NOAO Observing Proposal *CNTAC proposal* **Panel:** *For office use.*
Date: September 29, 2001 **Category:** Cosmology

Follow-Up of Gravitational Lens Candidates from the Sloan Digital Sky Survey

PI: Patrick B. Hall **Status:** P **Affil.:** P. U. Catolica de Chile
Depto. Astronomia y Astrofisica, Campus San Joaquin, Casilla 306, Santiago, 22 Chile
Email: phall@astro.puc.cl Phone: 011-562-686-6254 FAX: 011-562-686-4948

CoI: Bart Pindor **Status:** T **Affil.:** Princeton Univeristy
CoI: Edwin L. Turner **Status:** P **Affil.:** Princeton Univeristy
CoI: Gordon Richards **Status:** P **Affil.:** Penn State University
CoI: Francisco Castander **Status:** P **Affil.:** U. Chile / Yale
CoI: Joshua Frieman **Status:** P **Affil.:** FNAL
CoI: David Johnston **Status:** T **Affil.:** University of Chicago

Matthias Barttelma
Hans-Walter Rix

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We propose to spectroscopically follow-up a complete, unbiased sample of gravitationally lensed quasar candidates chosen from the Sloan Digital Sky Survey (SDSS) dataset. Candidates are chosen as objects which are confirmed as quasars by SDSS spectroscopy and which have non-point-source morphologies at high confidence in SDSS imaging. The primary scientific goal of this work is to compile a large sample of lenses with a well-defined and well-understood selection function. Such a sample could most obviously be used to set limits on the value of the cosmological constant, although individual lens systems are also of broad scientific interest.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	RCSP + BAS	2	dark	Feb - May	Feb - May
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

We are applying for 2 CNTAC nights and 2 regular nights for this proposal. A contiguous run would be most convenient, but is not strictly necessarily.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

The Sloan Digital Sky Survey (York et al. 2000) is using a drift-scanning camera and two multi-fiber double spectrographs on a dedicated 2.5m telescope to image 10,000 square degrees of sky in 5 bands. Spectra will be obtained for one million galaxies and 100,000 quasars to i=19-20 selected from the imaging data. Most theoretical models predict that the complete SDSS spectroscopic sample will contain of order 100 gravitationally lensed quasars, plus $\sim$1000 more lenses in the photometric sample (Mortlock 1999). Thus, identifying a substantial fraction of the lenses in the survey would greatly increase the number of known lens systems.

New individual systems are of considerable interest for H_0 measurements (eg Keeton and Kochanek 1997), absorption line studies (eg Srianand and Petitjean 2000), and detailed studies of the lens galaxy (eg Chiba 2001). However, of even greater interest would be the compilation of a large sample of lenses with a well-defined and well-understood selection function. Such a sample could most obviously be used to set limits on the value of the cosmological constant (Turner 1990, Kochanek 1996), although studying the properties of the population of deflectors will also be possible. The SDSS provides the best opportunity yet to obtain such a sample, both due to the sky coverage of the survey as well the uniformity of the dataset. A sample of lenses selected from the SDSS will have an advantage over a radio-selected sample such as CLASS (Helbig 2000) because the luminosity function and particularily redshift distribution of the parent population will be well measured right from the start. Such information regarding the parent population is a pre-requisite for extracting cosmological parameters from the sample.

We propose follow-up observations of lens candidates chosen from amongst objects previously confirmed as quasars by SDSS spectroscopy, with the primary goal of collecting a well-defined sample of lens systems. We will obtain spectra for both (or all) components of all candidates. This means that our survey will be unbiased against differential reddening (unless it is so strong that only the primary image is visible in the SDSS images). We will also be unbiased against very close quasar pairs with different colors (eg Junkkarinen 2001). For the range of RA and Dec available from Cerro Tololo in the upcoming observing period, we will choose, using the method described below, targets from approximately 5000 quasars. Conventional theory predicts that there will be $\sim$5 lenses in such a sample. (The largest single existing lens sample (CLASS) has only 17 lenses.) Failure to detect a significantly greater number of lenses would be a strong argument against cosmologies with $\Lambda > 0.7$. This requires that the selection function be well understood; as described below, we will quantify the selection function for our candidates rigorously through the use of simulated images. Although confirmation of double quasar systems as real lenses (as opposed to binary quasars) may require further observations, our systematic follow-up of targets chosen from confirmed quasars will allow an upper limit to be set on the lensing fraction from the proposed observations alone.

To achieve the goals stated above, it is necessary to be able to identify lenses with splittings as small as possible, for two reasons. Firstly, the majority of lens systems are expected to exhibit splittings < 2 arcseconds, and the recovery of a sizeable fraction of these would be required to lend statistical weight to any cosmological test. Secondly, lenses with considerably larger splittings are expected to be mostly produced by cluster-scale masses, and the statistics of such lenses turn out to be practically insensitive to the value of the cosmological constant (Mortlock and Webster 2000).

SDSS is sensitive to subarcsecond lenses, as demonstrated by the known lens system APM08279+5255. This system was imaged by the SDSS in April 2000 and our software successfully deblended the two components ($\Delta\theta = 0.38''$). This object is considerably brighter than most SDSS quasars, but it does show that objects with separations considerably below the seeing FWHM can be recovered. This example is illustrated in Fig. 1.

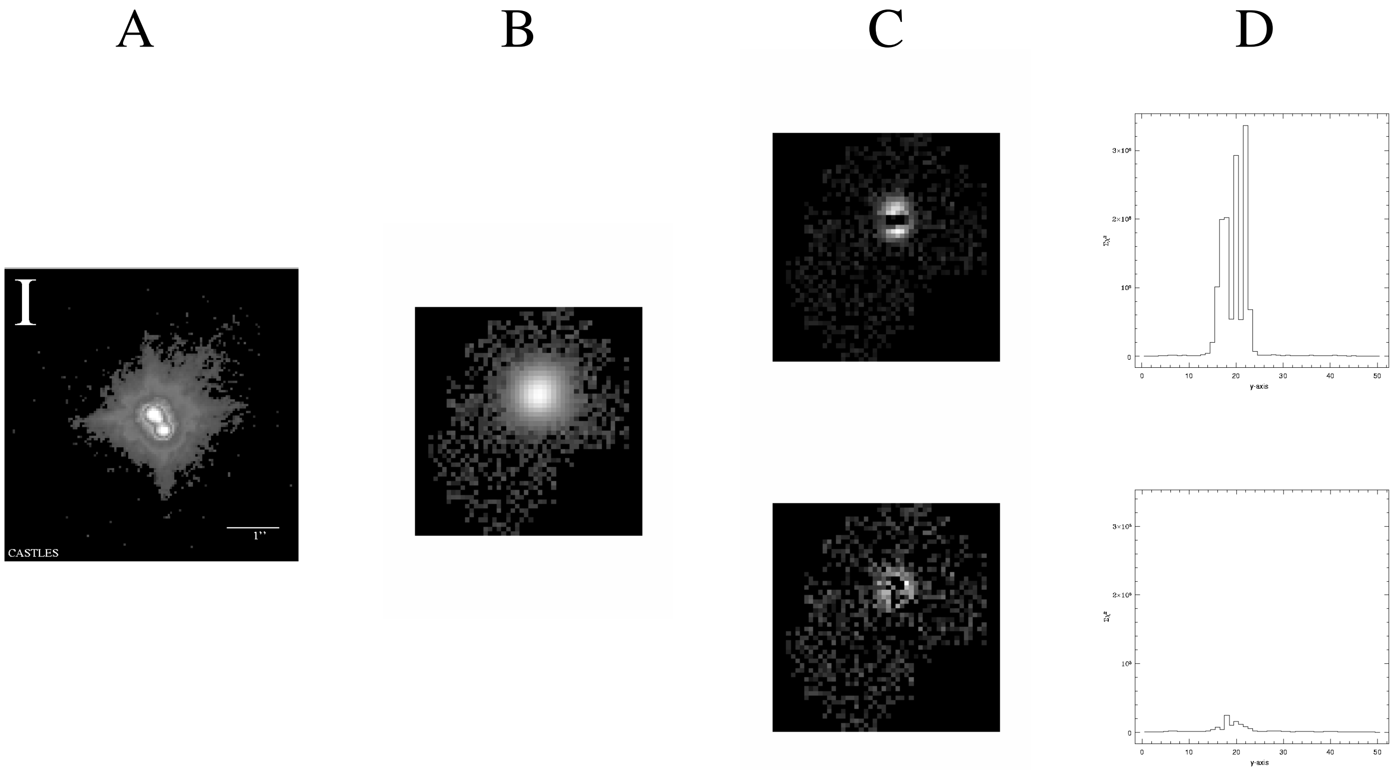

Fig. 1: A Demonstration of our selection technique as illustrated by the known lens APM08279+5255.
From left to right: (A) The HST I–band image of this system from the CASTLES survey.
(B) The SDSS r' band image of this system (Orientation differs between SDSS and HST images)
(C) The residuals of one–component (upper) and two–component (lower) fits.
(D) Histograms of the residuals squared summed along the x–axis. The ratio of these residuals squared is the statistic upon which our selection is based.

Note also that the scale differs between the HST and SDSS images. SDSS pixel scale is 0.4" per pixel.

References

Chiba, M. astro-ph/0109499

Helbig, P. astro-ph/0008197

Junkkarinen, V., et al. 2001 *ApJ.* **549L** 155

Keeton, C. R; Kochanek, C. S. 1997 *ApJ.* **487** 42

Kochanek, C. S. 1996 *ApJ.* **466** 638

Mortlock, D. J. 1999 PhD Thesis

Mortlock, D. J. ; Webster, R. L. 2000 *MNRAS* **319** 872

Srianand, R. ; Petitjean, P. 2000 *A&A* **357** 414

Turner, E. L. 1990 *ApJ.* **365L** 43

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

We select candidates by starting with all SDSS quasars with measured $z > 0.7$. Lower redshift-objects are rejected because they have a lower lensing probability, and due to possible extended emission from the host galaxy. Next we apply a simple morphological criterion which separates close pairs and other multiple component system from point sources. Using the point spread function automatically measured by the SDSS photometric pipeline, we fit both a single PSF and a pair of PSFs to the SDSS images of each quasar and compare the χ^2 of the two fits. If we define

$$D(\chi^2) \equiv \chi_1^2/\chi_2^2$$

we find that we can eliminate 90% of objects by requiring $D(\chi^2) > 1.1$. This is based on fitting 4800 SDSS quasars in the *g' r'* and *i'* images, as these are the highest S/N bands. Our candidate list is further reduced by requiring that the best-fit two component model of the object have a predicted separation of less than 3 arcseconds. Please see Use of Other Facilities regarding the completion of this sample at larger separations.

We have also developed tools which allow us to simulate objects corresponding to various lens geometries and to pass those objects through the same photometric reductions as the real SDSS imaging data. Consequently, we are able to identify the regions of the available parameter space in which our criteria are expected to successfully recover real lens systems. Our simulations indicate that pairs of point sources can be reliably identified down to a separation of about 0.5" and a flux ratio of about 10 between the two components. Although this technique is best suited for recovering lenses with two images, simulations of quadruply-lensed systems indicate that a large fraction of such systems should also be recovered. This is of particular interest since CLASS found about one-half of their lenses exhibited four (or more) components.

All together, these requirements eliminate about 99% of quasars, so that we expect to have a target list of about 50 candidates. We will not make any selection based upon colour information because a number of physical effects (eg. differential reddening by the lens galaxy) can make colour a poorly constrained component of the selection function and our goal is to obtain an unbiased sample whose selection function is understood as well as possible.

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

To date, we have been carrying on a program of lens candidate follow-up using the 3.5m ARC telescope at Apache Point Observatory. However, due to a combination of seeing and pixel scale, we have found it impractical to follow-up candidates with splittings < 3 arcseconds. Observations from Cerro Tololo would extend the follow-up effort down to smaller spiltings. As stated above, extending the sample to smaller separations is vital to many of our primary science goals.

SDSS lens candidates have been followed-up as targets of opportunity using Magellan, Subaru, and Keck. Objects revealed by the proposed observations to exhibit multiple quasar components at the same redshift would likely also receive such follow-up.

We are also submitting an ESO NTT proposal for imaging of SDSS lens candidates of lower priority (e.g. with $z < 0.7$), or selected by various other criteria, followed by spectroscopy of targets with multiple components of similar color. That proposal complements this one by exploring a larger range of parameter space, but one where lenses are less likely to be found, and it will not be complete since it will not include spectroscopy of objects with components of very different colors.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. If you wish to identify this proposal as a resubmission, include the old proposal ID number and semester.*

- **Hall**; 6 1.5m nights each 2001AB for spectroscopy of 2MASS-selected AGN candidates; AGN selection criteria about 65% efficient; letter submitted on 2 'contaminating' L dwarfs with strong Hα emission (only the 2nd & 3rd ever found); AGN results being analyzed
- **Hall**, Barrientos, Gladders, Yee, Sawicki, De Robertis; 2 4m nights 2001A for J followup of candidate brown dwarfs & z>5.5 quasars from Red-Sequence Cluster Survey; several BD candidates found and being analyzed along with additional 2MASS-detected candidates in $\sim$80 deg^2 RCS data
- **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/HYDRA+CTIO4m for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed, but key targets missed due to instrument software errors; data reduced, results now in online DMS database
- **Hall**, Ellingson, Carlberg, Yee, Lin & Marzke; 3 nights Feb. 1999 (2.5 usable) and 1 night June 1999 with ONIS on KPNO 2.1m for near-IR survey of CNOC1 cluster fields as a quasi-independent Ω_M measurement; data being analyzed, paper in preparation
- **Hall**, Green, Kennefick, Osmer, Smith: 8 nights (5 usable) Spring 1997 & 1998 w/BTC+CTIO4m for multicolor imaging for Big Faint Quasar Survey; processing pipelines up and running; data and catalog papers in preparation
- Yee, Barrientos, Gladders, Ellingson, **Hall**, Infante, Kodama; 16 nights 1999B - 2001B w/CTIO4m +MOSAIC for southern Red-Sequence Cluster Survey imaging; 9/13 useful nights to date; 3 upcoming in Nov. 2001; 35 deg^2 imaged; runs reduced to catalogs which are undergoing final calibrations and crosschecks; first RCS paper using CTIO data submitted (Hoekstra et al., cosmic shear)
- Kennefick, Falco, Green, **Hall**, Osmer, Smith, Monier, Conti; 8 CTIO 4m nights Fall 1999 - Fall 2000 for longslit spectra of candidate z>5 quasars & gravitational lenses from a 40 deg^2 BVIZ survey; two z$\sim$4.75 quasars found despite typically poor seeing & weather; paper in preparation

Observing Run Details for Run 1: CT-4m/RCSP + BAS

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

The most effective unbiased means of identifying a candidate as a possible lens system is to obtain spectra for each of the components. Thus, we intend to observe the candidates using long-slit spectroscopy with the slit aligned along the separation axis. Clearly, in order for this observation to be successful, the multiple components must be spatially-resolved. The generally excellent seeing conditions are our primary reason for choosing Cerro Tololo as the site for these observations.

The candidates will typically have magnitudes in the range 18-19 (SDSS r'), hence we expect to require integrations of 15-30 minutes, depending upon the predicted magnitude of the secondary component. We estimate an average of about 45 minutes per object,including aquisition and slit orientation. Consequently, we expect to able to observe 10-12 candidates per full night. Dark time is required due to the faintness of the targets. We propose to use the R-C Spectrograph with the Blue Air Schmidt camera and the G250 grating since we are primarily hoping to observe the broad emission lines of CIV, CIII, and MgII.

Instrument Configuration

Filters: none	Slit: 1.5”	Fiber cable:
Grating/grism: G250	Multislit:	Corrector:
Order:	λ_{start}: 3500	Collimator:
Cross disperser:	λ_{end}: 9000	Atmos. disp. corr.:

R.A. range of principal targets (hours): 7 to 17

Dec. range of principal targets (degrees): -5 to 5

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

The instrument must be configured to allow the slit to rotate between exposures.

NOAO observing proposal LaTeX macros v2.5.