NOAO Observing Proposal *CNTAC proposal* **Panel:** *For office use.*
Date: September 30, 2000 **Category:** Low Mass Stars

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

PI: Patrick B. Hall **Status:** P **Affil.:** P. Universidad Catolica de Chile
Dept. Astronomia y Astrofisica, Casilla 306, Santiago, 22 Chile
Email: phall@astro.puc.cl Phone: 011-56-2-686-4940 FAX: 011-56-2-686-4948

CoI: Felipe Barrientos **Status:** P **Affil.:** P. Universidad Catolica de Chile
CoI: Mike Gladders **Status:** G **Affil.:** University of Toronto
CoI: Howard Yee **Status:** P **Affil.:** University of Toronto
CoI: Marcin Sawicki **Status:** P **Affil.:** Caltech

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 a J-band snapshot survey to rapidly and efficiently assemble a large sample of L and T dwarfs complete to $2\overset{\mathrm{m}}{.}5$ fainter in J than 2MASS or Sloan.** We have in hand $35\square^\circ$ of a planned $100\square^\circ$ 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). Pilot J imaging of 28 z'<22 targets demonstrates our efficient selection: 23 have colors of M7-L8 dwarfs and 5 of L8-T dwarfs. The full $100\square^\circ$ survey ($50\square^\circ$ in the north and $50\square^\circ$ 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 ~1/12 its volume and our fainter brown dwarf sample will have lower $<T_{eff}>$ 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	Feb - Mar	Feb - Apr
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 the giant planets now known to orbit many nearby stars. L and T class brown dwarfs have been studied intensively since their discovery. Nonetheless, there are ≤12 published T dwarfs (see Reid 1999), 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 the 2MASS survey (Kirkpatrick et al. 2000). We propose a J-band snapshot survey to efficiently select brown dwarfs up to $2^{\rm m}_{\cdot}5$ fainter than 2MASS using different selection criteria (optical-IR colors). Pilot IR observations of 28 $r'-z'\gtrsim 4$ sources from our ongoing 100□° $(Rz)_{AB}$ Red-Sequence Cluster Survey (RCS; Gladders et al. 2000) have already discovered 28 candidate brown dwarfs (Figure 1 and Experimental Design). The full survey could find 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 $r'-z'$ and $z'-J$ 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, $2^{\rm m}_{\cdot}5$ fainter than possible with 2MASS or most of Sloan**. At these J magnitudes, we probe beyond the disk 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 with representative colors, 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; $B(t)$, 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 $2^{\rm m}_{\cdot}5$ 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 reionization of the intergalactic medium and the enrichment of it and 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 $1^{\rm m}_{\cdot}4$ magnitudes brighter than the Stern et al. object (and $2^{\rm m}_{\cdot}8$ 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.

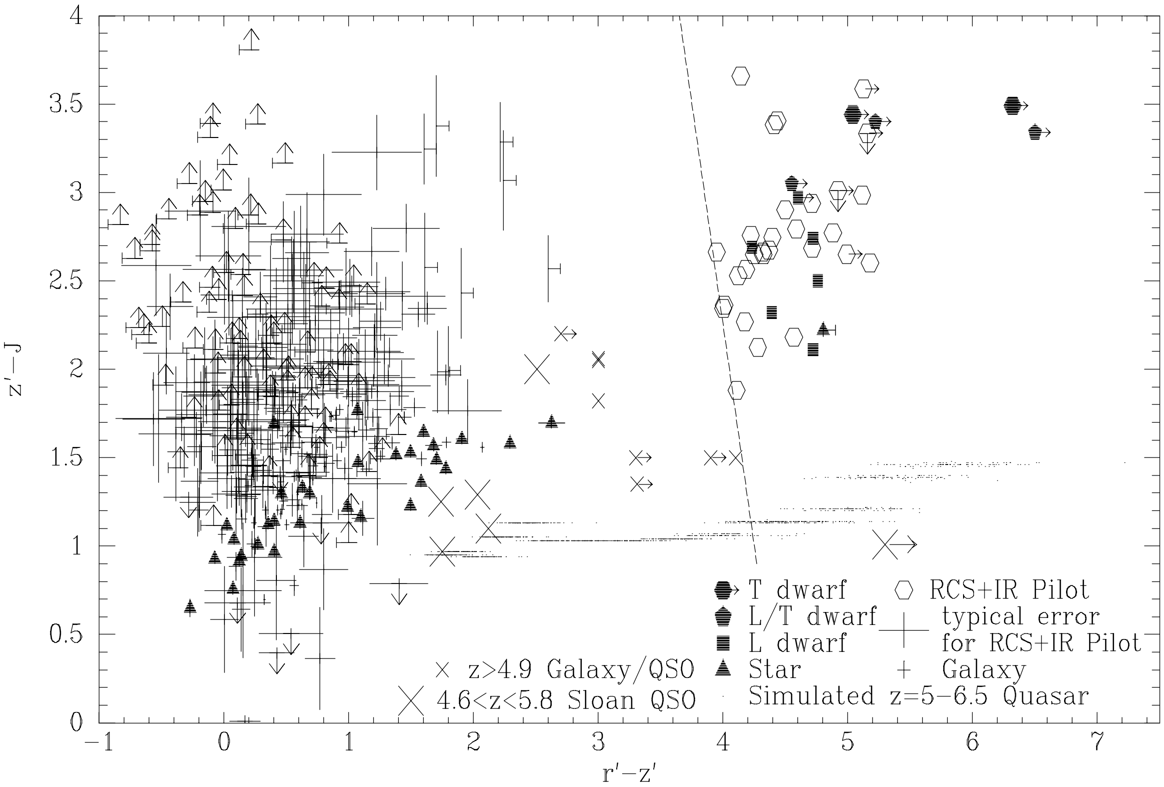

Figure 1: $r'-z'/z'-J$ color-color diagram, with a dashed line showing our **selection criterion** $(R-z)_{AB}\geq 3.2$ (the transformations from CFHT R_{AB} and z_{AB} to Sloan r' and z' tilt the line slightly). The various populations are, from left to right: Morphologically classified **Galaxies** (error bars) and **main sequence Stars** (filled triangles with error bars) from 17□′ 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 $\pm 0\overset{m}{.}5$ scatter around the points expected from the dispersion in quasar spectral properties. Of the 6 **4.6<z<5.8 Sloan QSOs** (big 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) selected from 4□° $(Rz)_{AB}$ imaging and IR pilot observations show the efficiency of our selection criteria. 23 of 28 observed are candidate M7 to L8 dwarfs, while the reddest 5 are candidate L8 to T dwarfs. We are 28 for 28 in confirming that our $(R-z)_{AB}\geq 3.2$ candidates 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 use the CFH8x12k at the CFHT 3.6m (11 nights observed, 2 scheduled), and in the South the MOSAIC-II 8x8k at the CTIO 4m (7 nights observed, 3 scheduled, 4 proposed). We have ∼57□° imaged (18.5□° from CTIO), of which ∼35□° is reduced to astrometrically and photometrically calibrated object catalogs (8□° from CTIO).

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 begin imaging such objects in the south using CTIO4m+OSIRIS.

Using 1 hour of exposure with CTIO4m+OSIRIS in one 3□° field, in March we obtained J data on 23 targets with $z'<22$ which demonstrates the feasibility of this technique (Figure 1): 18 have colors consistent with M7 to L8 dwarfs and 5 with L8 to T dwarfs. In another ∼1□° field, 5 of 5 candidates have colors consistent with L dwarfs, using pre-existing J data from IR followup of the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (Lin et al., in preparation). 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 begin 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 will be proposed to CFHT and/or KPNO in future semesters.

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). We have rough $(R-z)_{AB}\geq 3.2$ candidate counts to z'=22 from two fields: 148 in 3□° in the 1614+00 patch (l=50, b=+45) and 11 in 0.4□° in the 0920+37 patch (l=187, b=+45). Averaging the counts in these two independent patches, we estimate 3850±1000 candidates in 100□°. This very uncertain estimate is several times higher than predicted, but the difference is only significant at the ∼2.5σ level. We will have candidate counts over 35□° by the time of the proposed observations, enough for an accurate comparison with predictions. In the meantime, we use 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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Fan et al. 2000a, AJ 119, 928
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Hall 1998, PhD Thesis, University of Arizona
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Hu, Cowie & McMahon, 2000, in *The Hy-Redshift Universe*, 554
Kirkpatrick et al. 2000, AJ 120, 447
Leggett et al. 2000, ApJL, 536
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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 in press (astro-ph/0005247)

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.*

$\boxed{\star}$ • Yee, Barrientos, Gladders, Ellingson, **Hall**, Infante, Kodama; 10 nights Fall 1999 - Fall 2000 w/CTIO4m+MOSAIC for southern RCS imaging; 4.5/7 useful nights to date; 3 upcoming in Jan. 2001; 18.5□° imaged, 8□° data reduced to astrometrically and photometrically calibrated catalogs
• **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□° of imaging from CFHT and 50□° from CTIO. Similarly, we are requesting CTIO time for followup of candidates in southern fields and will request 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 $z \gtrsim 5.5$ 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 $z \gtrsim 5.5$ 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. Our pilot observing using OSIRIS on the CTIO 4m showed 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 have 15□° of reduced imaging data visible from CTIO this semester, and so we request 3 (summer) nights.

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. Optimal timing for the run would be February or March.

Instrument Configuration

Filters: JHK_s	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	$\lambda_{\rm start}$:	Collimator:
Cross disperser:	$\lambda_{\rm end}$:	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	0223-00	02 23 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	1102-04	11 02 06	-04 08 00	B1950								

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