Resubmission of 02B-0292

NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 30, 2002 **Category:** Active Galaxies

Completing Infrared Confirmation of $z > 5.5$ Quasar Candidates

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
Gunn-Peterson troughs (neutral hydrogen absorption) have been discovered in the spectra of two quasars from the Sloan Digital Sky Survey at $z = 6.28$ and $z = 6.4$. The lack of such troughs in the six other known $5.5 < z < 6$ 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 90 deg^2 of CTIO and CFHT Rz imaging which enables us to select candidate $z > 5.5$ quasars and L/T type stars and brown dwarfs as objects with very red $(R - z)_{AB}$ colors. Here we propose a final semester of KPNO near-IR imaging to efficiently and accurately separate the quasars among our equatorial and northern candidates from the more numerous L and T dwarfs (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 estimated to be 0.1 deg^{-2} in the $20 < z_{AB} < 22$ magnitude range of our survey, but could be as high as 1 deg^{-2}.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	KP-4m	SQIID	4	bright	Apr - May	Feb - Jul
2						
3						
4						
5						
6						

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

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.*

There are now eight AGN known at $z > 5.5$ (Stern et al. 2000a, Fan et al. 2001, Fan et al. 2003 in prep.), of which all but one have been found by the Sloan Digital Sky Survey (SDSS). The two most distant of these quasars, at $z = 6.28$ and $z = 6.4$, show Gunn-Peterson troughs 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 τ>5.3, whereas τ∼3.3 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∼6.6. These two seemingly disparate observations can be reconciled within the current theoretical picture of reionization (e.g., Loeb & Barkana 2001). After the recombination epoch at z∼1000, the hydrogen in the universe remained neutral 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 H I 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 the universe was past the early stages of reionization by then.) Later, once the Stromgren spheres overlap, the ionizing photon density within them rises quickly, creating rapidly expanding ionization fronts within the IGM. But even then, scattered regions of neutral hydrogen do exist, manifesting themselves via Gunn-Peterson 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 just a few lines of sight, we now know only that reionization started at z>6.56 and ended by z∼5.8±0.2 at the latest. Improving this constraint requires more z>5.5 quasars, to search for Gunn-Peterson troughs in a representative volume at z>5.5. The 90 deg^2 Red-sequence Cluster Survey (RCS; Gladders et al. 2002) can detect z>5.5 quasars via their very red colors ($r'-z'$>4), and is large enough to make such a search worthwhile. After discovering a faint z=5.5 quasar, Stern et al. (2000a) estimated a surface density of 4.3<z<5.8 AGN with $M_B \leq$–22.5 of 7.2 deg^{-2} using the lower-z results of Boyle et al. (1991) and Schmidt et al. (1995). Adjusted to our fainter z_{AB}=22 limit and z>5.5 redshift range, this yields ∼1 deg^{-2}, equal to the 99% confidence upper limit from the SDSS z>5.8 quasars (Fan et al. 2001). We have 6% of the area searched in the SDSS to date, but we go two magnitudes deeper. The SDSS results are consistent with the z∼2 quasar luminosity function (QLF), and predict between 1−12 z>5.5 quasars in the RCS, but again, the 99% confidence limit is much larger. The space density of low-luminosity quasars is interesting: Fan et al. (2001) show that if the QLF is sufficiently steep, low-luminosity quasars could provide enough ionizing photons to reionize the universe by z∼6. The RCS can reach $M \sim -24.8$ and double the magnitude range over which the z>5.5 QLF is measured If the QLF does not steepen over this range, it could not plausibly explain the entire ionizing background at z∼6. The 'unexplained' fraction must be due to star formation at z∼6.

Another astrophysically interesting population has $r'-z' \gtrsim 4$; namely, the L and T stars and brown dwarfs. Such objects have a higher surface density than z>5.5 quasars. Fortunately, they are quite red in $z'-J$, whereas quasars are quite blue. Fig. 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 $r'-z' \gtrsim 4$ objects from the RCS to efficiently identify robust z>5.5 quasar candidates,** assembling a large sample of L and T dwarfs in the bargain.

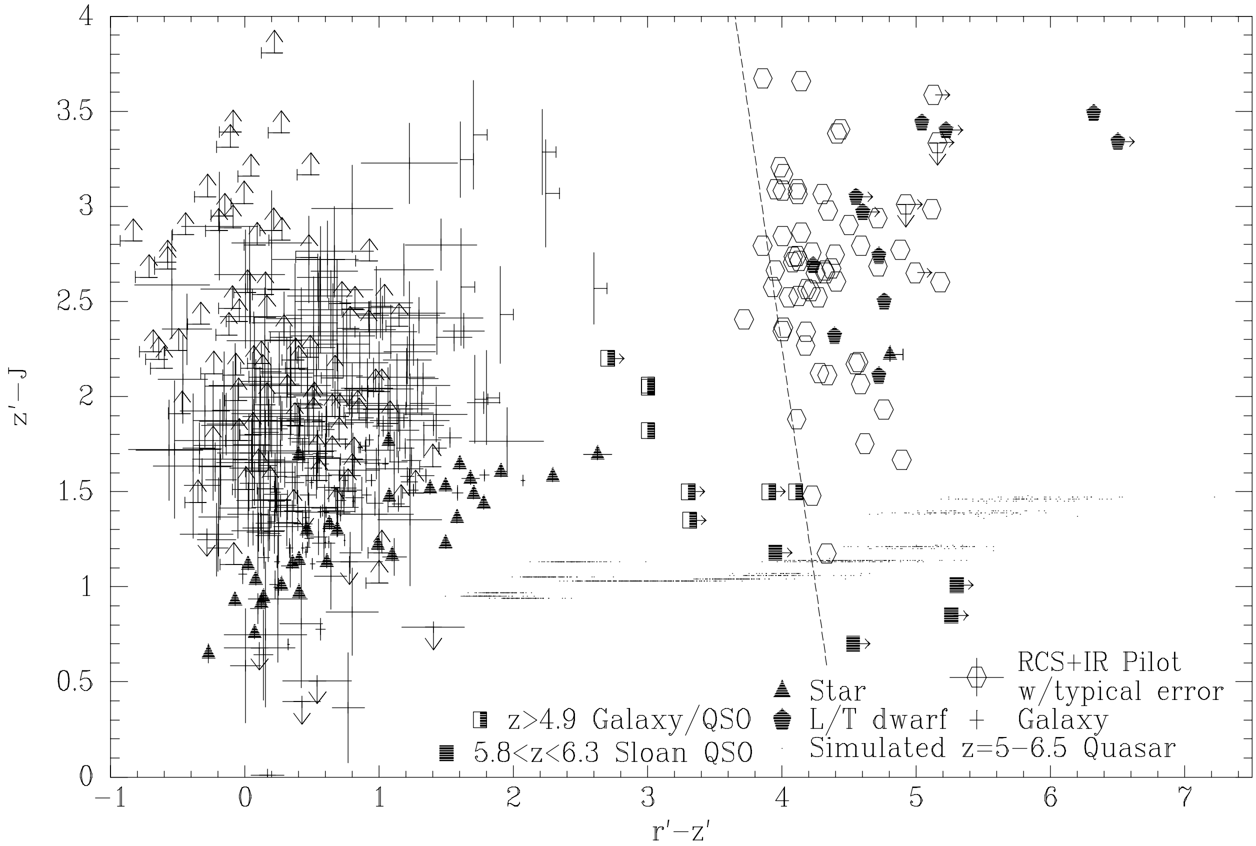

Figure 1: $r'-z'/z'-J$ color-color diagram, with a dashed line showing our **selection criterion** $(R-z)_{AB}\geq 3.2$ (the transformations from CFHT/CTIO R_{AB} and z_{AB} to Sloan r' and z' tilt the line slightly). The various populations are, from left to right: Morphologically classified **Galaxies** (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 $z'\leq 22$ 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 $0\overset{m}{.}5$ 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. Initial **RCS targets** observed in J at CTIO (open hexagons) 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 $(R-z)_{AB}\geq 3.2$ candidates observed to date are real and fall within the expected $z'-J$ color ranges.

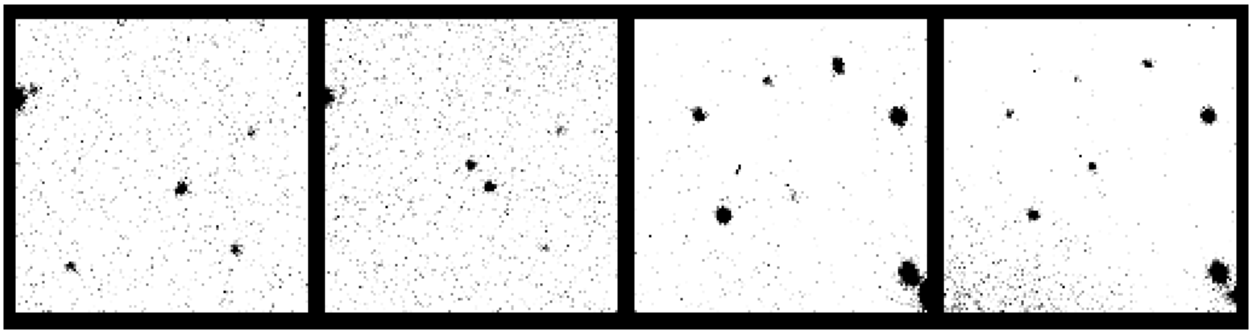

Figure 2: Two z>5.5 quasar candidates from RCS. In each pair, R band images are at left, and z band images at right; the candidates are visible at the center of the z band images.

References

Becker et al. 2001, AJ 122, 285
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D'Antona, Oliva & Zeppieri 1999, A&A 352, 567
Djorgovski et al. 2001, ApJL, 560, L5
Fan et al. 2000a, AJ 119, 928
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Hall 1998, PhD Thesis, University of Arizona
Hall, Green & Cohen 1998, ApJS, 119, 1
Hall et al. 2002, ApJS, 141, 267
Hu, Cowie & McMahon, 2000, in *The Hy-Redshift Universe*, 554
Hu et al. 2002, ApJL 568, L75
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, 123, 2151
Schmidt, Schneider & Gunn 1995, AJ 110, 68
Stern et al. 2000a, ApJL 533, 75

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)*

Existing Observations: The Red-sequence Cluster Survey (RCS, Gladders et al. 2000) obtained $\sim 45\square^\circ$ imaging in each hemisphere to R_{AB}=25.7 (3σ) and z_{AB}=23.1 (8σ completeness limit). The astrometrically and photometrically calibrated object catalogs are undergoing final crosschecks.

Ongoing 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 (Hall et al. 2002), 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). Demonstrating the feasibility of this project, the hexagons in this Figure show $\sim$60 $r'-z'>4$ targets imaged at the CTIO-4m in J, resulting in 1 or 2 $z>5.5$ quasar candidates with blue $z'-J$ colors. The rest of the $r'-z'>4$ targets imaged have redder $z'-J$ colors, consistent with known M7-M9, L, or T dwarfs.

This Proposal: We propose to *finish* our J-band snapshot observations of $r'-z' \geq 4$ candidates to z'=22 in the northern and equatorial $60\square^\circ$ of the RCS. We had 3 good nights of 4 with SQIID in late August, are scheduled for CFHT and Magellan in October and November, and have also applied for 2 CFHT nights in 2003A. To acquire snapshots of all candidates in the RCS to $J\sim$20-21 requires 4m+ telescopes for realistic allocations of telescope time. SQIID on the KPNO4m provides accurate photometry of point sources in minimal exposure time, with HKL data a useful addition.

Expected Number of Targets: As discussed in the Scientific Justification, the surface density of $z \gtrsim 5.5$ quasars to $z'<22$ is only constrained to be $\lesssim$1 per deg^2 (99% confidence). Extrapolating from the SDSS yields a predicted surface density of 1-12 $z>5.5$ quasars in the RCS, which would $\sim$double the number of $z > 5.5$ quasars known. The density of confirmed quasars in the RCS will constrain the $z>5.5$ quasar luminosity function two magnitudes fainter than the SDSS limit. The RCS is the only existing R- & z-band survey large and deep enough to do this.

As for brown dwarfs, the model predictions of D'Antona et al. (1999) suggest that we should find $\sim$1500 of them in $90\square^\circ$, including $\sim$50 T and $\sim$400 L class objects. This gives an average of $\sim$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. Experience with SQIID shows that a 5σ J=20 detection requires 2 minutes and a 5σ J=21 detection 12 minutes, for average exposure $\sim$7 minutes. Thus the exposure time will be on average 2 hours per deg^2 (16 targets), plus overhead. We request 4 nights to complete our IR followup by imaging $\sim$250 targets, all with $r'-z' \geq 4$.

Undesired Contaminants: The RCS took one 15min R_{AB} and 2x10min 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 $z\sim2$ can have the colors of $z>5.5$ quasars, but they are a minor contaminant (Fan et al. 2001).

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.*

The $90\square^\circ$ of Rz imaging data from which we select our targets consists of $45\square^\circ$ in the north from CFHT and $45\square^\circ$ in the south from the CTIO 4m.

Our overall goal is to observe a complete sample of $z>5.5$ quasar/brown dwarf candidates selected from this imaging data. For this we will use CFHT and KPNO for northern and equatorial fields, and CTIO and Magellan for southern fields. To finish the survey we are requesting 4 KPNO and 2 CFHT nights this semester.

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. Please include original proposal semesters and ID numbers when available.*

$\boxed{\star}$ **Hall**, Barrientos, Gladders, Yee, De Robertis: CTIO4m+OSIRIS 2 CNTAC nights 2001A, and KPNO4m+SQIID 4 nights 2002B, for near-IR imaging followup of candidate brown dwarfs & $z>5.5$ quasars from Red-Sequence Cluster Survey; deeper IR followup of 5 potential quasar candidates has ruled them out; many L and T dwarf candidates found, including a candidate L4-L5 10,000-AU binary; 3 good nights of SQIID data being reduced; 2002B runs upcoming at CFHT and Magellan

- **Hall** et al.: 4 CNTAC nights 2002B (Jan. 2003) for rest-frame optical survey of $1<z<3$ galaxies
- **Hall**: CTIO1.5m: 12 CNTAC nights 2001AB for 2MASS-selected AGN candidate spectroscopy; selection 65% efficient; paper on serendipitous flaring L dwarf published; AGN paper submitted
- **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/CTIO4m+HYDRA for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed; key BFQS targets missed due to instrument software errors; DMS results now in online DMS database
- Barrientos, Yee, Gladders, Ellingson, **Hall**, Infante, Kodama: CTIO4m+MOSAIC: 16 CNTAC+NOAO nights 1999B - 2001B for southern Red-Sequence Cluster Survey imaging; 45 deg^2 imaged; first results paper about to be submitted; first catalog paper in preparation
- Kennefick, Falco, Green, **Hall**, Osmer, Smith, Monier, Conti; 8 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; AJ paper in press (astro-ph/0209055)

Observing Run Details for Run 1: KP-4m/SQIID

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).*

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. Our experience with SQIID shows that a 5σ J=20 detection requires 2 minutes and a 5σ J=21 detection 12 minutes, for average exposure ~7 minutes. Thus the exposure time will be on average 2 hours per deg^2 (16 targets), plus overhead. We request 4 nights to image ~250 targets, all with $r'-z'\geq4$.

The KPNO4m is our preferred telescope because it makes snapshot observations of the required large target sample possible in a reasonable time allocation. SQIID is our preferred instrument because the HKL photometry will provide additional information on our targets' SEDs beyond that obtained from the J data, assisting in the discrimination between quasars and L/T dwarfs. However, Flamingos would be acceptable if required.

This request, along with a parallel J-band-only request at CFHT, will complete our IR imaging of z>5.5 quasar candidates from the RCS. All northern and equatorial spring RCS fields with candidates remaining are listed in the table below.

TARGET FIELDS

Name	RA (2000)	DEC (2000)	l,b
0923+37	09:23:00.0	+37:00:00.0	188,+45
1102−04	11:02:00.0	−04:00:00.0	259,+49
1120+25	11:20:00.0	+25:00:00.0	215,+70
1326+30	13:26:00.0	+30:00:00.0	53,+81
1417+53	14:17:00.0	+53:00:00.0	97,+60
1447+09	14:47:00.0	+09:00:00.0	5,+57
1614+30	16:14:00.0	+30:00:00.0	49,+45

Instrument Configuration

Filters: JHK_sL	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	$\lambda_{\rm start}$:	Collimator:
Cross disperser:	$\lambda_{\rm end}$:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 09 to 16

Dec. range of principal targets (degrees): -04 to +53

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