Date: September 18, 2000	Category: Structure and Dynamics of Galaxies	Proposal: C592

CFHT
OBSERVING TIME REQUEST
Semester: 2001A Agency: Canada

1. Title of the Program *(may be made publicly available for accepted proposals)*:

Finishing Mapping and Weighing a Sample of Spectroscopically Selected Gravitational Lenses

2. Principal Investigator: **Patrick Hall**

Postal address: University of Toronto, Astronomy Dept. 60 St. George St. Toronto, ON Canada M5S 3H8

Fax: 416-946-7287 Phone: 416-946-5832 E-mail: hall@astro.utoronto.ca

3. Co-Investigators:

Geraint Lewis	Institute: Anglo-Australian Observatory	E-mail: gfl@aaoepp.aao.gov.au
Mike Gladders	Institute: University of Toronto	E-mail: gladders@astro.utoronto.ca
Simon Morris	Institute: Dominion Astrophysical Observatory	E-mail: simon.morris@hia.nrc.ca
Howard Yee	Institute: University of Toronto	E-mail: hyee@astro.utoronto.ca

4. Summary of the Program *(may be made publicly available for accepted proposals)*:

The CNOC surveys have discovered 7 candidate spectroscopic gravitational lenses consisting of a normal galaxy spectrum plus a firmly detected emission line corresponding to no known transition. These lines are identified with Lyα from lensed background galaxies. Such lenses are likely to be full or partial Einstein rings, whose radially extended lensed emission provides unique constraints on the mass distribution of the lensing galaxy and the morphology of the lensed galaxy. We propose OASIS imaging spectroscopy of these lenses to confirm the Lyα identifications, determine the dynamical masses of the lensing galaxies from their velocity dispersions and/or rotation curves, and determine their lensing masses by mapping the spatial distribution of the lensed emission. Our resolution will be just sufficient to distinguish the [O II] $\lambda\lambda$3726,3729 doublet from Lyα and to measure the asymmetric Lyα profile caused by intervening absorption. Spectroscopic dynamical masses will be compared with lensing masses and photometric stellar mass estimates. Even in poor ($0\farcs9$) seeing, OASIS will be able to spatially resolve the expected $\sim1''$ radius full or partial Einstein rings, and the lenses will be modelled to determine the lensing galaxy masses (dark plus luminous matter), mass distributions, and mass-to-light ratios, as well as the lensed galaxy morphologies.

5. Summary of the Observing Run Requested:

Instrument	Detector	Moon (d)	Filters	Grisms
OASIS	EEV1	5	MR0 MR1 MR4	O300

Time Req.	Service/Queue?	Queue Mode	Image Quality	Opt. LST	Min. LST	Max. LST
3 nights	No	—	—	12:00	09:00	15:00

6a. Is this a joint proposal? NO 6b. If yes, total number of nights or hours requested from all agencies? —

7a. Is this a Thesis Project? NO 7b. If yes, indicate supervisor: —

8. Special instrument or telescope requirements:

9. Scheduling constraints:

10. Scientific Justification *(science background and objectives of the proposed observations: 1 page maximum)*:

Gravitational lensing can provide unique constraints on the mass distribution of the lensing galaxy and the morphology of the lensed galaxy when the lensed emission is radially extended [Kochanek 1995, Kochanek et al. 1998]. Most known lensed objects are point sources (quasars), but strongly lensed galaxies will be radially extended and form partial or full Einstein rings, since lensed galaxies are typically a few times $0''.1$ in size, comparable to the inner (diamond) caustic of a typical lensing galaxy [Blandford & Narayan 1992]. Miralda-Escude & Lehar (1992) show that many optical Einstein rings should exist if the faint background galaxy density is as high as now known, but only 2 optical Einstein rings are known [Warren et al. 1999, Hewett et al. 1999]. Spectroscopic searches for emission-line Einstein ring lenses determine the source and lens redshifts, and thus the lensing geometry, upon discovery, while optically-selected lenses suffer from confusion with morphologically complex galaxies [Ratnatunga et al. 1999], and radio-selected lenses have high-resolution discovery images but often faint optical counterparts, making z's difficult to obtain [Tonry & Kochanek 2000].

• We have searched for spectroscopic gravitational lenses in the CNOC1 and CNOC2 galaxy redshift surveys, which together obtained spectra of $\sim$8800 z<0.7 galaxies, most with R<21.5 [Yee et al. 2000]. One CNOC1 and six CNOC2 targets exhibit a strong emission line discrepant from the target redshift (Fig. 1; Hall et al. 2000). All these targets have redshifts based on several features, with a signal to noise ratio $\geq$4 in the redshift correlation peak. All discrepant lines are significant detections in all individual 2-D spectra, and possible causes of spurious lines are ruled out by visual inspection of the 2-D spectra. None of the discrepant lines match any emission line (or feature which mimics an emission line) at the target galaxy z, and the wavelength ratios with other observed emission lines do not match any known or reasonable pair of UV/optical lines. Thus the discrepant lines are likely to be background Lyα lensed into an Einstein ring. Deep followup CFH12k R imaging of several lenses shows no sign of the lensed emission visually or after rotating the objects 180° and subtracting, to search for asymmetric emission. This is expected if the lenses are Einstein rings, but double or quadratic lenses should have been detected this way (a candidate quad lens is in fact detected in another field). [O II] rather than Lyα emission is possible, but in two cases the spatial separation of the lensing and lensed emission is less than the Einstein radius, which means even [O II] must be lensed.

• With OASIS in TIGER integral field spectroscopy mode, we can map the lensed emission of these candidate optical Einstein rings, study the spectral profile of the lensed emission, and obtain a velocity dispersion and/or rotation curve for the lensing galaxy, thus measuring their masses, mass distributions, and mass-to-light ratios.

• Our 4.31Å spectral resolution will be just sufficient to distinguish any candidate Lyα lines which are actually [O II] [Manning et al. 2000]. Any lines which are not [O II] are most likely Lyα, which can be confirmed by looking for asymmetry in the line. High z Lyα lines are typically depressed by neutral hydrogen absorption blueward of the systemic redshift [Dey et al. 1998]. We will also search for other emission or absorption lines to confirm Lyα (none are obvious in the CNOC2 discovery spectra): Lyβ, N V, [O I], C II, or Si IV/O IV].

• Our spectral sampling and resolution will be enable σ_v measurements to $\pm 30\,\mathrm{km\,s^{-1}}$ using CN, CaH+K, Hδ & the G band. 5 of 7 lensing galaxies also show [O II] or [O III] emission which may yield rotation curves or σ_v's. These dynamical masses can be used to calibrate the D_n-σ_v and/or Tully-Fisher relations at $z\sim$0.4, and will be compared to the lensing masses to determine the ratio of stellar to dark matter velocity dispersions, important in predicting the surface density and angular separation distribution of lenses [Warren et al. 1998].

• OASIS has the unique ability to map the lensed emission and the brightness profile of the lensing galaxy during the spectroscopy. Each system will be modelled as an elliptical gravitational lens [Blandford & Narayan 1992] to obtain the lensing masses and mass-to-light ratios for comparison with estimates from other methods, as well as information on the lensed galaxy morphologies and the mass distributions of the lensing galaxies. Gravitational lensing is the only way to obtain such detailed information on distant galaxies.

• Lensing masses can also help calibrate photometric stellar masses estimated by comparing the CNOC2 UBVRI photometry to a range of Bruzual & Charlot models with varying ages, τ_{SFR}, and dust reddenings. Masses are available for two lenses; the predicted Einstein radii are $0''.62\,\Re^{0.5}$ for 0223.191225 and $2''.1\,\Re^{0.5}$ for 1447.111371, where $\Re\sim1$ is the ratio of the lensing mass (total mass in a cylinder within the Einstein radius) to the stellar mass of the whole galaxy. Comparison with observations will thus constrain $\Re$. Photometric stellar mass estimates will also be redone scaled to the lensing galaxy luminosity within the Einstein radius, allowing direct comparison of total and stellar mass-to-light ratios in the lensing galaxies' central regions.

11. References *(1 page maximum)*:

Blandford & Narayan 1992, ARA&A, 30, 311
Dey et al. 1998, ApJ, 498, L93
Hall et al. 2000, AJ, in press (astro-ph/0006434)
Hewett et al. 1999, astro-ph/9905316
Kochanek 1995, ApJ, 445, 559
Kochanek et al. 1998, astro-ph/9809371
Manning et al. 2000, astro-ph/0002241
Miralda-Escude & Lehar 1992, MNRAS, 259, 31P
Osterbrock 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*
Ratnatunga, Griffiths & Ostrander 1999, AJ, 117, 2010
Sandage, A. 1978, AJ, 83, 904
Tonry & Kochanek 2000, astro-ph/9910480
Warren et al. 1996, MNRAS, 278, 139
Warren et al. 1998, MNRAS, 299, 1215
Warren et al. 1999, A&A, 343, L35
Yee, Ellingson & Carlberg 1996, ApJS, 102, 269
Yee et al. 2000, ApJS, accepted (astro-ph/0004026)

12. Figures *(all figures must appear on a single page)*:

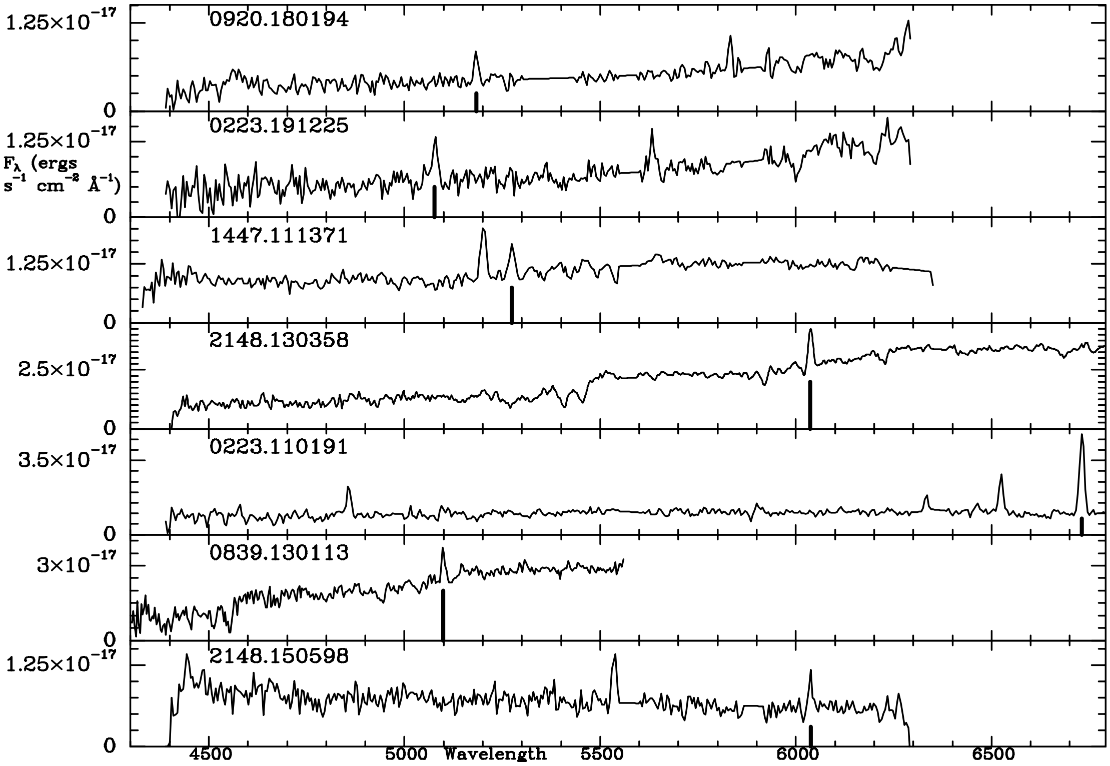

Figure 1: Observed spectra of CNOC spectroscopic gravitational lenses ordered by lens redshift, with the highest redshift at top. Discrepant lines are marked with a dash under the continuum.

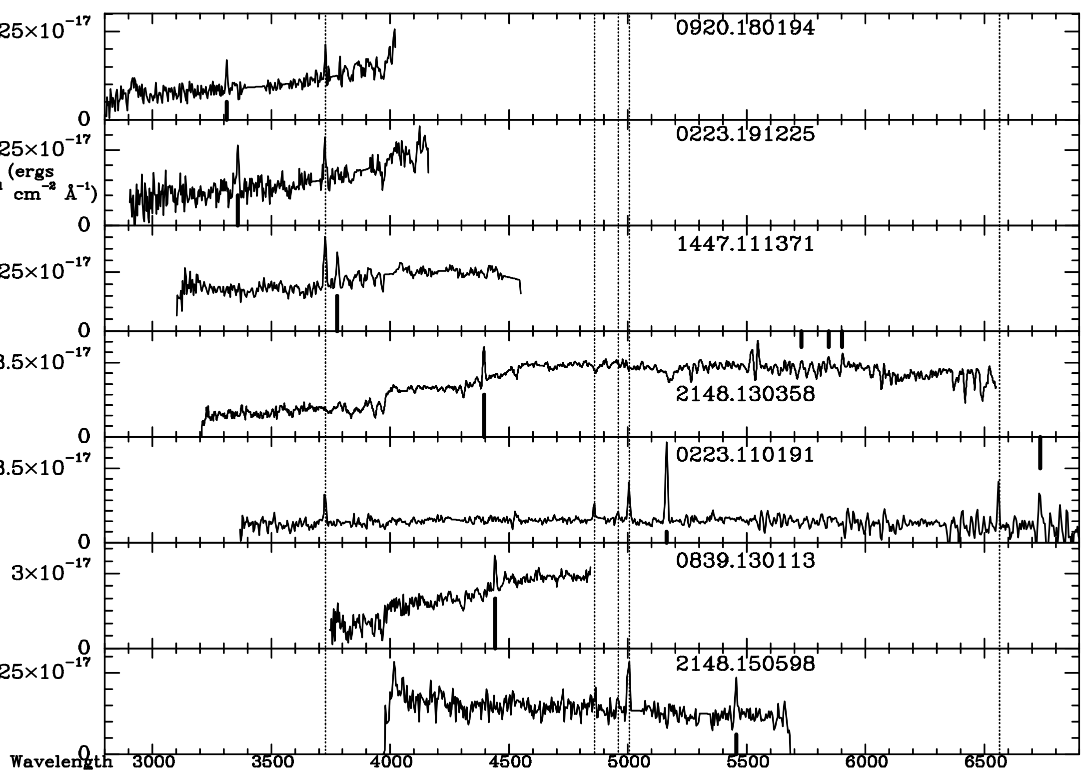

Figure 2: Spectra of CNOC candidate spectroscopic gravitational lenses after correction to the **lensing galaxy rest frame**. Dotted lines show the positions of [O II], Hβ, [O III] 4959, [O III] 5007, and Hα. Two systems have multiple lines at the discrepant redshift (marked by dashes above the continuum).

13. Technical Justification

(provide technical details of the proposed observations; justify the use of the CFHT, the requested instrument configuration, and the amount of telescope time requested: 1 page maximum):

• Since we lack suitable AOB guide stars, we will use OASIS in TIGER integral field spectroscopy mode without adaptive optics correction, with typically 4.31Å spectral resolution and $0\farcs27$ spatial sampling. The resulting $9\farcs4\times9\farcs4$ field is more than sufficient for these distant galaxies, which are only a few arcsec in extent. This spatial scale is sufficient to resolve Einstein rings ($\sim1''$ radius) even in poor conditions ($0\farcs9$ FWHM). In $\leq0\farcs65$ seeing we should be able to measure the Einstein radius to $\pm0.03''$ (1σ), sufficient to measure the lensing galaxy mass to $\pm5\%$ (1σ) [Warren et al. 1999].

• We will use the O300 grism with the MR0 (4150-4930Å), MR1 (4750-5550Å) or MR4 (5500-6350Å) filters, as appropriate to the observed wavelengths of the discrepant emission line and strong absorption lines of the object in question. We have four fall objects (observations scheduled for October 2000), and three spring objects (this proposal). Two spring objects require two spectral settings, one for the lensed emission mapping and one for the lensing galaxy velocity dispersion. The third requires only one spectral setting for both goals.

• In cases where the discrepant line is [O II] $\lambda\lambda$3726.0,3728.8 at $z\sim0.45$, our 4.31Å resolution will not cleanly resolve the $\sim$4 Å observed separation. However, modeling simulated [O II] emission as observed by OASIS will enable us to quantify the probability of an [O II] identification [Manning et al. 2000]. In addition, at least 4 of the 7 lensing galaxies have [O II] emission of their own, enabling a direct comparison of profiles with the discrepant emission line to test the possibility the discrepant line is [O II] from a projected galaxy. Of course, the lensed (or projected) and lensing galaxies are likely to have different intrinsic [O II] linewidths, but the rest-frame separation of the doublet will be the same. Thus, except in the case of intrinsic linewidths large compared to the doublet separation, superimposing the line profiles will give an indication whether the discrepant line is produced by an [O II] doublet or a single, albeit asymmetric, Lyα line [Manning et al. 2000]. Our rest-frame resolution for Lyα at $z\sim3.5$ will be $\sim$1 Å, which should be sufficient to observe the expected asymmetric profile of Lyα [e.g., Dey et al. 1998]. We should be able to measure the Lyα asymmetry despite the presence of underlying lensing galaxy emission [Warren et al. 1998] by selecting only lenslets with lensed emission and by using lenslets with only lensing galaxy emission to model its spectrum for subtraction.

• To estimate exposure times with the new EEV CCD we used the OASIS exposure time calculator, which gives the signal-to-noise ratio per pixel in the dispersion direction for 1 lenslet. We approximate the lensing galaxies as 6.25 arcsec^2 in size (86 lenslets), and the lensed emission as Einstein rings $1''$ in radius and unresolved in $0\farcs65$ seeing (4.1 arcsec^2 or 56 lenslets in size). This size will be an overestimate if the lens is only a partial Einstein ring or remains unresolved in better seeing, but will be an underestimate (lowering the SNR at our exposure times) if the ring is well resolved in the radial direction.

• Object 0920.180194 will require 5.2 hrs on-sky in MR1 to yield a spectrum of the lensed emission with SNR=2 per resolution element (2 pixels) for each lenslet (summed SNR=15/resolution element at the wavelength of the lensed emission). For the σ_v measurement, 6.4 hrs on-sky in MR4 will yield a combined spectrum of the lensing galaxy with summed SNR=13.35/resolution element in the required wavelength region. This SNR will enable velocity dispersion measurements to an accuracy of $\pm30\,\mathrm{km\,s^{-1}}$ [Warren et al. 1998].

• Object 1447.111371 will require 5.0 hrs on-sky in MR1 for both the lensed emission (SNR=6/resolution element for each lenslet; summed SNR=45/resolution element) and lensing galaxy velocity dispersion (summed SNR=13.35/resolution element).

• Object 0839.130113 will require 1 hr on-sky in MR1 for the lensed emission (SNR=5/resolution element for each lenslet; summed SNR=37/resolution element) and 2.8 hrs on-sky in MR0 for the lensing galaxy velocity dispersion (summed SNR=13.35/resolution element).

• Considering the required exposure times and overheads, we request 3 nights this semester to finish observing the full sample of seven lens candidates from CNOC1 and CNOC2. Scheduling in the first half of semester 2001-A will be sufficient to cover the three spring targets, and our scheduled observing in late October 2000 will be sufficient to cover the four fall targets (most of which have stronger emission lines than the spring objects).

14. Targets:

Object/Field	α	δ	Epoch	Mag/Flux	Comment
0920.180194	09:21:23.3	+36:36:13.0	2000	19.89	z_l=0.56; z_s=3.264; 0.6E-16; 5183.1Å; 11.6 hrs
1447.111371	14:49:51.4	+08:54:49.4	2000	19.94	z_l=0.40; z_s=3.338; 1.3E-16; 5273.6Å; 5.0 hrs
0839.130113	08:39:00.0	+28:59:59.8	1950	19.02	z_l=0.15; z_s=0.619; 1.5E-16; 5099.0Å; 3.8 hrs

15. General Target Information:

All magnitudes are R magnitudes. Comment line contains lensing galaxy redshift z_l, lensed (source) galaxy redshift z_s, discrepant line flux in units of ergs cm^{-2} s^{-1}, observed discrepant line wavelength, and total on-sky proposed exposure time for the object. Note that only the 3 targets observable in the spring are listed.

16. Is this program conducted in relation with other observations (optical, radio, space)?

NO

17. How many additional nights or hours at CFHT would be required to complete this project? 0 nights

18a. Is an extension of the one-year proprietary period required? NO

18b. If yes, justify the request for an extension:

19. Recent Allocations on CFHT and Other Telescopes:

• Hall et al.: 2.5 nights CFHT 2000-B (upcoming, Oct. 2000) w/OASIS for 4 other objects in this sample.
• Hall et al.: 3 nights CFHT 2000-B (upcoming, Jan. 2001) w/OSIS for Spectroscopy of CNOC2 AGN.
• Hall et al.: 2x0.5 nights CFHT 1999-B,2000-A for Photometric Redshifts in the Fields of Two Candidate Quasar Host Clusters at z=1.53. Data being reduced and analyzed.
• Hall & Nichol: 3 nights CFHT 1999-A for Adaptive Optics IR Imaging of Group and Cluster Candidates from the HST Medium Deep Survey. Faint and distant guidestars pushed AOB to its limits. Sufficient data was obtained for only a handful of targets and is being reduced. Data also obtained and reduced for complex gravitational lens B1359+154, paper published (Rusin, Hall et al. 2000, ApJL 533, L89).
• Hall, Gladders et al.: 2-hr WIYN 1999-A queue proposal for UB Imaging of an Optical Einstein Ring Candidate; data reduced and being analyzed in conjunction with Keck IR imaging & spectroscopy.
• Hall & Evans: 2 shifts JCMT 1999-A for SCUBA Imaging of Candidate z$\sim$1.5 Galaxy Cluster Fields; data reduced and included in Hall, Sawicki, Martini, Finn, Pritchet, Osmer, McCarthy, Evans, Lin & Hartwick (2000). 2 of 3 quasars detected in the shallow observations obtained, along with 1 additional source whose optical/IR counterpart may be an extremely red (presumably dusty) galaxy, possibly at the quasar redshift.
• Hall & Evans: 4 nights CFHT 1998-B for IR Spectroscopy of Extremely Red Objects in z>1 RLQ Fields. Instrument failed, no data obtained for this project; 1.5 nights of AOB data obtained instead, data reduced and included in Hall, Sawicki, Martini, Finn, Pritchet, Osmer, McCarthy, Evans, Lin & Hartwick (2000).
• Hall et al.: 9 nights CTIO 4-meter (Spring 1997, 1998, 1999) for Big Faint z=3.3–5.0 Quasar Survey Imaging & Spectroscopy (6 nights usable). 7.5 deg^2 imaged to B=26–26.8 (3σ) and $R\geq$25.4, $I\geq$24.2 (5σ). Data paper in preparation. Cataloguing and selection of candidate quasars to R=23–23.5 via B–R/R–I colors ongoing.

20. Publications Resulting from CFHT Observations *(only the 12 most recent contained in the database are displayed)*:

Hall, Sawicki, Martini, Finn, Pritchet, Osmer, McCarthy, Evans, Lin & Hartwick 2000, AJ, in preparation
Carlberg, Yee, Morris, Lin, Hall, Patton, Sawicki & Shepherd 2000, ApJ, accepted
Yee, Morris, Lin, Carlberg, Hall, Patton, Sawicki, Wirth, Ellingson & Shepherd 2000, ApJS, accepted
Rusin, D., Hall, P., Nichol, R., Marlow, D., Richards, A. & Myers, S. 2000, ApJ, 533, L89
Hall, Yee, Lin, Morris, Carlberg, Patton, Sawicki, Shepherd & Wirth 2000, AJ, accepted
Hall, Yee, Lin, Morris, Patton, Sawicki, Shepherd, Wirth, Carlberg & Elston 2000, AJ, accepted
Carlberg, Cohen, Patton, Blandford, Hogg, Yee, Morris, Lin, Cowie, Hu, Songaila, Hall, Sawicki & Wirth 2000, ApJ, 532, L1
Carlberg, Yee, Morris, Lin, Hall, Patton, Sawicki & Shepherd 2000, ApJ, submitted
Hoekstra, Franx, Kuijken, Carlberg, Yee, Lin, Morris, Hall, Patton, Sawicki, & Wirth 2000, ApJ, submitted
Patton, Pritchet, Carlberg, Marzke, Yee, Ellingson, Hall, Lin, Morris, Sawicki, Schade, Shepherd & Wirth 2000, ApJ, in preparation
Shepherd, Carlberg, Yee, Morris, Lin, Sawicki, Hall & Patton 2000, ApJ, in preparation