EUROPEAN SOUTHERN OBSERVATORY

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Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME PERIOD: **69**

To be submitted only to: proposal@eso.org
Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Panel: **A–6**

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

2. Abstract

We propose spectroscopic follow-up a assemble a complete sample of gravitationally lensed quasar candidates from the Sloan Digital Sky Survey (SDSS) dataset. Candidates are chosen as objects which are confirmed as quasars by SDSS spectroscopy and have non-point-source morphologies at high confidence in SDSS imaging. The primary scientific goal of this work is to set limits on the value of the cosmological constant using a large sample of lenses with a well-defined and well-understood selection function and parent population. Individual lens systems are also of broad scientific interest.

3.

Run	Telescope	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	NTT	EMMI	4n	apr	d	$\leq 1.0''$	THN	v
A/alt	3.6	EFOSC2	4n	apr	d	$\leq 1.0''$	THN	v

4. Number of nights/hours Telescope(s) Amount of time

a) already awarded to this project:
b) still required to complete this project:

5. Special remarks

6. Principal Investigator: P. Hall (P. U. Catolica de Chile, RCH, phall@astro.puc.cl)

CoI(s): F. Castander (U Chile, RCH), B. Pindor (Princeton, USA), M. Bartlemann (MPIA, D), H-W. Rix (MPIA, D), E. Turner (Princeton, USA)

7. Is this proposal linked to the PhD thesis preparation of one of the applicants?

Yes / B. Pindor / mid-course

8. Description of the proposed programme

A) Scientific Rationale: The Sloan Digital Sky Survey (York et al. 2000) is using a drift-scanning camera and two multi-fiber double spectrographs on a 2.5m telescope to image 10,000 deg^2 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 ~1000 more lenses in the photometric sample (Mortlock 1999). 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 absorption line studies (eg Srianand and Petitjean 2000), detailed studies of the lens galaxy (eg Chiba 2001). and H_0 measurements (eg Keeton and Kochanek 1997), The latter in particular benefits from new lens surveys: the more lenses known, the more likely it is that one of them will have a simple configuration and short time delay which make it optimal for H_0 studies; also, studies of many objects are needed to reduce the influence of systematic errors in the modelling of any one system.

However, of even greater interest is 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, independent of high-redshift supernovae searches (Turner 1990, Kochanek 1996). Studying the properties of the population of deflectors would 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 especially the 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.

Although many of the quasar candidates found in SDSS imaging will be observed using SDSS spectroscopy, in terms of discovering new lenses the SDSS spectroscopy is limited by a number of factors: 1) the spectrographs are not capable of simultaneously observing objects within 55″ of each other due to fiber collisions; 2) only quasars brighter than i=19 (i=20 for z>3 candidates) are targeted; 3) the fibers are 3″ in diameter, comparable to or larger than the angular separation expected for most lens systems.

Thus we propose follow-up observations of lens candidates chosen primarily from amongst objects previously confirmed as quasars by SDSS spectroscopy, with the primary goal of collecting a well-defined sample of lens systems. For the range of RA and Dec visible during our assigned observing run, we will choose, using the method described below, targets from approximately 5000 quasars. Conventional theory predicts that there will be ~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. Our systematic follow-up of targets chosen from confirmed quasars will allow an upper limit to be set on the lensing fraction using only the proposed observations. Confirmation of double quasar systems as real lenses (as opposed to binary quasars) *may* require further observations, depending on the similarity of the spectra. However, in Fig. 2 we show a lens candidate from SDSS which was found to be a binary quasar with Δv=660±240 km s^{-1} using only 30 minutes of NTT spectroscopy.

This project needs good seeing and delivered image quality to achieve the goals stated above, since 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. The statistics of such lenses are practically insensitive to the value of Ω_Λ, but are sensitive to Ω_M (Mortlock and Webster 2000). Between small and large separation lenses, the SDSS will independently constrain Ω_M and Ω_Λ to about 10%.

B) Immediate Objective: In the proposed observations we will use long-slit spectroscopy to obtain spatially-resolved spectra of the multiple components of SDSS lens candidates.

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. Denoting the one PSF fit by '1' and the two PSF fit by '2', 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

8. Description of the proposed programme (continued)

by requiring that the best-fit two component model of the object have a predicted separation of less than 3 arcseconds. Candidates with larger separation are followed-up using the ARC 3.5m telescope at APO.

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.

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.

We further require that the colors of components in the best-fit model be consistent. For candidates whose components have unreliable color measurements in the SDSS images, we will use EMMI's imaging capability to obtain images in Gunn gri (close to Sloan $g'r'i'$). Because quasars can be fairly reliably distinguished from stars based on color information (Richards et al. 2001), and from compact galaxies via the extended appearance of the latter in good seeing, we expect this to considerably increase the efficiency of the lens search by eliminating quasar-star and quasar-galaxy pairs. However, a number of physical effects (eg. differential reddening by the lens galaxy) can sometimes produce significant color differences in real lens systems. We have submitted a proposal for time on the CTIO-4m in which we will not use any color selection; this will be less efficient at finding real lens systems, but will allow us to quantify what fraction of lenses suffer such effects.

All together, these requirements eliminate about 99% of quasars, so that we expect to have a primary target list of about 50 candidates. We will also have a secondary target list consisting of SDSS quasar candidates which meet all the criteria outlined above but for which SDSS spectroscopy was not obtained, strong multiple-image candidates which fail our formal two-image χ^2 criterion, and bright $z<0.7$ quasars (which are more likely to be lensed than fainter ones, and less likely to be contaminated by host galaxy emission).

References

Chiba, M. astro-ph/0109499
Helbig, P. astro-ph/0008197
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
Richards et al. 2001 *AJ* **121** 2308
Srianand, R. ; Petitjean, P. 2000 *A&A* **357** 414
Turner, E. L. 1990 *ApJ.* **365L** 43

C) Telescope Justification: A 4m class telescope is required for the observations due to the magnitude range of the targets. The NTT is our first choice for the proposed observations due primarily to the excellent seeing conditions and image quality, which should allow separation of components down to well below 1 arcsecond. The 3.6m is an acceptable alternative, although the moderately poorer seeing conditions make it slightly less well suited.

D) Observing Mode Justification (visitor or service): These observations could be conducted in service mode, but visitor mode is also feasible since the seeing is reliably $<1''$ at the NTT. We request visitor mode, since it will also allow us to optimize our targets by choosing objects from the latest available SDSS imaging, avoiding objects already followed up at CTIO, etc. In the event of very poor seeing ($>1.5''$), we do have larger-separation candidates which can be followed up.

E) Strategy for Data Reduction and Analysis: Standard reduction techniques will suffice for most of these observations. Poorly resolved spectra of multiple components can be deblended with custom software we have written and tested on APO data.

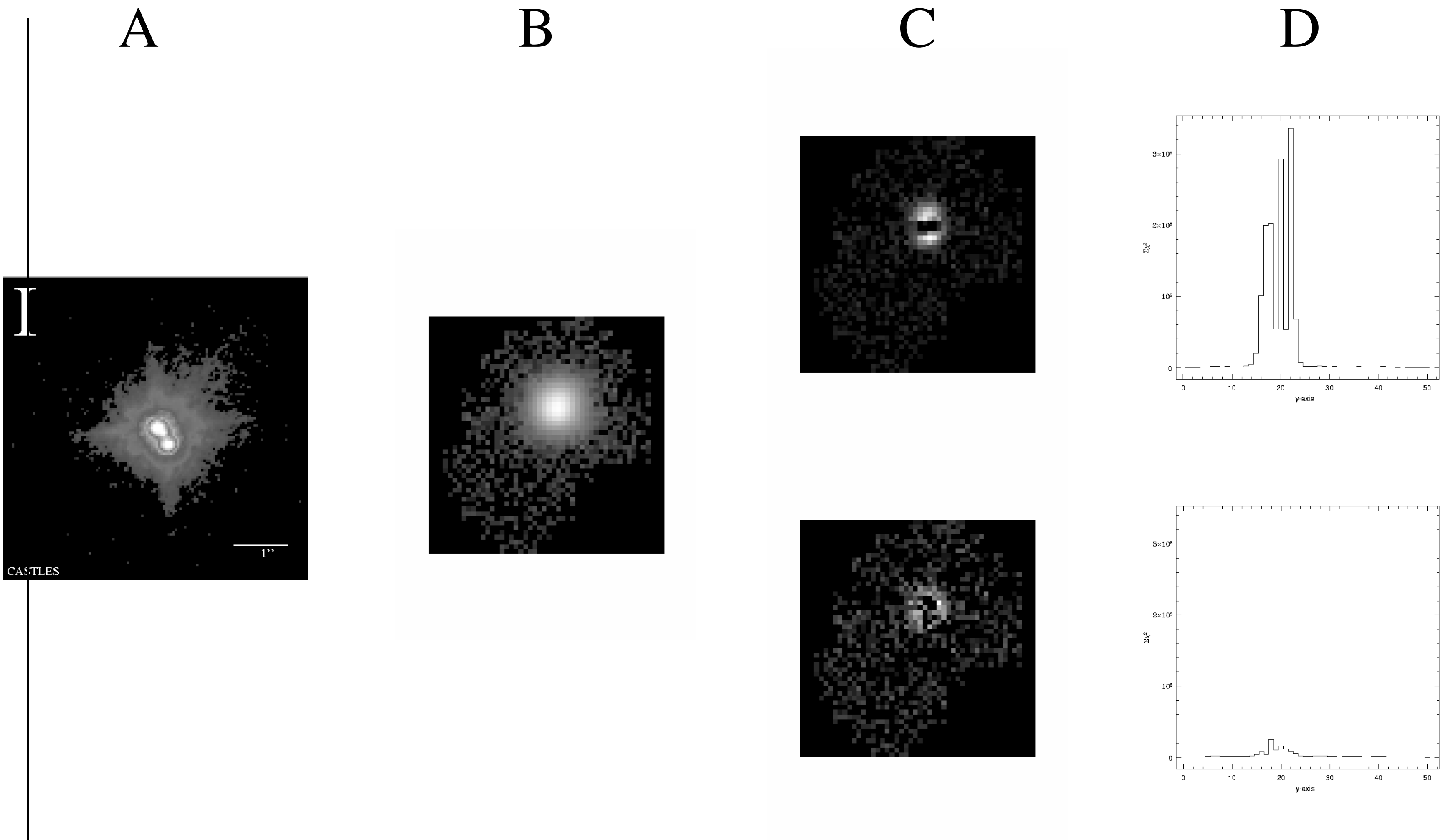

Fig. 1: A Demonstration of our selection technique as illustrated by the known lens APM08279+5255.
From left to right: (A) The HST I–band image of this system from the CASTLES survey.
(B) The SDSS r' band image of this system (Orientation differs between SDSS and HST images)
(C) The residuals of one–component (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.

8. Attachments (Figures)

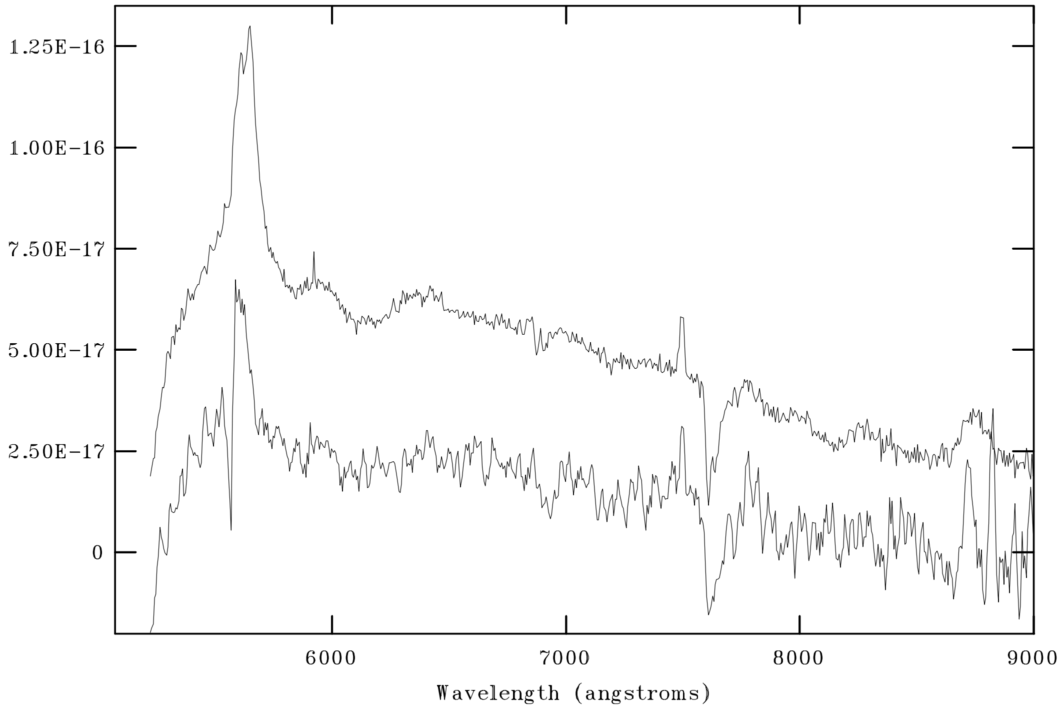

Fig. 2 - NTT-discovered binary quasar SDSSp J1600+0000

30-minute NTT spectra of the candidate lens SDSSp J1600+0000, obtained in April 2001 to take advantage of conditions of excellent seeing during an unrelated observing run. This target turned out to be a binary quasar. The fainter component B (bottom) is at a significantly lower redshift than the brighter component A (top), as can be seen in the emission lines (Mg II, left, and Hγ, right). Component B also has Hγ which is narrower and stronger relative to Mg II than in component A. (The y axis scale refers to component A; component B has been scaled and shifted arbitrarily.)

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Dark time is needed due to the faint magnitudes of the secondary lensed images.

Time Justification: The candidates will typically have magnitudes in the range 18-19 (SDSS r'), although the secondary component may be up to 2 magnitudes fainter.
For imaging we will use Gunn *gri*, since they are the filters most similar to SDSS *gri* which are available. Including overheads, we expect an average of 20 minutes' imaging per target will be sufficient to resolve secondary components which are actually compact galaxies and to provide colors accurate enough to determine which secondary components are stars.
For spectroscopy we have selected grism #2 because it provides broad wavelength coverage, allowing all of the quasar broad emission lines to appear in a single spectrum. Our goal will be get spectra with a S/N of 20 in the fainter component so as to be able to definitively determine whether both components have the *same* broad emission lines (needed to distinguish binaries from lenses). Using the EMMI ETC (version 2.8.0), we find that for the supplied QSO template integrations of 600 and 1600 seconds would be required at 19th and 20th magnitude, respectively. We estimate an average of about 40 minutes per spectroscopic target, including acquisition and slit orientation.
Consequently, we expect to able to obtain images, and spectra where indicated by the colors, for $\sim$12$-$15 candidates per full night. To produce a lens sample of comparable size to the largest existing survey (CLASS, 17 lenses), we estimate that another 4 clear nights at CTIO or NTT will be required in addition to the 4 nights proposed at each telescope this observing period. This is highly dependent on weather conditions, ability to distinguish binaries from lenses, etc. We prefer to request any additional time needed to reach 17 lenses once the survey has begun and we can better estimate how much time is needed, rather than request a fixed amount of time now which may or may not yield a sufficiently large sample of lenses.

Calibration Request: Standard Calibration

10. Report on the last use of ESO facilities

67.A-0544 / P. Hall / Spectroscopy of Candidate Reddened Quasars from SDSS+2MASS

Telescope	Instrument	Obs. Dates	Completion (%)	Time lost (%)	Reason
NTT	EMMI	17-20 Apr 2001	100%	5%	technical

Current status of obtained data: paper-submitted

Remarks: No reddened quasars found, indicating that SDSS is very complete even for very reddened quasars (paper in preparation). Several candidates were carbon stars, to appear in Margon et al. (submitted). Observations of a handful of SDSS gravitational lens candidates also made to take advantage of excellent seeing; no lenses found, but one quasar binary and one quasar companion galaxy found (paper in preparation). Observations also made of the strange [OII]-without-[OIII] galaxy RCS 1443+0805 (Hall et al., submitted).

11. Applicant's publications related to the subject of this application during the past two years

Bartelmann, M. 2000, A&A, 357, 31: High-redshift quasars lensed by spiral galaxies

Falco, E., et al., 2001, ApJ, 523, 617: Dust and Extinction Curves in Galaxies with z>0: The Interstellar Medium of Gravitational Lens Galaxies

Hall, P., et al., 2000, AJ, 120, 1660: Gravitational Lens Candidates in the CNOC2 Redshift Survey

Inada N., et al., 2001, AJ, to be submitted: A Gravitationally Lensed Quasar from the Sloan Digital Sky Survey

Keeton, C., et al., 2000, ApJ, 542, 74: The Host Galaxy of the Lensed Quasar Q0957+561

Kochanek, C., et al., 2000, ApJ, 543, 131: The Fundamental Plane of Gravitational Lens Galaxies and The Evolution of Early-Type Galaxies in Low-Density Environments

Lehar, J., et al., 2000, ApJ, 536, 584: HST Observations of 10 Two-Image Gravitational Lenses

Lidman, C., et al., 2000, A&A, 364, L62: Exploring the gravitationally lensed system HE 1104-1805: VLT spectroscopy of the lens at z=0.729

Ofek, E., et al., 2001, MNRAS, 324, 463: A survey for large-separation lensed FIRST quasars

Peng, C., et al., 1999, ApJ, 524, 572: Q1634+267A,B and the Binary QSO versus Dark Lens Hypotheses

Rusin D., Hall, P., et al., 2000, ApJL, 533, L89: CFHT AO Imaging of the CLASS Gravitational Lens B1359+154

Rusin D., et al., 2001, ApJ, 557, 594: B1359+154: A Six-Image Lens Produced by a z=1 Group of Galaxies

Wasmbsganss, J., et al., 2000, A&A, 362, L37: Microlensing results from APO monitoring of the double quasar Q0957+561A,B between 1995 and 1998

Winn, J., et al. 2000, AJ, 120, 2868: PMN J1838-3427: A New Gravitationally Lensed Quasar

Wyithe, J., et al., 2000, MNRAS, 318, 762: A small source in Q2237+0305?

12. List of targets proposed in this programme

Run	Target/Field	α	δ	Equinox	Mag.	Diam.	Additional information
A	SDSS run 752 start	09 40 00	−00 06 00	J2000			
A	SDSS run 752 end	16 39 00	−00 06 00	J2000			
A	SDSS run 756 start	07 49 00	+00 06 00	J2000			
A	SDSS run 756 end	15 36 00	+00 06 00	J2000			
A	SDSS run 994 start	05 16 38	+04 04 00	J2000			
A	SDSS run 994 start	06 20 00	−00 08 00	J2000			
A	SDSS run 1037 start	02 44 00	−08 12 00	J2000			
A	SDSS run 1037 end	04 38 00	−04 38 00	J2000			
A	SDSS run 1140 start	10 18 00	−02 03 00	J2000			
A	SDSS run 1140 end	13 41 00	−02 14 00	J2000			
A	SDSS run 1458 start	08 48 00	+01 37 00	J2000			
A	SDSS run 1458 end	16 06 00	+01 29 00	J2000			
A	SDSS run 1462 start	08 35 00	+01 17 00	J2000			
A	SDSS run 1462 end	14 59 00	+01 49 00	J2000			
A	SDSS run 1729 start	23 16 00	−09 43 00	J2000			
A	SDSS run 1729 end	04 12 00	−05 26 00	J2000			
A	SDSS run 1752 start	01 47 00	+00 06 00	J2000			
A	SDSS run 1752 end	05 04 00	+00 06 00	J2000			
A	SDSS run 1907 start	08 16 00	+01 19 00	J2000			
A	SDSS run 1907 end	10 16 00	+02 15 00	J2000			

Target Notes: Above is a list of the starting and ending coordinates of 10 SDSS imaging runs in the equatorial region of the sky. The list is non-exhaustive and more data may become available prior to the observing period. Specific candidates will be chosen depending upon assigned observing dates.

13. Scheduling requirements

3. Unsuitable period(s) of time

Run	from	to	reason
A	17-jun-02	29-aug-02	Lack of equatorial SDSS data at available RA

14. Instrument configuration

Telescope	Instrument	Parameter	Value or list
NTT	EMMI	Imag.-filt.-red-arm	772 (Gunn g)
NTT	EMMI	Imag.-filt.-red-arm	773 (Gunn r)
NTT	EMMI	Imag.-filt.-red-arm	774 (Gunn i)
NTT	EMMI	Grism-spectro-red-arm	Grism#2:385-870
NTT	EMMI	Grism-spectro-red-arm	1.0"slit