■ Scientific Justification

Galactic L- and T-type Brown Dwarfs: Standard Candles and Clocks

The L and T dwarf classes of low-mass stars and brown dwarfs encompass the coolest and lowest luminosity atmospheres available for detailed study outside of our Solar System (see Kirkpatrick 2005 and references therein). With effective temperatures $T_{eff} \lesssim 2500$ K, these objects exhibit complex spectral energy distributions governed by deep molecular absorption bands and scattering from atmospheric condensate grains. Chemistry, cloud formation and atmospheric mixing as revealed by spectroscopic and synoptic investigations has provided valuable input for theoretical models and search strategies for exoplanets (e.g., Baraffe et al. 2003), while the luminosity function and multiplicity statistics of cool brown dwarfs are critical for developing models of low-mass star formation (e.g., Bate 2009). Over 1000 L and T dwarfs have been identified to date, primarily through ground-based imaging surveys such as 2MASS, SDSS and UKIDSS (e.g., Burgasser et al. 2006; Cruz et al. 2007; Metchev et al. 2008; Reid et al. 2008; Burningham et al. 2010; Schmidt et al. 2010).

This rapidly growing population is also relevant for investigations of the Milky Way system. Brown dwarfs are ubiquitous in the vicinity of the Sun, roughly equal in number density to hydrogen-burning stars (Reid et al. 1999; Pinfield et al. 2010). Their complex spectral energy distributions, while a challenge for atmospheric models, provide distinct fingerprints for characterizing physical properties. Spectral signatures segregating temperature, surface gravity, and metallicity effects have been quantified and calibrated, and used to characterize individual field sources (e.g., Burgasser et al. 2006, Stephens et al. 2009). In addition, brown dwarfs serve as a unique population of Galactic "clocks", as their thermal evolution results in age-, mass- and metallicity-dependent T_{eff}s and spectral types, whose dependencies can in principle be disentangled through detailed spectral characterization (e.g., Liu & Leggett 2007; Burgasser & Blake 2009). As such, cool brown dwarfs are potentially powerful tracers of Galactic structure, star formation history and chemical enrichment through individual age, mass and metallicity diagnostics (Burgasser 2009).

Probing Deeply: Old and Cold Substellar Populations

The primary drawback of cool brown dwarfs of course is that they are faint, with luminosities reaching 10^{-6} $L_\odot$ (Smart et al. 2010). In addition, low temperatures and strong atomic and molecular absorption produce extremely red colors, so brown dwarfs are essentially invisible at optical wavelengths. They are also faint at near-infrared wavelengths; hence, the vast majority of known L and T dwarfs reside within ∼50 pc of the Sun. This restricted sample has been useful for characterization of the local space density of brown dwarfs (e.g., Metchev et al. 2008; Burningham et al. 2010), resolved imaging programs to study multiplicity (many with *HST*; e.g., Bouy et al. 2003; Gizis et al. 2003; Burgasser et al. 2003, 2006) and astrometric programs to measure distances and kinematics (e.g., Dahn et al. 2002; Vrba et al. 2004; Faherty et al. 2009). Nevertheless, it does not encompass brown dwarfs at scales well beyond the local bubble and off the Galactic plane (i.e., $d \gtrsim$500–1000 pc). This deep population of brown dwarfs remains essentially unexplored.

Distant brown dwarfs are nevertheless important for investigations of Galactic populations, in particular the thick disk and halo populations. Encompassing the bulk of stellar mass formed early in the Galaxy's history, the thick disk and halo probes star formation processes and chemical enrichment prior to the production of most of the stars and brown dwarfs in the immediate vicinity of the Sun. Questions remain, however, as to whether brown dwarf formation was an efficient process in this early, metal-poor environment. The most recent study by Digby et al. (2003) hints at a rising mass function down to 0.1 $M_{\odot}$, and hence a potentially vast reservoir of old, metal-poor halo brown dwarfs (albeit still insufficient to comprise dark matter). However, only a handful of halo L subdwarfs have been found to date, mostly serendipitously in the immediate vicinity of the Sun (e.g., Burgasser et al. 2003, 2007; Lodieu et al. 2010). Their are insufficient numbers to properly constrain the halo brown dwarf population. Metallicity also plays a role in dictating the evolution of substellar objects, as opacity effects drive the hydrogen burning mass limit from 0.072 $M_{\odot}$ for solar composition to 0.09 $M_{\odot}$ for zero-metallicity stars (Burrows et al. 1997). In addition, the long period of cooling that halo brown dwarfs have incurred produces a significant gap in the present-day luminosity function (Burgasser 2004), recently hinted at in *HST* studies of globular clusters (Richer et al. 2008). The location of this gap in color-magnitude diagrams is both an independent measure of cluster metallicity and a statistical probe into the physics low-temperature hydrogen fusion. Metallicity effects are also significant in shaping brown dwarf spectra. Studies of the existing population of metal-poor L subdwarfs indicate that metallicity modulates the abundances of molecular absorbers (e.g., reduced TiO/VO/CO absorption relative to FeH/CrH), the shapes of absorption features (e.g., strengthened K I pressure-broadened line wings and collision-induced H_2 absorption), and gas/condensate chemistry (e.g., reduced cloud formation and persistent atomic metal lines; Burgasser et al. 2003; Reiners & Basri 2004; Gizis & Harvin 2006; see Figure 1). The absence of H fusion, and the profound spectral peculiarities observed among even modestly metal-poor L dwarfs (e.g., Bowler et al. 2009; Cushing et al. 2010) further emphasize the potential role brown dwarfs may play as sensitive tracers of chemical enrichment in the Milky Way.

Deep probes of brown dwarfs sample another unique population: sources whose effective temperatures bridge the gap between known brown dwarfs ($\sim$500 K) and the Solar planets ($\sim$125 K). These "ultracold" dwarfs represent the end state of cooling for substellar objects over their 1–10 Gyr lifetimes, and they also encompass younger, planetary-mass objects (M $\lesssim$ 14 M_{Jup}) which fuse nothing in their cores. Ultracold dwarfs may also fill in a new spectral class, already dubbed the "Y dwarfs", with atmospheres containing abundant CH_4 and NH_3 gases and clouds of water ice (Burrows et al. 2003; Leggett et al. 2007). It remains unclear as to what the spectra of these sources actually look like, however; we only know that they are exceedingly dim, even in the near-infrared. Candidate Y dwarfs recently identified in *Spitzer* by Eisenhardt et al. (2010) and Luhman et al. (2011) have yet to be detected from the ground. Yet these unseen cold brown dwarfs likely make up the bulk of the local brown dwarf population (Burgasser 2004; Allen et al. 2005).

An *HST* Opportunity: Archival WFC3 Grism Parallels

Searching for faint, distant and cold brown dwarfs requires substantial investment in survey time and collecting area, as surface densities are exceedingly low. While all-sky mid-infrared surveys such as WISE are likely to detect several of these objects (e.g., Mainzer et al. 2011), the lack of knowledge about their spectral morphologies opens up the potential for significant selection biases. Ideally, a blind, deep, and wide near-infrared spectroscopic survey sampling the strong molecular absorption features that distinguish L, T and Y dwarfs is desired for a bias-free search of these objects both near and far. Fortunately, that survey has now been done through programs utilizing *HST*/WFC3 near-infrared slitless grism spectroscopy. Nearly 500 orbits have been allocated to WFC3 near-infrared spectroscopy using the G141 grism, sampling the 1.0–1.7 μm range where diagnostic H_2O, CH_4, FeH and H_2 absorption features reside (Figure 1). Roughly half of these observations have been done in slitless mode, providing spectroscopy of all sources in a roughly $2' \times 2'$ field of view (accounting for dispersion off of the detector). Four of these programs (see `Analysis Plan`) have obtained sizeable allocations, making the prospect of detecting distant L or T dwarfs a promising one.

To estimate the potential yield, we performed a simulation of the local brown dwarf population based on Burgasser (2004, 2007), examining thin disk, thick disk and halo components and incorporating empirical measures of local space density, mass function, absolute brightness, vertical scaleheights and relative thin/thick/halo population densities, and assuming a constant birthrate over 10 Gyr. The result of one such simulation is shown in Figure 2, where we have assumed a spectral depth of $H_{AB} = 24$ (M. Malkan, priv. comm.). In this single pointing, we predict 1.65 L dwarfs and 0.15 T dwarfs, of which $\sim$15% are members of the thick disk or halo populations. Integrating over the 264 fields targeted by the four programs listed below, and conservatively assuming a 50% loss due to source overlap, we estimate roughly 200 L dwarfs and 20 T dwarfs detected in these fields, including 30 thick disk and halo objects. This is an appreciable fraction of the known local sample of brown dwarfs, but located at distances well beyond those accessible by current ground-based surveys. More importantly, this is a *spectral sample*, so sources can be individually characterized. We have confirmed our expectations with the WISP survey team, identifing one promising T dwarf candidate (Figure 2) and several other candidates in a color-restricted sample. *Even if we relatively few such brown dwarfs, this survey can provide stringent constraints on the distribution, mass function and formation history of brown dwarfs in the Galaxy.*

I propose an Archival *HST* program to do a complete search for L and T dwarfs in archived WFC3 G141 slitless grism fields. In addition to identifying, classifying and characterizing any identified brown dwarfs, our group will utilize previously developed brown dwarf population synthesis simulations (Burgasser 2004, 2007) to constrain the mass function and Galactic distribution of these sources. We will also search for unusually cool and/or unusually metal-poor brown dwarfs in the sample, using both empirical templates and current atmospheric models to explore the physical properties of these extreme cases.

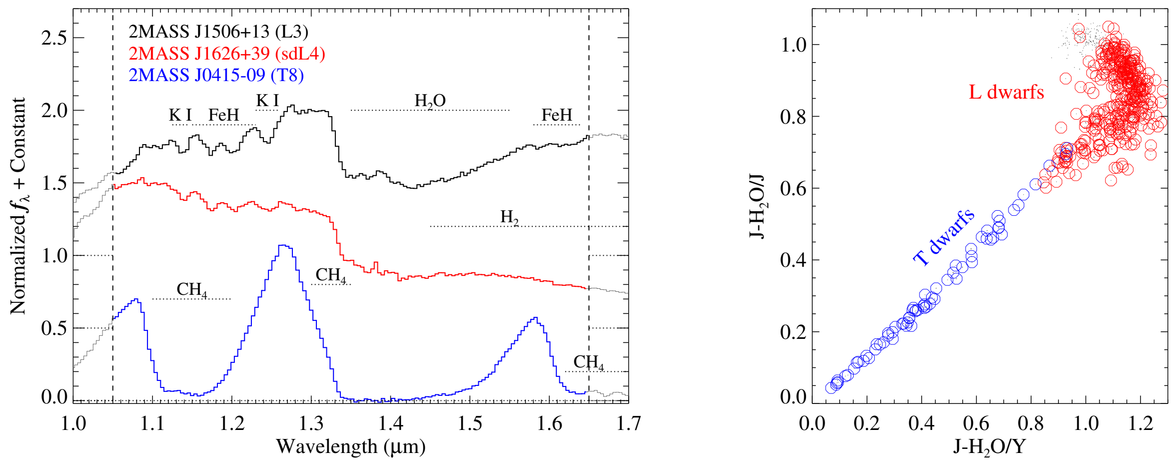

Figure 1: *(Left)* : Low-resolution spectra of representative L and T dwarfs sampling the 1.0–1.7 μm range of WFC3 G141 grism spectroscopy: a field L3 dwarf (black line, top), a halo L4 subdwarf (red line, middle) and a field T8 dwarf (blue line, bottom). Also labeled are prominent spectral features that distinguish these objects from background sources and provide diagnostics of temperature, surface gravity and metallicity. *(Right)*: An example pair of index ratios measurable in the 1.0–1.7 μm region of WFC3 G141 grism spectra that cleanly distinguish L- and T-type dwarfs (red and blue circles, respectively). J-H_2O/Y and J-H_2O/J measure the ratios of H_2O/CH_4 absorption at 1.15 μm to continuum flux at 1.05 μm and 1.25 μm, respectively. The measurements shown are based on 400 L and T dwarf spectra from the SpeX Prism Spectral Libraries (Burgasser et al., in prep.).

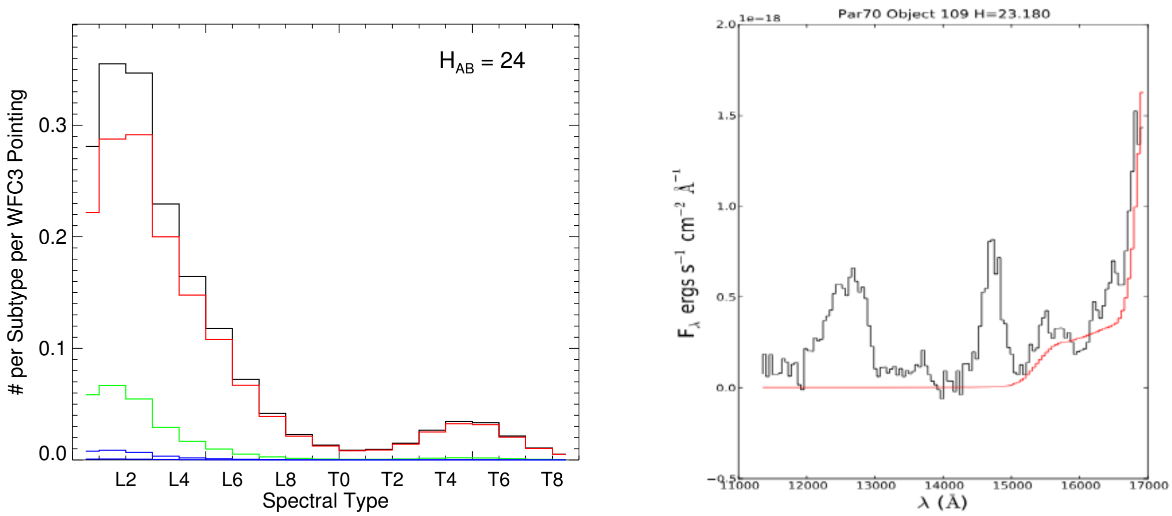

Figure 2: *(Left)*: Predicted surface densities (number of sources per subtype bin per pointing) of L and T dwarfs in WFC3 G141 slitless grism field, assuming a limiting magnitude of $H_{AB} = 24$. Shown from top to bottom are the total surface density (black), density for thin disk objects (red), density for thick disk objects (green) and density for halo objects (blue; two scalings are shown). These estimates are based on brown dwarf population simulations from Burgasser (2004, 2007), assuming a mass function $dN/dM \propto M^0$ (cf. Metchev et al. 2008; Burningham et al. 2010), a constant star formation rate, and absolute magnitude/spectral type relations from Looper et al. (2008) converted to AB magnitudes. For the Galaxy, we assumed thin disk and thick disk populations with vertical scale heights of 300 and 1000 pc (Pirzkal et al. 2009) and a relative thick disk density of 0.05; and a spherical halo with relative density 0.0005 or 0.005 (both lines are shown). To this brightness limit, we expect 1.65 L dwarfs and 0.15 T dwarfs per pointing, with 15% and up to 2% of the L dwarfs being members of the thick disk and halo populations, respectively. *(Right)*: A candidate T dwarf with H=23.18 identified in the WISP survey. The peak between 1.2 and 1.3 μm is suggestive of a late-type T dwarf (compare to Figure 1), although the 1.45–1.7 μm region appears to be contaminated by another source in the field (red line). We aim to do a thorough reanalysis of all of the WFC3 slitless grism fields to optimize extraction of these point sources.

Analysis Plan

The proposed investigation will conducted as follows:

- **Data Acquisition and Reduction:** We will download archival WFC3 G141 slitless grism data directly from the *HST* MAST archive to guarantee the most recent calibrations are applied. The datasets we have identified for this project are the GOODS-North Grism Survey (GO-11600, PI: Weiner, 28 pointings), the WFC3 Infrared Spectroscopic Parallel (WISP) Survey (GO-11696 & GO-12283, PI: Malkan, 216 pointings), the Supernova Follow-up for MCT program (GO-12099, PI: Reiss, 11 pointings), and 3D-HST (GO-12328, PI: van Dokkum, 9 pointings). These four datasets will be retrieved all at once, and as additional data become available we will augment our sample accordingly. We will then use the *aXe* package (Kümmel et al. 2009) for spectral extraction and data calibration. In this reduction phase, we will coordinate with members of the WISP team at UCLA to understand relevant data reduction issues (e.g., source overlap, flux calibration), although we intend to do an independent extraction optimized for brown dwarfs (i.e., point sources, non-continuum spectra). The data will be reduced to f_λ flux densities scaled to apparent magnitudes from pre-spectral acquisition images.

- **Source Identification:** We will define a series of spectral index (Figure 1) and data quality selection criteria to identify L, T and cooler dwarfs from the resulting library of reduced WFC3 grism spectra. The index criteria will be based on empirical templates acquired from the PI's library of ~1000 SpeX prism spectra, which have a similar resolution as the WFC3 G141 spectra ($\lambda/\Delta\lambda \approx 100$). Sources which satisfy the index selection will then be visually confirmed (both spectra and imaging data) to assure detected absorption features are robust.

- **Spectral Characterization:** All L and T dwarfs identified in our study will be classified and characterized using both empirical spectral templates and theoretical models. In particular, we aim to expand the techniques described in Burgasser et al. (2006) using a complete grid of brown dwarf benchmarks (i.e., companions to well-studied stars, cluster members, astrometric binaries with mass measurements) to establish a *fully empirical* calibration of spectral indices in the 1.0–1.7 μm range.

- **Population Synthesis:** Once we are confident that all viable sources have been extracted and characterized, we will augment population synthesis simulation code developed in Burgasser (2004, 2007) to constrain the mass function and Galactic distribution of L and T dwarfs in the WFC3 fields. These techniques have previously been applied to investigate late-type M and L dwarfs in the GRAPES (Pirzkal et al. 2007) and PEARS programs (Pirzkal et al. 2009), allowing measurement of the thin disk scaleheight for these objects (see also Ryan et al. 2009). We anticipate similar outcomes from this investigation in the brown dwarf mass regime.

- **Expected Outcomes and Dissemination of Results:** The anticipated outcome of this investigation is a sample of up to 200 L and T dwarf spectra from the WFC3 IR grism fields, classification and physical characterization of these sources, and constraints on the mass function and Galactic distribution of brown dwarfs in general. This work will comprise a significant portion of a graduate student's thesis work at UC San Diego, who will lead publication of the results (at least one paper on the entire survey, with the possibility of a second paper should a remarkable source be identified) and present the work at relevant conferences (e.g., AAS). We will also make the L and T dwarf spectra publicly available to the community through a local website for the purpose of mission planning (e.g., optimal filter definitions and selection criteria) and as templates for spectral models. We have already had considerable success with our public library of SpeX prism spectra (http://www.browndwarfs.org/spexprism), which has been used in over 50 publications since 2007.

Budget Narrative

To perform the analyses described above, I am requesting 2 months summer salary for myself to begin preliminary analysis and set up extraction tools; and 12 months regular salary (at 50% time) for one graduate student in my group who will undertake the data analysis, source selection and spectroscopic characterization of any L and T dwarfs identified in the WFC3 grism fields (total labor costs are $63k unloaded). In addition, funds are requested for 1 domestic trip each for myself and a graduate student to attend an American Astronomical Society meeting and present the results of this study (total of $4k unloaded), and costs for one publication to *Astronomical Journal* or *Astrophysical Journal* ($2k unloaded). Additional costs will be supported by internal funding. Including institutional overhead and tuition waiver, the total budget request for this AR proposal is $100,000.

Past HST Usage and Current Commitments

Past Usage

- **GO-9833: T Dwarf Companions: Searching for the Coldest Brown Dwarfs** (PI Burgasser): This Cycle-12 program imaged 22 T dwarfs with NICMOS/NIC1 to search for faint companions. *Status:* All observations were completed and analyzed. *Publications:* Burgasser et al. (2006), ApJS, 166, 585 reported the results of this survey, including the discovery of five T dwarf binaries spanning separations of $0\farcs05$–$0\farcs35$. This survey identified one of the first L/T transition "flip" binaries, whose secondary is brighter at J but fainter at K (see also Liu et al. 2006; Looper et al. 2008). The existence of these systems indicate that the sudden depletion of condensate clouds is an essential evolutionary stage of brown dwarfs as they cool from L to T. We also found a binary excess among L/T transition objects that further indicates the transition is rapid (see also Burgasser 2007).

- **GO-11666: Chilly Pairs: A Search for the Latest-type Brown Dwarf Binaries and the Prototype Y Dwarf** (PI Burgasser): This Cycle-17 program used WFC3 to image 27 late-type T dwarfs to search for faint companions. *Status:* All observations have been completed, and analysis of the data is currently underway. We have identified at least two well-resolved companions, but have yet to perform full PSF deconvolution of the data. *Publications:* None to date.

- **GO-12217: Spectroscopy of faint T dwarf calibrators: understanding the substellar mass function and the coolest brown dwarfs** (PI Lucas): This Cycle-18 program used the WFC3 G141 grism to measure the spectra of 6 T dwarfs, with a focus on young objects too faint too study from the ground. *Status:* Data have been obtained and reduced for five sources, with one source appearing to be a background galaxy. *Publications:* A paper is currently in preparation on σ Orionis brown dwarfs (Lucas et al., in prep.).

Current Commitments

I am PI of GO-11666, for which I am advising a graduate student (D. Looper) on the data reduction and analysis. 0.5 months of summer salary is currently committed to this project. No other commitments beyond my academic commitments are pending.