An Efficient Survey for Faint L Dwarfs, T dwarfs, and $z > 5.5$ Quasars

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
The discovery of L and T dwarfs has opened a new window on the study of brown dwarfs. **We propose to continue a J-band snapshot survey to rapidly and efficiently assemble a large sample of L and T dwarfs complete to $2.^{\rm m}5$ fainter in J than 2MASS or Sloan.** We have in hand 77□° of a planned 100□° of deep $(Rz)_{AB}$ imaging from which we can identify candidate L and T dwarfs and $5.5\lesssim z \lesssim 7$ quasars to z'=22 through J-band followup of $r'-z'\geq 4$ objects. These three populations of objects are well separated in the $r'-z'/z'-J$ color-color diagram, and are relatively bright (L & T dwarfs, J<20; quasars, J<21.5). The full 100□° survey (50□° in the north and 50□° in the south) could find more than 50 J<18.5 T dwarfs, 450 J<19.5 L dwarfs, 1000 J<20 M7-M9 dwarfs and up to 100 $z \gtrsim 5.5$ quasars. We will use our magnitude-limited brown dwarf sample to constrain the slope of the mass function α, the Milky Way's historical stellar birthrate $B(t)$, and the M-L and L-T transition temperatures. Despite covering only 1/400 the area of 2MASS, we probe $\gtrsim$1/12 its volume and our brown dwarf sample will have lower average $T_{\it eff}$ than 2MASS or Sloan. We are also far more sensitive to L-T transition objects than 2MASS since we do not select on IR-IR colors.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	OSIRIS	3	bright	Aug - Jan	Aug - Jan
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.*

Brown dwarfs occupy a unique regime between stars on the hydrogen-burning main sequence and giant planets which never burn deuterium. L and T class brown dwarfs have been studied intensively since their discovery. Nonetheless, there are ≤23 published T dwarfs (Burgasser et al. 2001), and while ≥100 spectroscopically confirmed L dwarfs are known, the faintest has only J=17.3 and most have been found using a single technique: IR color selection from 2MASS (Kirkpatrick et al. 2000). We are conducting a J-band snapshot survey to efficiently select brown dwarfs up to $2^{\mathrm{m}}.5$ fainter than 2MASS using different selection criteria: optical-IR colors. The spectral energy distributions of late M to T dwarfs peak in J due to opacity effects. Thus, J observations of $r'-z' \gtrsim 4$ sources from the 100□° Red-Sequence Cluster Survey (RCS; Gladders et al. 2000) could yield more than 50 J<18.5 T dwarfs, 450 J<19.5 L dwarfs, and 1000 J<20 M7-M9 dwarfs (D'Antona et al. 1999), plus ≤100 quasars at $5.5 \lesssim z \lesssim 7$. With $r'-z'/z'-J$ colors for this sample, we will:

• **determine the relative surface densities of L and T dwarfs to J=18.5 and the L dwarf surface density to J=19-20, $2^{\mathrm{m}}.5$ fainter than possible with 2MASS or most of Sloan**. At these J magnitudes, we probe beyond the disk scale height at high T_{eff} (D'Antona et al. 1999), which means our sample's average T_{eff} will be lower than in 2MASS or Sloan samples. T dwarfs, L dwarfs, and $z \gtrsim 5.5$ quasars are well separated in the $r'-z'/z'-J$ color-color diagram, and the Sloan L dwarfs of Fan et al. (2000a) suggest that $z'-J$ correlates well with spectral type (Figure 1). If this is confirmed by spectroscopy of a somewhat larger sample, we will be able to determine subtypes for our entire sample from colors alone. By modelling the magnitude and spectral type distributions using theoretical $L-T_{eff}$ tracks for different masses, we will constrain α, the slope of the brown dwarf mass function (providing an estimate of their contribution to Galactic dark matter; Chabrier & Baraffe 2000); $B(t)$, the Milky Way's historical stellar birthrate; and the M-L and L-T transition temperatures (Reid et al. 1999).

• **assemble an L and T dwarf sample selected only by optical-IR color**, complementing 2MASS samples which are probably biased by IR-IR color selection (Kirkpatrick et al. 2000). In particular, the $J-H/H-K$ colors of L/T transition objects (in which methane absorption is becoming prominent) overlap those of main sequence stars (Leggett et al. 2000), making 2MASS selection difficult. However, $r'-z'/z'-J$ colors appear to vary smoothly from L to T dwarf, so our sample is sensitive to transition objects and will reach $2^{\mathrm{m}}.5$ deeper than possible with optical-IR selection using Sloan. Kirkpatrick et al. (2000) argue that the L/T transition happens over a narrow range in temperature, ≤100 K, so large samples such as ours are needed to constrain their surface and space densities relative to L and T dwarfs.

• **search for T dwarfs cooler than currently known** ($T_{eff} \lesssim 750$ K), to study atmospheres at such temperatures. We sample ∼1/12 the volume of 2MASS, and are sensitive to $T_{eff} \geq 400$ K objects within 5.5 pc (the distance of Gl229B, which has J=14.3), and $T_{eff} \geq 700$ K objects within 18 pc.

• **search for $5.5 \lesssim z \lesssim 7$ quasars**, needed to study the origin and homogeneity of the reionization of the universe and the formation and enrichment of massive halos at very early epochs. Following their discovery of a z=5.5 quasar, Stern et al. (2000a) estimate 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 $1^{\mathrm{m}}.4$ magnitudes brighter than the Stern et al. object (and $2^{\mathrm{m}}.8$ magnitudes fainter than the most distant known quasar at z=5.8, found in 600□° of Sloan data, Fan et al. 2000b). However, our color cut is sensitive only to quasars at $z \gtrsim 5.5$ (the z=5.5 quasar has $r'-z' \gtrsim 3.9$, and the z=5.8 quasar $r'-z' \gtrsim 5.3$). Thus the corresponding surface density estimate is ∼1 deg^{-2}. We regard this as an upper limit, however, given the fact that most z>5 quasar searches over the past few years have had unpublished null results.

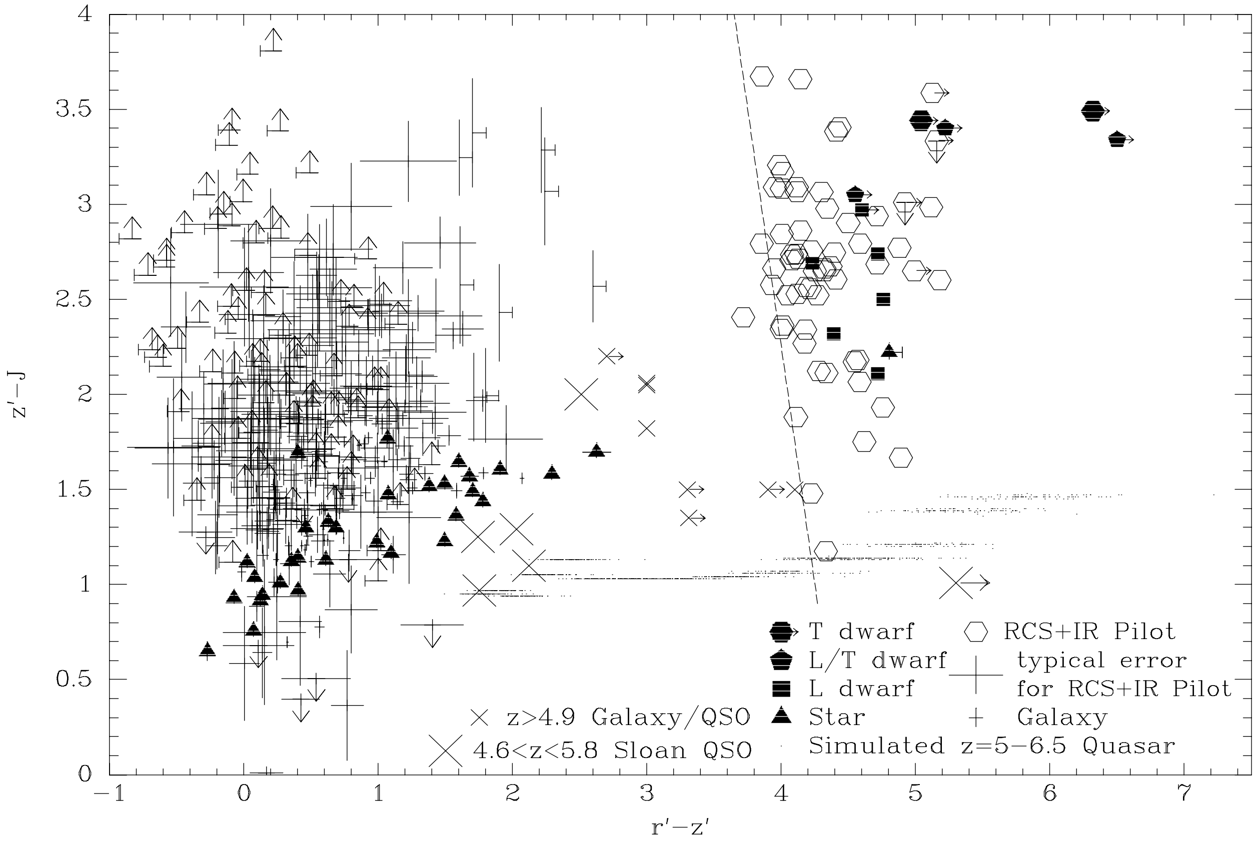

Figure 1: $r'{-}z'/z'{-}J$ color-color diagram, with a dashed line showing our **selection criterion** $(R{-}z)_{AB}{\geq}3.2$ (the transformations from CFHT R_{AB} and z_{AB} to Sloan r' and z' tilt the line slightly). The various populations are, from left to right: Morphologically classified **Galaxies** (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. Note that one star is a candidate brown dwarf, as noted by Hall (1998), but that most objects in deep imaging samples are far too blue to meet our selection criteria. $z{>}$**4.9 Galaxies/QSOs** (small crosses) 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 $\pm0\overset{\mathrm{m}}{.}5$ scatter around the points expected from the dispersion in quasar spectral properties. Of the 6 **4.6**$<z<$**5.8 Sloan QSOs** (large crosses; Fan et al. 2000b & Zheng et al. 2000), we would have selected the one at $z{=}5.8$ ($r'{-}z'{\gtrsim}5.3$) but none at $4.6{<}z{<}5.3$ ($r'{-}z'{\sim}2$), as expected. **Confirmed L dwarfs** (filled squares; Fan et al. 2000a) define the brown dwarf locus from M7 (lowest filled square, $z'{-}J{\sim}2$) to L8 (highest filled square, $z'{-}J{\sim}3$). **Confirmed L/T dwarfs** (filled pentagons; Leggett et al. 2000) and **Confirmed T dwarfs** (filled hexagons; Strauss et al. 1999 & Tsvetanov et al. 2000) show that objects L8 and later have $z'{-}J{\gtrsim}3$. *The separation of T dwarfs, L dwarfs, and z>5 quasars from each other and from typical stars and galaxies is obvious.* **RCS targets** (open hexagons) observed in J to date show the efficiency of our selection criteria. One or two have colors consistent with $z{>}5.5$ quasars, and about 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.

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. List all telescopes on which you have applied for or been granted time for observations related to this project. For each, indicate the nature of the observations, and describe the importance of the observations proposed here in the context of the entire program. (limit text to one page)*

Existing Observations: The Red-Sequence Cluster Survey (RCS, Gladders et al. 2000) is a program to obtain 50□° 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 (completed in 13 nights), and in the South the MOSAIC-II 8x8k at the CTIO 4m (10 nights observed, 3 scheduled, 4 proposed). We have ∼77□° imaged (27□° from CTIO), which is reduced to astrometrically and photometrically calibrated object catalogs within a year of the observations.

Proposed Observational Program: We can construct a brown dwarf sample (types M7-L-T) to z'=22 by requiring $(R-z)_{AB}\geq$3.2 (Sloan $r'-z'\geq$4). The only expected contaminants are themselves interesting: $z\gtrsim$5.5 quasars and $z\gtrsim$5 galaxies with SFR$\gtrsim$500 $M_\odot$/yr. This sample will be dominated by M7-L8 dwarfs, but adding 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). We propose to continue imaging such objects in the south using CTIO4m+OSIRIS.

We have reduced J data for ∼60 targets which demonstrates the feasibility of this technique (Figure 1): 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 to continue J-band snapshot observations of all $(R-z)_{AB}\geq$3.2 candidates to z'=22 in the southern 50□° of the RCS. Because of the required depth, this project is feasible as a snapshot project only at the 4m, not the 1.5m. The OSIRIS pixel scales at the 4m are also better matched to those in the optical (CFHT 0.″2, CTIO 0.″25). Followup of candidates in the northern 50□° of the RCS has been proposed to CFHT.

Expected Number of Targets: The modelling of D'Antona et al. (1999) predicts that we should find 925 to 1500 brown dwarfs in 100□°: 25 to 50 $J<18.5$ T dwarfs, 260 to 450 $J<19.5$ L dwarfs, and 640 to 1000 $J<20$ M7-M9 dwarfs. (Low numbers assume α=1 and high numbers α=2 for the mass function $M^{-\alpha}$; both use the Bahcall & Soneira (1978) Milky Way, solar galactocentric distance 8 kpc, and scale height 325 pc for these stars). We could also find up to 100 $z\gtrsim$5.5 quasars (see Scientific Justification, last paragraph). Our preliminary candidate counts are consistent with the high (α=2) estimates of D'Antona et al. (1999).

Sensitivity to Exotic Undesired Contaminants: One 15-minute R_{AB} and two 10-minute z_{AB} images are taken **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.

References

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Zheng et al. 2000, AJ, AJ 120, 1607

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the Principal Investigator 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.*

$\boxed{\star}$ • **Hall**, Barrientos, Gladders, Yee, Sawicki, De Robertis; 2 nights 2001A for this project, 1 night of data reduced (see Figure 1).
$\boxed{\star}$ • Yee, Barrientos, Gladders, Ellingson, **Hall**, Infante, Kodama; 13 nights 1999B - 2001A w/CTIO4m+MOSAIC for southern RCS imaging; 7/10 useful nights to date; 3 upcoming in Apr. 2001; 27 deg^2 imaged; run 1 reduced to catalogs; runs 2-4 being processed.
• **Hall**; 6 nights 2001A for spectroscopy of 2MASS-selected AGN candidates; run ongoing, AGN selection criteria about 65% efficient.
• **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/HYDRA+CTIO4m for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed, but key targets missed due to instrument software errors; data reduced, results now in online DMS database
• **Hall**, Ellingson, Carlberg, Yee, Lin & Marzke; 3 nights Feb. 1999 (2.5 usable) and 1 night June 1999 with ONIS on KPNO 2.1m for near-IR survey of CNOC1 cluster fields as a quasi-independent Ω_M measurement; data being analyzed, paper in preparation
• **Hall**, Green, Kennefick, Osmer, Smith: 8 nights (5 usable) Spring 1997 & 1998 w/BTC+CTIO4m for multicolor imaging for Big Faint Quasar Survey; processing pipelines up and running; data and catalog papers in preparation

Why CTIO? *(For CTIO proposals only.) Explain why access to the southern hemisphere is needed to achieve your scientific goals.*

The RCS survey from which our candidates are drawn consists of 50$\square^\circ$ of imaging from CFHT and 50$\square^\circ$ from CTIO. Similarly, we are requesting CTIO time for followup of candidates in southern fields and have requested CFHT time for northern followup.

Observing Run Details for Run 1: CT-4m/OSIRIS

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).*

The model predictions of D'Antona et al. (1999) which we have adopted (see Experimental Design) predict that we should find 1500 brown dwarfs in 100□°, and we could also find up to 100 $z\gtrsim5.5$ quasars, for 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 $z\gtrsim5.5$ quasars can be detected.

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 3 nights to image 300 targets.

We list all observed RCS patches visible from CTIO this semester. All these patches have been at least partially observed and reduction of those observations is complete or underway.

Instrument Configuration

Filters: JHK_s	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

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

Target Table for Run 1: CT-4m/OSIRIS

Obj ID	Object	α	δ	Epoch	Mag.	Filter	Exp. time	# of exp.	Lunar days	Sky	Seeing	Comment
1	0224+00	02 24 00	+00 00 00	B1950								
2	0349-00	03 49 00	-00 00 00	B1950								
3	0332-27	03 32 40	-27 56 00	B1950								
4	0438-28	04 38 03	-28 51 00	B1950								
5	0516-44	05 16 00	-44 00 00	B1950								
6	2116-63	21 16 00	-63 00 00	B1950								
7	2150-06	21 50 00	-06 00 00	B1950								
8	2232-61	22 32 00	-61 00 00	B1950								
9	2316-00	23 16 00	-00 00 00	B1950								
10	2345-40	23 45 00	-40 00 00	B1950								
11	0226-04	02 26 00	-04 00 00	B1950								

NOAO observing proposal LaTeX macros v2.4.