Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Subaru IR Spectroscopy of Candidate Young Brown Dwarfs and Planetary-Mass Objects in IC 348

Michael C. Liu[1]

Institute for Astronomy, 2680 Woodlawn Drive, University of Hawai`i, Honolulu, HI 96822

Abstract. We present preliminary results for candidate substellar objects in the young cluster IC 348 observed with the IRCS spectrograph on the Subaru 8.2-m Telescope. Our sample has been selected from a novel HST NICMOS narrow-band imaging survey tuned to the 1.9 μm water absorption in cool stars; the sample is unique in that it is complete down to the fiducial boundary between brown dwarfs and planets. It contains many potential free-floating planetary mass objects. We have obtained K-band spectra of the very coolest candidates in order to measure their spectral types, and hence obtain mass estimates. Since objects in young clusters are differentially extincted, we discuss methods of determining spectral types from reddening independent indices, analogous to the narrow-band HST imaging originally used to find the candidates. We demonstrate such techniques can be applied to ground-based spectra across the entire range of M and L-type atmospheres. Preliminary results from this work suggest the spectroscopic sample contains both background stars and cluster members of very low mass.

1. Introduction

Young ($\lesssim$ 10 Myr) clusters are excellent hunting grounds for finding substellar objects and for studying their properties. Their advantages are numerous: (1) Star clusters provide a population of common age, distance, and metallicity, providing us a snapshot of stellar (and substellar) evolution. (2) Substellar objects are much brighter in their youth ($L_{bol} \sim t^{-1}$), so by observing younger clusters we can probe to lower mass limits. (3) Clusters occupy a relatively small angular extent on the sky compared to older open clusters where the stars have dispersed (e.g., the Pleiades). This means clusters are easier to survey, and the number of foreground/background interlopers is reduced. (4) Finally, little dynamical evolution is expected, allowing us to measure the initial mass function (IMF).

However, there are also challenges associated with observing young clusters. The clusters still have considerable amounts of dust, so cluster members suffer differential reddening, which must be corrected for each member individually. Emission from circumstellar disks contribute to the observed spectral

[1]Beatrice Watson Parrent Fellow. mliu@ifa.hawaii.edu

energy distribution, impeding measurements of the stellar SED, e.g., determining the spectral type. In addition, there remain significant uncertainties in the theoretical evolutionary models used to interpret the physical properties of the population, such as the masses. (4) Also, the conversion from the $T_{\rm eff}$ produced by the models to the actual observable, the spectral type, remains uncertain at pre-main sequence gravities.

Located at one end of the Perseus molecular cloud, IC 348 is an appealing young cluster for studies of substellar objects. In fact, it played a significant role in the early study of *stellar* objects, as the physical connection between its T Tauri stars and the Per OB2 association suggested that T Tauri stars had young ages (Herbig 1954, 1998). The cluster population has a mean of age of $\sim$3 Myr (Luhman 1999), slightly older than well-studied star-forming regions such as Taurus and Orion. The cluster's stellar population has a modest frequency ($\sim$20%) of near-IR excesses indicating that the circumstellar disks are more evolved (Lada & Lada 1995), presumably because of its slightly older age. Likewise, the amount of cluster extinction is modest ($A_V \sim 5$ mag). These characteristics help to make identifying substellar objects easier.

Given its proximity (300 pc) and its rich pre-main sequence population, imaging surveys of IC 348 can probe deep into the substellar mass regime. For an assumed age of 3 Myr, substellar objects will be bright in the infrared and still relatively warm. Using the models of Burrows et al. (1997), objects at the H-burning limit ($\sim$75 $\rm M_{Jup}$) are predicted to have bolometric luminosities of $10^{-1.5} L_{\odot}$, spectral types of M6, and unreddened K-band magnitudes of K_0=13 mag. (Here we adopt the conversion from $T_{\rm eff}$ to spectral type of Luhman 1999, which is intermediate between that of dwarf and giant stars.) Objects near the D-burning limit ($\sim$15 $\rm M_{Jup}$) are predicted to have $L_{bol} \approx 10^{-3}\ L_{\odot}$, spectral types of L0, and K_0=16.5 mag. Note that at such a young age, essentially all the substellar objects are predicted to still have their primordial deuterium abundance (Chabrier et al. 2000).

Recently, Najita, Tiede, & Carr (2000) have performed an HST NICMOS imaging survey of the central $5' \times 5'$ core of the cluster. They employed an innovative new technique using three narrow-band filters to measure the 1.9 μm H_2O absorption seen in very cool photospheres. This provided an efficient means to do simultaneous imaging and spectral typing in a single survey, enabling them to determine spectral types and extinctions for all the objects, thereby distinguishing the cluster members from background sources. This is necessary since the surface density of contaminating sources is significant at the flux levels needed to find many substellar objects. The result is a sample $\sim$4 mag deeper than the previous complete IR spectroscopic survey, allowing them to measure the IMF from stellar masses down to $\sim$15 $\rm M_{Jup}$. They find the IMF continues smoothly from the stellar to substellar regime, down to the limit of their survey. The resulting sample is valuable in that it is *complete* down to very low masses, and it provides a rich population of substellar objects amenable to follow-up studies.

The current mass determinations for IC 348 are limited by increasing uncertainties in the spectral types at the lowest masses. These errors arise because the 1.9 μm H_2O index used by Najita et al. was poorly calibrated for objects later than $\sim$M6. In addition, the latest type objects are quite faint so their formal classification errors are substantial (several subtypes). The coolest objects from their sample are later than M9, beyond the current 1.9 μm calibration. Spectroscopic verification that these are L-type objects would prove that these are genuine free-floating planetary-mass objects. Since the evolutionary tracks are nearly vertical at young ages and low masses, improving the $T_{\rm eff}$'s of the IC 348 members will directly improve the mass estimates and the determination of the substellar/planetary IMF. Here we present preliminary results from a spectroscopic program to study the substellar population in IC 348.

2. Observations

Our sample comprises the very coolest objects from the Najita et al. (2000) imaging survey. On the basis of their NICMOS 3-band photometry, all were classified as spectral type M8 or later, albeit many of them had large formal errors in the types due to (1) low S/N photometry and (2) having apparently deeper H_2O absorption than the NICMOS calibration sample, which was restricted to objects warmer than about M8. The objects are quite faint ($K \approx 17 - 17.5$) even for a large telescope, and many have indications of substantial extinction — these factors led us to choose the K-band for followup spectroscopy.

We observed our targets in February 2001 using the Subaru 8.2-m Telescope located on Mauna Kea, Hawaii. We obtained K-band spectroscopy with the facility near-IR spectrograph IRCS (Kobayashi et al. 2000) using the low-resolution grism and the $0\farcs6$ slit. The spectral resolution was $R \sim 450$. The spectrograph contains an Aladdin-2 1024×1024 pixel InSb array with a pixel scale of $0\farcs058$/pixel. Our observing used an engineering grade array; the quantum efficiency of the final science-grade array is expected to be $\sim$2 times higher. A total of 1800 s of integration was obtained for most of the targets. We interlaced observations of bright late-F/early-G dwarf stars in order to calibrate for the relative atmospheric transmission through the bandpass.

The reductions were done primarily with custom scripts written for RSI's Interactive Data Language (IDL). Individual images were bias-subtracted, flat-fielded, and cleaned of bad pixels. Pairs of images taken at successive nods were subtracted to remove the sky emission. Images were then registered, shifted, and stacked to form a final 2-d mosaic of the spectrum. Extractions of 1-d spectra from the 2-d images were done in a manner to produce reliable error measurements; the accuracy of the error spectra were validated by tests involving both artificial sources and measurements of subsets of the actual data. Details will be presented in a future paper. The spectra are highly oversampled in wavelength, so we smoothed with a Gaussian kernel of the instrumental resolution (8 pixels FWHM), and then rebinned the spectra by a factor of 2, i.e., to a sampling of 4 pixels per resolution element. The spectra have lower S/N around 2.0 μm because of strong telluric CO_2 absorption. We interpolated over this region when doing our analysis. The resulting spectra and their 1σ errors are shown in Figure 1.

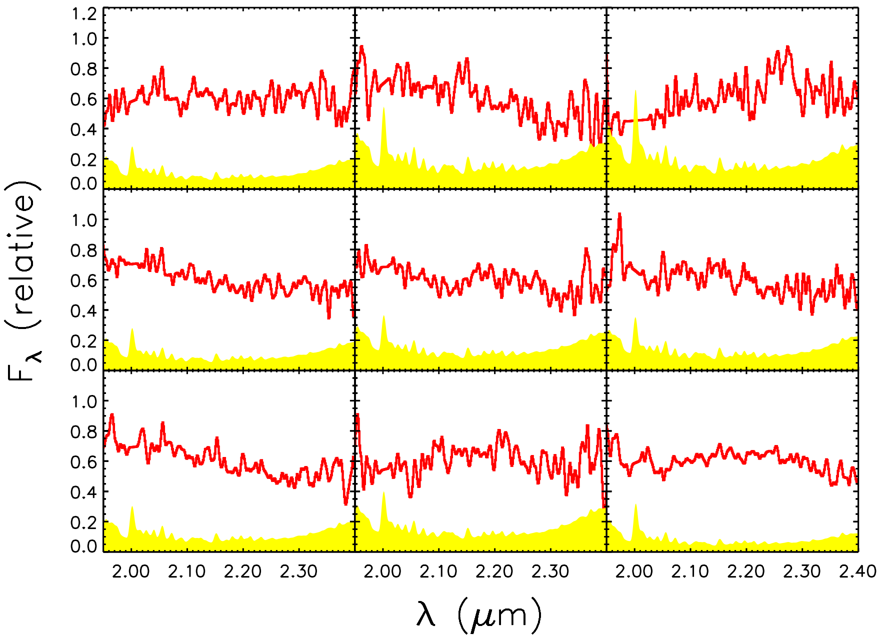

Figure 1. K-band spectra for our IC 348 targets, smoothed and binned to 4 pixels per spectral resolution element. The corresponding 1σ errors are shown by the shaded region at the bottom of the plots.

3. Analysis

The resulting spectra have relatively modest S/N and while the continua of the objects are well-detected, no strong spectral features are apparent. A few objects have smooth linear continua which suggests they have spectral types no later than early-M, and hence are probably background object. The rest cannot be classified by eye, especially since reddening may be affecting the continua.

However, there is in fact a significant amount of information contained simply in the shape of the spectra. To demonstrate this, Figure 2 shows K-band spectra for very cool dwarfs from the solar neighborhood (Leggett et al. 2000, 2001), covering a range of spectral types applicable to the IC 348 sample. The only obvious spectral feature is the 2.3 μm CO bandhead. However, the curvature of the spectra also steadily tracks the spectral type. Later type objects have depressed $\lambda \lesssim 2.1$ μm continua due to increasing H_2O absorption. In the same figure, we show the original spectra processed such that their spectral resolution and their S/N as a function of wavelength are the same as the IRCS spectra of the IC 348 objects. The CO bandhead is no longer obvious; however the trend of increasing curvature is still apparent at this S/N. This demonstrates that we can determine spectral types.

We define three bands to track the changes in spectral curvature. Then we combine the fluxes of the three bands into a numerical ratio constructed to be immune to the effects of extinction:

$$Q \equiv \frac{f_1}{f_2}\left(\frac{f_3}{f_2}\right)^x \tag{1}$$

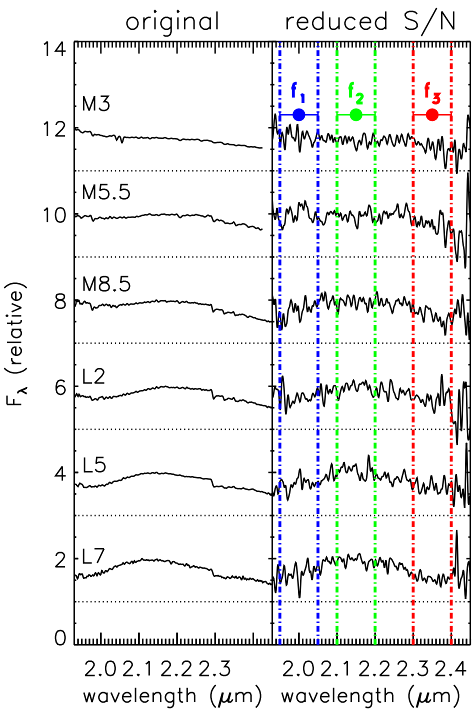

Figure 2. *Left:* Spectra of very cool stars in the solar neighborhood. *Right:* Same spectra with noise added such that the S/N as a function of wavelength is the same as the Subaru/IRCS spectra. While the 2.3 μm CO feature is no longer obvious, the strong trend of the spectral curvature with increasing spectral type remains, implying spectral classification is still possible. The three bands used to compute the Q index are indicated.

where f_i is the average flux in the i-th band and x depends only on the slope of the extinction law. This is analogous to the UBV Q index used to determine spectral types of early-type stars (Johnson & Morgan 1953). Guided by intuition, we have chosen bands from 1.95–2.05, 2.1–2.2, and 2.3–2.4 μm. The corresponding exponent is $x = 0.935$ assuming an extinction law which follows $A_\lambda \sim \lambda^{-1.75}$ (Tokunaga 1999). Since we are working over a relatively small wavelength range, adopting different extinction laws has little consequence. To calibrate the index, we perform synthetic photometry using spectra of M and L dwarfs from Leggett et al. (2000, 2001) and Reid et al. (2001). (We remove the subdwarfs from this sample as their very different metallicities lead to increased scatter.) Figure 3 shows the resulting calibration.

This approach is conceptually similar to the NICMOS narrow-band photometry done by Najita et al. (2000). In effect, we are converting the spectra into narrow-band photometry of 0.1 μm wide filters. Najita et al. chose their filters to track the depth of 1.9 μm absorption. Here, we are tracking the K-band spectral curvature, the blue side being driven by the wing of the same H_2O absorption. This approach was also used by Wilking, Greene, & Meyer (1999) to analyze K-band spectra of brown dwarf candidates in ρ Oph, though they chose their wavelength regions in the 2.07–2.5 μm range, significantly redder than ours. As a consequence, their index saturates at late-M dwarfs. Ours is a useful diagnostic down to late-L dwarfs since it tracks the increasing depth of H_2O absorption at $\lambda < 2.1$ μm.

Preliminary classification of our spectroscopic sample using this Q index suggests that there is a mix of background stars and very late-type cluster members which extend the IMF down to even lower masses. We are in process of obtaining optical (far-red) and near-IR spectra in other bandpasses to

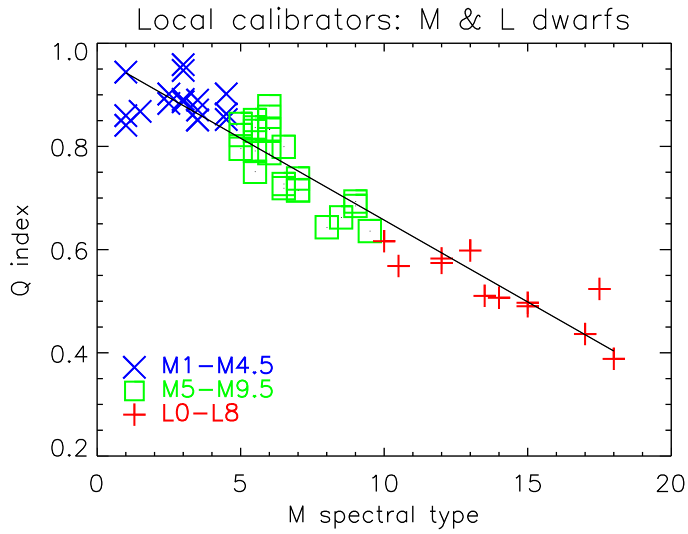

Figure 3. Calibration of our reddening-independent Q index. The calibration sample is based on spectra of M and L dwarfs in the solar neighborhood. The index is sensitive to spectral types from early-M down to late-L.

improve the spectral classifications, and hence the mass estimates. The evidence to date is that the IMF in IC 348 continues smoothly down to $\sim$15 M_{Jup} and likely beyond. This is at the upper mass limit for close ($\lesssim$3 AU) companions to old solar-type (FGK) stars found by radial velocity surveys; however, such surveys find essentially no brown dwarf companions (Marcy, Cochran & Mayor 2000). So while the free-floating cluster population seems to be abundant in objects which approach the "planetary-mass" regime, the companion population is completely missing brown dwarf-mass objects. This suggests that free-floating substellar objects and extrasolar planetary companions represent two distinct physical populations.

Acknowledgments. I thank my collaborators, Joan Najita and Alan Tokunaga, for valuable input and research support. It is also a pleasure to thank the Subaru IRCS team, Hiroshi Terada, Naoto Kobayshi, and Miwa Goto, for assistance with the observations. I also thank the Cool Stars 12 SOC and LOC for organizing a very enjoyable conference. This work has been supported by the NSF and the Beatrice Watson Parrent Foundation.

References

Chabrier et al. 2000, ApJ, 542, 119

Herbig, G. 1954, PASP, 66, 19

Herbig, G. 1998, ApJ, 497, 736

Johnson, H. & Morgan, W. 1953, ApJ, 117, 313

Kobayashi, N. et al. 2000, SPIE, 4008, 1056

Lada, E. & Lada, C. 1995, AJ, 109, 1682

Leggett, S. et al. 2000, ApJ, 535, 965

Leggett, S. et al. 2001, ApJ, 548, 908

Luhman, K. 1999, ApJ, 525, 466

Marcy, G., Cochran, W., & Mayor, M. 2000, in *Protostars and Planets IV*, eds. V. Mannings, A. Boss, & S. Russell (Tucson: University of Arizona Press), 1285

Najita, J., Tiede, G. & Carr, J. 2000, ApJ, 541, 977

Reid et al. 2001, AJ, 121, 1710

Tokunaga, A. 1999 in *Astrophysical Quantities*, ed. A. N. Cox (Berlin: Springer-Verlag)

Wilking, B., Greene, T., & Meyer, M. 1999, AJ, 117, 469