DIFFERENCE IMAGING OF LENSED QUASAR CANDIDATES IN THE SLOAN DIGITAL SKY SURVEY SUPERNova SURVEY REGION

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ABSTRACT

Difference imaging provides a new way to discover gravitationally lensed quasars because few nonlensed sources will show spatially extended, time variable flux. We test the method on the fields of lens candidates in the Sloan Digital Sky Survey (SDSS) Supernova Survey region from the SDSS Quasar Lens Search (SQLS) and one serendipitously discovered lensed quasar. Starting from 20,536 sources, including 49 SDSS quasars, 32 candidate lenses/lensed images, and one known lensed quasar, we find that 174 sources including 35 SDSS quasars, 16 candidate lenses/lensed images, and the known lensed quasar are nonperiodic variable sources. We can measure the spatial structure of the variable flux for 119 of these variable sources and identify only eight as candidate extended variables, including the known lensed quasar. Only the known lensed quasar appears as a close pair of sources on the difference images. Inspection of the remaining seven suggests they are false positives, and only two were spectroscopically identified quasars. One of the lens candidates from the SQLS survives our cuts, but only as a single image instead of a pair. This indicates a false positive rate of order ~1/4000 for the method, or given our effective survey area of order 0.82 deg², ~5 per deg² in the SDSS Supernova Survey. The fraction of quasars not found to be variable and the false positive rate would both fall if we had analyzed the full, later data releases for the SDSS fields. While application of the method to the SDSS is limited by the resolution, depth, and sampling of the survey, several future surveys such as Pan-STARRS, LSST, and SNAP will significantly improve on these limitations.

Key words: gravitational lensing – quasars: general

Online-only material: color figures

1. INTRODUCTION

Gravitational lensing has many applications, from exoplanet searches to large-scale structure (see the reviews by Kochanek 2006, Schneider, and Wambsganss 2006). Galaxy scale lenses can be used to study the matter mass profile of the lens galaxy (e.g., Kochanek 1991; Rusin & Kochanek 2005; Koopmans et al. 2006; Jiang & Kochanek 2007). When the background source is a quasar, microlensing by individual stars in the lens galaxy can be used to probe the structure of the quasar’s accretion disk (Point Dexter et al. 2008; Morgan et al. 2007) and broad line regions (Eisenbrod et al. 2008). Galaxy scale lenses can also constrain cosmological parameters (Refsdal 1964; Oguri 2007). Unfortunately, most applications require large samples of gravitational lenses to be competitive with other methods, while fewer than a hundred lensed quasars are known. Moreover, these lenses were discovered using different methods with different biases, which are especially problematic if homogeneous samples with well-understood selection functions are needed (see Kochanek 2006).

The known lenses were found by their morphological structure or the presence of higher redshift features in the spectrum of a lower redshift galaxy. Morphological surveys examine optical or radio images of quasars for evidence that they are lensed. This works best for pointlike sources such as optical quasars and flat spectrum radio sources. The two largest searches for lensed active galactic nuclei (AGNs) are the Cosmic Lens All-Sky Survey of flat spectrum radio sources (Myers et al. 2003; Browne et al. 2003) and the Sloan Digital Sky Survey (SDSS) Quasar Lens Search (SLS; Oguri et al. 2006). The radio samples are limited by the number of sufficiently bright radio sources and the difficulties in obtaining source redshifts. The optical quasar samples suffer from confusion from stars and galaxies and the effects of color changes, from both starlight and dust in the lenses, on sample selection. The spectroscopic method made several serendipitous discoveries of lensed quasars, such as Q2237+0305 (Huchra et al. 1985) and SDSSJ090334.92+502819.2 (Johnston et al. 2003). Following theoretical investigations (e.g., Kochanek 1992; Miralda-Escudé & Lehár 1992; Mortlock & Webster 2000, 2001), the SLACS survey (e.g., Bolton et al. 2004, 2006, 2008) used the spectroscopic method on massive early-type galaxies in the SDSS to identify ~100 candidate lensed star-forming galaxies, and confirmed 70 of 131 using Hubble Space Telescope images. The spectroscopic method is limited by its low yield (about one lens candidate per 1000 luminous red galaxy spectra) and biases in its mass range (due to the size of the spectroscopic aperture). Moreover, by selecting targets based on the properties of the lens galaxy, these lenses are mainly useful for studying the lens galaxies rather than for cosmology (see Kochanek 2006).

Kochanek et al. (2006) proposed a new method to find lensed quasars based on difference imaging. Difference imaging, also known as image subtraction, is a way to measure the variable intensity in a region of sky (Tomaney & Crotts 1996; Alard & Lupton 1998; Alard 2000). It has been used to search for a broad range of variable sources, such as planets transiting stars (e.g., Hartman et al. 2004), microlenses (e.g., Alcock et al. 1999; Wóźniak 2000), and supernovae (e.g., the SDSS II Supernova Survey; Sako et al. 2008). In difference imaging, a reference image is made by averaging a set of the best images for a field. Then, for each epoch of observation, a difference image is created by subtracting the reference image convolved to the
point-spread function (PSF) and flux scale of that epoch. If a source is variable, there will be a flux residual in the difference image corresponding to the variability of the source.

In difference images, lensed quasars are recognizable because they consist of multiple variable images that are close together. Since most quasars are variable, with 60% having a variability over two years (e.g., Sesar et al. 2007), each of these images is variable. The level of variability is then enhanced by microlensing of the quasar images by the stars in the lens galaxy (see the review by Wambsganss 2006). Thus, lensed quasars look like compact clusters of variable sources or extended variable sources, which allows us to easily search for lensed quasars in difference images. The number of false positives from pairs of variable stars, pairs of quasars (related or not), variable star–quasar blends, and supernovae–AGN pairs is expected to be low (Kochanek et al. 2006). Candidates found this way can be confirmed by light curve analysis, since each image will have the same intrinsic variability, but with time delays between the images and some additional uncorrelated variability from microlensing by the stars of the lens galaxy (e.g., Pindor 2005). Difference imaging can also resolve variable lensed sources blended with nonvariable sources, such as the lens galaxies. This is important because, as we search for fainter lensed quasars, contamination from the lens galaxy becomes a steadily greater problem. Tests of image subtraction on the lens Q2237+0305 show that the method can find quasars even when they are buried by the flux of an extraordinarily bright foreground galaxy (Kochanek et al. 2006).

The forthcoming, large-scale synoptic surveys, such as LSST (Tyson et al. 2002) and Pan-STARRS (Kaiser 2004), will be ideal for this method, since they will cover large areas of the sky, sample variable sources frequently, and have deep magnitude limits. In the meantime, the SDSS II Supernova Survey (Frieman et al. 2008; Sako et al. 2008) is the best survey currently available for our goals. Intended to find supernovae for dark energy studies, the Supernova Survey repeatedly images SDSS Stripe 82, a 2.5° wide swath along the celestial equator, covering 300 deg² and stretching across the Southern Galactic Cap from right ascension 300° to right ascension 60° (Frieman et al. 2008). About 50–60 public epochs were available for a given field for this project.

We applied the method outlined in Kochanek et al. (2006) to the SDSS Supernova Survey fields that contained 26 previously identified candidates for gravitational lenses, with 39 total components, from the initial SQLS candidate list. These include 15 candidates with 24 components in the main statistical sample (Inada et al. 2008), and 11 additional candidate systems, with 15 images, that were outside the final selection criteria. The SQLS lens candidates had already been rejected for other reasons, such as different spectral energy distributions for the postulated lensed images, or the lack of a lens galaxy. These candidates are listed in Table 1. We also included a recently discovered lensed quasar in Stripe 82 (P. Garnavich et al. 2009, in preparation), the only one known in Stripe 82. In addition to looking for extended objects on the difference images, we checked to see if any pair of images in a candidate lens appeared on the difference images,

### Table 1

**SQLS Lens Candidates in the SDSS Supernova Survey Region**

| Lens Candidate | α₁ [°] | δ₁ [°] | α₂ [°] | δ₂ [°] |
|----------------|-------|-------|-------|-------|
| SDSSJ0020−0011b | 00°20′23″18 | −01°11′00″7 | ... | ... |
| SDSSJ0141+0031b | 01°41′11″62 | 0°31′44″8 | 01°41′10″34 | 0°31′07″0 |
| SDSSJ0212+0032c | 02°12′49″50 | 0°34′48″7 | ... | ... |
| SDSSJ0338+0033c | 03°30′23″24 | 0°32′56″9 | ... | ... |
| SDSSJ0216−0037c | 02°16′49″26 | −0°37′23″6 | 02°16′49″16 | −0°37′11″5 |
| SDSSJ0216−0102c | 02°16′45″80 | −1°02′04″8 | ... | ... |
| SDSSJ0323+0106c | 03°23′32″09 | 1°06′40″3 | 02°32′05″19 | 1°06′34″2 |
| SDSSJ0248+0009b | 02°48′20″78 | 0°09′56″5 | 02°48′21″41 | 0°09′56″9 |
| SDSSJ0249+0025b | 02°49′00″67 | 0°25′36″1 | ... | ... |
| SDSSJ0249+0037b | 02°49′00″75 | 0°39′16″6 | ... | ... |
| SDSSJ0258−0010c | 02°58′40″27 | −0°11′00″0 | 02°58′30″82 | −0°11′18″2 |
| SDSSJ0238+0055c | 20°38′45″36 | 0°55′32″1 | 20°38′46″09 | 0°55′41″4 |
| SDSSJ0240−0030c | 20°40′30″53 | −0°30′15″9 | 20°40′30″71 | −0°30′10″6 |
| SDSSJ0252+0011b | 20°52′32″82 | 0°11′37″5 | 20°52′31″85 | 0°11′16″4 |
| SDSSJ0257+0006b | 20°57′52″49 | 0°06′35″3 | ... | ... |
| SDSSJ0212−0026c | 21°22′43″02 | −0°26′53″7 | ... | ... |
| SDSSJ0214−0047c | 21°24′29″33 | −0°47′27″1 | 21°24′30″91 | −0°47′25″3 |
| SDSSJ0219−0051c | 21°30′56″45 | −0°51′50″5 | 21°29′56″57 | −0°51′52″5 |
| SDSSJ0213+0000c | 21°32′36″62 | 0°00′17″6 | 21°32′33″72 | 0°00′09″4 |
| SDSSJ0213−0054c | 21°34′14″02 | −0°45′33″1 | 21°34′14″18 | −0°45′14″7 |
| SDSSJ0219−0114c | 21°39′32″17 | −11°14″05″8 | ... | ... |
| SDSSJ0220−0107c | 22°00′00″02 | −1°07′48″0 | ... | ... |
| SDSSJ0211−0009c | 22°11′10″99 | −0°09′53″4 | ... | ... |
| SDSSJ0222−0059c | 22°28′22″17 | −0°59′43″6 | 22°28′22″19 | −0°59′49″4 |
| SDSSJ0233+0056c | 23°27′33″67 | 0°56′10″9 | ... | ... |
| SDSSJ0235+0047c | 23°51′48″36 | 0°47′51″6 | ... | ... |

**Notes.**
- Component 1 is always a spectroscopically identified quasar given in Schneider et al. (2005). If the candidate images are less than 2.5′ apart, the components are blended, and no position is given for Component 2. If they are more than 2.5′ apart, Component 2 is selected by color criteria and the position is given.
- Positions from initial SQLS candidate list, but these candidates were outside the final selection criteria for Inada et al. (2008).
- Positions listed in Inada et al. (2008).
since the images can be well separated. We had three goals. First, to use the variability method as an independent check of the SDSS candidates. Second, to get a sense of the false positive rate from any other variable sources in the fields. Third, to verify again that our method does in fact work by testing it against significantly fainter lensed quasars than those considered in Kochanek et al. (2006). We outline the method, our approach to source selection, and the results when applied to targets in Section 2. We discuss the variable sources in the lens candidate fields in Section 3, including the P. Garnavich et al. (2009, in preparation) lens (Section 3.1), quasars (Section 3.3), and extended variable sources (Section 3.4). Finally, we conclude in Section 4 by discussing prospects for finding gravitational lenses in future surveys with difference imaging.

2. PROCEDURE

2.1. Preparation and Image Subtraction

For each field around the lens candidates, we downloaded the r-band images from the SDSS Data Server, which had epochs through 2007 at the time. The number of epochs per field ranged from 46 to 62 with a median of 52. We chose r-band because the r-band SDSS images have the greatest effective depth (York et al. 2000). We then created images centered on the candidate’s R.A. by combining the image containing the candidate with either the previous or next image in the drift scan with an appropriate R.A. offset. The R.A.-centered images had the same dimensions and pixel scale as the original SDSS images—2048 × 1489 pixels with a pixel scale of 0′′.396. The median FWHM seeing in the images was 3.21 pixels (1′′.3). We masked data within 10 pixels of the bad pixels, because these prevent clean image subtraction. The bad pixels were usually caused by saturation on the images, so the masked areas differed little from one epoch to the next. Since the blank areas could not be used for either the reference image or image subtraction, we merged the masks from all observations of a particular field into a common mask. We also enlarged the masks on the difference images themselves before creating the “absolute value” images (see Section 2.2), in order to minimize edge effects. We lost 18.0% of the area covered by the images to masking.

After using ISIS (Alard 2000) to register the images, we created a reference image. Images where the registration used less than 50 sources were discarded at this point. We used the nine epochs with the best seeing, as measured by the PSF size. If fewer than 18 epochs were available, we instead used only images with better than median seeing. The median seeing of the reference images was 2.13 pixels, or 0′′.84. Finally, we created the difference images. We used ISIS to align the images, determine the convolution kernel needed to convert the PSF of the reference image to that for each epoch, and then carry out the image subtraction. We used similar standard parameters for ISIS, similar to those in Hartman et al. (2004). The image was left as one subframe (sub_x = sub_y = 1); we note that our field of view is much smaller than Hartman et al. (2004). Both the background and the spatial variation in the kernel were fit with first-order polynomials (deg_bg = deg_spatial = 1). Like Hartman et al. (2004), we fit three Gaussians to the spatial variation in the kernel, with degrees 6, 4, and 3 and widths of 0.7, 2.0, and 4.0. Our kernel and stamp sizes were also the same as Hartman et al. (2004) (half_mesh_size = 13 pixels and half_stamp_size = 19 pixels).

2.2. Photometry

The next step was to select candidate variable sources in each field. SExtractor produced a catalog of sources in each field’s reference image, as well as measuring a baseline flux from the reference image. We used ISIS to extract the variable flux of each source in the SExtractor catalog for each difference image to create a light curve relative to the reference image. We added the flux from the reference image to the variable flux from the difference images to produce uncalibrated light curves for each source in a field. While we were not usually concerned with the absolute flux of the sources, only their variability and their relative brightnesses, we did set an approximate calibration using SDSS stars (point sources) within 3′ of each quasar. In the SDSSJ0249+0039 field there were no such sources identified, because few epochs registered cleanly and the SLSQ candidate was near the south edge of the frame; we therefore used the sources within 3′ of a point 6′ north of the quasar for this field. We used the average offset between the ISIS light curves and the SDSS magnitudes to calibrate each field. However, these offsets were only used when we needed an absolute measurement for the r-band magnitude, r. For calculating other statistics of the light curve, such as the standard deviation \( \sigma_r \) or the F-test quantity \( S_F \) (see below), we used only the magnitude differences calculated from the difference images and the reference image. The calibration of the field does not matter for these quantities.

As a general philosophy of difference imaging large data samples, we chose to eliminate suspect epochs rather than to understand them in detail (e.g., Hartman et al. 2008). Typical problems are that the interpolation, PSF correction, and final subtraction have increasing systematic problems as the seeing gets worse, as the background rises, or if cirrus is slightly altering the effective filter bandpass. While our present data sample is small enough that we could individually examine problematic frames, our goal is to demonstrate the method as it could be applied to far larger data samples where this becomes impractical. Using the uncalibrated light curves that ISIS extracted from the science images, we identified and dropped epochs that might have been problematic. We first eliminated epochs that may have been affected by clouds by dropping images in which the average observed fluxes in the images differed from the mean for all images of the same field by more than 1\( \sigma \). Then for each source light curve, we eliminated the two epochs that were furthest from the source’s mean flux. For quasars this will eliminate little real variability because quasar generally show gradual flux changes, with variability increasing on larger timescales (e.g., Vanden Berk et al. 2004). We selected our lens candidates in three steps. First, we made a variability cut on the \( r - \sigma_r \) (magnitude–magnitude standard deviation) plane. If the sky background dominates the noise for faint sources and bright sources variability comes from Poisson noise only, we expect that the standard deviation will go as

\[
\sigma_r = 10^{r+0.4\sigma} \sqrt{1 + 10^{-0.4(r-r_0)}}. \tag{1}
\]

In this equation, \( r_0 \) is the characteristic magnitude where background noise begins to dominate over photon statistics, and \( \sigma \) is a normalization from the photon statistics. We therefore fit a function of the form

\[
\sigma_{r,0} = 10^{r+0.4\sigma} \left[ 1 + 10^{-0.4(r-r_0)} \right] g \tag{2}
\]

to all sources with 16 < r < 24, with varying \( \sigma \) and \( g \) to get a better fit. Here, \( g \) is the slope in the sky-noise-dominated
regime. We found that $a = -2.047$, $r_0 = 18.90$, and $g = 0.931$ for our sources, where $g > 0.5$ implies that the noise was super-Poisson for bright sources. This gave us a typical standard deviation $\sigma_{r,0}$ for a given magnitude $r$. We defined our cut to be $\sigma_r > b \sigma_{r,0}$, where $b$ was some constant. We chose $b = 1.512$ so that 5% of sources with $16 < r < 24$ would pass. We also wished to exclude sources with more than 30,000 counts, because they had large residuals in the difference images. The residuals of these bright sources came from the systematics of image subtraction, so Equation (2) does not apply. We chose to conservatively cut on $r \geq 17.1$ based on our absolute calibration of $r$. Since the calibration between counts and magnitude varied slightly between fields (usually $\lesssim 0.25$ mag for a given number of counts), in some fields this cut corresponds to fewer than 30,000 counts, though never more than 30,000 counts. These cuts are shown in Figure 1.

Second, quasars have long-term, nonperiodic variability rather than periodic variability, so we identified quasars as objects whose light curves are significantly better fit as parabolas than constants. Following Hartman et al. (2004), we used the $F$-test to gauge the significance of the improvement of a parabolic fit over a constant light curve. The $F$-test is based on the ratio

$$F = \frac{\chi^2_p/(N - 3)}{\chi^2_c/(N - 1)},$$

where $\chi^2_p/(N - 3)$ is the $\chi^2$ per degree of freedom for the parabolic fit, $\chi^2_c/(N - 1)$ is the $\chi^2$ per degree of freedom of a constant light curve, and $N$ is the number of epochs being fit. We calculated $F$ after dropping the two epochs most poorly fit by a constant light curve, and those epochs with bad images, as described in Section 2.1. The expected mean of $F$, if $\chi^2_p$ and $\chi^2_c$ are independent $\chi^2$ distributions and $\chi^2_c$ has $(N - 1)$ degrees of freedom, is

$$\mu_F = \frac{N - 1}{N - 3},$$

and the expected dispersion in $F$ is

$$\sigma^2_F = \frac{2(N - 1)^2(2N - 6)}{(N - 3)^3(N - 5)},$$

so we use

$$S_F = \frac{F - \mu_F}{\sigma_F}$$

to estimate the significance of the improvement from using a parabola. Since $\chi^2_p$ and $\chi^2_c$ are not independent, with $\chi^2_p \leq \chi^2_c$ for each light curve, $\mu_F$ is not the actual mean of the calculated $F$. It can be shown that $S_F \leq 0$ for all sources. We chose a cut of $S_F \lesssim -0.64$ such that 5% of the sources with light curve statistics and $16 < r < 24$ pass the test. This choice seems to work well when we examine light curves by eye. Raising the threshold would increase the sample completeness at the price of introducing more false positives, while lowering it has the opposite effect.

Finally, to evaluate the structure of the variable flux, we summed the absolute values of the difference images from each epoch. Variable sources appear as positive peaks in these absolute difference or “absdiff” images, whatever their light curves. We analyzed the peaks in the “absdiff” images as follows. First, we searched for peaks on the image with a signal-to-noise ratio (S/N) of $\geq 5$, where the noise was estimated from the observed fluctuations in the “absdiff” image. Then, using the data from a $7 \times 7$ pixel box centered at the peak, we calculated

![Figure 1. Standard deviation of the light curves vs. average magnitudes. Our variability cut is marked by the black line segments—sources above the boundary are considered to be variable.](image-url)
the second moments of the peak using

\[ \frac{\int QF(x,y)dxdy}{\int F(x,y)dxdy}, \tag{7} \]

where \( F(x,y) \) is the “absdiff” value minus the local median background, and \( Q \) is \( x^2, xy, \) or \( y^2 \). The moments were calculated relative to the center of light of each peak, where the center of light was defined by the position about which Equation (7) equals zero when \( Q \) is \( x \) or \( y \). These moments were then converted into an estimate of the source FWHM assuming that the intrinsic profile of the source is a Gaussian. Once we calculated the HWHM (FWHM/2) major and minor axes for the peaks, we matched them to the ISIS sources. We then calculated elongations \( \epsilon \), defined by the ratio of the major axis to the minor axis fit to the source. Sources that either were elongated (\( \epsilon > 1.559 \)) or had large effective radii were considered extended. Since the different fields have different seeing for each epoch, we measured the FWHM seeing for each epoch, we measured the seeing for each field, and found the mean and standard deviation. We defined an effective radius cut for each field as the mean seeing of the field plus two standard deviations of the seeing. We then measured the HWHM (FWHM/2) major and minor axes for the peaks, we matched them to the ISIS sources. We then calculated elongations \( \epsilon \), defined by the ratio of the major axis to the minor axis fit to the source. Sources that either were elongated (\( \epsilon > 1.559 \)) or had large effective radii were considered extended. Since the different fields have different seeing, we measured the FWHM seeing for the field.

As an order of magnitude estimate of the false positive rate, suppose the chances of a source passing the variability, \( F \)-test, elongation, and radii tests are independent, and suppose it appears as a peak on the difference image. Then the chance of a source being flagged as a candidate extended object is roughly 5% \( \times \) 5% \( \times \) (10% + 20% − 2%), or \( \sim 1/1400 \). More stringent cuts would lower this false positive rate but also the completeness; conversely, more inclusive cuts would increase the false positive rate and the completeness.

3. VARIABLES IN THE FIELDS

Table 2 lists the number of sources that survive each cut and some alternate combinations of the cuts. When we consider all sources, after excluding bad images (usually due to low transparency) and dropping two epochs from each light curve, we could analyze all 27 fields. In these 27 fields, which cover an unmasked area of 0.82 deg\(^2\), we can measure light curve statistics, such as \( \sigma \) and \( SF \), for 19,829 objects. We have statistics for 32 candidate images from 23 candidate lens systems of the SQLS, as well as 48 spectroscopically identified quasars in Schneider et al. (2007). Fourteen variable candidate lensed images and 31 variable spectroscopic quasars could be analyzed in the “absdiff” images, with only two spectroscopic quasars being extended. Finally, the known lens from P. Garnavich et al. (2009, in preparation) has light curve statistics and is variable.

Figure 1 shows the mean magnitude and the standard deviation of each light curve, excluding any dropped epochs. Our sources span the range \( 14 \lesssim r \lesssim 25 \). The standard deviation shows the usual dependence on magnitude, dominated by saturation effects \( r \lesssim 15 \), and then scaling with photon noise and sky background noise at the faint end. At the typical magnitude of an SDSS quasar, \( r \sim 19.5 \), the typical standard deviation is of order 0.02 mag. Variable sources lie above the \( r-\sigma \) curve, and we see that these include some, but not all, of the SQLS lens candidates and the other quasars in the field. If we apply the cuts described in Section 2.2, we find 794 variable sources of all kinds.

In Figure 2, we plot the distribution of the sources in the space of \( SF \) and \( \sigma \). We chose \( SF \lesssim -0.64 \) as our cut, since it works well in combination with the cut on the overall variability. After making those two cuts, we were left with 174 sources, including 16 of the SQLS lens candidates and 35 of the SDSS quasars. A quick inspection of the light curves shows that the \( F \)-test does in fact pick out those light curves with a
Figure 2. F-test significance $S_F$, as described in Section 2.3, plotted against the standard deviation of the magnitudes. Our cut of $S_F \lesssim -0.64$, indicating long-term (LPV-like) behavior, is drawn on the plot as a solid line. We also show a cut of $S_F > -1.0$ (dashed line) for comparison.

(A color version of this figure is available in the online journal.)

Figure 3. Light curves of variable sources passing the $r-\sigma_r$ cut with different $S_F$ values. Epochs that were cut are marked in red, with crosses meaning the epoch was on average more than 1σ away for all sources, and rings meaning the epoch was one of the two furthest from the mean for that particular source. The sources on top are not known quasars, while the two on the bottom are SDSS spectroscopic quasars (Schneider et al. 2007).

(A color version of this figure is available in the online journal.)

long-term trend. In Figure 3, we show four light curves for sources that pass the $r-\sigma_r$ cut, three of which also pass the $F$-test. The light curve at upper left (SDSSJ203903.37+010123.7) is one of the sources that did not pass the $F$-test. This source...
is neither a Schneider et al. (2007) spectroscopic quasar nor an SQLS lens candidate (Inada et al. 2008). Note that some points are outliers, appearing half a magnitude or more from the mean, but only for one epoch at a time. The two most extreme outliers for each source were dropped to reduce spurious variability, as described in Section 2.2. While the light curve has some variability, especially in the earlier epochs, there is no overall trend, and so it fails the F-test. The other three light curves pass the F-test and show trends in their variability. These three variable sources consist of a nonquasar, an SQLS lens candidate (Inada et al. 2008), and a spectroscopic quasar which also seems to be extended. These light curves are for sources that either clearly fail the F-test \( S_F < -1 \) or clearly pass it \( S_F > -1 \)—for sources near the cut \( S_F ∼ -0.64 \), the light curves and the F-test results are more ambiguous. Our F-test cut is generous, in that most of the sources passing it do not clearly pass \( S_F < -1 \), as can be seen in Figure 2. A few of the sources that do pass the variability cuts and the F-test cannot be analyzed on the “absdiff” images. One hundred nineteen of the 174 sources that passed the variability cut and the F-test were found with \( S/N > 5 \) on the sums of the absolute values of the difference images. So, we find that 119 sources have significant long period variability and measurable spatial structure to their variability, out of the 19,829 initial sources with light curves.

As we survey in Table 2, we can compare these results with those obtained by omitting either the \( r-σr \) cut or the F-test. In the former case, we are left with 1081 sources altogether that pass the F-test. Of these, 630 were detected on the absdiff images. If, on the other hand, we include the \( r-σr \) cut but ignore the F-test, then out of the 794 variable sources, 208 were detected on the “absdiff” images. The combination of the two cuts is very effective at reducing the number of candidates relative to the number of quasars known to be present in the fields.

3.1. The P. Garnavich et al. (2009, in preparation) Lens

P. Garnavich et al. (2009, in preparation) have reported the discovery of a lens in Stripe 82 of the Sloan Survey. The source has two images, as can be seen in Figure 6, and has a combined magnitude of \( r ∼ 19.6 \); SExtractor did not resolve the two images. ISIS identified only one source at the position of the lens, because the two images were blended. We found that the lensed quasar did pass our variability cut, if marginally. It also easily passed the F-test, with \( S_F = -2.201 \). Our program did find two peaks on the “absdiff” difference image, which are the two lensed images. The P. Garnavich et al. (2009, in preparation) lensed source was the only very close pair of sources on the difference images that our method identified. The brighter component was also flagged as extended because of its elongation, given the criteria in Section 2.2. However, the lensed quasar is somewhat faint, and the \( S/N \) of the “absdiff” detections was relatively low, with \( S/N = 10.1 \) for the brighter image and \( S/N = 9.0 \) for the fainter image. While there is only one known lens in the SDSS Supernova Survey region, the fact that it was flagged both as a close pair and as an extended object on our “absdiff” image despite its faintness and limited variability is encouraging.

3.2. The SQLS Lens Candidates

We looked for both extended SQLS sources and for pairs of sources for the SQLS candidates in the difference images. Of the original 26 lens candidates in the SDSS Supernova Survey region, we find that some have variable components, and one is extended. As Table 2 shows, only 16 passed the F-test, and 14 could be analyzed on the “absdiff” images. Only one satisfied the criteria given in Section 2.2, one image of the SDSSJ1041+0031 lens, but on closer inspection, it is almost certainly a low significance false positive. A small separation lensed quasar can also appear as a cluster of variable sources on a difference image. Thirteen of the SQLS candidates are well-separated image pairs, but in all these candidate lensed sources at most one image survives the F-test, and the component that passes the tests is almost always the spectroscopically identified quasar from Schneider et al. (2005), and not the candidate second component selected by color criteria. The only exception is SDSSJ2052+0011, in which only the second component passes the F-test; however, both candidate images of SDSSJ2052+0011 have been identified as quasars. Since only one of the SQLS lens candidates show extended variability, and since no pair of candidate images have two variable components, none of them are selected by our method either. We conclude, on independent grounds, that Inada et al. (2008) were correct to reject the others as lens candidates. Furthermore, we conclude that Inada et al. (2008) were correct to reject SDSSJ1041+0031 as a pair of lensed images. SDSSJ1041+0031 will be discussed in more detail in Section 3.4.

3.3. Quasars in the Candidate Fields

Using extended variability to find gravitationally lensed quasars assumes that each quasar is in fact variable enough to appear on difference images. To address this question, we also examined the images of the 60 SDSS spectroscopic quasars (Schneider et al. 2007) in the fields of the candidate lenses, including the SQLS lens candidates themselves. As summarized in Table 2, 49 of the 60 were detected by SExtractor. We were able to perform the least-squares fitting necessary for the F-test on 48 quasars. Of these 48, 35 passed our usual variability cuts and had \( S_F ≤ -0.64 \), and we could measure the spatial structure for 31 of these. So, about two-thirds (65%) of the quasars for which we have light curve statistics show variability on the difference images. Only two of the quasars in the candidate lens fields, SDSSJ104111.61+003145.9 and SDSSJ233700.73+050456.7, were extended using the criteria given in Section 2. The latter was not one of the lens candidates in the SQLS, and we discuss both in Section 3.4.

Sesar et al. (2007) examined the Supernova Survey region and found that the majority of unresolved quasars listed in an earlier release of the SDSS Quasar Catalog (Schneider et al. 2005) with \( g < 20.5 \) were variable. Specifically, over the two years of the survey, over 60% of the quasars had variabilities over \( σ_g > 0.5 \), and over 90% of the quasars had variabilities over \( σ_g > 0.3 \). When we consider \( σ_r \), alone, we find comparable variability to Sesar et al. (2007). Of the 42 quasars with statistics and \( r < 20.5 \), we find that 26 (62%) have variabilities greater than \( σ_r > 0.5 \), and 40 (95%) have variabilities greater than \( σ_r > 0.3 \). According to our variability cut on \( r \) and \( σ_r \), 38 quasars with \( r < 20.5 \) (90%) are variable. We confirm that most quasars are variable, even though we use \( r \)-band images and variability is greater in bluer bands (Cutri et al. 1985; Vanden Berk et al. 2004; Wilhite et al. 2005).

3.4. Other Candidate Extended Objects

Figure 4 shows the elongations \( ϵ \) (ratios of major-to-minor axes) and effective HWHM of the major axes for the sources that are variable, or have \( S_F ≤ -0.64 \). Most sources cluster around
HWHM ~ 2 pixels; since the pixel scale for SDSS is 0′.396/pixel, this is consistent with a seeing of about 0′.8. Most also have elongations of $\epsilon \lesssim 1.5$. To compare each source’s extendedness with the seeing, we scale the HWHM radius to our seeing cuts in Figure 5. There are some outliers, that are either elongated ($\epsilon > 1.56$) or big (HWHM more than the mean plus two standard deviations of the seeing for the field). Seven sources passed all the cuts, one of which was the real lens (Section 3.1). Furthermore, the only close (less than 5′′.0) pair of sources on the difference images that passed all the cuts was the real lens (Section 3.1). These sources are listed in Table 3 and shown in Figure 6. The others have higher $S/N$ (~12–14), somewhat better than the P. Garnavich et al. (2009, in preparation) lens. SDSSJ014111.61+003145.9 was identified as an SQLS lens candidate with widely separated images, however our method flags only one lensed image, which means that we are flagging it for a different reason than Inada et al. (2008). It only marginally passes our elongation cut ($\epsilon = 1.59$, compared to our cut of $\epsilon = 1.56$); in terms of HWHM radius, it is comparable to a median high-variability source (HWHM = 1.8 pixels compared to the median of 1.9 pixels; see Figure 4). Both the SDSSJ0141+0031 and the SDSSJ2228−0059 fields had relatively few epochs with clean registration (24 and 20, respectively, compared with ~40–50 for the others), so that the light curve statistics are not as robust for these fields. Visually, we do not see multiple lensed components for any of the five remaining sources on the “absdiff” image, unlike the P. Garnavich et al. (2009, in preparation) lens. Although it is possible that lensed image components are blended together, most lensed quasars are expected to have separations of at least 1′′.5 (3.8 SDSS pixels; e.g., Mitchell et al. 2005), so we consider it unlikely that these are true lenses.

We checked these sources by reconstructing the difference images using a different method to register the input images. We then defined new variability, $F$-test, and extendedness cuts as in Section 2.2 for these fields. The elongation cut turned out to be very strong ($\epsilon > 2.814$). Only one source passed: a highly elongated source in the P. Garnavich et al. (2009, in preparation) lens field with low signal-to-noise variability ($S/N \approx 6.1$). Using a weaker elongation cut similar to the one we used in the previous analysis ($\epsilon > 1.5$), we now found eleven sources with $S/N > 5$ that passed. Of these, all were elongated, and six were
Figure 5. Sources that passed our extendedness cuts. In addition to the elongation $\epsilon$, we plot for each source here the ratio of the HWHM radius to the seeing cut for its field (compared to Figure 4). Sources above or to the right of the cutlines are considered extended.

(A color version of this figure is available in the online journal.)

Figure 6. Candidate extended sources, both on their reference images (above) and the “absdiff” images (below). The images are centered on the objects, and all have the same scale. SDSSJ233700.73+005456.6 at bottom near-left is a quasar. In the bottom right is a known lensed quasar (P. Garnavich et al. 2009, in preparation), which clearly has two close images in both the reference and the “absdiff” images. The third variable source off to the right in the P. Garnavich et al. (2009, in preparation) field is unrelated to the lens.

in the SDSSJ2038+0055 field. The P. Garnavich et al. (2009, in preparation) lens weakly passed because the brighter image was measured as slightly elongated. The fainter component of the lensed quasar was not measured, because the absdiff image was noisier. Of the other 10 extended sources, only one was flagged in our previous analysis, SDSSJ222836.80−010101.8. This source was neither a Schneider et al. (2007) quasar nor an SQLS lens candidate. Since the P. Garnavich et al. (2009, in preparation) lens passed but almost all of the other lens candidates did not survive this alternate analysis, this supports our conclusion that most of the other candidates are false positives and that our method works for finding lensed quasars.
4. CONCLUSION AND FUTURE PROSPECTS

We searched for sources with the spatially extended variability characteristic of gravitationally lensed quasars by applying difference imaging to the Sloan Supernova Survey fields of the SQLS lens candidates and their surroundings. We found five sources that passed simple criteria for long-term, nonperiodic variability, and which appeared extended on its “absdiff” image. One of these was an actual known lensed quasar (P. Garnavich et al. 2009, in preparation). Another was clearly due to registration problems and proper motion; the other five are relatively faint and did not show the compelling structure seen in difference images of known lensed quasars (Kochanek et al. 2006). Furthermore, only one was among the SQLS lens candidates in the SDSS Supernova Survey region, and only two were spectroscopically identified quasars (Schneider et al. 2007). Our criteria successfully rejected the other SQLS candidates, as had Inada et al. (2008) using other criteria. The remaining candidate was a candidate pair of images, but only one of the images passed. A reanalysis of the fields with candidate extended objects found several new candidate extended sources, but only two that could be matched with the previous candidates including the real lens. Our interpretation is that since most candidate extended sources did not pass both methods of analysis, while the P. Garnavich et al. (2009, in preparation) lensed quasar did, most of the candidate extended sources are false positives.

If used with other lens search techniques, such as color or morphological criteria (Oguri et al. 2006), difference imaging could substantially reduce the number of false positives, although it would only work for quasars that are variable during the observation period. Only one close pair of sources was found on the difference images, the P. Garnavich et al. (2009, in preparation) lens. This suggests that searching for clusters of distinct sources, instead of large or elongated sources, on the difference images may produce fewer false positives while still finding lensed quasars. Two-thirds of the quasars detected by ISIS passed our quasar variability tests and could be analyzed for spatial structure in the difference images. More generally, as a variability survey for lensed quasars covering 0.82 deg$^2$, we successfully identified two-thirds of the SDSS quasars in the field and had few false positive detections of lenses (six out of 20,536 sources and 794 variable sources in the fields). We note, however, that stellar proper motions are still a source of false positives in our analysis, although these will be relatively straightforward to identify and remove.

In many ways, our experiment was limited by the data. First, there is only one known lensed quasar in Stripe 82. While it passed our criteria, ideally we would test the method against several lenses to better explore the problem of false negatives. The performance of our approach would also improve with more epochs, because we could focus on epochs with better seeing. One could also add the variability information from the ugriz bands as well. Additionally, the relatively poor resolution of the SDSS survey is not ideal for identifying quasar lenses. This is also true for color and morphological techniques, such as in Inada et al. (2008), where candidate lenses with image separations of less than 1”0 were rejected. With better resolution and more epochs, false positives in the method would decrease. Finally, a survey that went deeper than the SDSS Supernova Survey would provide better data to evaluate the variability of each source. We found that the real lens and several of the candidate extended objects had low S/N because they were faint.

While these shortcomings will be partly solved by the full SDSS Supernova Survey data set, the real future for the method lies with ground-based surveys such as LSST (Tyson et al. 2002) and Pan-STARRS (Kaiser 2004) and proposed surveys from space such as the SuperNova Acceleration Probe (SNAP; Aldering et al. 2002). Pan-STARRS and LSST would repeatedly survey very large areas ($10^3$–$10^4$ rather than $10^2$ deg$^2$) with improved resolution (0.5′–1.0′ rather than >1.0′) and depth ($\simeq$24 mag rather than $\simeq$22 mag). Kochanek et al. (2006) estimated that LSST can discover $\sim 10^3$ lensed quasars with $V <$ 23. The space-based surveys would cover far less area (15 deg$^2$ for SNAP) but with vastly improved resolution ($\simeq 0.05$′) and depth ($\simeq$28 mag). Since few lenses have separations this small (1/5 is the expected median, e.g., Mitchell et al. 2005), any lens identified by variability is easily confirmed by its morphology. More important for the space missions is that their great depth allows searches for other lensed, time variable sources such as the supernovae themselves.

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