle = -0.12 \pm 0.18$ and $\langle R - I \rangle = -0.21 \pm 0.49$ giving an estimated $\langle V - I \rangle = -0.33 \pm 0.52$. Our final best estimate of the average colors for quasars in our sample are $V - R = 0.1 \pm 0.1$ and $V - I = 0.3 \pm 0.3$. These estimates are consistent with the Irwin et al. (1991) estimate that the average $R - I = 0.2$ for $z < 3$ quasars. We note the nine objects that were rejected as outlying points in Table 3.

Eleven images were dropped from the study because there was insufficient dynamic range between the quasar and the detection limit to make them useful for the survey. The eleven were R images of Q0112+030, Q0947+482, Q1115+180, Q1116+128, Q1226+112, Q1124+571, Q1130+107, Q1131+112, Q1216+487, and Q1308+297, and a V image of Q0313+344. Three of these quasars have anomalously large $V_{tab} - R$ values. Q0112+030 has a tabulated $V = 18.6$ and we observed $R = 20.02$; Q0947+482 has a tabulated $V = 17.65$ and we found $R = 20.01$; and Q1308+297 has a tabulated $V = 17.4$ and we observed $R = 19.68$. The remaining objects did not have such large magnitude differences, but they tended to be near the fainter end of the magnitude selection limit and lie on the fainter side of the distribution of magnitudes relative to the tabulated magnitude, or they were observed under very poor atmospheric conditions.

3 CANDIDATE LENSES AND CLOSE IMAGE PAIRS

In this section we consider quasars that are poorly fit by the point spread function or have a companion detected within less than $3''$ (Q=3 objects). Figure 3 shows the distribution of the quasar images as a scatter diagram in χ^2 and sharpness and histograms of the χ^2 and sharpness separately after fitting one PSF to the quasar. Figure 4 shows the same distributions for the two stars closest in magnitude to the quasar in each image. For each image we made a Monte Carlo simulation to determine the expected statistical variations in the χ^2 and sharpness distributions given the noise, the FWHM of the seeing, and the PSF stars used in the analysis (see §5). In the simulations we find that that 5.4% of stars have $\chi^2 > 1.10$, 2.3% have $\chi^2 > 1.15$, 0.8% have $\chi > 1.20$, and 0.3% have $\chi^2 > 1.25$. Simply scaling from these numbers we expect 7.6, 3.2, 1.1, and 0.4 quasar images with $\chi^2 > 1.10$, 1.15, 1.20, and 1.25 in a sample of 139 observations just from statistical spread of the χ^2 distribution for stars. In 139 observations of the quasars we found 13, 7, 6, and 6 images with $\chi^2 > 1.10$, 1.15, 1.20, and 1.25. Several of the observations are of the same quasar, and there are 11 different quasars that have at least one image with $\chi^2 > 1.1$, 7 with $\chi^2 > 1.15$ and 6 with $\chi^2 > 1.2$. We treat all objects with $\chi^2 > 1.15$ as a candidate for being a lens. The sharpness distribution also has a sharp cutoff, with only 0.8% and 0.1% above sharpnesses of 0.5 and 1.0 respectively. It appears from Figure 3, however, that the Monte Carlo simulations overestimate the rate at which the distribution drops off for large sharpnesses, so we include only objects with sharpness greater than 1 as candidates.

For each image we generated a Monte Carlo simulation of the observation including the sky/noise, the FWHM, the number and magnitudes of the PSF stars used in the analysis to determine the statistically expected spread of the values of the χ^2 and sharpness for that particular frame. Figure 5 compares the Monte Carlo distributions and the observed value for four randomly selected images from the survey. Particularly in the MDM image of UM 497, the Monte Carlo simulations underestimate the width of the sharpness distribution, so we are conservative in using the sharpness to select candidates.

We have seven quasars with $\chi^2 > 1.15$ or sharpness greater than 1 in at least one image. Each of the candidates was reduced several times with different PSF stars by different people. In each case there are multiple PSF stars, the PSF is self-consistent ($\chi^2 < 1$), stars of comparable magnitude to the quasar have acceptable χ^2 values for stellar objects, and the sharpness and χ^2 values are stable when the PSF stars are changed. It is unlikely that the objects are selected as candidates because of problems in the PSF stars. We discuss the candidates in order of decreasing values of the χ^2 and we show the Monte Carlo scatter plots, the original and the subtracted images for each of the candidates.⁴

Q0010+023 ($z = 2.27$, $V = 15.5$): The quasar was discovered in the Zhan & Chen (1987b) grism survey. We obtained R and V images with 5 minute exposure times in $2''.0$ FWHM seeing. In both images the quasar residuals after subtracting a PSF are clearly “doughnut” shaped with $\chi^2 = 2.99$ and 2.02 respectively and in both cases the quasar is flagged as a galaxy (see Figure 6). As expected for objects more extended than the PSF, they both have large positive sharpnesses of 4.86 and 4.13. Figure 9 shows the R and V images of the quasar, the residuals after subtracting a quasar, and the star nearest to the quasar in magnitude and its residual. Fitted as a single point source the quasar has $R = 18.14$ and $V = 18.37$, much fainter than the tabulated magnitude. Using an aperture of radius 9.7 (3 seeing radii), we find that $R = 17.7$ and $V = 17.9$ by comparison with GSC stars in the field of view. Even so, the quasar is much fainter than the tabulated magnitude, with $V - V_{tab} = 2.4$ magnitudes. Of the 13 objects within 0.5 mag of the quasar, only one has a χ^2 larger than 1.2. That object has a $\chi^2 = 2.77$ (2.20) and sharpness 4.8 (4.78) in the R (V) frames, but the χ^2 is suspect because the image is five pixels from a column defect in the CCD. The morphology of the quasar image is certainly inconsistent with stellar, so the object must be either a bad identification, a real galaxy, or a (probably quad) lens. The identification appears to be unambiguous because of the bright, close pair of stars almost directly North of the quasar. A. Filippenko and T. Matheson obtained a spectrum of Q0010+023 on 11 October 1994 with the 3m Lick telescope, and identified the object as a redshift $z = 0.088$ galaxy. This confirms the non-stellar identification made based on the $48''$ images, but it completely rejects the possibility of it being a lens.

Q1318-050 (MMB 90, $z = 3.7$, $V = 17.43$): The quasar was found in the Mitchell, Miller & Boyle (1990). A 10 minute R exposure with FWHM = $2''.3$ on the $48''$ telescope has $\chi^2 = 0.95$

⁴Because we repeatedly reanalyze the images with high χ^2 values, we may produce fewer false positives than expected from a single, blind subtraction of a PSF from the quasar. We may also bias the χ^2 values for real lenses downwards.

FIG. 3.—The distribution of the quasar images in the space of daophot χ^2 and sharpness. The three panels show a scatter plot of the χ^2 and the sharpness and histograms of the χ^2 and the sharpness. Quasars with anomalously high or low values are labeled. Two observations of the known lens PG1115+080 and one observation of the known lens H1413+117 are included in the figure. The two images of PG1115+080 appear only the sharpness histogram because the χ^2 of the images (4.00 and 4.75) are too large to fit in the plotted range. The light solid lines in the histograms are the distributions of the approximately 27000 stellar images in the Monte Carlo simulations of the observations.

FIG. 4.—The distribution of the two stellar images closest in magnitude to the survey quasar in the space of daophot χ^2 and sharpness. The three panels show a scatter plot of the χ^2 and the sharpness and histograms of the χ^2 and the sharpness. The light solid lines in the histograms are the distributions of the approximately 27000 stellar images in the Monte Carlo simulations of the observations.

FIG. 5.—Scatter plots of the χ^2 and sharpness from the Monte Carlo simulations of four randomly selected survey quasars. The horizontal and vertical lines show the measured values for the quasar. The panels are labeled by the quasar name and the observational filter.

FIG. 6.—Scatter plots of the χ^2 and sharpness from the Monte Carlo simulations of the R and V images of the two best lens candidates Q0010+023 and Q0011-002. The horizontal and vertical lines show the measured values for the image. Note the change in the scales of the figures from the randomly selected quasars shown in Figure 5.

FIG. 7.—Scatter plots of the χ^2 and sharpness from the Monte Carlo simulations of three lens candidates MMB90, Q0847+100, and Q1038+311. The horizontal and vertical lines show the measured values for the image. We believe the image of Q0847+100 is a $1''.08$ separation double with a 2.13 magnitude difference. The crosses show the expected distribution of the χ^2 and the sharpness for such doubles. Note that the distribution for stellar objects (squares) and the distribution for doubles (crosses) are well separated.

FIG. 8.—Scatter plots of the χ^2 and sharpness from the Monte Carlo simulations of two lens candidates LBQS1009-0252 and Q0456+025. The horizontal and vertical lines show the measured values for the image. We know that LBQS 1009-0252 is a 1".6 separation double with a 2.26 magnitude difference. The crosses show the expected distribution of the χ^2 and the sharpness for such doubles. Note that the distribution for stellar objects (squares) and the distributions for doubles (crosses) are well separated.

FIG. 9.—The images of Q0010+023 and Q0011-002. The two columns for each quasar show the image and subtraction residuals for a 50 pixel region centered on the R and V images of the quasar (top) or the star (bottom) nearest the quasar in magnitude. The contours are drawn at $\pm 2, 4, 8, 16, 32$, and 64 times the estimated background noise relative to the sky. Positive contours are solid and dashed contours are negative. QSO means the original quasar image, QSO R1 means the residual image after the first round of PSF subtraction, and QSO R2 means the residual image after the second round of PSF subtraction. STAR means the original image of a star as close to the quasar in magnitude as possible, and STAR R1 means the residual image after the first round of PSF subtraction.

FIG. 10.—The images of Q1318-050 and Q0847+100. The two columns for Q1318-050 show the image and subtraction residuals residuals for a 50 pixel region centered on the R and I images of the quasar or the star nearest the quasar in magnitude. The pixel scale changes for $0''.326$ for the R image to $0''.275$ for the I image. The first column for Q0847+100 shows the quasar, the residuals after subtracting one PSF, and the residuals after subtracting two PSFs, while the second columns shows the two stars nearest the quasar in magnitude and their residuals. The contours are drawn at $\pm 2, 4, 8, 16, 32$, and 64 times the estimated background noise relative to the sky. Positive contours are solid and dashed contours are negative.

FIG. 11.—The images of Q1038+311 and LBQS 1009-0252. The two columns for Q1038+311 show the image and subtraction residuals residuals for a 50 pixel region centered on the R images of the quasar or the star nearest the quasar in magnitude. The first column for LBQS 1009-0252 shows the quasar, the residuals after subtracting two PSFs, and the residuals after subtracting three PSFs, while the second columns shows the two stars nearest the quasar in magnitude and their residuals. The contours are drawn at $\pm 2, 4, 8, 16, 32,$ and 64 times the estimated background noise relative to the sky. Positive contours are solid and dashed contours are negative.

FIG. 12.—The images of Q0456+025. The two columns show the image and subtraction residuals for a 50 pixel region centered on the R and V images of the quasar or the star nearest the quasar in magnitude. The quasar is the image closest to the center of the top frames. The contours are drawn at $\pm 2, 4, 8, 16, 32$, and 64 times the estimated background noise relative to the sky. Positive contours are solid and dashed contours are negative.

and sharpness 0.27, but a 5 minute I exposure with FWHM= 1"3 on the MDM telescope has $\chi^2 = 1.67$ and sharpness -0.34 . Close examination reveals that the excess χ^2 is caused by single bright pixel. We believe this is caused by a cosmic ray hit in the quasar PSF, consistent with the anomalous negative sharpness of the image. Figure 7 shows the Monte Carlo scatter plots for the two images, and Figure 10 shows the images and their residuals.

Q0011-002 ($z = 3.10$, $V = 17.5$): The quasar was discovered in the grism survey of Zhan & Chen (1987a). We obtained R and V images with 5 minute exposure times in 2"3 and 2"8 FWHM seeing. In the R image, the quasar has $\chi^2 = 1.55$ and sharpness 2.89, whereas in the V image it has $\chi^2 = 1.21$ and sharpness 4.33. In the R image the quasar is flagged as a "galaxy". The V image of the quasar was taken in worse seeing and has 50% fewer counts, so the smaller significance of the χ^2 is expected. The R and V magnitudes of the quasar are 17.84 and 18.19, somewhat fainter than the tabulated value. There were three other objects within 0.5 mag of the quasar on the R frame that were flagged as galaxies, all with $\chi^2 > 2$, and nine stellar objects with $\chi^2 < 1.2$. The same three objects were flagged as galaxies in the V frame with χ^2 that were significantly smaller. The stellar objects of similar magnitude in the R frame are also stellar objects in the V frame. Figure 6 shows the Monte Carlo scatter plots for the two images and Figure 9 shows the images and their residuals. A. Filippenko and T. Matheson obtained a spectrum of Q011-002 on 11 October 1994 with the 3m Lick telescope, and identified the object as a redshift $z = 0.11$ galaxy. This confirms the non-stellar identification made based on the 48" images, but it completely rejects the possibility of it being a lens.

Q0847+100 ($z = 2.8$, $V = 18.5$): An object from the HB catalog. From a 15 minute R exposure in 1"2 FWHM seeing, we found $\chi^2 = 1.42$ and sharpness 0.23 for the quasar, after a single round of daophot. The quasar magnitude was $R = 18.76$. A second round of daophot split the quasar into a 1"08 separation double with $R_1 = 18.82$ ($\chi^2 = 1.05$, sharpness 0.01) and $R_2 = 20.95$ ($\chi^2 = 0.96$, sharpness 0.12). Additional images in poorer seeing (2"0 FWHM) and with lower total flux did not confirm the χ^2 .

Figure 7 shows the Monte Carlo scatter plot for this image, and Figure 11 shows the image and its residuals. Figure 7 also shows the distribution of χ^2 and sharpness for image pairs with 1"08 separations and magnitude differences of 2.1 mags using the same number and magnitude of PSF stars as in the real image. Monte Carlo simulations of 192 stellar objects with the instrumental magnitude of Q0847+100 have a median χ^2 of 0.99, with 95% less than 1.15 and all were smaller than 1.22. The median sharpness was -0.03 with 95% less than 0.07 and all were smaller than 0.13. Thus, the quasar parameters lie well outside the expected distribution for point sources. Monte Carlo simulations of 1"08 separation, 2.13 magnitude difference pairs have an average χ^2 of 1.37 and 90% of the realizations lie between $1.12 < \chi^2 < 1.61$. The average sharpness is 0.24, with 90% of the realizations between 0.14 and 0.37. After the second round of daophot, the image is split into a double 65% of the time, flagged as a "galaxy" 7% of the time, has a $\chi^2 > 1.15$ 24% of the time, and is missed as a candidate 3.6% of the time. In the images where the quasar is split, the measured separations and magnitude differences are $1"08 \pm 0"16$ and $\Delta m = 2.1 \pm 0.3$ mags at 90% confidence.

From the separation, the magnitudes, and the known number counts of stars, galaxies, and quasars, and a statistical model of lenses we estimate that the relative likelihoods that the fainter image is a star, a galaxy, a lens, an unassociated (different redshift) quasar, or an associated quasar are 44%, 37%, 18%, 0.8%, and 2%. The QSO is a radio source, and a VLA snapshot (Perley 1994, *private communication*) at 8.6 GHz in the A array (0".2 FWHM) with a signal-to-noise ratio of 450:1 reveals a single point source with flux 25 ± 1 mJy. Therefore we rule out the lensing hypothesis. If the splitting is real and the object is not a lens, then we estimate that the relative likelihoods that the fainter image is a star, a galaxy, an unassociated (different redshift) quasar, or an associated quasar are 53%, 46%, 1.0%, and 2.3%. Just as a test of our detection capabilities we will try to confirm the double nature of Q0847+100.

Q1038+311 (CSO 55, $z = 1.45$, $V = 17$): The quasar was discovered in the Case survey (Pesch & Sanduleak 1986). A 10 minute R exposure in 1".5 FWHM seeing yielded $\chi^2 = 1.30$ and sharpness -0.11 . A high residual peak (~ 6.7 standard deviations of the background noise) is probably caused by a cosmic ray, as is apparent in the subtracted image. Figure 7 shows that quasar parameters in the I image lie well outside the expected range, and Figure 11 shows the quasar and its residual. We expect a few cosmic ray hits inside the quasar images for a sample this large. We plan to acquire a second image to confirm the cosmic ray hypothesis.

LBQS 1009-0252 ($z = 2.75$, $V = 17.62$): The quasar was discovered in the LBQS (see Foltz et al. 1989). It was recognized as a lens candidate by Surdej et al. (1994) and again by Hewett et al. (1994). We included the object because it is not in any of the published, completed surveys. In our 10 minute R image with 1".6 FWHM seeing, we initially find that there is a quasar with $\chi^2 = 1.28$ and sharpness 0.42 located 4".6 from an $R = 19.93$ stellar companion ($\chi^2 = 0.77$). A second round of daophot splits the quasar into an $R_1 = 18.72$ ($\chi^2 = 0.97$, sharpness -0.01) image and an $R_2 = 20.98$ ($\chi^2 = 0.57$, sharpness 0.87) companion 1".6 away (see Figure 11). The relative likelihoods that the nearer image is a star, a galaxy, a lens, an unassociated quasar or an associated quasar are 41%, 45%, 12%, 1.0% and 1.6% simply based on the image separations and magnitudes. Given that it is known to have the same redshift as the primary quasar, the odds are 13:1 in favor of it being a lens rather than an associated quasar.

Figure 8 shows the expected range of daophot parameters for stellar images and for pairs with the nominal properties of the LBQS 1009-0252 system. The median χ^2 of stellar images under these conditions is 0.94 and 90% of the realizations have χ^2 between 0.81 and 1.07. The median sharpness of stellar images is -0.03 , and 90% of the realizations have a sharpness between -0.2 and 0.12. After the first round of daophot, the median χ^2 of pairs with the properties of LBQS 1009-0252 is 1.25, and 90% of the realizations have a χ^2 between 1.09 and 1.43. The median sharpness is 0.35, and 90% of the realizations have a sharpness between 0.20 and 0.50. The distribution of pairs is clearly distinct from the distribution of stellar images. After the second pass of daophot 68% of the images are split into a pair, 5% are flagged as galaxies, 21% have $\chi^2 > 1.15$, and 6% satisfy none of the criterion. We would consider LBQS 1009-0252 as a lens candidate in 94% of the trials under these observational conditions. In the cases where the quasar is split into a pair, the separation is $1".60 \pm 0".17$

and the magnitude difference is 2.26 ± 0.20 at 90% confidence.

Q0456+025 ($z = 1.43$ and $V = 17.5$): The quasar was discovered by Sramek & Weedman (1978). Two ten minute exposures in R and V with $2''.0$ FWHM seeing yielded $\chi^2 = 0.99$ and $\chi^2 = 1.16$, and sharpness 0.24 and 0.99 respectively (see Figure 8). The instrumental magnitudes of the quasar in the R and V images are 19.18 and 19.95 compared to estimated limiting magnitudes of 20.8 and 21.0. Since the R image has more dynamic range (1.6 magnitudes from the quasar to the limit instead of 1.1 magnitudes), the low χ^2 of the R image leads us to believe that the high χ^2 in the V image is a false positive. The quasar has an $R = 18.6$ mag and $V = 18.4$ mag stellar companion $6''.4$ away from it. The large χ^2 may also be due in part to the presence of the nearby objects seen in Figure 12.

Of the seven objects and nine images with $\chi^2 > 1.15$, two (Q1318-050 and Q1038+311) are probably caused by cosmic ray events in or near the quasar image, one is a known, real gravitational lens (LBQS 1009-0252), one (Q0847+100) is probably a real double image but not a lens, one is a marginal candidate (Q0456+025), and two are low redshift galaxies (Q0010+023, Q0011-002). Once it became clear that both Q0010+023 and Q0011-002 were neither lenses nor quasars and that both objects came from the same Zhan & Chen (1987ab) survey, we examined other quasars from the same survey more closely. We found a persistent pattern of poorly defined positions, and large magnitude differences with any plausible identification for the quasar given the positions. We expected to find three statistical false positives with this limit on the χ^2 , and it is likely that Q0456+025 is such a false positive.

4 ANALYSIS OF NEAREST NEIGHBORS

Table 4 lists all Q=1 and Q=2 systems where the quasar has a neighbor more than $3''$ and less than $12''$ away. Columns 1 through 9 show, respectively, the name of the quasar, and the position (column then row), χ^2 , sharpness, instrumental magnitude, estimated magnitude, the magnitude error, and the separation from the quasar of the neighbor. There are 4 Q=2 objects ($3''.0$ to $6''.0$) and 18 Q=1 objects ($6''.0$ to $12''.0$). Of the 22 objects, one is flagged as a “galaxy”, one is identified as an unassociated quasar (LBQS 1009-0252), and seven are brighter than the quasar. Two quasars (Q0456+025 and Q0913-025) have two objects within $12''.0$, and we have V–R colors for four objects and R–I colors for one object. One object (CSO 0261) is found only in the high resolution MDM images, and missed in the R images. The expected sources of quasar neighbors in our images are galactic stars, galaxies, unassociated quasars (a quasar at a different redshift), associated quasars (a quasar at the same redshift), and gravitationally lensed images. From the statistics of stars, galaxies, quasars, and lenses we know that the overwhelming majority of the neighbors will be foreground stars and galaxies. In this section we will prove this statistically.

Figure 13 shows the integral number counts of stars and “galaxies” as a function of distance from the quasar between $3''.0$ and $60''.0$. In each quasar field the density of stars and galaxies is uniform and spatially uncorrelated with the quasar. Our statistics are too poor to attempt to examine the question of quasar-galaxy correlations. For a region with inner radius $\theta_{min} = 3''.0$ and outer radius $\theta_{max} = 60''.0$ containing N_T background sources,

FIG. 13.—The average spatial distribution of detected stars and “galaxies” relative to the survey quasars. The expected distribution is a parabola (dashed lines) normalized to produce the observed totals in a 60” region around the quasar. The upper and lower dashed lines show the expected $N^{1/2}$ fluctuations in the number of objects.

the integral distribution should be parabolic with $N(< \theta) = N_T(\theta^2 - \theta_{min}^2)(\theta_{max}^2 - \theta_{min}^2)^{-1}$. If we pick the deepest image for each quasar we find there are 478 stars and 75 “galaxies” within 60” of the sample quasars. The average density of detected stars is 1.26 ± 0.06 per arcmin², and the average density of detected “galaxies” is 0.20 ± 0.02 per arcmin². The Kolmogorov-Smirnov (K-S) test probability that the distributions of stars and galaxies are consistent with parabolic are 99% and 97% respectively.

The K-S test is most sensitive to errors near the middle of the distribution, so it gives lower weight to any deviations in the inner region. If we examine only the 21 unidentified objects within 12” of each quasar, the average density of stars is 1.40 ± 0.31 per arcmin² and the average density of “galaxies” is 0.07 ± 0.07 per arcmin², consistent with the average density in larger fields. The K-S test probability that the stars have a parabolic distribution is 67%, and the probability that the combined sample does is 85%. In the $3''.0 < \theta < 12''.0$ annulus we expected to find 20.8 ± 0.9 objects based on the background, and we found 21. In the $3''.0 < \theta < 6''.0$ Q=2 region we expected 4.2 ± 0.2 objects and we found 3 unidentified objects. Thus the Q=1 and Q=2 regions show a density of objects consistent with a uniform background normalized using the sources found in a 60''.0 radius area surrounding the quasar. Our current sample of neighbors appears to be too small to see the reduced number of bright stars near spectrally selected quasars noted by Gould, Bahcall & Maoz (1993).

The spatial distribution test only examines whether the density of sources is consistent with a uniform density uncorrelated with the quasar. It indirectly checks the absolute value of the density near the quasar because we normalized the counts sufficiently far from the quasar that the normalization must be set by the real background counts of galaxies and quasars. It does not directly check the density of stars and galaxies, nor does it check the

FIG. 14.—Panel (a) shows average differential number counts of stars (squares) and “galaxies” (triangles) in a $120''$ radius around the survey quasars. The smooth lines show the predicted star and galaxy counts for the sample. Fainter galaxies are misidentified as stars leading to the under (over) counting of galaxies (stars) at the fainter magnitudes. Panel (b) shows that the sum of the star and “galaxy” counts matches the predicted sum more closely than the separate components.

magnitude distribution of the sources.

We use model number counts of stars (Bahcall & Soneira 1980), galaxies (Tyson 1988), and quasars (Boyle et al. 1990) to check the absolute number density and magnitude distribution of the sources. The stellar count model is generated by adding the Bahcall & Soneira (1980) models for the galactic coordinates of each survey quasar, while the galaxy counts are assumed to be independent of the location of the quasar (see Kochanek 1993a for a detailed development). The lens estimates are based on the expected distribution produced by E/S0 galaxies with their masses estimated from the separations of the known lenses (see §5.4). Figure 14 shows the differential number counts as a function of magnitude for all detected objects within $120''$ of the quasar. For $14 \lesssim R \lesssim 20.5$ the number counts match the models accurately. The deviations between the “galaxy” counts and the Tyson (1988) model are caused by the crudeness of the galaxy flagging procedures; faint galaxies are labeled as stars because they do not have large enough residuals to be flagged as “galaxies”. The average sample is 90% complete at $R \simeq 20.2$, 50% complete at $R \simeq 20.5$, and 10% complete at $R \simeq 21.1$ magnitudes.

Since the star and galaxy count models closely match the observed sample inside a $120''$ radius region, we next examine the much smaller sample within $12''$ of the quasar. We combine the stars and “galaxies” because the number of objects is too small to examine a separate “galaxy” sample. Figure 15 shows the integral number counts with magnitude of the objects within $12''$ of the quasar, as compared to the predicted number counts based on either the Bahcall & Soneira (1980) and Tyson (1988) number counts model or the observed counts within $120''$ of the quasar. The shape of the distribution matches the two predictions,

FIG. 15.—The integral number counts of stars and “galaxies” in a 12” region around the survey quasars. The predicted number in the region based on the Bahcall & Soneira (1980) star count model is shown by the solid line, and the predicted number based on the counts in a 120” region around the quasar is shown by the dashed line. The deviation in the total number of objects is consistent with Poisson fluctuations.

and the difference in the number of objects is consistent with Poisson fluctuations.

We now discuss each of the four $Q=2$ candidates individually.

Q0805+047 ($z = 2.06$, $V = 18.5$): The quasar was discovered by Sramek & Weedman (1978). The primary quasar image has $R = 18.89$ ($\chi^2 = 1.10$ and sharpness 0.24). There is an $R = 19.61$ magnitude companion 4.2” away to the South. We estimate the relative likelihoods that this companion is a star, a lens, or another quasar to be 99%, 0.3% and 0.8% respectively. At the galactic coordinates of this quasar the stellar density at $R = 19.6$ is 4.4 times higher than in the direction normal to the galactic plane.

LBQS 1009-0252 ($z = 2.75$, $B_J = 17.62$): The quasar is also in the close pair/lens list because of a lensed companion 1.6” from the primary quasar (Surdej et al. 1994, Hewett et al. 1994). There is a second quasar with $m_R = 19.93$ and redshift 1.627 (the primary quasar pair has $z = 2.739$) 4.6” from the brighter quasar and at right angles to the separation of the close pair (see Figure 11). The relative likelihoods that this unassociated quasar is a star, a lens, or another quasar based simply on the magnitudes and separations are 96%, 1.2% and 2.9%. Given that the image is a quasar, the relative likelihoods of it being a lensed image, an associated quasar, or a unassociated quasar are 27%, 31%, and 41%. This estimate assumes that the lower redshift quasar is not associated with the lens.

Q0333+321 (NRAO 140, $z = 1.26$, $V = 17.5$): The quasar was discovered by Kristian & Sandage (1970). The primary quasar image has $R = 17.1$, $\chi^2 = 0.83$, and sharpness -0.21 . There is an $R = 18.74$ magnitude companion 5.3” away, almost due East. The relative likelihoods that the companion is a star, a lens, or another quasar are 99.4%, 0.3%, and

0.3%. The stellar density in this field is 4.2 times higher than in the direction normal to the galactic plane. A spectrum by A. Filippenko and T. Matheson obtained on 11 October 1994 with the 3m Lick telescope shows that the companion is a star.

Q0840+450 ($z = 2.73$, $V = 19.1$): The quasar was discovered by Weedman (1985). The primary quasar image has $R = 18.33$ ($\chi^2 = 0.93$ and sharpness -0.01). There is an $R = 18.57$ magnitude companion 6".0 away to the North-West. The relative likelihoods that this image is a star, a lens, or another quasar are 98.6%, 0.5%, and 0.8%. A spectrum with the FAST spectrograph on the Tillinghast telescope obtained on 24 February 1995 shows that the companion is a star.

5 MONTE CARLO MODELS

The most effective way to calibrate the survey is by Monte Carlo simulation. We make Monte Carlo simulations on four levels: (1) simulations of the individual observations to estimate the expected distributions of the daophot parameters given the real noise, FWHM, and PSF stars; (2) simulations of the known optical and radio lenses under our typical observing conditions to see under what conditions we can detect real lens geometries, combined with observations of the known lenses to compare to the simulations; (3) simulations of large samples of image pairs and quadruples under varying observational conditions to estimate a selection function; and (4) simulations of full statistical samples of lenses based on a theoretical model. In each case, we produce an artificial image and then reduce it using the same techniques applied to the real data. The Monte Carlo simulations focus on the statistical aspects rather than the systematic aspects of the analysis. We do not, for example, include cosmic rays, because the requirement that an "anomalous" image be reproducible in successive images screens out such a systematic error. All the artificial data were generated using the `artdata` package of IRAF with a $\beta = 2.5$ circular Moffat model PSF. Fits to the PSF of the 48" showed this Moffat profile is a reasonable match to the shape of the empirical PSF.

5.1 Statistical Properties of Point Sources

Even for point sources, both the χ^2 and the sharpness have a distribution about their nominal values of one and zero from statistical fluctuations in the images of the quasar and the PSF stars. We can use Monte Carlo simulations of the individual frames to estimate whether the properties of the quasar in the data are compatible with the expected statistical distributions. For each image we know the seeing FWHM, the sky/noise level, the magnitudes of the PSF stars, and the magnitude of the quasar. We use the same number of PSF stars in each Monte Carlo simulation as we used in analyzing each real image, and we give them the same magnitudes as in the observed image. Each simulated image is reduced in the same way as the observations. These simulations are a lower bound on the variance of the χ^2 and sharpness because they include only statistical fluctuations and are based on an idealized, linear CCD model. Our current standard model is to make one realization of the PSF stars and many realizations of the quasars. Experiments with multiple realizations of the PSF stars did not markedly broaden the distributions.

Figures 3 and 4 compared the distribution of observed and Monte Carlo values for the χ^2 and sharpness based on the simulations of each individual frame. The two distributions are very similar, although not identical. In particular, the simulations slightly underestimate the width of the sharpness distribution, probably because we use a fixed shape for the PSF rather than the real empirical PSF. We avoided doing the Monte Carlo simulations with the empirical PSF because then the simulations would start with a noisy model PSF from the data and then add additional noise. In future simulations we will try to fit a smooth function to the empirical PSF for each frame, and allow the PSF to be elliptical. The summed data of Figure 3 are adequate for a summary presentation, but the individual simulations of each frame are the more fundamental data. Figure 5 shows four randomly chosen quasars and their Monte Carlo models, Figures 6, 7, and 8 show the comparison for the best lens candidates, and Figure 16 shows the comparison for two known lenses.

Every image is reduced using at least two and preferably more stars to build the empirical PSF. Such a procedure gives an internal control for bad PSF stars from the requirement that a good set of PSF stars must build an empirical PSF that will give all the PSF stars $\chi^2 \leq 1$. The Monte Carlo simulations also give us an estimate for the expected χ^2 of the PSF stars. In general we find that we can match the data reasonably well for the 48" images, but for many of the MDM images we have trouble finding PSF stars that produce as low a χ^2 for the PSF stars as predicted from the Monte Carlo simulations. We also find that the χ^2 and sharpness values for the MDM images are much more likely to lie outside the Monte Carlo distributions because of the difficulty of finding good, unsaturated PSF stars. Nonetheless, there is broad numerical agreement between the Monte Carlo simulations and the observations on the properties of stellar images.

5.2 Detectability of Existing Lenses

Next we examine the detectability of objects that match the observed properties of lenses by simulating observations of seven optical and three radio lenses. The seven optical lenses (or close pairs if you wish to be conservative) are 2237+0305, 1208+101, 1413+117, 1115+080, 0142-100, 1009-025, and 0952-01 (see review by Angonin-Willaime et al. 1994) and the three radio lenses that contain systems of point images are 0218+357, MG0414+053, and 1422+231 (see review by Patnaik 1994). The brightest image in the radio lenses is arbitrarily assigned a magnitude of 18. We make Monte Carlo models of observations of the lenses under varying seeing conditions and fixed sky levels (at the 48" median sky of 220 ± 10 ADU per pixel), setting the instrumental magnitude to be the observed or assigned magnitude plus a random addition of 0 to 2 magnitudes in steps of 0.5 magnitudes. In our images, the median difference between instrumental and true magnitudes is 1 mag, and 90% of the images have shifts between 0.3 and 1.8 magnitudes. We studied the detectability for seeing FWHM of 1".2, 1".7, 2".2 and 2".7, and four Monte Carlo realizations were made for each FWHM. Each Monte Carlo frame contained approximately 500 images generated by randomly selecting from the ten systems, shifting the magnitude, shifting the images by a random fraction of a pixel in position, and randomly orienting them. The frame is then analyzed in the same way as the data. We obtain an average of 37 realizations for each lens at each magnitude and FWHM.

The large separation (about $2''.0$) quad lenses Q2237+0305, PG1115+080, and MG0414+053 are almost impossible to miss. Only for MG0414+053 in $2''.7$ seeing with a total instrumental magnitude of 19.1 (a 2 magnitude shift) are any large numbers of lenses missed. There is an interesting trend that, as the seeing or signal-to-noise ratio declines, a larger fraction of the lenses are flagged as galaxies instead of being split into multiple images. The two smaller-separation quads (about $1''.3$) 1413+117 and 1422+231 are also found under all but the worst conditions ($2''.7$ seeing and $\Delta m = 2$ mags), but with a larger fraction flagged as galaxies instead of being split into multiple images. In the worst-case conditions, we find 96%, 100%, 34%, 30% and 81% of the realizations of 2237+0305, PG1115+080, MG0414+053, 1413+117, and 1422+231 respectively. MG0414+053 is difficult to find in poor seeing and low fluxes despite its large separation, because most of the flux is in a close bright pair of images and we assigned it a fainter optical magnitude.

The largest-separation pair is Q0142-100 ($\Delta x = 2''.2$) and it is easily found except for the worst case conditions. The next largest pair is LBQS 1009-025 ($\Delta x = 1''.6$) where we can find the lens when Δm is smaller than 2, 2, 1.5, 0.5 mags for seeing of $1''.2$, $1''.7$, $2''.2$ and $2''.7$. Next is 0952-01 ($\Delta x = 1''.0$) which is also much fainter than the rest of the lenses and fainter than the selection criterion for our survey. In $1''.2$ FWHM seeing, we find this lens even for $\Delta m = 2$, but the limit on the instrumental magnitude drops rapidly as the seeing worsens to 1 mag in $1''.7$ FWHM seeing and 0.5 mag in $2''.2$ seeing. The lens is essentially undetectable under poorer seeing conditions. In good seeing 0952-01 is easier to detect than LBQS 1009-025, because the two images have a smaller flux ratio (0.3 mag instead of 2.4 mag). The smallest optically detected lens is 1208+101 ($\Delta x = 0''.48$); we can detect this pair in $1''.2$ FWHM seeing if $\Delta m < 2$ and in $1''.7$ seeing if $\Delta m < 0.5$. The smallest known lens is 0218+357 ($\Delta x = 0''.34$); we could not find it even under our best conditions (for a FWHM of $1''.2$ and giving the bright image an instrumental magnitude of 18, we split the lens in 30% of the realizations and it has $\chi^2 > 1.15$ in another 13% of the realizations).

We can summarize these simulations by the fraction of known lenses we could detect as a function of the observational properties. Of the seven known optical lenses, the number we would find in $1''.2$ FWHM seeing with $\Delta m = 0, 0.5, 1.0, 1.5$, and 2.0 mags is 7, 7, 7, 6.9, and 6.2; in $1''.7$ seeing we would find 6.9, 6.4, 6.2, 6.2, and 4.3; in $2''.2$ seeing we would find 6.1, 5.7, 5.7, 5.1, and 3.8; and in $2''.7$ seeing we would find 5.0, 4.5, 4.1, 3.6, and 2.3 lenses. Our nominal seeing conditions of $1''.9$ with $\Delta m = 1.0$ allow us to find 6 of the 7 known optical lenses, with 1208+101 being missed.

As the program proceeds, we image the existing optical lenses to study their properties using the real selection biases and systematic effects of the telescope and camera. So far, we obtained images of PG1115+080, H1413+117, and LBQS 1009-025 (see §3).

PG1115+080: We observed the known lens PG1115+080 (Weymann et al. 1980) with 15 minute and 8 minute observations in the R and V bands in $2''.0$ and $1''.9$ FWHM seeing. The lens was easily detected with $\chi^2 = 4.75$ and 4.00 . The sharpnesses were 1.77 and 1.98. Figure 16 shows the expected distributions of stars and PG1115+080 and the measured values. On the second pass of daophot the quasar is split into three images. The bright, close image pair is not split into its component images, but it is flagged as a “galaxy” with $\chi^2 = 1.29$ and

FIG. 16.—A scatter plot of the χ^2 and sharpness from the Monte Carlo simulations of the images of the known lenses PG1115+080 and H1413+117. The horizontal and vertical lines show the measured values for the image. The squares show the simulations of stellar objects, and the crosses show simulations with the known lens properties.

sharpness 0.64. The Monte Carlo simulations of PG1115+080 shown in Figure 16 include the four images of the quasar but not the lens galaxy, so they underestimate the true χ^2 and sharpness of the system. This explains why the χ^2 and sharpness of the data is greater than that of the Monte Carlo simulations in Figure 16.

H1413+117: We observed the known lens H1413+117 (Magain et al. 1988) with a 10 minute V image in 2"4 FWHM seeing. The quasar had a $\chi^2 = 1.08$ and a sharpness of 1.82. The observation was made under deteriorating weather conditions and with significant cloud cover, which significantly reduced the flux in the image over what would be obtained in better conditions. With our standard χ^2 criteria, we would not find H1413+117 under these conditions. Note, however, that the sharpness of the image lies well outside the distribution for the Monte Carlo simulations and all the other quasar images that are not known lenses or our best lens candidates (see Figure 3). Thus, our added criterion of examining images with sharpnesses greater than 1 means we would consider H1413+117 as a candidate despite the appallingly poor image.

In Monte Carlo simulations, the median χ^2 of H1413+117 under these conditions is 1.10 with 90% of the realizations between 0.98 and 1.22. With our $\chi^2 > 1.15$ selection criterion we would consider H1413+117 a candidate only 21% of the time. The median sharpness is 1.51 with 90% between 0.77 and 2.25. With our sharpness greater than 1 selection criterion, we would consider it a candidate 89% of the time. The observed χ^2 and sharpness lie near the center of the distribution of Monte Carlo realizations. For comparison, stars of the same magnitude under the same observing conditions have a median χ^2 of 0.98 with 90% of the realizations between 0.89 and 1.05, and a median sharpness of -0.02 with 90% between -0.65 and 0.62 . As shown in Figure 16, the properties of the lens are clearly different from the properties of stars.

5.3 The Selection Function

For the theoretical interpretation of the survey, it is more useful to have an expression for the detectability of image pairs as a function of image separation and magnitude. For the moment we will develop a simplified selection function to let us make approximate theoretical comparisons and to quantify what the detection thresholds for the χ^2 mean for lensed image separations and flux ratios. When we do a true theoretical analysis of our survey we will construct a more elaborate selection function.

We build the selection function by Monte Carlo studies of image pairs. Our standard synthetic frame consists of 500 images with 22 PSF stars spread randomly from 15.5 to 17 magnitudes and 462 trial objects. The trial objects all have the same total magnitude, but 25% are single stars and 75% are star pairs with separations $\Delta\theta$ and magnitude differences Δm distributed uniformly over $0''.0 < \Delta\theta < 4''.0$ and $0 < \Delta m < 5$ magnitudes for the 48" telescope and over $0''.0 < \Delta\theta < 3''.0$ and $0 < \Delta m < 6$ for the MDM telescope. The artificial data are analyzed in exactly the same way as the real data. Four PSF stars are selected from the known PSF stars added to the frame, using stars with magnitudes comparable to those used in the real observations. These experiments do not examine the use of bad PSF stars

in the data reduction process. At no point during the data reduction is any information included about which of the 462 trial objects are stars and which are pairs. Only after the full analysis is completed is the resulting daophot catalog and the residual map compared to the input data. We track the correct and incorrect identification of stars and pairs to monitor both our ability to detect real image pairs and the false positive rate.

For these simulations we define “detection” of a pair as (1) having $\chi^2 > 1.15$, or (2) being flagged as a “galaxy”, or (3) splitting the image into multiple components. Each of these three conditions will mean that the quasar will be followed up with additional observations. In the current version of the selection function we do not include selection based on the sharpness of the image. We know from both the data and the Monte Carlo studies that about 2.3% of point sources will also exceed the threshold of $\chi^2 > 1.15$. Since the theoretical expectation for the number of lenses in the survey is about 1% of the survey quasars, we explicitly accept a false positive rate in the selection of candidates for follow up studies of about two to three false positives per lens. For each frame we divide the sample into the detected and undetected subsamples and use the two-dimensional Kolmogorov-Smirnov (KS) test to fit a top-hat selection function to each simulation (see Figure 17). The top-hat selection function has a limiting magnitude m_{lim} and a minimum resolvable separation $\Delta\theta$.

For the 48” observations we ran a complete set of simulations for seeing FWHM of 1”2, 1”7, 2”2, 2”7, and 3”0 and instrumental magnitudes of 17, 18, 19, 20, and seeing FWHM of 1”2 and 1”7 at an instrumental magnitude of 21, all at the median background noise level of 220 ± 10.4 ADU per pixel. These values cover the full range of FWHM and quasar magnitudes. We also ran simulations for 17, 18, 19, and 20 mag objects at a fixed FWHM of 2”2 and background levels of 100 ± 7.5 and 400 ± 13.4 ADU per pixel. Each case was run twice with different PSF stars. The result is a suite of 60 simulations containing approximately 7400 trial stars and 22000 trial image pairs covering the range of magnitudes, backgrounds and resolutions of the real observations. For the MDM observations we computed nine similar simulations for FWHM of 0”7, 1”0 and 1”3, quasar instrumental magnitudes of 16, 17, and 18, and a background of 800 ± 15.4 ADU per pixel, and six simulations for FWHM of 0”7, 1”0, and 1”3, a quasar magnitude of 17 and background levels of 500 ± 12 and 1000 ± 17 ADU per pixel. Each case was run twice with different PSF stars. We obtain a total of 30 simulations containing 3700 trial stars and 11000 trial image pairs.

For large-separation lenses, we need to know the limiting magnitude for detecting an isolated point source. If the PSF is many pixels in area, then a simple analysis of the χ^2 residuals as a function of the flux of the star near the detection threshold shows that the limiting flux of a detectable object increases linearly with the noise and the FWHM of the PSF, if the area being fit is large compared to the FWHM of the PSF. These properties are borne out by the Monte Carlo simulations. We fit a limiting instrumental magnitude for well-separated stars to the limiting magnitude derived from the two-dimensional K-S test analysis of each image using

$$m_{lim} = m_{lim0} - 2.5 \log \left(\frac{\text{FWHM}}{1"0} \frac{N}{10} \right) \quad (3)$$

where N is the noise in ADU per pixel and m_{lim0} is a fitting parameter. The value

of m_{lim0} depends on the arbitrary value of the magnitude zero point used by daophot, and for various historical reasons the zero point was chosen to be 29.7 mags, because that roughly converted instrumental to observed magnitudes in some of the early observations. The discussion of detection thresholds must be referenced to the instrumental magnitudes because they contain all of the information on the actual numbers of counts in each image. For the 48" we find $m_{lim0} = 21.94 \pm 0.06$, and for the MDM we find $m_{lim0} = 21.75 \pm 0.04$ from the Monte Carlo simulations.

We compare these estimates to the real data by fitting the zero point with the same dependence on the noise and seeing as in the real data to the fifth from faintest object on the individual frames. Fitting the fifth faintest star in the 48" images we find $m_5 = 21.81 \pm 0.06$ (21.88 ± 0.04) mags with (without) outlying points, and fitting the fifth faintest star in the MDM images we find $m_5 = 21.8 \pm 0.1$ mags. We attempted to estimate the limiting magnitude from the star/galaxy counts on each frame, but for most frames there were too few objects to use this technique. The limits estimated from the fifth faintest star are slightly brighter than the limits from the Monte Carlo estimates.

As the two images of a pair begin to merge, the detection threshold for the fainter image rises. The simplest model for this behavior is a "top hat" selection function in which images at separations larger than some minimum separation are detected up to the detection threshold for isolated objects, and smaller-separation images are missed. Such a selection function will exaggerate the magnitude limit for separations just above the cutoff, and underestimate it just below the cutoff. The minimum detectable separation is a function of both the FWHM of the observations and the signal to noise ratio of the image. We find that a good estimate for the minimum separation is

$$\Delta\theta_{min} = FWHM [a_0 + a_1(m - m_{lim})] \quad (4)$$

where a_0 and a_1 are fitting parameters. If we ignore the magnitude dependence (set $a_1 = 0$) the best fit values for a_0 are 0.47 ± 0.04 for the 48" and 0.36 ± 0.03 for the MDM images. When we also fit the value of a_1 we find that $a_0 = 0.72 \pm 0.07$ and $a_1 = 0.10 \pm 0.03$ for the 48" and that $a_0 = 0.61 \pm 0.13$ and $a_1 = 0.06 \pm 0.03$ for the MDM images.

When the seeing is poor compared to the image separations, daophot may not treat unresolved, high-symmetry quads such as 1413+117 like a hierarchy of image pairs, if we use the previous selection function. Therefore we also examined our ability to recognize symmetric, cruciform images. Other four-image systems such as PG1115+080 closely resemble a hierarchy of image pairs because of the segregation of the image fluxes. Because symmetric, roughly equal-flux, four-image systems may have no sensible decomposition into pairs, we examine their detectability separately. Figure 18 shows a Monte Carlo simulation of cruciform quads with varying sizes and total magnitudes. Superimposed on the diagram is the selection function deduced from the detectability of image pairs. The magnitude limit for large separations is set by the limit for detecting an individual image in the lens, each of which is 1.5 mag fainter than the total for all four images. The figure shows that the pair-wise selection function is a good model for the detectability of even the least "pair-like" quad systems.

FIG. 17.—Monte Carlo simulations of pairs observed on the 48" with FWHM $1''.6$ and sky 245 ± 10 ADU/pixel, matching the conditions of the observation of LBQS 1009-0252. In Panel (a) the squares are undetected pairs and the crosses are detected pairs. The heavy and light solid lines show the top hat selection function derived by fitting the detected or undetected pairs respectively. The real pair in LBQS 1009-0252 has a separation of $1''.6$ and a magnitude difference of 2.3 mags. Panel (b) shows contours of the probability from the two-dimensional Kolmogorov-Smirnov test used to determine the limiting magnitudes and separations of the observations. The peak probability is marked by the cross, and the three contours are at 50%, 25%, and 12.5% of the peak probability. The heavy and solid lines again show the fit to either the detected or undetected pairs.

FIG. 18.—Monte Carlo simulation of symmetric, cruciform quad lenses observed on the 48" in FWHM $= 2''.2$ seeing with a background of 220 ± 10.4 ADU/pixel. The squares are undetected quads and the crosses are detected quads. The horizontal line at the top is the estimated limit on the total magnitude such that all four images are above the limiting magnitude of the observation, and the angled line is the minimum separation as a function of total magnitude from the top hat model of the selection function.

5.4 Completeness for the Isothermal Model

The final Monte Carlo study examines the detectability of lenses generated by the standard statistical model detailed in Kochanek (1991) using a Schechter (1976) function distribution of E/S0 galaxies $dn/dL = n_*(L/L_*)^{-1} \exp(-L/L_*)$ with a comoving density of $0.005h^3 \text{ Mpc}^{-3}$ galaxies (Efsthathiou et al. 1988, Postman & Geller 1984), a Faber-Jackson (1976) relation with $L/L_* = (\sigma/\sigma_*)^4$, and the apparent magnitude quasar number counts model from Maoz & Rix (1993). The lenses are modeled as singular isothermal spheres in a $\gamma = 0.2$ external shear field. Statistical fits to the lens sample (Kochanek 1993b) and dynamical analyses (Kochanek 1994b) suggest that $\sigma_* \simeq 220 - 240 \text{ km s}^{-1}$. The lens size and morphology are independent of the source redshift in this model. A catalog of 1000 two-image and 1000 four-image lenses at each of 16.0, 16.5, 17.0, 17.5, 18.0, 18.5, 19.0, and 19.5 magnitudes is generated from the model.

We then generated four realizations, each containing 426 lenses, of samples with $\sigma_* = 160 \text{ km s}^{-1}$, 200 km s^{-1} and 240 km s^{-1} in 1".2, 1".7, 2".2 and 2".7 FWHM seeing and with a background of $220 \pm 10 \text{ ADU}$ per pixel. Each lens was randomly selected from the overall catalog and given a correction of 0.5, 1.0 or 1.5 magnitudes (randomly selected) for the difference between the actual quasar magnitude and the instrumental magnitude. Nominally we obtain 70 objects per combination of quasar magnitude and instrumental magnitude correction. In practice, we find that simply presenting completeness (the fraction of objects that pass the criteria $\chi^2 > 1.15$, or being split, or being flagged as a galaxy) as a function of instrumental magnitude gives a good representation of the results. There was also no significant difference in the completeness for two-image and four-image lenses, so we present only the joint results.

The completeness as a function of daophot magnitude is shown in Figure 19. The median daophot magnitude of the quasars is 18.7, with 90% between 17.1 and 19.7. The completeness at the median quasar (instrumental) magnitude of 18.7 is between 35% and 77% for $\sigma_* = 240 \text{ km s}^{-1}$, between 25% and 73% for $\sigma_* = 200 \text{ km s}^{-1}$, and between 10% and 62% for $\sigma_* = 160 \text{ km s}^{-1}$, depending on the seeing. For the median seeing of approximately 1".9, the survey completeness will be approximately 60%, 50%, and 40% for $\sigma_* = 240 \text{ km s}^{-1}$, 200 km s^{-1} , and 160 km s^{-1} . Most two-image systems are explicitly split, while about half of the four-image systems are flagged as galaxies, as expected from the earlier simulations of the known lens geometries. For comparison, Kochanek (1991) estimates that the completenesses of the ESO/Liège Survey at the equivalent magnitude are 85%, 70%, and 50%, and of the Snapshot Survey are about 90%, 90%, and 85% for $\sigma_* = 240 \text{ km s}^{-1}$, $\sigma_* = 200 \text{ km s}^{-1}$, and $\sigma_* = 160 \text{ km s}^{-1}$ respectively.

Figure 20 shows the expected number of lenses as a function of the cosmological model and the velocity dispersion scale σ_* for E/S0 galaxies, using circular isothermal lenses and our top hat model for the pair-wise selection function for each quasar. For comparison, we show the expected number of lenses using the Snapshot Survey selection function. The best-fit value for σ_* from dynamics is $220 \pm 20 \text{ km s}^{-1}$ and the best-fit value from fitting the other lens surveys is $240 \pm 20 \text{ km s}^{-1}$. Under these assumptions, we would expect to find between 0.8 and 2.5 lenses in the current sample for normal cosmological models with

FIG. 19.—Completeness for a statistical sample selected from the standard isothermal model in a dimensionless shear of $\gamma = 0.2$, with velocity dispersion scales of $\sigma_* = 160, 200 \text{ km s}^{-1}$ and $\sigma_* = 240 \text{ km s}^{-1}$ as a function of the daophot magnitude of the quasar. The results are shown for seeing FWHM of $1''.2, 1''.7, 2''.2$ and $2''.7$ and a fixed background of $220 \pm 10 \text{ ADU}$ per pixel.

FIG. 20.—The expected number of lenses in the survey for normal cosmologies (Panel (a)) and flat cosmologies with a cosmological constant Λ (Panel (b)) as a function of the matter density Ω and the velocity dispersion σ_* of an L_* elliptical galaxy. The contours are spaced every 0.5. The solid lines include the model selection function for the survey, and the dashed lines show the expected number given the selection function of the Snapshot Survey. Smaller numbers of lenses are produced to the bottom and right in the figures, and the lowest contour in each panel is labeled with its value, 0.5.

$0 \leq \Omega \leq 1$ and $220 \text{ km s}^{-1} \lesssim \sigma_* \lesssim 240 \text{ km s}^{-1}$. We know that the sample contains one lens (LBQS 1009-0252) and there are two more very good candidates (Q0010+023, Q0011-002). If we expect one lens, the Poisson likelihoods of finding 0, 1, 2, 3, or 4 lenses are 37%, 37%, 18%, 6%, and 1.5% respectively. The estimated completeness of the survey compared to the Snapshot Survey examining the same sample of quasars is approximately 60%.

6 CONCLUSIONS AND FUTURE PLANS

The goal of the FKS survey is primarily a systematic selection of good lens candidates from a large sample of quasars. In this paper we present an ordered list of 3 candidates found in the first sample of 121 quasars. The best candidates on the list lie so far outside the expected distribution of point sources that there must be something peculiar about the images. As far as we can tell there is no problem with the PSF for these images, and no other stellar images of comparable magnitude on the same frame show comparable distortions. The weaker candidates in the list overlap the tail of the expected distributions of real stellar images. Most, if not all, of the weaker candidates are unlensed. This survey should not be used for statistical purposes using the estimated selection function from §5 until all candidates with $\chi^2 > 1.15$ are identified.

The most important difference between our survey and earlier optical surveys is the combination of deriving and fitting empirical PSFs with Monte Carlo simulations of what to

expect from the fitting procedure. We are thus able to systematically present the evidence for the individual candidates and to quantify the reliability of the measurements. The Monte Carlo simulations use a simplified, linear CCD model, a fixed, analytic, circular $\beta = 2.5$ Moffat profile PSF, and exclude systematic errors like cosmic rays and chip defects. Nonetheless, the simulations reproduce the statistical properties of stellar images and our observations of the known lenses very well.

The PSF subtraction and Monte Carlo analysis procedures do not significantly lengthen the analysis process, but they greatly enhance the effectiveness and reliability of the survey. Because we are using a smaller telescope in (typically) 1".9 FWHM seeing, we need PSF subtraction to achieve reasonable levels of completeness in the survey. The Monte Carlo simulations are required to understand the significance of the residuals from the PSF subtraction and to derive the selection function of the survey. We have tried to supply all of the information needed to reproduce our selection function in an independent analysis. One of the primary problems with all earlier optical surveys is that they do not include the necessary information to independently analyze their selection effects.

The three candidates are Q0010+023, Q0011-002, and Q0456+025 in decreasing order of their strength as candidates. Spectra of Q0010+023 and Q0011-002 showed that they are low redshift galaxies and were falsely identified as quasars. Both objects were from the same quasar survey, and examinations of other quasars from that survey have lead us to discard them from inclusion in our lens survey. There is a persistent pattern of low accuracy for the positions and large magnitude differences between the tabulated and apparent magnitudes of plausible identifications in our fields. On the positive side, we correctly identified these two objects as non-stellar. We expect some statistical false positives given our selection function, and it is likely that Q0456+025 is such a false positive. We also rediscovered the lens LBQS 1009-0252 (Surdej et al. 1994, Hewett et al. 1994). We found one definite false positive in Q0847+100. Our analysis split the quasar into a 1"1 separation double with a magnitude difference of 2.1 magnitudes, but a radio snapshot at the VLA (Perley 1994) shows a single point source in an image with a FWHM of 0".24 and a dynamic range of 450:1. We will examine Q0847+100 again to determine if there is a real optical pair because of its implications for the reliability of the PSF subtraction procedures. For each of the candidates we present the images of the quasar, the residuals after subtracting the PSF, Monte Carlo simulations of the observations, and comparisons to stars of similar magnitude.

In an $\Omega_0 = 1$ cosmological model we expect to find between 0.8 and 1.5 lenses in our sample, while in an $\Omega_0 = 0.2$ cosmological model we expect to find between 1.6 and 2.5 lenses. Flat models with a cosmological constant predict 1.5 to 2.5 lenses if $\Lambda_0 = 0.5$ (comparable to $\Omega_0 = 0.2$) while they predict 2.5 to 4.5 lenses if $\Lambda = 0.75$. The cosmological models have somewhat overlapping predictions because of the uncertainties in the dynamical normalization for the lens galaxies. Obviously the sample is too small to draw any cosmological conclusions, except that large values for the cosmological constant are ruled out even in very small lens surveys.

Our philosophy is to release the short candidate lists and to encourage any interested observers to examine them. The quasar images (as FITS files), and finding charts are

available for interested researchers with no proprietary restrictions. We will conduct follow-up observations as they become feasible, but the final identification of lens candidates is so dependent on ideal observational conditions that the delays could be unacceptable. We have reduced a sample of 120 objects containing 1 to 4 lenses down to a subsample of four objects containing 0.5 to 2.5 lenses using quantifiable and reproducible techniques. This is the essential and difficult part of a lens survey.

We keep track of all objects found within $12''$ of the quasar. We found five objects within $6''$ of the quasars and 22 objects within $12''$ of the quasar. The number, spatial distribution and magnitude distribution of the companions is statistically consistent with the expected distributions of stars and galaxies. We intend to individually identify the objects as the survey proceeds. The database of stars and galaxies derived from the images is a powerful means of estimating the completeness of the survey, the significance of companions near the quasar, and the success of the PSF subtraction procedures.

We have acquired about twice as much data as have been presented in this paper, and we are continuing the acquisition of images in sequences of several dark nights each observing trimester. Several minor problems in the $48''$ telescope have been corrected, so the resolution of the images should improve somewhat in newer observations. As the observations begin to overlap earlier right ascension ranges we will observe new quasars or old quasars depending on which will improve the lensing constraints most, given the current atmospheric conditions. We gain more by reobserving a bright or high-redshift quasar in better seeing than by adding a new faint or relatively low-redshift quasar to the sample. The data reduction will be done in the standard manner described in §3 combined with a steady expansion of the data base of Monte Carlo simulations to validate the observational results. The latter will become more important as the size of our sample grows toward its design goal.

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Table 1: Input Catalog

Name	α			δ			z	V	disc.	ℓ^{II}	b^{II}
LBQS 0009+0219	0	9	45.76	2	19	53.9	2.6416	17.99	O	103.8140	-58.8027
HB89 0009+027	0	9	8.50	2	43	47.0	3.1700	16.00	O	103.7528	-58.3767
HB89 0010+023	0	10	39.70	2	19	34.0	2.2700	15.50	O	104.2264	-58.8729
HB89 0011-002	0	11	25.20	-0	13	21.0	3.1000	17.50	O	103.0851	-61.3646
HB89 0011+016	0	11	39.60	1	41	2.0	3.2200	17.50	O	104.3357	-59.5596
HB89 0131+055	1	31	8.08	5	32	32.2	1.8470	18.25	C	141.7486	-55.5203
HB89 0206+293	2	6	14.97	29	18	34.7	2.1950	19.00	R	142.5232	-30.3526
HB89 0240-021	2	40	36.70	-2	10	29.0	1.9000	19.00	O	174.4446	-53.2734
CLB91 0244-0044	2	43	30.30	-0	44	47.0	1.5960	18.82	O	173.6824	-51.7411
HB89 0243-007	2	43	59.10	-0	44	47.0	2.1470	19.16	C	173.8229	-51.6586
HB89 0252+016	2	52	40.09	1	36	21.2	2.4646	17.85	C	173.7559	-48.4582
HB89 0258+058	2	58	54.10	5	50	14.0	2.3130	19.00	R	171.2641	-44.2902
HB89 0259+015	2	59	27.60	1	34	32.0	1.7340	18.50	C	175.6026	-47.2972
HB89 0303+011	3	3	37.89	1	10	23.1	1.3347	17.40	C	177.0976	-46.8367
HB89 0307+172	3	7	28.90	17	16	37.0	2.2800	19.20	O	163.9445	-34.1231
LBQS 0308+0129	3	8	50.74	1	29	43.2	2.3346	18.49	O	178.0610	-45.6712
HB89 0313+344	3	13	46.22	34	26	19.5	1.1560	18.50	R	154.0665	-19.3092
PKS 0319+12	3	19	8.21	12	10	31.5	2.6700	18.00	R	170.5908	-36.2375
HB89 0326+277	3	26	56.10	27	46	0.0	1.5330	17.50	R	160.7030	-23.0743
HB89 0333+321	3	33	22.40	32	8	36.6	1.2580	17.50	R	158.9997	-18.7650
HB89 0456+025	4	56	22.30	2	31	15.0	1.4300	17.50	O	196.7937	-23.4723
HB89 0640+448	6	40	18.20	44	53	39.0	1.8050	18.20	O	170.9290	17.5146
HB89 0640+449	6	40	43.10	44	54	24.0	2.1230	18.30	O	170.9450	17.5875
HB89 0645+349	6	45	39.70	34	55	46.0	1.3600	18.00	R	180.9206	14.6488
MRK 0380	7	13	29.40	74	33	27.0	2.7370	17.00	C	140.4413	27.9564
HB89 0736-063	7	36	30.20	-6	20	2.9	1.9140	18.50	R	224.1712	7.5168
HB89 0746+483	7	46	39.94	48	22	30.4	1.9510	18.50	R	170.5952	29.3950
HB89 0755+147	7	55	32.60	14	45	29.0	2.3900	18.50	R	206.9160	21.2855
HB89 0801+303	8	1	34.90	30	21	10.9	1.4460	18.50	R	191.3822	28.1086
HB89 0802+103	8	2	3.76	10	23	56.3	1.9560	18.40	R	211.8724	20.9013
HB89 0804+499	8	4	58.39	49	59	23.1	1.4300	17.50	R	169.1640	32.5647
HB89 0805+046	8	5	19.17	4	41	20.5	2.8770	18.16	R	217.6948	19.0785
HB89 0805+047	8	5	29.00	4	45	31.0	2.0600	18.50	O	217.6493	19.1468
HB89 0814+578	8	14	16.00	57	52	54.0	2.4000	18.90	C	159.7620	34.1498
HB89 0820+560	8	20	53.20	56	2	27.5	1.4170	18.00	R	161.9581	35.1177
HB89 0821+394	8	21	37.31	39	26	28.3	1.2160	18.50	R	182.1417	34.1922
HB89 0833+585	8	33	23.75	58	35	30.3	2.1010	18.00	R	158.6609	36.6059
HB89 0833+654	8	33	18.02	65	24	4.4	1.1120	18.21	R	150.3441	35.5121
HB89 0834+250	8	34	42.34	25	4	54.2	1.1220	18.00	R	199.7583	33.5693
HB89 0835+580	8	35	10.02	58	4	51.8	1.5340	17.62	R	159.2600	36.8964

Table 1 (continued): Input Catalog

Name	α			δ			z	V	disc.	ℓ^{II}	b^{II}
HB89 0836+443	8	36	11.30	44	18	48.0	1.4730	17.60	C	176.5491	37.4365
HB89 0836+710	8	36	21.53	71	4	22.5	2.1700	16.50	R	143.5408	34.4257
HB89 0839+186	8	39	58.38	18	41	6.4	2.0520	18.40	C	207.4484	32.6113
HB89 0839+444	8	39	59.00	44	24	48.0	2.2200	18.50	O	176.4711	38.1194
HB89 0840+450	8	40	24.70	45	3	36.0	2.7300	19.10	O	175.6538	38.2245
HB89 0840+501	8	40	0.03	50	10	0.3	2.8000	19.40	C	169.1533	38.1838
CSO 0203	8	42	30.50	34	31	54.0	2.1260	17.00	C	188.9755	37.4797
HB89 0847+100	8	47	7.50	10	1	49.0	2.8000	18.50	R	217.5867	30.7349
HB89 0850+140	8	50	22.79	14	3	58.3	1.1100	17.42	R	213.6671	33.1565
HB89 0855+188	8	55	40.17	18	48	48.4	1.0130	17.30	C	208.9092	36.1285
HB89 0856+170	8	56	4.09	17	3	9.1	1.4490	17.40	C	210.9762	35.5779
HB89 0901+285	9	1	30.64	28	31	30.8	1.1210	17.60	R	197.5762	40.2455
HB89 0903+167	9	3	52.60	16	46	15.0	2.4000	18.20	O	212.1675	37.2052
HB89 0906+015	9	6	35.18	1	33	48.2	1.0180	17.79	R	228.9446	30.9247
HB89 0913-025	9	13	48.50	-2	32	2.0	1.2030	18.05	R	234.0831	30.2329
CBS 101	9	21	39.40	35	23	30.0	1.3583	18.00	C	189.2242	45.5411
HB89 0922+005	9	22	33.72	0	32	12.4	1.7200	18.07	R	232.4946	33.7546
HB89 0927+217	9	27	53.07	21	42	31.7	2.0000	19.40	C	208.5861	44.2142
HB89 0936+368	9	36	32.30	36	53	48.0	2.0300	17.00	O	187.2397	48.6175
HB89 0943+329	9	43	42.00	32	54	0.0	1.3000	17.00	O	193.4696	49.8835
HB89 0945+114	9	45	4.76	11	27	51.0	1.7600	18.00	R	223.9975	44.1156
HB89 0950+080	9	50	12.20	8	4	47.7	1.4500	17.69	X	228.9537	43.5894
HB89 0952+179	9	52	11.81	17	57	44.7	1.4720	17.23	R	216.4551	48.3636
CSO 0239	9	52	40.90	33	49	30.0	2.5000	17.00	C	192.1963	51.8140
MRK 0132	9	58	8.30	55	9	7.0	1.7510	16.00	C	158.9035	48.6252
CBS 125	10	4	38.80	36	53	42.0	1.0342	16.00	C	187.0656	54.2349
HB89 1004+141	10	4	59.79	14	11	11.0	2.7070	19.00	R	223.6088	49.6749
LBQS 1009-0252	10	9	43.58	-2	52	11.6	2.7455	17.62	O	244.8606	41.1486
HB89 1009+334	10	9	17.70	33	24	17.0	2.2600	17.50	R	193.0788	55.2583
LBQS 1011-0144	10	11	41.30	-1	44	23.2	2.2360	17.91	O	244.1423	42.2576
HB89 1015+416	10	16	3.60	41	22	5.0	2.0290	18.10	C	178.8151	55.8426
CSO 0261	10	16	53.60	35	56	54.0	2.6700	17.00	C	188.4567	56.7538
HB89 1017+109	10	17	30.85	10	55	8.1	3.1560	18.40	O	230.3681	50.8337
HB89 1019+309	10	19	39.86	30	56	14.9	1.3160	17.47	R	197.6723	57.3597
HB89 1022-102	10	22	27.50	-10	16	30.0	2.0000	17.00	R	254.6234	38.2369
HB89 1033+137	10	33	47.30	13	42	26.0	3.0700	18.00	R	229.6009	55.6670
HB89 1038+311	10	38	31.20	31	10	54.0	1.4500	17.00	O	197.4816	61.4037
CC91 1042+0547	10	41	33.60	5	47	20.0	2.0920	17.95	O	242.6821	52.8094
HB89 1042+349	10	42	49.87	34	56	59.0	2.3470	18.50	R	189.4240	62.1063

Table 1 (continued): Input Catalog

Name	α			δ			z	V	disc.	ℓ^{II}	b^{II}
HB89 1054-034	10	54	10.35	-3	24	38.7	2.1150	18.00	O	256.5460	48.5847
YDG81 1115+080	11	15	41.50	8	2	24.0	1.7180	16.99	C	249.8876	60.6448
HB89 1129+315	11	29	51.20	31	33	10.0	1.1450	18.20	C	194.6702	72.3086
HB89 1147+339	11	47	43.70	33	58	25.0	1.4900	18.50	R	182.6965	75.3005
HB89 1151+105	11	51	49.47	10	35	20.3	2.9440	19.50	O	261.5931	68.4734
HB89 1151+489	11	51	6.50	48	55	24.0	2.0300	18.00	C	146.5665	65.7492
HB89 1158+122	11	58	22.21	12	14	0.4	2.0180	17.60	R	262.4958	70.7490
HB89 1206+119	12	6	44.63	11	55	10.6	3.1060	17.90	O	268.3224	71.6222
HB89 1209+154	12	9	59.19	15	24	6.3	3.0595	18.27	O	263.9696	74.9683
SBS 1220+567	12	20	5.20	56	43	2.0	1.4000	18.50	O	130.9944	60.2328
UM 497	12	22	44.90	2	23	33.0	2.0500	17.00	O	287.7799	64.2159
HB89 1225+086	12	25	46.25	8	36	50.8	1.4707	17.83	O	285.6238	70.4284
HB89 1226+105	12	26	4.61	10	35	16.4	2.3041	18.50	R	284.1176	72.3444
CSO 0151	12	31	26.90	29	24	24.0	2.0110	16.00	C	184.4985	85.6503
HB89 1235+089	12	35	22.73	8	57	34.2	2.8982	18.17	O	292.4656	71.2811
HB89 1237+151	12	37	39.08	15	8	10.6	2.0642	18.56	O	290.2912	77.4561
HB89 1239+099	12	39	4.17	9	55	57.0	2.0132	18.38	O	294.8985	72.3765
LBQS 1240+1607	12	40	33.35	16	7	13.6	2.3596	18.84	O	292.7294	78.5521
UM 516	12	42	50.82	0	6	44.5	2.0749	17.72	O	299.6478	62.6724
HB89 1244+097	12	44	26.77	9	47	7.2	2.3400	18.30	O	299.2970	72.3527
HB89 1244+170	12	44	6.08	17	3	18.0	1.5879	17.47	O	296.5049	79.5933
HB89 1245+345	12	45	3.20	34	31	31.5	2.0680	17.94	C	129.5218	82.8247
LBQS 1246-0059	12	46	6.02	-0	59	15.7	2.4421	17.87	O	301.4758	61.6037
UM 524	12	52	21.30	1	16	23.0	2.3800	18.00	O	304.9037	63.8607
UM 531	12	55	44.20	0	23	24.0	2.0800	18.00	O	306.7043	62.9417
HB89 1306+274	13	6	33.09	27	24	10.1	1.5370	18.50	R	34.0513	86.1046
CSO 0832	13	7	38.83	29	39	4.0	2.9500	16.60	C	62.8923	85.3269
HB89 1308+382	13	8	16.63	38	12	42.1	2.0900	17.56	C	103.7341	78.4593
HB89 1309+340	13	9	16.86	34	2	44.5	1.0350	17.43	C	91.0069	82.0555
UM 556	13	13	57.04	1	7	14.7	2.3928	18.13	O	316.8678	63.0487
MMB90 1318-050	13	17	54.07	-5	7	51.9	3.7000	17.70	C	316.1991	56.7283
HB89 1323-107	13	23	21.70	-10	41	30.0	2.3600	17.00	O	316.4898	51.0083
HB89 1332+552	13	32	15.83	55	16	45.6	1.2490	16.00	R	110.2476	61.0392
CCS88 1334+2725	13	33	51.60	27	25	25.0	2.4250	17.70	O	35.7236	80.0476
HB89 1334+119	13	34	41.28	11	55	27.9	1.7600	17.22	R	339.9165	71.1807
CCS88 1338+2832	13	37	46.40	28	32	5.0	2.5170	17.10	O	41.8599	79.1758
HB89 1338+416	13	38	52.20	41	38	22.0	1.2190	16.08	C	90.5850	72.4834
HB89 1341+472	13	41	43.70	47	17	11.0	1.0880	18.20	O	99.0574	67.5931
HB89 1343+386	13	43	26.59	38	38	11.4	1.8440	18.50	R	81.1120	74.0195
HB89 1348+384	13	48	5.60	38	26	57.0	1.3900	18.00	R	78.5489	73.4312
H 1413+117	14	13	20.08	11	43	37.8	2.5460	17.00	O	358.7322	64.7731
HB89 2149+069	21	49	2.06	6	55	21.0	1.3640	18.00	R	64.5000	-34.5991

Table 2: Summary of Observations

Name	date	type	filter	exp.	phot?	FWHM	sky	σ_{sky}	M_{cal}	M_{tab}
LBQS 0009+0219	201093	2	R	10	P	2.4	298	13	15.94	14.79
HB89 0009+027	201093	2	R	5	P	1.7	147	11	17.06	15.09
HB89 0009+027	201093	2	V	10	P	2.0	161	11	17.35	15.09
HB89 0010+023	201093	2	R	5	P	2.0	145	11	15.22	14.39
HB89 0010+023	201093	2	V	5	P	2.0	83	8	16.03	14.39
HB89 0011-002	201093	2	R	5	P	2.3	146	11	16.50	15.53
HB89 0011-002	201093	2	V	5	P	2.8	82	9	17.21	15.53
HB89 0011+016	201093	2	R	5	P	2.0	142	10	15.83	14.96
HB89 0011+016	201093	2	V	5	P	3.0	86	9	16.48	14.96
HB89 0131+055	201093	2	R	10	P	2.0	275	13	15.56	15.14
HB89 0206+293	201093	2	R	15	P	2.1	359	14	15.21	15.33
HB89 0240-021	160194	1	R	10	C	2.1	290	11	14.81	14.85
CLB91 0244-0044	160194	1	R	10	C	1.9	271	11	14.85	15.13
HB89 0243-007	160194	1	R	10	C	2.0	285	11	14.85	15.13
HB89 0252+016	201093	2	R	10	P	2.8	290	15	16.18	15.58
HB89 0258+058	211093	2	R	15	P	2.7	420	15	14.69	14.74
HB89 0258+058	211093	1	V	15	P	2.9	192	9	15.49	14.74
HB89 0259+015	110294	1	R	15	C	1.4	431	14	15.44	15.13
HB89 0259+015	110294	1	V	15	C	1.5	175	9	16.26	15.13
HB89 0303+011	110294	1	R	15	C	1.7	390	13	14.83	14.79
HB89 0303+011	110294	1	V	15	C	1.6	180	9	15.54	14.79
HB89 0307+172	201093	2	R	15	P	2.5	422	15	15.19	14.92
LBQS 0308+0129	201093	1	R	10	P	2.6	291	11	16.25	15.29
HB89 0313+344	201093	1	R	10	P	2.9	272	11	15.05	14.23
PKS 0319+12	201093	2	R	10	P	2.2	310	13	14.71	13.95
HB89 0326+277	201093	2	R	10	P	1.8	312	13	15.35	14.90
HB89 0333+321	201093	2	R	5	P	2.2	162	11	16.08	15.33
HB89 0456+025	201093	2	R	10	P	2.0	320	14	15.47	14.94
HB89 0456+025	201093	2	V	10	P	2.0	160	11	16.67	14.94
HB89 0640+448	201093	2	R	10	P	1.9	319	13	15.08	14.36
HB89 0640+448	201093	2	V	10	P	2.2	155	11	15.66	14.36
HB89 0640+449	201093	2	R	10	P	1.9	318	14	15.71	14.92
HB89 0645+349	160294	1	R	10	C	1.7	223	10	14.75	13.78
MRK 0380	160194	1	R	10	C	1.3	290	11	15.73	15.10
HB89 0736-063	160194	1	R	10	C	1.6	235	11	14.68	14.06
HB89 0746+483	160194	1	R	10	C	1.3	200	9	15.77	14.85
HB89 0755+147	160194	1	R	10	C	1.5	214	10	15.41	14.60
HB89 0801+303	140194	1	R	10	C	2.8	265	11	14.61	13.69
HB89 0801+303	140194	1	R	20	C	2.2	450	14	14.52	14.59
HB89 0802+103	100394	1	R	10	P	1.5	240	10	15.23	14.41
HB89 0804+499	140194	1	R	10	C	2.0	220	10	15.19	14.19
HB89 0805+046	100394	1	R	10	P	1.5	220	10	15.00	14.22
HB89 0805+047	100394	1	R	15	P	1.6	313	12	14.78	14.50
HB89 0814+578	140194	1	R	10	C	2.1	215	10	15.89	14.83

Table 2 (continued): Summary of Observations

Name	date	type	filter	exp.	phot?	FWHM	sky	σ_{sky}	M_{cal}	M_{tab}
HB89 0820+560	140194	1	R	10	C	2.3	203	9	14.31	13.60
HB89 0821+394	140194	1	R	10	C	2.3	200	9	14.12	13.10
HB89 0833+585	140194	1	R	10	C	2.2	200	10	14.12	13.10
HB89 0833+654	140194	1	R	10	C	2.0	245	10	14.12	13.10
HB89 0834+250	140194	1	R	10	C	2.9	190	9	14.61	13.95
HB89 0835+580	140194	1	R	10	C	2.1	189	9	14.61	13.95
HB89 0836+443	140194	1	R	10	C	2.4	182	9	13.76	13.23
HB89 0836+710	100394	1	R	10	P	1.8	270	11	15.26	14.31
HB89 0836+710	050494	3	I	5	P	1.2	970	17	14.36	14.72
HB89 0839+186	100394	1	R	15	P	1.3	312	12	15.22	14.82
HB89 0839+444	140194	1	R	10	C	2.4	180	10	13.90	13.40
HB89 0840+450	110394	1	R	20	C	1.4	438	13	14.84	14.75
HB89 0840+501	110394	1	R	20	C	1.7	581	15	15.66	14.90
CSO 0203	100394	1	R	10	C	1.1	205	10	16.18	14.46
CSO 0203	030494	3	I	3	P	0.8	524	13	14.78	14.72
CSO 0203	030494	3	I	5	P	0.8	770	15	14.36	14.72
HB89 0847+100	100394	1	R	15	P	1.2	325	11	15.22	14.90
HB89 0850+140	100394	1	R	10	C	1.2	200	9	15.55	14.62
HB89 0855+188	100394	1	R	10	C	1.3	190	10	15.32	14.79
HB89 0856+170	100394	1	R	10	C	1.3	190	10	15.32	14.79
HB89 0901+285	140194	1	R	10	C	2.9	200	10	15.93	15.19
HB89 0903+167	140194	1	R	10	C	2.9	210	10	14.37	13.26
HB89 0906+015	160194	1	R	10	C	1.6	203	10	14.64	14.62
HB89 0913-025	160194	1	R	10	C	1.5	200	9	14.88	14.29
CBS 101	140194	1	R	10	C	2.4	230	10	15.48	14.73
HB89 0922+005	160194	1	R	10	C	1.5	205	9	15.22	14.71
HB89 0927+217	140194	1	R	10	C	2.6	238	10	15.96	15.11
HB89 0936+368	100394	1	R	10	C	1.3	170	8	15.73	15.00
HB89 0943+329	100394	1	R	10	C	1.4	170	9	16.39	15.00
HB89 0945+114	160194	1	R	10	C	1.5	217	9	15.26	15.26
HB89 0950+080	160194	1	R	10	C	1.5	205	9	15.26	15.26
HB89 0952+179	160194	1	R	10	C	1.5	200	9	15.26	15.26
CSO 0239	050494	3	I	5	C	1.2	870	16	14.36	14.72
MRK 0132	050494	3	I	5	C	1.2	1010	18	14.36	14.72
CBS 125	140194	1	R	10	C	2.2	235	10	14.64	13.43
HB89 1004+141	140194	1	R	10	C	2.4	258	11	14.43	13.43
LBQS 1009-0252	160194	1	R	10	C	1.6	245	10	15.26	15.26
HB89 1009+334	140194	1	R	10	C	2.2	258	11	14.43	13.43
LBQS 1011-0144	100394	1	R	10	C	1.4	185	9	16.36	15.27
HB89 1015+416	140194	1	R	10	C	1.7	295	11	15.62	14.14
CSO 0261	140194	1	R	10	C	1.6	265	11	15.58	15.08
CSO 0261	050494	3	I	5	C	1.1	920	17	14.36	14.72

Table 2 (continued): Summary of Observations

name	date	type	filter	exp.	phot?	FWHM	sky	σ_{sky}	M_{cal}	M_{tab}
HB89 1017+109	160194	1	R	10	C	1.6	232	10	16.00	14.95
HB89 1019+309	160194	1	R	10	C	1.4	234	10	15.91	14.90
HB89 1022-102	100394	1	R	10	C	1.5	197	9	14.98	14.94
HB89 1033+137	100394	1	R	10	C	1.3	184	9	15.88	14.88
HB89 1038+311	100394	1	R	10	C	1.5	177	8	15.91	15.20
CC91 1042+0547	100394	1	R	10	C	1.4	200	9	15.28	15.20
HB89 1042+349	160194	1	R	10	C	1.3	273	11	15.91	14.90
HB89 1054-034	100394	1	R	10	C	1.4	195	9	16.36	15.27
YDG81 1115+080	070594	1	R	15	C	1.9	438	13	14.51	14.70
YDG81 1115+080	070594	1	V	8	C	2.0	103	7	15.78	14.70
HB89 1129+315	140194	1	R	10	C	2.2	268	11	15.85	15.01
HB89 1147+339	160194	1	R	15	C	1.5	490	14	16.39	15.04
HB89 1151+105	160194	1	R	15	C	1.9	400	13	15.85	15.35
HB89 1151+489	100394	1	R	10	P	1.6	168	9	15.10	14.70
HB89 1158+122	160194	1	R	11	C	1.7	258	11	15.13	14.53
HB89 1206+119	100394	1	R	10	C	1.4	195	9	15.70	14.99
HB89 1209+154	100394	1	R	10	C	1.5	195	10	15.70	14.99
SBS 1220+567	140194	1	R	10	C	2.2	330	12	15.85	15.01
UM 497	050594	3	I	3	P	1.3	423	12	15.11	14.72
HB89 1225+086	160194	1	R	10	P	1.9	236	10	15.17	14.27
HB89 1226+105	160194	1	R	10	C	1.6	235	10	14.79	14.29
CSO 0151	050494	3	I	3	P	1.3	452	12	14.93	15.77
HB89 1235+089	100394	1	R	10	P	1.6	202	10	15.01	14.70
HB89 1237+151	160194	1	R	10	P	1.6	218	10	15.23	14.54
HB89 1239+099	160194	1	R	10	P	1.6	225	10	14.90	14.73
LBQS 1240+1607	160194	1	R	10	P	1.4	204	10	15.52	14.56
UM 516	160194	1	R	10	P	1.5	240	11	15.87	15.24
HB89 1244+097	160194	1	R	10	P	1.5	230	10	15.87	15.24
HB89 1244+170	100394	1	R	10	P	1.7	200	10	15.48	14.70
HB89 1245+345	160194	1	R	10	P	1.5	215	10	15.01	14.30
LBQS 1246-0059	100394	1	R	10	P	1.5	211	10	14.74	14.60
UM 524	110394	1	R	10	C	1.4	262	10	14.84	14.75
UM 531	110394	1	R	10	C	1.4	260	10	14.84	14.75
HB89 1306+274	110394	1	R	15	C	1.4	351	11	14.84	14.75
CSO 0832	100394	1	R	10	P	2.4	193	10	15.77	14.91
CSO 0832	030494	3	I	5	P	0.8	1883	23	14.36	14.72
HB89 1308+382	100394	1	R	5	P	2.9	115	8	15.71	14.24
HB89 1308+382	100394	1	R	5	P	3.0	116	8	15.73	14.24
HB89 1309+340	110394	1	R	10	C	1.5	263	10	14.84	14.75
UM 556	110394	1	R	15	C	1.6	505	14	15.87	15.09
MMB90 1318-050	100394	1	R	10	P	2.3	245	11	15.15	15.13
MMB90 1318-050	050494	3	I	5	P	1.3	800	15	14.36	14.72

Table 2 (continued): Summary of Observations

name	date	type	filter	exp.	phot?	FWHM	sky	σ_{sky}	M_{cal}	M_{tab}
HB89 1323−107	100394	1	R	10	P	2.0	320	12	15.48	14.81
HB89 1323−107	050494	3	I	5	P	1.3	800	15	14.36	14.72
HB89 1332+552	100394	1	R	10	P	3.2	215	10	14.95	14.23
CCS88 1334+2725	100394	1	R	10	P	2.8	200	10	14.24	13.43
HB89 1334+119	100394	1	R	10	P	2.9	230	10	14.31	14.30
CCS88 1338+2832	100394	1	R	10	P	2.2	191	10	14.45	13.71
CCS88 1338+2832	030494	3	I	5	P	0.9	2230	25	14.36	14.72
HB89 1338+416	100394	1	R	10	P	2.6	215	10	15.99	15.29
HB89 1341+472	100394	1	R	10	P	2.7	1090	20	15.89	15.34
HB89 1343+386	100394	1	R	10	P	3.2	232	10	15.51	14.42
HB89 1348+384	100394	1	R	10	P	2.7	286	12	15.51	14.27
H 1413+117	070594	1	V	10	C	2.4	137	7	17.54	14.19
HB89 2149+069	201093	2	R	10	P	2.0	280	13	14.74	13.96
HB89 2149+069	201093	2	V	10	P	1.7	160	11	15.47	13.96

Table 3: Quasar Results

Name	col	row	Q	χ^2	sharp	M_{dao}	M_{est}	σ_M	θ_{NN}	M_{NN}	Note
LBQS 0009+0219	1060	1118	1	1.07	0.93	18.37	16.93	0.03	8.3	18.33	
HB89 0009+027	981	1180	0	0.88	0.04	18.98	16.71	0.02	30.4	18.57	
HB89 0009+027	984	1182	0	1.02	-0.27	18.92	16.66	0.03	30.4	18.59	
HB89 0010+023	996	1209	3	2.99	4.86	19.27	18.14	0.10	57.1	18.67	1
HB89 0010+023	1000	1211	3	2.02	4.13	20.02	18.37	0.06	57.1	19.21	1
HB89 0011-002	1035	1110	3	1.55	2.89	19.11	17.84	0.04	52.1	19.11	2
HB89 0011-002	1039	1111	3	1.21	4.33	19.87	18.19	0.09	97.1	19.65	2
HB89 0011+016	1008	1148	0	1.05	0.05	18.91	17.74	0.02	94.6	19.34	
HB89 0011+016	1012	1150	0	1.04	-0.29	19.53	18.01	0.06	104.9	18.61	
HB89 0131+055	1012	1168	0	0.94	0.12	18.71	18.00	0.03	77.5	18.15	
HB89 0206+293	1018	1146	0	1.00	-0.16	19.51	19.33	0.06	23.0	19.93	
HB89 0240-021	442	463	0	0.93	0.09	18.69	18.43	0.03	25.6	20.09	
CLB91 0244-0044	455	427	0	0.96	-0.08	19.28	19.26	0.10	22.3	21.14	
HB89 0243-007	467	431	0	0.88	0.00	19.37	19.35	0.10	89.2	19.89	
HB89 0252+016	1024	1143	0	0.95	0.32	18.20	17.29	0.03	35.2	17.86	
HB89 0258+058	936	1192	0	0.95	0.42	18.84	18.59	0.04	34.7	20.30	3
HB89 0258+058	444	772	0	0.87	-0.66	19.43	18.68	0.04	38.2	19.44	3
HB89 0259+015	568	494	0	0.87	0.11	18.68	18.07	0.02	84.9	18.50	
HB89 0259+015	572	496	0	0.86	0.23	19.25	18.12	0.03	84.9	19.38	
HB89 0303+011	598	493	0	0.86	0.11	17.24	16.90	0.03	20.3	19.42	
HB89 0303+011	602	494	0	1.08	0.22	17.93	17.17	0.03	20.3	19.78	
HB89 0307+172	1031	1152	0	1.04	0.61	18.85	18.29	0.04	47.3	20.03	
LBQS 0308+0129	631	760	0	0.89	0.38	19.40	18.13	0.06	32.2	18.96	
HB89 0313+344	604	585	1	0.89	-0.34	19.40	18.28	0.06	22.3	19.31	
PKS 0319+12	1010	1166	0	0.99	0.61	19.13	18.07	0.04	77.1	18.29	
HB89 0326+277	1079	1058	0	1.05	0.03	18.50	17.75	0.03	26.8	19.48	
HB89 0333+321	1061	1100	2	0.83	-0.21	18.15	17.10	0.02	5.3	18.74	
HB89 0456+025	1086	1169	1	0.99	0.24	19.18	18.35	0.03	6.4	18.55	
HB89 0456+025	1090	1171	1	1.16	0.99	19.95	18.22	0.07	6.4	18.39	
HB89 0640+448	1075	1171	1	1.05	0.17	18.38	17.36	0.03	48.1	18.47	
HB89 0640+448	1079	1173	1	1.09	-0.04	19.05	17.74	0.04	48.0	19.16	
HB89 0640+449	1086	1133	1	0.90	0.23	19.43	18.35	0.06	30.3	18.89	
HB89 0645+349	518	487	0	1.00	0.00	18.44	17.17	0.01	17.5	19.47	
MRK 0380	590	485	0	0.99	-0.03	17.52	16.59	0.10	14.9	19.60	4
HB89 0736-063	429	461	1	0.85	0.00	18.81	17.89	0.10	18.5	20.50	
HB89 0746+483	549	461	0	0.90	0.10	19.40	18.18	0.03	12.2	20.46	
HB89 0755+147	461	471	0	0.91	0.20	19.09	17.98	0.03	32.5	19.75	
HB89 0801+303	519	646	0	0.99	-0.12	18.94	17.72	0.03	17.0	19.78	
HB89 0801+303	519	646	0	0.92	-0.20	18.01	17.78	0.03	16.9	19.82	
HB89 0802+103	539	386	0	0.84	0.13	18.88	17.76	0.03	29.2	19.94	
HB89 0804+499	513	619	1	1.06	0.40	19.17	17.87	0.03	19.8	19.47	
HB89 0805+046	575	412	0	0.82	0.03	18.89	17.81	0.03	24.3	19.44	
HB89 0805+047	584	502	2	1.10	0.24	19.47	18.89	0.03	4.2	19.61	

Table 3 (continued): Quasar Results

Name	col	row	Q	χ^2	sharp	M_{dao}	M_{est}	σ_M	θ_{NN}	M_{NN}	Note
HB89 0814+578	580	605	0	0.91	-0.22	19.28	17.92	0.03	59.9	18.00	
HB89 0820+560	550	564	0	0.91	0.12	18.93	17.91	0.03	32.4	19.75	
HB89 0821+394	519	535	0	0.97	0.24	18.39	17.06	0.03	22.8	18.78	5
HB89 0833+585	582	552	0	0.92	0.26	18.85	17.53	0.10	52.4	18.41	
HB89 0833+654	563	550	0	0.87	0.09	18.90	17.58	0.10	44.8	19.41	
HB89 0834+250	479	455	0	0.84	0.25	18.28	17.32	0.03	21.6	19.35	
HB89 0835+580	595	544	0	0.88	-0.14	17.98	17.02	0.10	20.5	17.95	
HB89 0836+443	581	517	0	0.98	0.10	17.94	17.10	0.03	21.1	19.44	
HB89 0836+710	578	643	0	0.97	0.24	17.77	16.52	0.10	31.4	19.69	
HB89 0836+710	499	503	0	0.56	0.03	16.50	15.86	0.10	31.0	17.58	
HB89 0839+186	568	477	0	1.14	0.01	18.69	17.99	0.03	29.5	20.97	
HB89 0839+444	619	524	0	0.91	-0.05	19.39	18.60	0.03	20.0	18.96	
HB89 0840+450	673	453	2	0.93	-0.01	18.72	18.33	0.03	6.0	18.57	
HB89 0840+501	605	474	1	0.65	0.03	19.71	18.65	0.06	66.8	19.84	
CSO 0203	620	472	0	0.82	0.02	18.03	16.01	0.03	34.4	19.05	
CSO 0203	535	533	0	0.97	-0.03	17.12	16.06	0.06	18.1	19.16	
CSO 0203	547	533	0	1.00	-0.04	16.71	16.07	0.09	18.1	19.15	
HB89 0847+100	539	416	3	1.42	0.23	19.39	18.76	0.03	42.9	19.54	
HB89 0850+140	512	434	1	0.86	0.09	19.15	17.92	0.03	7.8	20.53	
HB89 0855+188	594	426	0	0.79	0.01	18.62	17.78	0.03	14.3	20.58	
HB89 0856+170	601	423	0	0.92	0.06	18.68	17.85	0.10	15.5	19.01	
HB89 0901+285	555	463	1	0.93	-0.21	18.00	16.96	0.03	47.1	17.57	
HB89 0903+167	564	455	0	1.00	-0.28	19.27	17.86	0.03	17.7	19.10	
HB89 0906+015	412	497	0	0.73	0.03	17.83	17.51	0.03	17.0	19.06	
HB89 0913-025	394	362	1	0.88	-0.01	18.62	17.73	0.03	8.1	20.29	
CBS 101	596	489	1	0.93	0.02	18.91	17.86	0.03	11.4	19.60	
HB89 0922+005	401	387	0	0.93	0.02	18.17	17.37	0.03	21.9	20.13	
HB89 0927+217	520	508	0	0.85	0.20	19.54	18.39	0.06	83.2	20.11	
HB89 0936+368	630	419	0	0.94	-0.05	19.22	18.18	0.03	23.8	19.91	6
HB89 0943+329	661	372	0	0.92	0.01	17.72	16.03	0.10	31.6	18.01	
HB89 0945+114	398	468	0	1.01	-0.10	19.44	19.14	0.10	53.2	21.06	7
HB89 0950+080	524	266	0	1.09	-0.15	18.79	18.49	0.10	42.4	21.37	
HB89 0952+179	447	452	0	0.93	0.00	17.90	17.60	0.10	13.6	20.11	
CSO 0239	544	555	0	0.94	0.15	17.13	16.49	0.10	31.8	19.86	
MRK 0132	288	440	0	0.99	0.10	15.71	15.07	0.10	23.7	18.18	
CBS 125	539	466	0	1.01	0.23	17.99	16.49	0.10	35.8	17.75	
HB89 1004+141	526	429	0	0.88	-0.10	19.63	18.33	0.10	75.4	19.58	
LBQS 1009-0252	385	452	3	1.28	0.42	18.98	18.68	0.04	4.6	19.93	8
HB89 1009+334	576	472	0	0.89	-0.08	19.11	17.81	0.03	82.7	19.69	
LBQS 1011-0144	587	430	0	1.03	0.09	19.40	18.00	0.03	26.6	18.67	9
HB89 1015+416	545	438	0	0.94	0.48	20.06	18.28	0.03	52.8	18.52	
CSO 0261	553	458	0	0.92	0.06	18.89	18.08	0.03	30.5	19.12	10
CSO 0261	476	565	1	0.84	0.07	17.48	16.84	0.10	6.9	20.13	10

Table 3 (continued): Quasar Results

Name	col	row	Q	χ^2	sharp	M_{dao}	M_{est}	σ_M	θ_{NN}	M_{NN}	Note
HB89 1017+109	402	459	0	0.89	0.07	18.90	17.55	0.03	34.9	18.82	
HB89 1019+309	470	461	0	1.02	0.09	18.56	17.25	0.06	32.0	20.00	
HB89 1022-102	587	366	0	0.97	-0.03	17.99	17.65	0.10	52.3	21.75	
HB89 1033+137	592	495	0	0.86	-0.06	18.73	17.43	0.03	28.8	17.50	
HB89 1038+311	730	486	0	1.30	-0.11	18.39	17.38	0.10	44.7	19.01	
CC91 1042+0547	600	382	1	1.09	0.05	18.65	18.27	0.03	10.5	20.20	
HB89 1042+349	558	544	0	0.82	-0.01	19.72	18.41	0.10	27.1	19.44	
HB89 1054-034	546	407	0	0.92	0.08	18.67	17.28	0.10	55.6	19.86	
YDG81 1115+080	526	497	3	4.85	1.48	16.16	16.05	0.10	12.8	20.82	11
YDG81 1115+080	531	499	3	4.00	1.98	17.16	16.08	0.10	22.7	20.24	11
HB89 1129+315	569	395	0	0.97	-0.19	18.49	17.35	0.03	84.9	19.39	12
HB89 1147+339	494	423	0	0.86	0.00	19.78	18.13	0.06	59.4	18.95	
HB89 1151+105	390	389	0	0.90	0.14	19.33	18.54	0.03	23.1	20.28	
HB89 1151+489	656	458	0	1.06	0.14	19.29	18.59	0.03	25.4	20.90	
HB89 1158+122	410	402	0	0.94	-0.13	18.33	17.43	0.03	28.5	19.11	
HB89 1206+119	580	376	0	0.90	-0.08	18.47	17.46	0.10	93.1	20.80	
HB89 1209+154	617	403	0	1.07	0.19	18.63	17.61	0.03	24.6	20.26	
SBS 1220+567	540	519	0	0.90	0.17	19.42	18.28	0.10	13.4	19.63	
UM 497	547	503	0	1.04	-0.17	17.83	16.44	0.10	68.7	19.51	
HB89 1225+086	408	471	0	0.89	0.05	17.95	16.75	0.03	48.7	19.61	
HB89 1226+105	403	407	0	0.94	0.05	19.46	18.66	0.03	49.3	20.22	
CSO 0151	231	443	0	1.02	0.12	16.74	16.58	0.10	30.3	18.90	
HB89 1235+089	559	407	0	0.86	0.00	18.38	17.76	0.03	13.0	20.86	
HB89 1237+151	457	470	0	0.89	-0.10	19.37	18.38	0.03	24.0	19.13	
HB89 1239+099	421	455	0	0.88	0.04	18.68	18.22	0.02	39.4	21.00	
LBQS 1240+1607	479	406	0	1.05	0.02	19.42	18.17	0.04	41.2	19.23	
UM 516	453	369	0	0.87	0.11	18.62	17.69	0.02	35.4	19.14	
HB89 1244+097	427	419	0	0.94	-0.15	18.94	18.01	0.03	36.0	20.45	
HB89 1244+170	628	434	0	0.86	-0.06	18.41	17.33	0.03	24.1	20.49	
HB89 1245+345	494	422	0	1.00	0.02	18.77	17.75	0.02	27.4	19.00	
LBQS 1246-0059	573	384	0	0.92	-0.09	19.05	18.61	0.03	60.7	20.59	
UM 524	623	275	0	1.13	0.05	19.03	18.64	0.10	51.0	21.55	
UM 531	391	483	0	0.83	0.01	18.28	17.89	0.10	64.7	19.89	
HB89 1306+274	648	357	0	0.95	0.10	18.40	18.01	0.10	61.5	20.12	
CSO 0832	674	399	1	0.89	0.35	18.21	17.06	0.03	8.3	19.15	
CSO 0832	482	587	1	0.47	-0.01	17.52	16.88	0.10	8.2	18.87	
HB89 1308+382	723	370	0	1.02	-0.49	18.99	17.22	0.03	62.1	17.55	
HB89 1308+382	724	370	0	1.09	-0.37	19.02	17.23	0.03	62.1	17.54	
HB89 1309+340	718	343	0	0.82	0.11	18.66	18.27	0.10	13.9	19.75	
UM 556	704	336	0	0.90	0.18	19.29	18.21	0.04	28.7	19.34	
MMB90 1318-050	552	268	0	0.95	0.27	18.42	18.09	0.03	18.5	20.79	
MMB90 1318-050	638	568	0	1.67	-0.34	17.60	16.96	0.10	18.4	19.71	

Table 3 (continued): Quasar Results

Name	col	row	Q	χ^2	sharp	M_{dao}	M_{est}	σ_M	θ_{NN}	M_{NN}	Note
HB89 1323-107	579	410	0	0.83	0.14	18.43	17.46	0.10	57.1	20.18	
HB89 1323-107	709	515	0	0.80	-0.06	17.87	17.23	0.10	28.2	19.56	
HB89 1332+552	716	400	0	0.85	0.76	19.17	18.14	0.03	18.2	19.06	13
CCS88 1334+2725	646	396	0	0.88	-0.08	18.52	17.41	0.03	26.6	18.90	
HB89 1334+119	644	326	0	0.91	0.09	19.19	18.89	0.03	85.5	20.27	14
CCS88 1338+2832	624	308	0	0.86	0.05	18.07	17.02	0.03	16.5	19.26	
CCS88 1338+2832	499	590	0	0.94	0.07	17.62	16.98	0.10	16.4	19.22	
HB89 1338+416	719	343	0	0.91	0.07	17.01	16.02	0.03	41.4	19.42	
HB89 1341+472	783	342	0	0.85	-0.97	18.83	17.98	0.06	26.1	19.20	
HB89 1343+386	703	359	0	0.86	0.18	18.45	17.06	0.03	13.0	18.53	15
HB89 1348+384	709	326	0	0.89	0.35	18.73	17.19	0.03	39.3	18.98	
H 1413+117	503	480	0	1.08	1.82	19.95	16.61	0.10	18.8	18.28	16
HB89 2149+069	964	1081	1	1.12	0.12	18.68	17.60	0.02	10.5	18.48	
HB89 2149+069	968	1083	1	1.12	-0.17	19.49	17.98	0.04	10.4	19.36	

Notes to Table 3:

- 1- 0010+023: An object from the HB catalog with $R = 18.14 \pm 0.10$ and $V = 18.37 \pm 0.06$ mag, as estimated from our observations, compared to a tabulated value of $V = 15.5$. There is no real question about the identification of the quasar because a bright close star pair almost directly North of the quasar makes the identification unambiguous. The question is important, because we will see in §3 that this object is also our best lens candidate. The object is assigned $Q = 3$ due to its high χ^2 , although the nearest, fainter stellar neighbor is beyond $12''$. A spectrum by A Filippenko & T. Matheson obtained on 11 October 1994 with the 3m Lick telescope is that of a redshift $z = 0.088$ galaxy.
- 2- 0011-002: An object from the HB catalog with $R = 17.84 \pm 0.04$ and $V = 18.19 \pm 0.09$ mag, as estimated from our observations, compared to a tabulated value of $V = 17.5$. The object is assigned $Q = 3$ due to its high χ^2 , although the nearest, fainter stellar neighbor is beyond $12''$. A spectrum by A Filippenko & T. Matheson obtained on 11 October 1994 with the 3m Lick telescope is that of a redshift $z = 0.11$ galaxy.
- 3- 0258+058: An object from the HB catalog. The confirmed position (Wills & Wills 1979) was $\sim 36''$ from its catalog position, but otherwise unremarkable.
- 4- MRK 380: An object from the HB catalog. The tabulated nearest neighbor overlaps a satellite trail and may not be real. For the next nearest object, $\Delta R = 27''.8$ and $R = 21.1$. A new observation will be obtained to confirm the existence of the first neighbor.
- 5- 0821+394: An object from the HB catalog with $R = 17.06 \pm 0.03$ mag, as estimated from our observations, and a tabulated value of $V = 18.5$.
- 6- 0936+368: An object from the HB catalog with $R = 18.18 \pm 0.03$ mag, as estimated from our observations, compared to a tabulated magnitude of $V = 17$.
- 7- 0945+114: An object from the HB catalog with $R = 19.14 \pm 0.10$ mag, as estimated from our observations, and a tabulated value of $V = 18$.

Notes to Table 3 (continued):

- 8– LBQS 1009–0252: An object from the LBQS survey, also a confirmed lens system (Hewett et al. 1994). If we adopt the labels A, B and C for the three objects analyzed in Hewett et al. (1994), our (their) estimates for the separations and magnitude differences for objects B and C from A are: $\Delta\theta_B = 1''.65 \pm 0''.14$ ($1''.48$), $\Delta\theta_C = 4''.13 \pm 0''.04$ ($4''.47$); $\Delta R_B = 2.3 \pm 0.2$ mag (2.26 mag, r band), $\Delta R_C = 1.2 \pm 0.1$ mag (1.16 mag, r band). Our uncertainties were estimated by Monte Carlo simulations of the configuration of the quasars with sky and noise levels appropriate for our observation. We disagree marginally with Hewett et al. (1994) only in the measurement of $\Delta\theta_C$.
- 9– LBQS 1011–0144: An object from the LBQS survey with $R = 18.00 \pm 0.03$ mag, as estimated from our observations, and a tabulated value of $V = 17.91$. An extended object, probably a galaxy, is seen by eye, about $5''.1$ West of, and about 1 mag fainter than the quasar (also confirmed by the LBQS survey group; Foltz 1994, *private communication*). The object escaped detection, because it was below our fixed threshold, but its proximity to the quasar implies that a new, longer exposure would be useful.
- 10– CSO 0261: An object from the Case survey (Pesch & Sanduleak 1986) with $R = 18.08 \pm 0.03$ mag and $I = 16.84 \pm 0.10$ mag, based on our observations, and a tabulated magnitude of $V = 17$.
- 11– YDG81 1115+080: An object from the HB catalog with $R = 16.05 \pm 0.10$ mag and $V = 16.08 \pm 0.10$ mag, as estimated from our observations, compared to a tabulated magnitude of $V = 16.99$; also a known lens system (Weymann et al. 1980). If we adopt the labels A, B and C for the three objects analyzed in Henry & Heasley (1986), our (their) estimates for the separations and magnitude differences for objects B and C from A are: $\Delta\theta_B = 1''.7 \pm 0''.1$ ($1''.74$), $\Delta\theta_C = 2''.4 \pm 0''.1$ ($2''.16$); $\Delta V_B = 2.3 \pm 0.2$ mag (2.8 mag), $\Delta V_C = 1.9 \pm 0.1$ mag (1.9 mag). Our uncertainties were estimated by Monte Carlo simulations of the configuration of the quasars with sky and noise levels appropriate for our observation. We agree very well with the measurements of Henry & Heasley (1986), and with similar measurements with HST’s planetary camera (which resolve image A into a double) by Kristian et al. 1993.
- 12– 1129+315: An object from the HB catalog. The quasar image was found in the wings of a saturated star that probably contaminates our magnitude estimate for the quasar.
- 13– 1332+552: An object from the HB catalog with $R = 18.14 \pm 0.03$ mag, as estimated from our observations, compared to a tabulated magnitude of $V = 16$. An extended object, probably a galaxy, is seen by eye, about $5''.8$ North-West of, and about 1.5 mag fainter than the quasar. The object escaped detection, because it was below our fixed threshold, but its proximity to the quasar implies that a new, longer exposure would be useful.
- 14– 1334+119: An object from the HB catalog with $R = 18.89 \pm 0.03$ mag, as estimated from our observations, compared to a tabulated magnitude of $V = 17.22$.

Notes to Table 3 (continued):

- 15– 1343+386: An object from the HB catalog with $R = 17.06 \pm 0.03$ mag, as estimated from our observations, and a tabulated value of $V = 18.5$.
- 16– 1413+117: An object from the HB catalog with $V = 16.61 \pm 0.10$ mag, as estimated from our observations, and a tabulated value of $V = 17.$; also a known lens system (Magain et al. 1988).

Table 4: Nearest-neighbor Results

Name	col	row	χ^2	sharp	Filter	M_{dao}	M_{est}	σ_M	θ_{NN}	ID
LBQS 0009+0219	1049	1095	0.99	1.19	<i>R</i>	19.77	18.32	0.08	8.25	(Star)
HB89 0313+344	640	584	0.97	0.01	<i>R</i>	17.28	16.16	0.01	11.84	
HB89 0333+321	1064	1116	0.86	-0.11	<i>R</i>	19.79	18.74	0.05	5.31	(Star)
HB89 0456+025	1100	1183	0.99	0.57	<i>R</i>	19.38	18.55	0.05	6.38	(Star)
HB89 0456+025	1112	1162	3.61	3.62	<i>R</i>	18.47	17.64	0.09	8.79	
HB89 0456+025	1104	1184	0.94	0.65	<i>V</i>	20.12	18.39	0.07	6.43	(Star)
HB89 0456+025	1116	1163	1.98	2.63	<i>V</i>	19.17	17.44	0.06	8.83	
HB89 0640+448	1069	1190	1.42	-0.20	<i>R</i>	15.49	14.47	0.01	6.30	
HB89 0640+448	1073	1192	1.10	-0.23	<i>V</i>	16.19	14.89	0.01	6.30	
HB89 0640+449	1110	1114	0.97	0.27	<i>R</i>	19.43	18.34	0.04	9.96	
HB89 0736-063	435	479	1.18	-0.11	<i>R</i>	17.55	16.63	0.10	6.24	
HB89 0804+499	506	639	1.00	-0.05	<i>R</i>	15.59	14.29	0.01	6.85	(Star)
HB89 0805+047	596	497	0.96	0.12	<i>R</i>	20.20	19.62	0.08	4.19	
HB89 0840+450	668	435	0.82	0.01	<i>R</i>	18.95	18.56	0.03	5.99	(Star)
HB89 0840+501	633	484	0.90	-0.02	<i>R</i>	18.97	17.91	0.04	9.78	(Star)
HB89 0850+140	488	435	0.92	-0.25	<i>R</i>	21.76	20.53	0.18	7.83	
HB89 0901+285	556	492	0.97	-0.23	<i>R</i>	18.34	17.31	0.02	9.55	(Star)
HB89 0913-025	370	363	0.83	0.12	<i>R</i>	21.18	20.30	0.11	8.06	
HB89 0913-025	404	397	0.88	0.75	<i>R</i>	21.72	20.83	0.18	11.80	
CBS 101	628	474	0.91	-0.85	<i>R</i>	20.65	19.60	0.12	11.41	
LBQS 1009-0252	379	438	0.77	0.10	<i>R</i>	20.23	19.93	0.05	4.59	
CSO 0261	463	543	1.15	1.09	<i>I</i>	20.75	20.11	0.15	6.93	
CC91 1042+0547	593	351	0.82	0.00	<i>R</i>	20.58	20.20	0.07	10.53	
CSO 0832	656	381	0.87	-0.26	<i>R</i>	20.31	19.15	0.08	8.33	
CSO 0832	460	608	0.80	-0.01	<i>I</i>	19.51	18.87	0.06	8.25	
HB89 2149+069	992	1066	0.88	-0.06	<i>R</i>	19.56	18.48	0.04	10.48	(M Star)
HB89 2149+069	996	1068	0.96	-0.54	<i>R</i>	20.87	19.36	0.11	10.44	(M Star)

Note: The parenthesis on the ID entries indicate preliminary identifications from partially reduced spectra. A Filippenko & T. Matheson obtained spectra of LBQS 0009+0219, HB 0333+321, the closer companion of HB89 0456+025, and HB89 2149+069 on 11 October 1994 with the 3m Lick telescope, and J. Huchra obtained spectra of HB89 0804+499 and HB89 0901+285 on 29 January 1995 with the FAST spectrograph on the Tillinghast telescope at Mt. Hopkins, AZ. Spectra of HB89 0840+450 and HB89 0840+501 were obtained with the FAST spectrograph on 24 February 1995.