Proposal # ______________

LAS CAMPANAS OBSERVATORY	2002

Principal Investigator	
Pat Hall	
Institution Mailing Address P. Universidad Catolica Depto. Astronomia, Casilla 306 Santiago 22, CHILE	Office Telephone 011-562-354-6254 Email Address phall@astro.puc.cl

Project #	Project Title
1	An efficient survey for $z > 5.5$ quasars and L & T dwarfs

Project #	Co-Investigators (Names and Institutions)
1	Felipe Barrientos (P. U. Catolica)
1	Mike Gladders (OCIW)
1	Howard Yee (U. Toronto)

Project #	Run #	# of Nights	Preferred Run(s)	Max Moon 1st/2nd Half Dark	Telescope & Instrument	Observer(s)
1	1	1	L6 (L9)	|14|	Baade+ClassicCam	Hall,Barrientos,Gladders
1	2	1	L11	|14|	Clay+PANIC	Hall,Barrientos,Gladders

Run [ ]must
1) I [X]cannot observe from July 20 to July 31. Reason Paris AGN Meeting

[ ]must
2) I [X]cannot observe from Sep. 03 to Sep. 11. Reason ESO run

[ ]must
3) I [ ]cannot observe from ______________ to ______________. Reason ____________

Priorities for reasons are: 1: Scientific 2: Professional responsibilities 3: Other

Remarks on Instrumentation, scheduling requirements, other needs: Should ClassicCam end up still available on Baade during the Chilean L9 time (Sept. 23-26), we would be open to observing then instead of during L6 (June 28 - July 1). Not all our high-priority targets are visible during L6, however, hence the request for 1 night of Clay time late in the semester as well.

LAS CAMPANAS
OBSERVING PROPOSAL
DESCRIPTION
(Please Type)

ABSTRACT: Provide a concise description of the proposed research program and the scientific objectives.

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∼6 could be 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 CFHT and CTIO 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. We propose 2 nights of snapshot J-band imaging to efficiently and accurately separate the quasars among **all our southern candidates** (with equatorial ones as backup) 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 a sample of lower-temperature L and T dwarfs, on average). 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}.

Observing List: (The purpose of this list is to assist in resolving scheduling conflicts.)

Object Name(s)	Approximate RA	Approximate Dec
1. 12 deg^2 Rz imaging	21h to 24h	−63 to −35
2. 12 deg^2 Rz imaging	3.5h to 5.5h	−43 to −27
3. 20 deg^2 Rz imaging	11h to 15h	−15 to +09
4. 8 deg^2 Rz imaging	22h to 23h	−06 to −00
5. 8 deg^2 Rz imaging	02h to 04h	−10 to +00

An Efficient Survey for $z > 5.5$ Quasars and L & T Dwarfs

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 seemingly disparate observations can be reconciled within the current theoretical picture of reionization (e.g., Loeb & Barkana 2001). After the recombination epoch at $z\sim1000$, 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 $\lesssim1h^{-1}$ Mpc across, the radiation damping wings of neutral hydrogen will absorb the region around Lyα in the spectrum of any object (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. Nonetheless, even at this late stage of the reionization epoch, 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 provide strong constraints on small scale mass fluctuations and the star formation rate density at very early epochs. However, with just a few lines of sight, we now know only that reionization ended by $z\sim5.8\pm0.2$ 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. However, requiring $r'-z'>4$ is not sufficient to uniquely identify $z>5.5$ quasars, because L and T class stars and brown dwarfs also have such colors, as well as a much higher surface density. Fortunately, L and T dwarfs 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 $r'-z'\gtrsim4$ 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.

How many $z>5.5$ quasars might the RCS find? After discovering a faint z=5.5 quasar, Stern et al. (2000a) estimated a surface density of $4.3<z<5.8$ quasars with $M_B\leq-22.5$ of 7.2 deg^{-2} by scaling the Boyle et al. (1991) z=2 quasar luminosity function (QLF) using the density evolution measured by Schmidt et al. (1995): a factor of 2.7 drop per unit z at $z>3$. Adjusted to our fainter z_{AB}=22 limit and $z>5.5$ redshift range, this yields $\sim$1 deg^{-2}. This is 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 2 magnitudes deeper. The SDSS results are consistent with the $z\sim2$ QLF, and predict between **1−12 $z>5.5$ quasars in the RCS**. Thus the RCS should at least double the number of $z>5.5$ quasars known.

The space density of the low-luminosity $z>5.5$ quasars to which the RCS is sensitive is of scientific interest. 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 $z\sim6$. 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 does not steepen over this range, it could not plausibly explain the entire ionizing background at $z\sim6$. The 'unexplained' fraction can be directly attributed to star formation at $z\sim6$.

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, on average, a fainter stellar effective temperature (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).

Experimental Design and Technical Justification

Existing Observations: The RCS obtained ∼45□° imaging in each hemisphere to R_{AB}=25.7 (3σ) and z_{AB}=23.1 (8σ completeness limit). The astrometrically & photometrically calibrated object catalogs are undergoing final checks.

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, heavily dust-reddened galaxies or quasars (though the reddest known quasar (Gregg et al. 2002) has only $r'-z'$=3), 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 (Fig. 1). The hexagons in this Figure show ∼60 $r'-z'>4$ targets imaged at the CTIO-4m in J with exposure times comparable to those proposed here, including one excellent z>5.5 quasar candidate with $z'-J$=1.1. The rest of the $r'-z'>4$ targets imaged have redder $z'-J$ colors, consistent with known M7-M9, L, or T dwarfs.

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 ∼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. 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 90□°, including ∼50 T and ∼400 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. This means observing to $J=z'-1$ so that even $z\gtrsim 5.5$ quasars can be detected (Fig. 1).

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. Using the Magellan+ClassicCam exposure time calculator, we find that in one minute we can achieve SNR=15 at J=20 and SNR=7 at J=21 for a point source in a 1-arcsec diameter aperture. Thus our snapshot observations will be dominated by overhead. We assume a total of 3 minutes per object, including ≤1 minute exposure plus readout and slewing.

This Proposal: Our overall goal is to obtain J-band snapshot observations for a complete sample of z>5.5 quasar/brown dwarf candidates (objects with $r'-z'\geq 4$ and $z'\leq 22$) from the RCS imaging data. We have proposed to CFHT and KPNO for our northern and equatorial fields. Here we propose to use Magellan to observe *all* candidates in the southern 24□° of the RCS this semester (with a further equatorial 36□° as backup).

To acquire snapshots of all candidates in the RCS to J∼20-21 requires 4m+ telescopes for realistic allocations of telescope time. For our estimated 16 targets per deg^2, completely surveying our southern fields with Magellan will require only 2 nights, assuming 3 minutes total (pointing + observation + readout) per target. Our fields are situated such that 1 night in late June and 1 night in late November offers essentially complete coverage. For the November run, if PANIC is delayed or otherwise unavailable, ClassicCam would be acceptable since **the small field of view of ClassicCam is not a problem for this project.**

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∼2 can have the colors of z>5.5 quasars, but they are a minor contaminant (Fan et al. 2001).

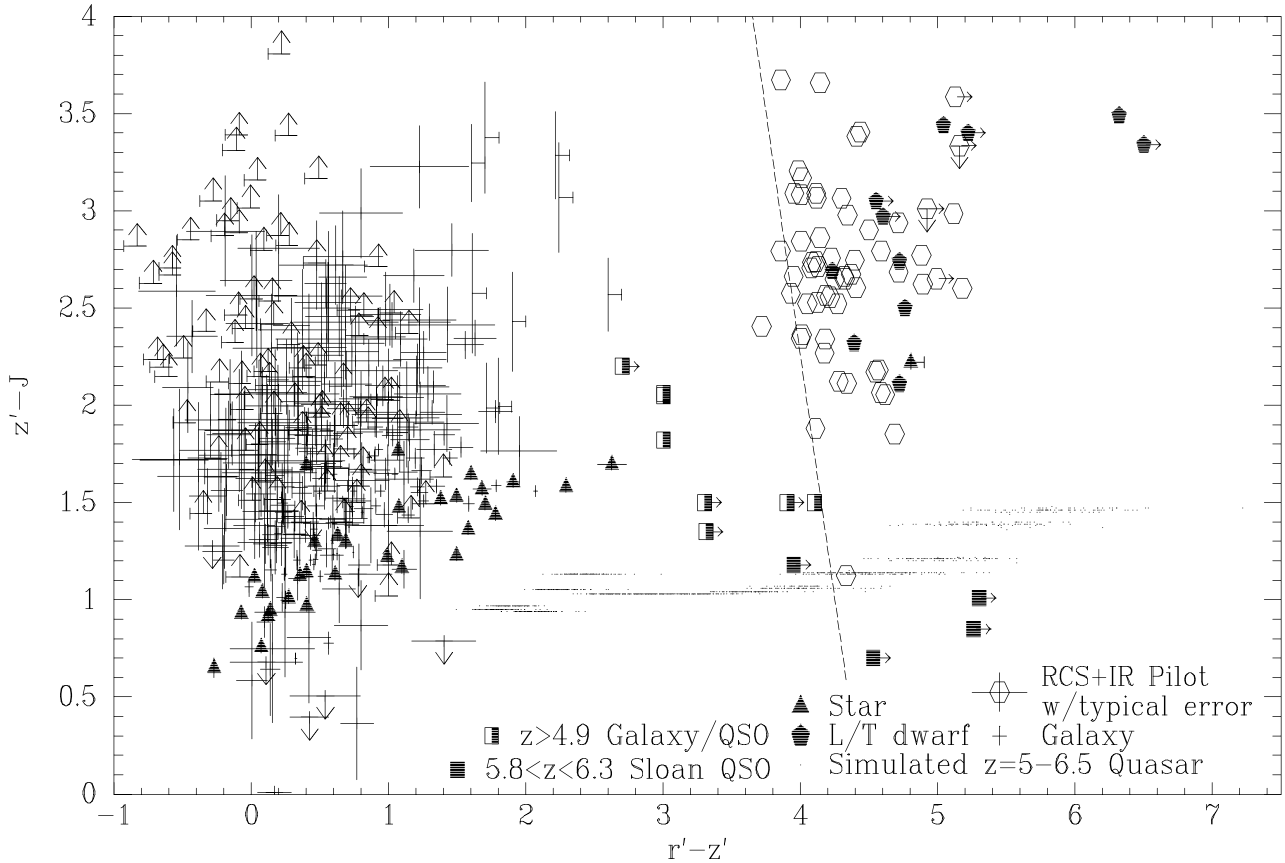

Figure 1: $r'-z'/z'-J$ color-color diagram, with a dashed line showing our **selection criterion** $(R-z)_{AB} \geq 3.2$ (the transformations from CFHT/CTIO R_{AB} and z_{AB} to Sloan r' and z' tilt the line slightly). The various populations are, from left to right: Morphologically classified **Galaxies** (error bars) and **main sequence Stars** (filled triangles with error bars) from $17\square'$ of $r'z'JK$ imaging to $K\sim21$ around two $z\sim1.5$ 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 ($r'-z'\sim2$) to z=6.5 ($r'-z'\sim$5-6) lie below the stellar and brown dwarf loci, even when accounting for the $0^{\rm m}\!.5$ 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 ($z'-J\sim2$) to L8 ($z'-J\sim3$) and beyond. **RCS targets** observed in J to date at CTIO (open hexagons) show the efficiency of our selection criteria. One target is consistent with being a $z>5.5$ quasar, and $\sim$6 with being T dwarfs. 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.

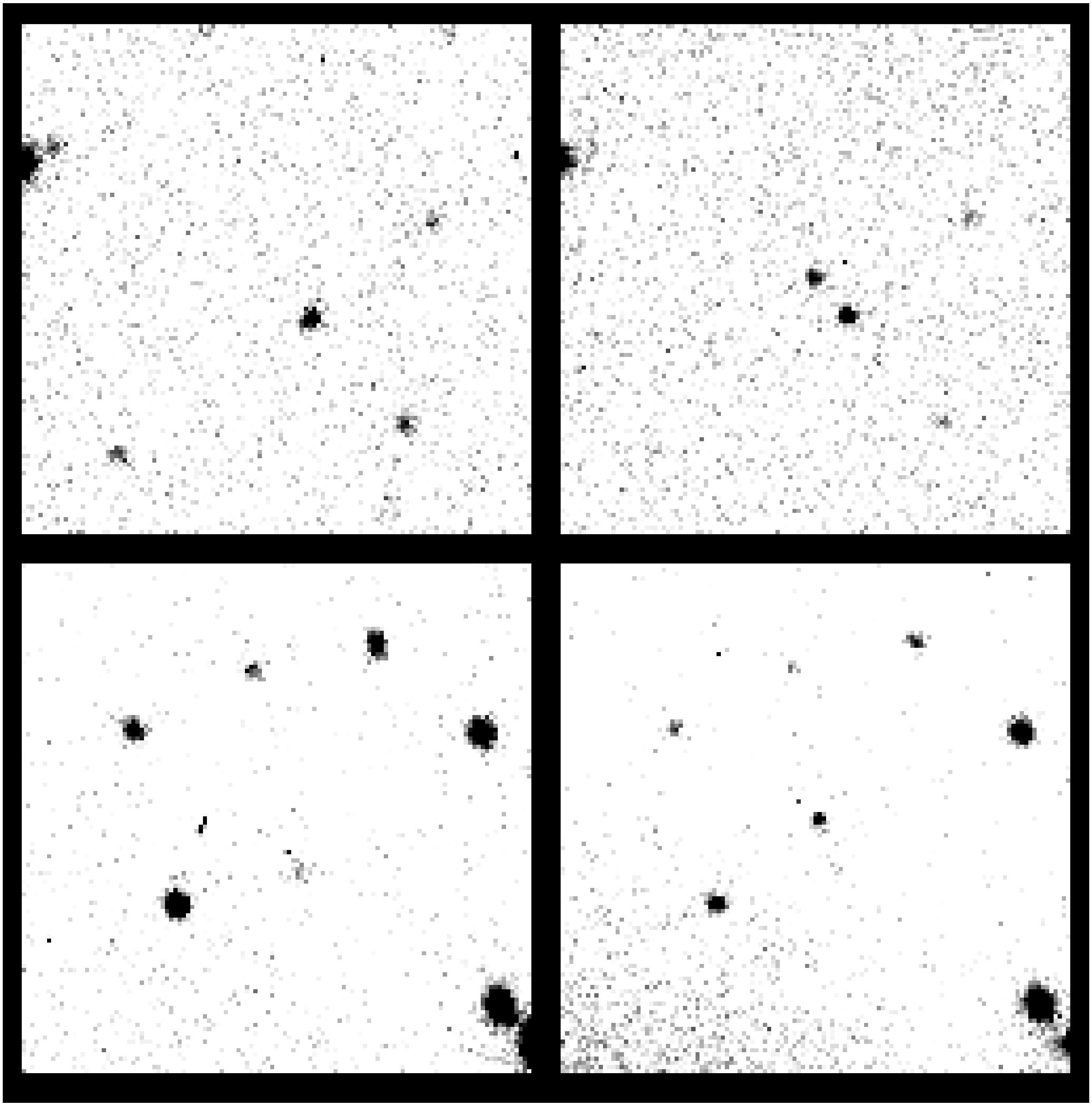

Figure 2: Two z>5.5 quasar candidates from the RCS. The candidates are visible at the center of the z band images (right), but are invisible in the R-band images (left). The top-row candidate is located above and to the left of a brighter, bluer galaxy; the bottom-row candidate is located above and slightly to the left of a very faint, blue galaxy.

References

Becker et al. 2001, AJ 122, 285
Boyle, B. J. 1991, in *Space Distribution of Quasars* (ASP: San Francisco), 191
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
Gladders, Yee & Ellingson 2002, AJ, 123, 1
Gregg et al. 2002, ApJ, 564, 133
Hall 1998, PhD Thesis, University of Arizona
Hall, Green & Cohen 1998, ApJS 119, 1
Hall et al. 2002, ApJS in press (astro-ph/0203252)
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, in press (astro-ph/0112075)
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1995, AJ 110, 68
Stern et al. 2000a, ApJL 533, 75