

# The Origins of Sub-stellar Mass Objects: Probing Brown Dwarfs and Extra-Solar Planets in Star-Forming Regions

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Scientific category: STAR FORMATION

Instruments: NIR/CAM, NIR/SPEC

Days of observation: 28

## Abstract

One of the fundamental questions in the study of star-formation, and indeed all of galactic astronomy, is: what determines the distribution of stellar masses produced by the star-formation process? Are the masses of stars fixed by the set of “initial conditions” (i.e. temperatures and densities) that characterize the molecular material from which they form? Or is this process self-regulating, tied to the physics of the star-formation process itself resulting in a truly universal initial mass function? Perhaps the most direct way of testing these disparate hypotheses is to compare the low-mass end of the IMF in regions found to be forming stars under a variety of physical conditions. Current efforts aimed at addressing this question are able to probe the IMF down to  $\sim 0.1 M_{\odot}$ . The new generation of 6–10m class IR optimized telescopes (as well as NICMOS on HST) have the potential to push such studies into the brown dwarf regime. However NGST, with its combination of resolution, sensitivity and field of view, uninterrupted wavelength coverage, and low thermal background, will be able to; i) sample the emergent mass distributions of young clusters down into the realm of planetary mass objects; ii) catalog their circumstellar properties; and iii) investigate atmospheric chemistry for a representative sample of these astrophysically interesting objects. An aggressive campaign of near- and mid-infrared imaging combined with follow-up multi-object spectroscopy will be crucial in order to assess whether or not the IMF is truly universal down to the minimum mass for molecular cloud fragmentation, as well as define *empirically* the boundary between brown dwarfs and planets.

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**Observing Summary:**

Target	RA	Dec	$K_{AB}$	Configuration/mode	Days
10 EMBEDDED CLUSTERS	$d < 1kpc$		$K < 29.9^m$	NIR/CAM,MIR/CAM R5	6
10 EMBEDDED CLUSTERS	$d < 1kpc$		$K < 25.7^m$	NIR/SPEC R300	20
10 EMBEDDED CLUSTERS	$d < 1kpc$		$L < 23.2^m$	NIR/SPEC R3000	2
				Grand total days	28

## ■ Scientific Objectives

### 1 Background

Since late autumn 1995, the study of brown dwarfs and extra-solar giant planets (EGPs) has moved from academic speculation to the front page of the New York Times. Bona fide brown dwarfs have been found in open clusters as well as in the solar neighborhood (Basri et al., 1996; Nakajima et al., 1995). Extra-solar planets detected indirectly through radial velocity search programs now outnumber the planets of our solar system (Marcy and Butler, 1998; Mayor et al., 1998). That objects with masses below the hydrogen burning limit exist outside the solar system has now been demonstrated. However, the frequency of such objects in our galaxy (and other galaxies) remains unknown. In the context of star formation, the question is whether or not the initial mass function (IMF) turns over below the hydrogen burning limit and if so why. The answer is elusive and remains one of the most important problems in galactic astronomy.

Studies of field stars in the solar neighborhood suggest that the IMF is flatter below  $\sim 1.0M_{\odot}$  than at higher masses (Kroupa, Tout, and Gilmore, 1993; see also Scalo, 1998). However, there is considerable disagreement about whether or not the field star IMF continues to rise, is flat, or turns-over at masses below  $0.1 M_{\odot}$ . Deeply embedded young clusters are excellent places to study the distribution of sub-stellar mass objects because; i) deriving energy from gravitational contraction, they are easier to detect when young; ii) field star contamination is minimized due to their compactness and association with opaque molecular cloud cores; iii) they provide a unbiased stellar census free from the effects of stellar and dynamical evolution; and iv) we stand a chance of relating the outcome of the star-formation process to the *initial conditions* of formation in the parent molecular cloud core.

Previous near-IR photometric surveys have uncovered rich embedded clusters in such star-forming regions as Orion (Lada et al., 1991) and Mon R2 (Figure 1). There exist several rich clusters located within 1 kpc which appear to be forming stars spanning the range of stellar masses from  $0.1 M_{\odot}$  to  $> 10 M_{\odot}$ . Based on H-R diagrams constructed from ground-based optical/IR spectra, researchers have been able to investigate the mass and age distributions in young clusters through comparison with pre-main sequence (PMS) evolutionary tracks. Studies to date suggest that; i) the ratio of high-to-low mass stars does not vary wildly from region to region; and ii) most regions have mass distributions roughly consistent with the field. However, as in the solar neighborhood, the frequency of brown dwarfs and EGPs in star-forming regions remains a mystery. By combining near-IR and mid-IR photometry with low- to medium resolution IR spectroscopy we plan to attack this question in a survey of a nearby embedded young clusters, characterizing their mass distributions from  $0.1-0.001 M_{\odot}$ .

## 2 Significance to Astronomy

Results from micro-lensing surveys in the halo of the Milky Way (Alcock et al. 1997), HST observations of globular clusters, spheroid, and bulge populations as well as analysis of luminosity functions in the solar neighborhood (Chabrier et al. 1997; Gould et al. 1997) suggest that very low mass stars do not contribute significantly to the baryonic dark matter in the Milky Way. Yet, it is still vitally important to know whether or not the IMF varies as a function of star-forming environment (e.g. stellar density, metallicity, etc.); both from the point of view of star formation theory as well as interpreting the integrated light of other galaxies. Combining results from this study of nearby embedded young clusters with observations of more distant clusters found in extreme environments in the Milky Way and local group as well as Population II will be crucial in order to; i) provide constraints on the dependence of the initial mass function on metallicity and star-forming environment; and ii) test its evolution over cosmic time.

In addition to probing the origins of the IMF, this program will provide valuable insight into the physics that governs the formation, structure, and evolution of sub-stellar mass objects. Radial velocity searches for planetary companions to solar-type stars have led to the discovery of many more Jupiter mass objects than predicted by any extrapolation of the mass ratio distribution of binary stars or the field star IMF. By defining the characteristic break between brown dwarfs and planetary mass objects we can begin to establish an *empirical* break between the brown dwarf and planetary regimes (Figure 3). By searching for evidence for circumstellar disks we will determine whether or not disk accretion plays a role in the formation of extremely low mass objects. The proposed spectroscopic survey at infrared wavelengths not observable from the ground for a representative sample of objects from 0.1–0.001  $M_{\odot}$  will provide fundamental insights into their atmospheric structure. By comparing these data with similar observations of older brown dwarfs and extra-solar planets, we can investigate the evolution of their properties from 0.001–10 Gyr.

## 3 Scientific Goals

We propose to test the following hypothesis: the distribution of stellar masses in embedded young clusters exhibit turnovers between the hydrogen burning limit (0.08  $M_{\odot}$ ) and the minimum mass for fragmentation of a molecular cloud (0.01  $M_{\odot}$ ). We will perform this test in three steps. First, we will conduct a deep multi-color photometric imaging survey that will provide a thorough census of sub-stellar mass objects in 10 deeply embedded clusters associated with nearby regions of massive star formation. Ten regions seems a reasonable compromise between having too small a sample to draw meaningful conclusions and requesting too large a sample to justify the investment of time. Fortunately there are ten rich deeply embedded clusters within 1 kpc for which we can sample the IMF down to 2  $M_{JUP}$  in a reasonable amount of time. In addition to obtaining flux estimates, longer wavelength photometry will permit a search for IR excess emission indicative of circumstellar disks. Next, we will construct an H–R diagram from  $R = 300$  spectra obtained for a flux-limited

sample of stars that probes at least half-way into the depth of the molecular cloud cores. We can then estimate stellar masses for each star from comparison with PMS evolutionary tracks (e.g. D’Antona and Mazzitelli, 1998; Burrows et al., 1997). Finally, we will obtain medium resolution IR spectra for a representative sample of objects least obscured by cloud material. From these spectra, abundances and surface gravities (i.e.  $M/R$ ) can be obtained which will provide crucial checks on the parameters derived from the PMS tracks as well as interesting insights into the atmospheric chemistry of sub-stellar mass objects.

## ■ NGST Uniqueness/Relationship to Other Facilities

This program exploits three unique capabilities crucial to the success of the NGST mission; i) sensitivity and resolution over wide-fields; ii) continuous wavelength coverage in the near-infrared; and iii) tremendous sensitivity gains in the thermal IR. Even with full adaptive-optics correction (e.g. laser guide star + tip-tilt) expected in 2007, ground-based infrared-optimized 8m class telescopes will not be competitive with NGST for projects requiring fields larger than  $\sim 30$  arcseconds. The sensitivity achievable over a full 4 arc-minute FOV enables studies requiring statistically significant samples such as the one proposed here, providing an increase in speed of  $\times 64$  over a ground-based 8m telescope. It is difficult to quantify the enormous scientific benefit of providing continuous 1–5  $\mu\text{m}$  wavelength coverage for stellar spectroscopy. While NICMOS will provide a glimpse of the richness of stellar spectra in the telluric water bands unobservable from the ground, realizing the true diagnostic potential of these wavelength regimes will await NGST. We anticipate *at least* a factor of  $\times 4$  improvement in our ability to derive effective temperatures from low resolution spectra from this added wavelength coverage as well as in analysis of the atmospheric constituents resulting in a total gain of  $64 \times 4 = 256$  for the near-IR imaging/low resolution spectroscopic portion of this proposal. Compared to a ground-based 8m class telescope, the relative SNR achieved by NGST’s in the thermal IR is  $10^3$  at all resolving powers  $< 10^4$ . This corresponds to a speed advantage of many orders of magnitude in the background-limited case. The ability to obtain broad-band photometry out to 10  $\mu\text{m}$  for sub-stellar mass objects will enable, for the first time, studies of their circumstellar properties. In addition, obtaining medium resolution ( $R = 3000$ ) spectra from 2.5–5.0  $\mu\text{m}$  for a representative sample of brown dwarfs and EGPs will open a new window into the chemistry of these fascinating astrophysical objects.

## ■ Observing Strategy

We propose to characterize the distribution of sub-stellar mass objects in the 10 nearest regions of massive star formation, all located within 1 kpc. We will conduct an imaging survey over a  $4 \times 4$  arc-minute region centered on the associated embedded clusters. Continuum observations of the spectral energy distributions (SEDs) at five discrete points will be made between 1.0–10.0  $\mu\text{m}$  (JHKLN). Shorter wavelength measurements between 1–2.0  $\mu\text{m}$  are required to determine the individual extinction toward each source ( $J - H$ ) as well as derive the photospheric flux ( $M_J$ ) free from continuum excess. Measurements between 2–5  $\mu\text{m}$  will be used to search for accretion signatures ( $K - L$ ) in the inner 0.1 AU of any circumstellar

disks. Ten micron observations probe the terrestrial planet regions of the circumstellar environment ( $\sim 1.0$  AU). The detection limits were chosen to sample  $2 M_{JUP}$  through the entire column density of the cloud cores  $A_V < 100^m$  at  $2.2 \mu\text{m}$ . Three-hours of integration meets this goal as well as corresponds to reaching the background-limited performance regime for an assumed read-noise of  $5e^-$ . We will survey other wavelengths to comparable depths for a total of 13 hours of imaging per target region. We request  $13 \times 10$  hours = 130 hours for the photometric survey portion of this project.

In phase two of this program, we will obtain spectra for all objects from  $0.1$ – $0.001 M_\odot$  found within the FOV of our imaging survey. Assuming a log-normal IMF that peaks near  $0.1 M_\odot$ , we can anticipate approximately 1500 sub-stellar objects per cluster extrapolating from the observed stellar populations in these regions. Given the strong features which populate the near-infrared spectra of these low temperature objects,  $R = 300$  should be sufficient to estimate effective temperatures for objects in our sample (Figure 3). Combining these temperature estimates with the photometric flux estimates described above we can place each object on the H-R diagram for comparison with PMS tracks to estimate individual masses and ages. This sample will be statistically comparable to those constructed in the solar neighborhood and nearby open clusters to define the stellar portion of the IMF. With a three hour exposure we will obtain complete  $1$ – $5 \mu\text{m}$  spectra for a  $2 M_{JUP}$  object obscured by  $A_V < 25^m$ . Using the near-IR MOS, we can obtain 100 spectra per integration requiring 15 exposures resulting in  $15 \times 3 = 45$  hours per cluster. Obtaining classification spectra for the stellar populations in our 10 regions of massive star formation will require 450 hours of integration time.

Finally, we will conduct follow-up observations at higher spectral resolution ( $R = 3000$ ) with the goal of deriving abundances and surface gravities for a subset of the less obscured objects in our sample. By concentrating on the wavelength range  $2.5$ – $5.0 \mu\text{m}$  we can study important atmospheric constituents such as CO, OH, H<sub>2</sub>O, CH<sub>4</sub>, SiO, and NH<sub>3</sub>. The surface gravities will provide a crucial check on masses derived from PMS evolutionary models and the abundances will give important insights into the chemistry of brown dwarf and EGP atmospheres that will not be obtainable from ground-based studies. Approximately 100 objects from each cluster will be selected from the comprehensive low-resolution survey for follow-up. A five hour integration should probe down to  $A_V < 15^m$  into the cloud for a  $2 M_{JUP}$  object. This phase of the program should require  $5 \times 10 = 50$  hours total integration time.

## ■ Special Requirements

*Diffraction-limited imaging at  $1.0 \mu\text{m}$ :* Required over the full field of view in order to assess the frequency of binary star companions in our census of the stellar populations. At the distance of Orion (500 pc), the diffraction-limit at  $1.0 \mu\text{m}$  (63 mas) corresponds to the typical separation of binary stars in the field ( $\sim 30$  AU).

*Minimum resolving power of 3000 from  $2.5$ – $5.0 \mu\text{m}$ :* According to calculations of Burrows and collaborators, this should be adequate to derive accurate surface gravities for the nu-

merous brown dwarfs and EGPs uncovered in our survey. Surface gravities will provide a crucial check on the masses derived from comparison to the theoretical evolutionary tracks.

*Minimum field  $4 \times 4$  arc-minutes:* This is the smallest sensible field of view for this program. It corresponds to the typical size of the target clusters. With smaller fields, multiple pointings would be required to obtain statistical samples comparable to that of the field.

## ■ Precursor/Supporting Observations

Deep wide-field infrared imaging and spectroscopic surveys, constraining the IMF in deeply embedded young star-forming regions down to the hydrogen-burning limit will have been completed by 2007. Studies of PMS binary systems (both astrometric and spectroscopic) will have calibrated the evolutionary models down to the hydrogen burning limit. Detailed spectroscopic studies of brown dwarfs uncovered by 2MASS and SIRTf will have been made at wavelengths accessible from the ground. Considerable progress in the theory of brown dwarf and extra-solar giant planets will have been made. In particular, laboratory work on the molecular spectra spanning the range of temperatures and pressures relevant to the atmospheres under study will be available.

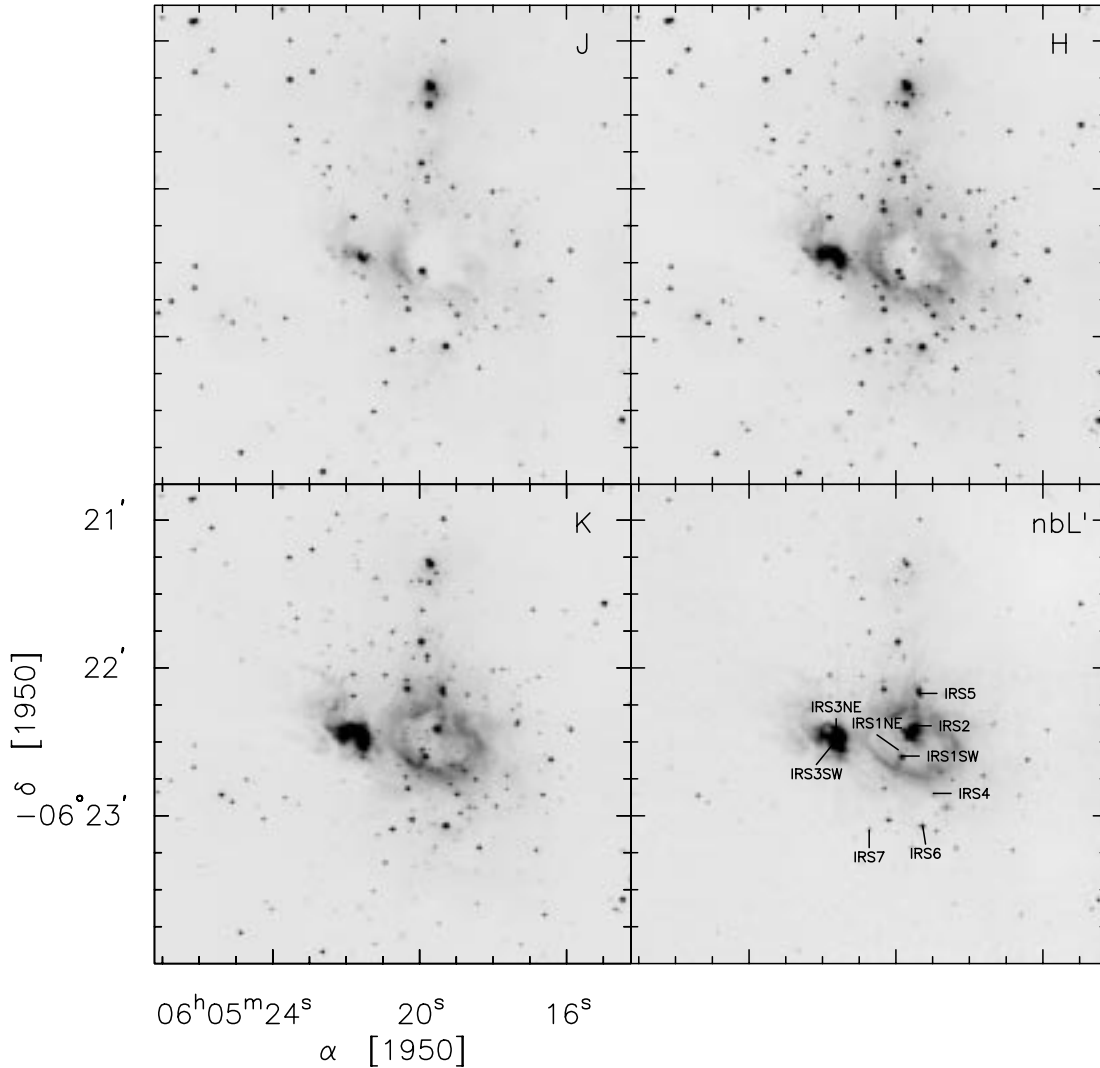


Figure 1: Near-infrared images of one of our target clusters (Mon R2) at J-, H-, K-, and L-band. Each mosaic is  $3.2 \times 3.2$  square arc-minutes with seeing-limited spatial resolution of  $\sim$  about 1.0 arcsec and 90 % completeness of  $K < 17.0^m$  ( $\sim$  500 stars). Note how the stellar population reveals itself as one observes farther into the infrared. However the loss in sensitivity imposed by thermal background emission on the ground severely limits our ability to penetrate the cluster core at wavelengths  $> 2.3\mu\text{m}$ .



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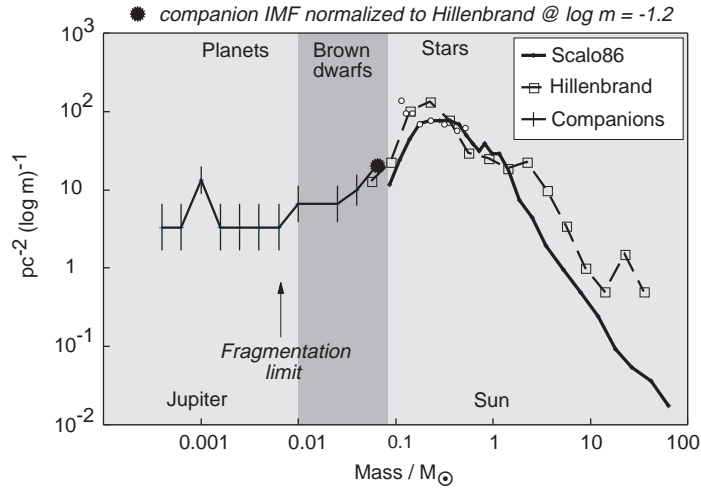


Figure 2. The IMF from 0.001 to 100  $M_{\odot}$  constructed using the Scalo IMF and the companion IMF derived from extant data on stellar companions. The open circles are Probst & Liebert's (1987) modifications of Scalo's IMF by using a different mass-to-luminosity function for converting the observable luminosity function to the physical initial mass function; they indicate the uncertainties in determining the shape of the IMF at low masses to understand the turnover. For comparison, the IMF of Hillenbrand (1997) using Scalo's M/L function for Orion is also shown.

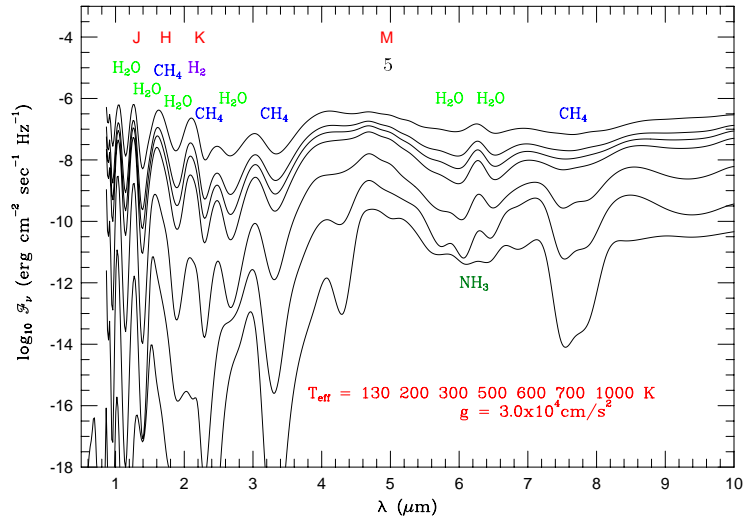


Figure 2: Low resolution near-IR spectra of brown dwarfs and EGP atmospheres from Burrows et al. (1997). Note the diagnostic power of the 1–5  $\mu\text{m}$  region for estimating effective temperatures as well as the potential for investigating important atmospheric constituents from 2.5–5.0  $\mu\text{m}$  at higher resolution.