Date: March 21, 2002Category: QSO's, Active Galaxies	Proposal: C1114

CFHT
OBSERVING TIME REQUEST
Semester: 2002B Agency: Canada

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

Infrared Confirmation of $z > 5.5$ Quasar Candidates

2. Principal Investigator: **Patrick Hall**

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3. Co-Investigators:

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

A Gunn-Peterson trough (neutral hydrogen absorption) has been discovered in the spectrum of a $z = 6.28$ quasar from the Sloan Digital Sky Survey. The lack of such troughs in the four other known $z > 5.5$ quasars suggests that $z \sim 6$ is the tail end of the reionization epoch, when the spheres of ionized hydrogen around quasars and star-forming galaxies finally overlap. To better determine the timescale over which reionization occurred and how the distribution of neutral hydrogen evolved during that epoch requires more quasars at $z > 5.5$. We have in hand 45 deg^2 of CFHT Rz' imaging which allows us to select $z > 5.5$ quasar candidates as R-band dropouts. Here we propose CFHT-IR J-band imaging to efficiently and accurately separate the quasars in the candidate list from the more numerous L and T stars and brown dwarfs which have similarly red $R - z'$ colors (and which are scientifically interesting in their own right). Our survey reaches two magnitudes fainter than the SDSS, providing a tighter constraint on the quasar contribution to the UV flux needed for reionization (and enabling the discovery of more distant L and T dwarfs). The surface density of $z > 5.5$ quasars is unknown in the $20 < z' < 22$ magnitude range of our survey, but could be as high as 1 per deg^2.

5. Summary of the Observing Run Requested:

Instrument	Detector	Moon (d)	Filters	Grisms
CFHTIR	N/A	14	JHK_s	

Time Req.	Service/Queue?	Queue Mode	Image Quality	Opt. LST	Min. LST	Max. LST
2 nights	No	—	—	13:00	10:00	16:00

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)*:

There are now five AGN known at $z > 5.5$ (Stern et al. 2000a, Fan et al. 2001), of which the four most distant have been found by the Sloan Digital Sky Survey (SDSS). The most distant of these quasars, at $z = 6.28$, shows a Gunn-Peterson trough at $5.95<z<6.16$, where no flux from the quasar is detectable due to absorption from neutral hydrogen (Becker et al. 2001, Pentericci et al. 2002; cf. Djorgovski et al. 2001). The optical depth in this trough is $\tau>5.3$, whereas $\tau\sim3.3$ is expected from an extrapolation of observed absorption at $5<z<6$. This suggests that the universe was not completely reionized at z=6. However, the discovery of a Lyα-emitting z=6.56 galaxy by Hu et al. (2002) suggests that reionization was largely complete by $z\sim6.6$.

These two observations can be reconciled within the current theoretical picture of reionization (e.g., Loeb & Barkana 2001). After the recombination epoch at $z \sim 1000$, the hydrogen in the universe was completely neutral, a state which lasted until the first stars began to form and re-ionize it. As more star formation occurred and quasars began to shine, the Stromgren spheres of ionized hydrogen surrounding galaxies and quasars expanded outwards into the neutral intergalactic medium (IGM). In the early stages of reionization, when the characteric Stromgren sphere is $\lesssim 1h^{-1}$ Mpc across, the radiation damping wings of neutral hydrogen will absorb the region around Lyα in the spectrum of any object at this redshift (Miralda-Escude 1998). Hence the Hu et al. z=6.56 galaxy suggests reionization occurred at $z>6.56$. However, once the Stromgren spheres overlap, the ionizing photon density within them rises rapidly, creating rapidly expanding ionization fronts within the IGM. At this late stage of the reionization epoch, scattered regions of neutral hydrogen still exist and manifest themselves via absorption troughs in the spectra of objects at slightly higher redshift.

Thus the start of reionization can be constrained by searching for the highest-redshift Lyα emitting objects, and the end of reionization by searching for the lowest-redshift Gunn-Peterson troughs. The reionization redshift range constrains small scale mass fluctuations and the star formation rate density at very early epochs. With only a handful of lines of sight, we now know only that reionization started at $z>6.56$ and ended by about $z\sim5.8\pm0.2$. Improving these constraints requires more accurate surface densities for $z>6.56$ Lyα emitters and more $z>5.5$ quasars, to sample Gunn-Peterson troughs in a representative volume at $z>5.5$.

The 90 deg^2 Rz'-band Red-Sequence Cluster Survey (RCS; Gladders et al. 2000) can detect $z>5.5$ quasar candidates via their very red $r'-z'$ colors. The depth of the RCS enables selection of candidates to z'=22, two magnitudes deeper than the SDSS, and its area is large enough to detect $z>5.5$ quasars. Following their discovery of a z=5.5 quasar, Stern et al. (2000a) estimated the surface density of $4.3<z<5.8$ quasars with $M_B\leq-22.5$ as 7.2 deg^{-2} by scaling the Boyle et al. (1991) z=2 quasar luminosity function using the density evolution predicted by Schmidt et al. (1995): a drop of 2.7 per unit redshift at $z>3$. Our z'=22 limit is $1^{\rm m}\!\!.4$ magnitudes brighter than the Stern et al. object, but our color cut is sensitive only to quasars at $z\gtrsim5.5$. The corresponding surface density estimate is $\sim$1 deg^{-2}, but we regard this as an upper limit.

Another population of astrophysically interesting objects also has $r'-z'\gtrsim4$; namely, the L and T dwarf objects that span the border between stars and brown dwarfs. Such objects are more numerous than $z>5.5$ quasars. Fortunately, their spectral energy distributions peak in J due to opacity effects. Thus they are quite red in $z'-J$, whereas quasars are quite blue. Figure 1 shows that $z>5.5$ quasars and L/T dwarfs are well separated from each other and from normal stars & galaxies in $r'-z'$ vs. $z'-J$. Therefore **we propose snapshot J observations of $r'-z'\gtrsim4$ objects from the RCS to efficiently identify $z>5.5$ quasar candidates.**

Broad metal line emission in such quasars constrains the enrichment of massive halos at early epochs. Pentericci et al. find no abundance decrease at z=6.28, but of course more objects need to be studied. Fan et al. (2001) also show that if the quasar luminosity function (QLF) is sufficiently steep, low-luminosity quasars could provide enough ionizing photons to reionize the universe by $z \sim 6$. The RCS samples the QLF down to $M \sim -24.8$, doubling the magnitude range over which the QLF is measured at $z > 5.5$. If the QLF is not observed to steepen over this range, it would have to steepen implausibly quickly at lower luminosities to explain the entire ionizing background at $z \sim 6$. Better knowledge of the QLF thus improves our handle on star formation in the early universe. Lastly, even our contaminating L and T dwarfs are interesting; despite covering only 1/400 the area of 2MASS, we probe 1/12 its volume to fainter average $T_{\rm eff}$ (since we go $\sim$2 magnitudes deeper). Such an L/T dwarf sample can constrain the slope of the stellar mass function, the historical Galactic stellar birthrate, and the M-L and L-T transition temperatures (e.g. Liu et al. 2002).

11. References *(1 page maximum)*:

References Bahcall & Soneira 1978, ApJS 44, 73
Becker et al. 2001, AJ 122, 285
Boyle et al. 1991, in *The Space Distribution of Quasars*, 191
Burgasser et al. 2001, astro-ph/1010243
Chabrier & Baraffe 2000, ARAA 38, 337
D'Antona, Oliva & Zeppieri 1999, A&A 352, 567
Djorgovski et al. 2001, ApJL, 560, L5
Fan et al. 2000a, AJ 119, 928
Fan et al. 2000b, AJ 120, 1167
Fan et al. 2001, AJ 122, 2833
Fan et al. 2002, AJ in press (astro-ph/0111184)
Gladders et al. 2000, to appear in *Cosmic Evolution and Galaxy Formation* (astro-ph/0002340)
Hall 1998, PhD Thesis, University of Arizona
Hall, Green & Cohen 1998, ApJS, 119, 1
Hu, Cowie & McMahon, 2000, in *The Hy-Redshift Universe*, 554
Hu et al. 2002, ApJL 568, L75
Kirkpatrick et al. 2000, AJ 120, 447
Leggett et al. 2000, ApJL, 536
Liu et al. 2002, ApJL, 568, L107
Loeb & Barkana 2001, ARA&A 39, 19
Miralda-Escude, J., 1998, ApJ, 501, 15
Pentericci et al. 2002, AJ, in press (astro-ph/0112075)
Reid et al. 1999, ApJ 521, 613
Schmidt, Schneider & Gunn 1995, AJ 110, 68
Stern et al. 2000a, ApJL 533, 75
Strauss et al. 1999, ApJL 522, L16
Tsvetanov et al. 2000, ApJ 531, L61
Zheng et al. 2000, AJ, AJ 120, 1607

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

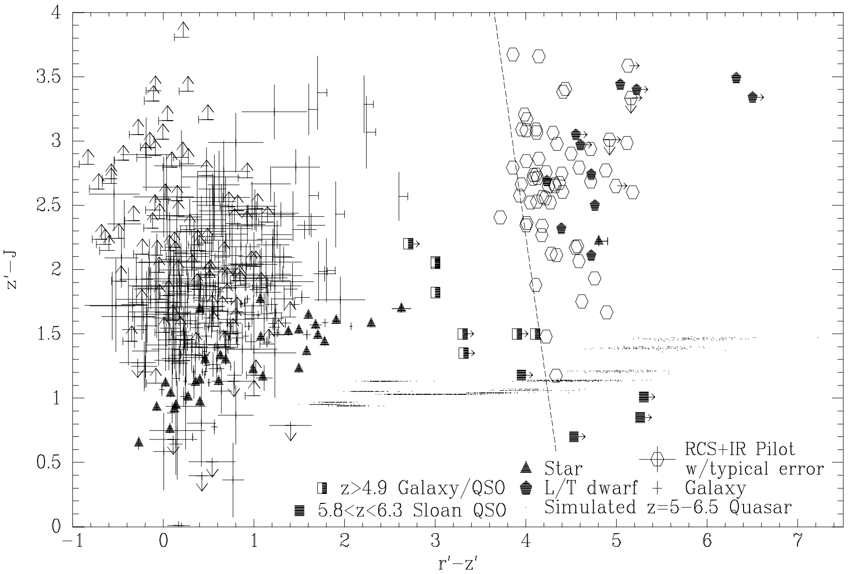

Figure 1: $r'-z'/z'-J$ color-color diagram, with a dashed line showing our **selection criterion** $(R-z)_{AB}\geq3.2$ (the transformations from CFHT R_{AB} and z_{AB} to Sloan r' and z' tilt the line slightly). The various populations are, from left to right: Morphologically classified **Galaxies** (error bars) and **main sequence Stars** (filled triangles with error bars) from $17\square'$ of $r'z'JK$ imaging to $K{\sim}21$ around two $z{\sim}1.5$ quasars (Hall et al. 1998). Upper/lower limits are indicated with arrows or error bars with tick marks. One star is a candidate brown dwarf, as noted by Hall (1998), but most objects in deep imaging samples are far too blue to meet our selection criteria. $z>$**4.9 Galaxies/QSOs** (half-filled squares) from the literature are plotted at their measured or estimated colors (Hu et al. 2000). Our color criterion might select some $z>4.9$ galaxies; any in our $z'\leq22$ sample would be extremely luminous and well worth studying. **Simulated Quasars** (points) at z=5 ($r'-z'{\sim}2$) to z=6.5 ($r'-z'{\sim}$5-6) lie below the stellar and brown dwarf loci, even when accounting for the $\pm0\overset{\rm m}{.}5$ scatter around the points expected from the dispersion in quasar spectral properties. RCS would select all 4 **5.8<z<6.3 Sloan QSOs** (filled squares; Fan et al. 2001); the one to the left of our color cut only appears there because of the weak limit on $r'-z'$ caused by the shallow SDSS r' data. Also selected by our criteria are **L and T dwarfs** and transition objects (filled pentagons; Fan et al. 2000a & references therein) which define the brown dwarf locus from M7 ($z'-J{\sim}2$) to L8 ($z'-J{\sim}3$) and beyond. **RCS targets** (open hexagons) observed in J to date at CTIO show the efficiency of our selection criteria. One or two have colors consistent with $z>5.5$ quasars, and ${\sim}6$ with T dwarfs or L/T transition objects. The remainder are consistent with known dwarfs from M7 through L8, given the typical error bar shown. All $(R-z)_{AB}\geq3.2$ candidates observed to date are real and fall within the expected $z'-J$ color ranges.

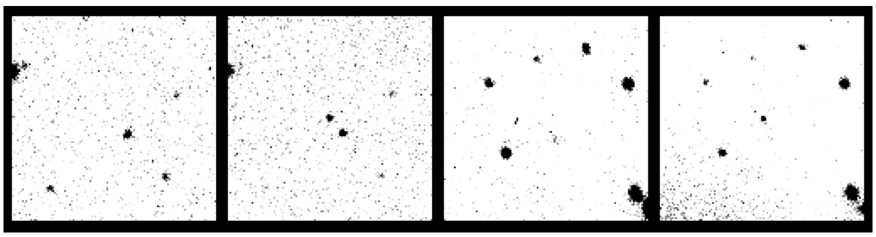

Figure 2: Two $z>5.5$ quasar candidates from RCS. In each pair, R band images are at left, and z band images at right; the candidates are visible at the center of the z band images.

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):

Existing Observations: The Red-Sequence Cluster Survey (RCS, Gladders et al. 2000) obtained ∼45□° imaging in each hemisphere to R_{AB}=25.7 (3σ) and z_{AB}=23.1 (8σ completeness limit). In the North we used the CFH8x12k at the CFHT 3.6m and in the South the MOSAIC-II 8x8k at the CTIO 4m. The astrometrically and photometrically calibrated object catalogs are undergoing final crosschecks.

Proposed Observational Program: We can isolate $z > 5.5$ quasars in our imaging data by requiring $(R-z)_{AB}\geq 3.2$ (Sloan $r'-z'\geq 4$). The only expected contaminants are themselves interesting: $z\gtrsim 5$ galaxies with SFR$\gtrsim$500 $M_\odot$/yr, extremely absorbed BAL quasars (see the end of the section), and stars and brown dwarfs of types M7 through L and T. The latter objects will dominate the sample, but J imaging allows efficient separation of T dwarfs ($z'-J\gtrsim 3$), L dwarfs ($z'-J\approx 2$–3), and $z\gtrsim 5.5$ objects ($z'-J\lesssim 2$) in the $r'-z'/z'-J$ color-color diagram (Figure 1). The hexagons in this Figure show CTIO 4m J data for ∼60 targets, demonstrating the feasibility of this technique: 1 or 2 have colors consistent with high-redshift quasars, while the rest have colors consistent with known M7, L, or T dwarfs. Thus snapshot IR followup of $r'-z'\gtrsim 4$ RCS sources efficiently identifies L dwarf, T dwarf, and $z\gtrsim 5.5$ quasar candidates, with no spurious candidates so far.

This Proposal: We propose J-band snapshot observations of $(R-z)_{AB}\geq 3.2$ candidates to z'=22 in the northern 45□° of the RCS. Followup of candidates in the southern 45□° of the RCS is being conducted with Chilean telescopes. All RCS patches visible from CFHT this semester are listed in the next session. Optimal timing for these observations would be April or May.

Why CFHT and CFHT-IR? To acquire snapshots of candidates in a significant fraction of the northern RCS survey to $J \sim 20 - 21$ requires a 4-m telescope for a realistic allocation of telescope time (ruling out the DAO). Note that the limit of 2MASS is $J \sim 16$. The pixel scale of CFHT-IR and seeing at CFHT are well suited to providing accurate photometry of point sources in a minimum amount of exposure time.

Expected Number of Targets: As discussed in the Scientific Justification, extrapolating from Stern et al. (2000) yields a surface density of $z\gtrsim 5.5$ quasars of up to 1 per deg^2 to the RCS limits. This value is an upper limit, but even a surface density a tenth of this estimate would allow the northern RCS alone to double the number of $z > 5.5$ quasars known. In any case, the surface density of candidate (and hopefully eventually confirmed) quasars in the RCS will constrain the $z > 5.5$ quasar luminosity function two magnitudes fainter than the SDSS limit. RCS is the only existing survey large and deep enough to do this.
As for brown dwarfs, the model predictions of D'Antona et al. (1999) predict that we should find 1500 of them in 100□°, including ∼50 T and ∼450 L class objects. This gives an average of 16 targets per deg^2 to z'=22. With so many targets, we want to observe each one only once. Thus we need to observe each target long enough to detect it regardless of its IR magnitude. As seen in Figure 1, this means observing to J=z'-1 so that even $z\gtrsim 5.5$ quasars can be detected.

Time Required: We approximate the magnitude distribution of our targets as half z'<21 and half z'=21–22. We estimate the total exposure time for this project as the time required to observe the z'<21 targets to J=20 and the z'=21–22 targets to J=21, though we will tailor total exposure times per target to the objects' z' magnitudes. Previous observations using OSIRIS on the CTIO 4m show that a 5σ J=20 detection requires 1 minute and a 5σ J=21 detection 6 minutes, for average exposure ∼3.5 minutes. Thus the exposure time will be on average 1 hour per deg^2 (16 targets), plus overhead. We request 2 nights to image ∼250 targets.

Sensitivity to Exotic Undesired Contaminants: The RCS took one 15-min. R_{AB} and two 10-min. z_{AB} images **in succession** for each field. The two z_{AB} images allow visual confirmation of the reality of all candidates, even those not detected in R_{AB}, and the temporally adjacent R_{AB} and z_{AB} images mean that *objects* **must** *be extremely red to be selected as candidates.* This means we are insensitive to solar system objects, extreme emission line galaxies, and distant SNe. Extremely absorbed BAL quasars at $z \sim 2$ can have the colors of $z > 5.5$ quasars (Hall et al. 2002), but such objects are a minor contaminant (Fan et al. 2001).

14. Targets:

Object/Field	α	δ	Epoch	Mag/Flux	Comment
0920+37	09:20:00.0	+37:00:00.0	1950	21	
1120+25	11:19:59.9	+25:00:00.0	1950	21	
1325+30	13:24:59.9	+29:59:59.4	1950	21	
1415+53	14:15:00.0	+53:00:00.0	1950	21	
1447+09	14:47:00.0	+08:59:59.4	1950	21	
1614+30	16:14:00.0	+30:00:00.0	1950	21	

15. General Target Information:

The faintest J magnitude we will need to reach to distinguish quasars from stars is $J = 21$ (to show that a $z' = 22$ candidate has $z' - J \leq 1$, consistent with a $z > 5.5$ quasar rather than a brown dwarf).

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. Proposed proprietary period? 12 months

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

19. Recent Allocations on CFHT and Other Telescopes:

- **Hall**, Barrientos, Gladders, Yee, Sawicki, De Robertis; 2 nights CTIO-4m 2001A for IR imaging of southern RCS $z > 5.5$ quasar candidates; data reduced (see Figure 1).
- **Hall**; CTIO-1.5m, 12 nights 2001AB for spectroscopy of 2MASS-selected AGN candidates; AGN selection criteria about 65% efficient; paper on serendipitous discovery of flaring L dwarf published; AGN paper in preparation
- **Hall** & Ivezic; ESO NTT 3.5m, 3 nights 2001A for spectroscopy of Candidate Reddened Quasars from SDSS + 2MASS; none found; papers in preparation.
- **Hall** et al.; ESO VLT 8m, 5 hours 2001A for Identification of Unusual Objects from SDSS; paper in preparation.
- **Hall** et al.; 5.5 nights CFHT 3.6-meter (2000-2001) for Mapping and Weighing a Sample of Spectroscopically Selected Gravitational Lens Candidates; one run lost, data on 2 objects from other run being analyzed.
- **Hall** et al.; 3.0 nights CFHT 3.6-meter (Fall 2000) for Spectroscopy of a Unique Sample of Low-Luminosity Active Galactic Nuclei; data being analyzed.
- **Hall** et al.; 1.0 nights CFHT 3.6-meter (Fall 1999 & Spring 2000) for Photometric Redshifts in the Field of Two Candidate z=1.5 Quasar Host Clusters; data being analyzed.

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

Patton, Pritchet, Carlberg, Marzke, Yee, Ellingson, Hall, Lin, Morris, Sawicki, Schade, Shepherd & Wirth 2002, ApJ, 565, 208
Hall et al. 2002, ApJS, 141, accepted
Hoekstra, Yee, Gladders, Barrientos, Hall & Infante 2002, ApJ, accepted
Hall, Sawicki, Martini, Finn, Pritchet, Osmer, McCarthy, Evans, Lin & Hartwick 2001, AJ, 121, 1840
Carlberg, Yee, Morris, Lin, Hall, Patton, Sawicki & Shepherd 2001, ApJ, 552, 427
Shepherd, Carlberg, Yee, Morris, Lin, Sawicki, Hall & Patton 2001, ApJ, 560, 72
Carlberg, Yee, Morris, Lin, Hall, Patton, Sawicki & Shepherd 2001, ApJ, 563, 736
Carlberg, Yee, Morris, Lin, Hall, Patton, Sawicki & Shepherd 2000, ApJ, 542, 57
Yee, Morris, Lin, Carlberg, Hall, Patton, Sawicki, Wirth, Ellingson & Shepherd 2000, ApJS, 129, 475
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, 120, 1660
Hall, Yee, Lin, Morris, Patton, Sawicki, Shepherd, Wirth, Carlberg & Elston 2000, AJ, 120, 2220