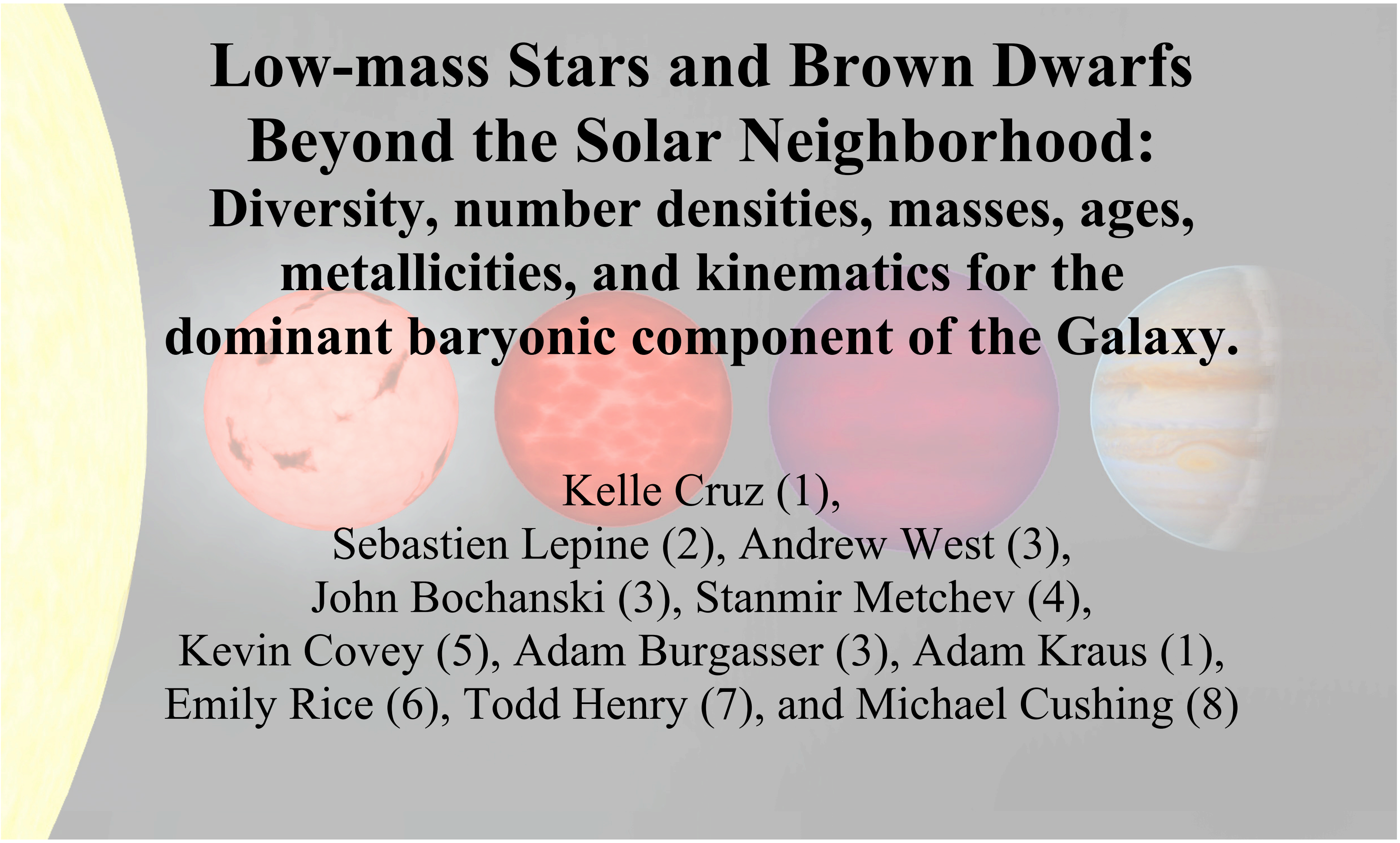

Low-mass Stars and Brown Dwarfs Beyond the Solar Neighborhood:

Diversity, number densities, masses, ages, metallicities, and kinematics for the dominant baryonic component of the Galaxy.

Kelle Cruz (1),
Sebastien Lepine (2), Andrew West (3),
John Bochanski (3), Stanmir Metchev (4),
Kevin Covey (5), Adam Burgasser (3), Adam Kraus (1),
Emily Rice (6), Todd Henry (7), and Michael Cushing (8)

1- California Institute of Technology, kelle@astro.caltech.edu
2- American Museum of Natural History
3- Massachusetts Institute of Technology
4- Stony Brook University
5- Harvard Smithsonian Center for Astrophysics
6- University of California, Los Angeles
7- Georgia State University
8- Universiy of Hawaii

Low mass stars and brown dwarfs are the dominant baryonic component of the Galaxy. A full understanding of the composition, structure and dynamics of galaxies requires a full understanding of this unassuming, low-luminosity component. With evolutionary timescales longer than a Hubble time, low-mass stars and brown dwarfs retain the chemical signature of their epoch of formation, and are reliable witnesses of the evolutionary history of the Galaxy.

A volume complete sample of low-mass stars and brown dwarfs out to at least 200 pc, reaching beyond the Local Bubble, will profoundly advance to our understanding of these objects and their place in the Galaxy. This sample, extending into planetary masses, will be the benchmark for the study of the fundamental properties of low-mass objects in every Galactic environ. With this sample, combined with appropriate astrometric and spectroscopic follow-up, we will be able to measure their mass function, their age-dependent properties, and their distribution in different Galactic populations (thin disk, thick disk, halo). By significantly improving the calibration of ages, metallicities, masses, and distances, we will also use these long-lived objects to study the formation and evolution of the Galaxy and to map out the bulk of these numerous, dim objects to unprecedented distances away from the Sun.

With the coming generation of wide-field surveys (e.g., UKIDSS, WISE, PanStarrs, LSST, JDEM) and their onslaught of discoveries, the next decade will be an exciting time for the study of the bottom of the Main Sequence. However, these imaging surveys alone are not sufficient to answer the most pressing, outstanding questions. A full complement of follow-up observations is required to determine the fundamental parameters of these objects and characterize their populations. An extensive program of low- and high-resolution spectroscopy, photometric monitoring, adaptive optics imaging, and parallax measurements, will allow us to determine reliable distances, calibrate metallicities and ages, constrain the mass and luminosity functions, determine the multiplicity fraction, and map out the kinematics of significant numbers of low-mass stars and brown dwarfs from both the young (disk) and old (halo) populations.

Context

In large part due to the Two Micron All Sky Survey (2MASS) and the Sloan Digital Sky Survey (SDSS), the past 15 years have seen great advances in the exploration of the end of the main sequence. In particular, brown dwarfs, previously only theorized to exist, have finally been discovered in large numbers. Brown dwarfs are stars that do not sustain hydrogen burning in their core and thus cool and dim throughout their lifetimes. The spectral analysis of these discoveries necessitated the extension of the spectral sequence to include two new classes cooler than M type: the L and T dwarfs (Kirkpatrick 2005). There is likely a yet cooler spectral class, tentatively dubbed Y dwarfs, but none have yet been found and their discovery is the topic of their own White Paper (Burgasser et al.).

Moreover, the combination of infrared magnitudes with proper motions from both older (Luyten 1979) and newer (Lepine & Shara 2005) catalogs of high proper motion stars, is now providing near complete identification of all low-mass stars within the Solar neighborhood (d<25 pc). Based on current progress, it is now possible to envision obtaining a complete census of hydrogen-burning objects to at least 100 parsecs within the next 5 years. However, such a census for substellar objects remains a challenge.

Census, Luminosity Function, and Mass Function

A volume complete sample, free of complicated selection biases, offers the gold standard measurement of the fundamental properties of stars and brown dwarfs and the fiducials against which absolute predictions of atmosphere and evolution models can be evaluated. This ideal sample, however, is far from being realized.

Much of the work on low-mass stars and brown dwarfs in the previous decade has focused on using wide-field surveys such as 2MASS and SDSS to simply locate these needles within the haystack of more luminous background stars. While there has been significant progress, there is much left to be done: a largely complete census of M dwarfs has been made to 1 kpc (Bochanski 2008), but only for a fraction of the sky at high galactic latitudes; the all-sky census of nearby stars has been expanded to at least 33 parsecs (Lepine 2005), but remains significantly biased by proper motion selection; the census of L dwarfs is complete only to 20 pc (Cruz et al. 2007), and remains deficient in low galactic latitudes; numerous T dwarfs have been discovered, but a volume-complete sample does not even yet exist. In addition, distances have mostly been determined only crudely from spectroscopic and photometric color-magnitude relationships. *In the next decade, the major advancements for completing the census will come from measuring trigonometric parallaxes, expanding the census of L dwarfs, and finally measuring the number densities of T and Y dwarfs.*

We are currently operating under the assumption that the brown dwarfs we see locally accurately reflect those found in the rest of the Galaxy. However, because our entire understanding of brown dwarfs is limited to the very nearest population (<20 pc), we are biased to a younger population; dynamical heating causes older stars to spend the majority of their time further from the Plane (West et al. 2006; Loebman et al. 2009). West et al. (2008) found that M dwarfs at larger Galactic heights have statistically different properties than those found locally—presumably, the same is true for brown dwarfs. A volume-limited sample out to 200 pc is vital for assessing brown dwarfs in a Galactic context as it will include a significant range of stellar ages.

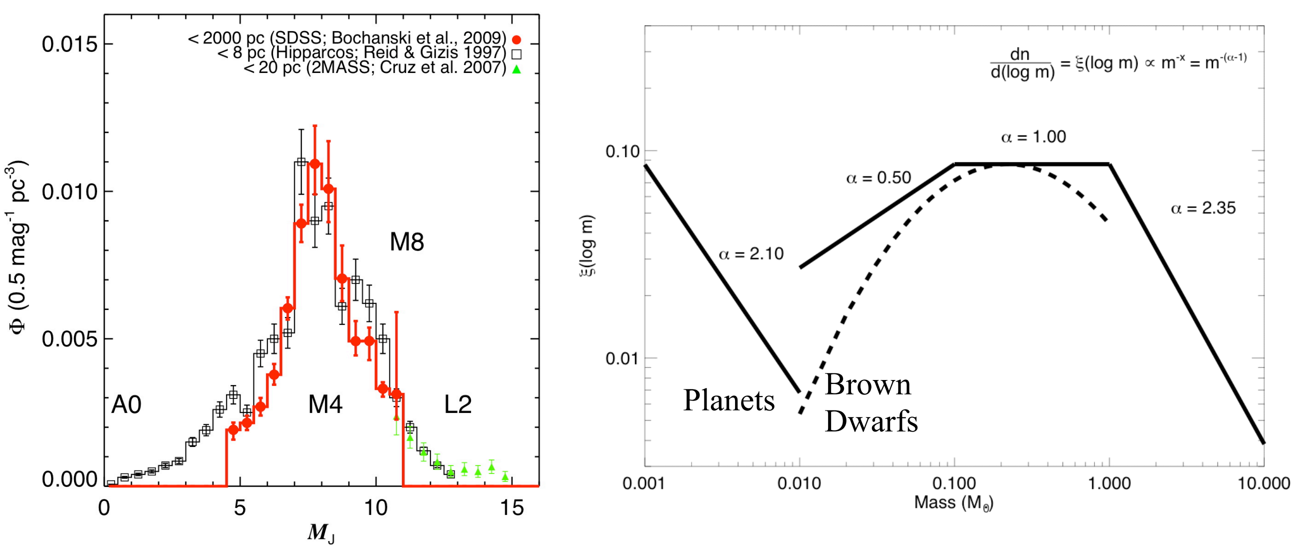

Figure 3 —**LEFT:** Stellar luminosity function of the Solar Neighborhood. Number densities are needed for late-L dwarfs and T dwarfs. **RIGHT:** Mass function of stars and planets.

..

The mass function (MF) for brown dwarfs is still poorly constrained. While we have a handle on the luminosity function through the mid-L dwarfs, there are no good numbers for T dwarfs. Because of evolutionary effects, L dwarfs are not sufficient to constrain the overall mass function of the brown dwarfs. The stellar mass function (MF) is generally characterized by a segmented power-law $\psi(M)=dN/dM \propto M^{-\alpha}$ with a break at $1M_{\odot}$ and 0.1-0.3 $M_{\odot}$. The past decade has seen consensus reached on the mass function for M dwarfs, but the form of the mass function at masses less than $0.1M_{\odot}$ remains uncertain. Results in young clusters suggest α=0.5 but the field MF is basically unconstrained and could range from 0.5 to 2. A volume complete sample of T and Y dwarfs is crucial to finally pinning down this fundamental parameter.

While the prospects for expanding the census of brown dwarfs in the next decade are quite good, even deeper surveys are required to answer many of the outstanding questions. LSST and PanSTARRS will provide valuable contributions to the volume complete sample for M and early L dwarfs, where Gaia becomes less useful. Even these samples, however, will be limited to <50 pc for late L and T dwarfs: deeper, NIR synoptic surveys are needed to probe the coolest, most numerous low-luminosity objects.

Young Objects and Age Calibration

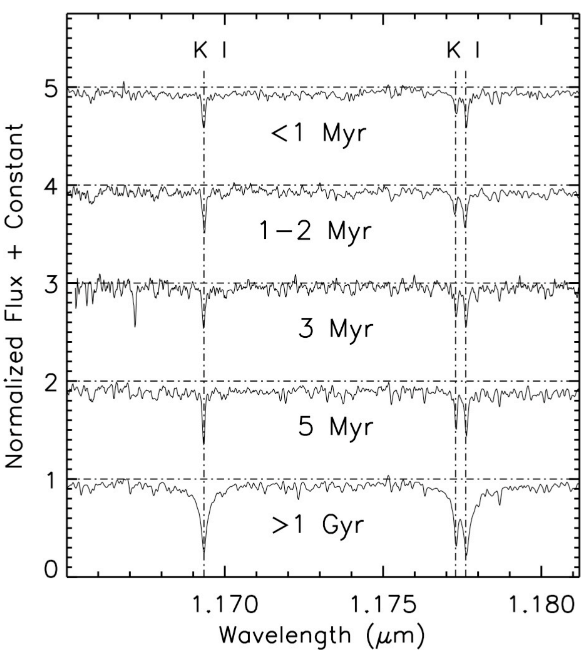

Figure 2—High-resolution near-infrared spectra of five M6-type dwarfs at a range of ages. The line profile of the K I atomic absorption lines is clearly age dependent (Rice et al. 2009)

A significant problem that continually challenges progress in measuring the fundamental properties of brown dwarfs is the observational degeneracy between age and mass: without any information about one, the other cannot be determined. This degeneracy prohibits a mass-luminosity relation, since luminosity depends on both age and mass. At the same time, there are currently no well-calibrated age indicators for brown dwarfs. Unlike for M dwarfs, there does not appear to be a correlation between age and activity (e.g., Hα emission). A major goal in the next decade will be to characterize the indicators that allow the degeneracy to be broken.

The most promising avenue for constraining the ages of brown dwarfs is by using gravity as a proxy for age. Low gravity is indicative of both a lower mass and more extended atmosphere—hallmarks of young brown dwarfs still undergoing gravitational contraction. It is expected that late-type objects will have low-gravities up to ages of 1 Gyr. Several gravity-sensitive spectral features have been identified, but the alkali absorption lines appear to be the most sensitive (Cruz et al. 2009). As shown in Figure 2, younger late-M dwarfs have much narrower K I lines due to the weaker pressure broadening in lower gravity photospheres.

However, much work remains before this effect can be a useful age indicator: it needs to be studied and calibrated in both cooler (L and T dwarfs) and older objects.

Deep surveys in the Southern Hemisphere are required to identify the brown dwarf members in the intermediate-age (8-100 Myr) associations within 100 pc that have known ages (Zuckerman & Song 2004) and sensitive high-resolution spectrographs are needed to study the age-sensitive features.

Old objects in the thick disk and halo, and the metallicity calibration

Cool subdwarfs have historically been identified among the high-velocity stars, and identified as the low-mass end of the local Galactic halo population (Eggen 1973; Dawson & De Robertis 1988). Cool subdwarfs are the surviving member of the earliest generations of stars, and their long evolutionary timescales (well exceeding a Hubble time - Laughlin et al. 1997) make them true fossils of the early ages of Galactic formation, retaining important clues about the initial chemical composition and dynamical layout of the Galaxy in the early ages.

Cool subdwarfs however have low luminosities, and a relatively low density in the vicinity of the Sun, with 1 halo subdwarf for about 200 disk dwarfs (Gizis & Reid 1999). Up until recently, they were a rare occurrence, with less than 100 systems confirmed (Gizis 1997, Lepine et al. 2007b). However recent progress based on new proper motion surveys and SDSS spectroscopy has uncovered a vast population of local, cool subdwarfs. These were discovered to be to be an easy pick in deep imaging surveys, thanks to metal-poor stars exhibiting a very distinct locus in *gri* color-color space at the low-mass end (Figure 3 - from Lepine et al. 2009, in preparation). Though based on a limited sample, the Galactic orbits of late-type subdwarfs suggests distinct kinematic classes, characterized as “inner” and “outer” halo populations, with potentially different formation histories and bulk properties (e.g. Carollo et al. 2007; Cushing et al. 2009).
Current red optical and near-infrared imaging surveys have also extended our sample of metal-poor halo stars down to ultra-cool temperatures (Teff < 2000 K), including the first discoveries of L subdwarfs (Burgasser et al. 2003; Sivarani et al. 2009). These objects probe the halo population down to the substellar limit, and provide templates for examining metallicity effects in the chemistry and opacities of low-temperature atmospheres. Indeed, evidence thus far indicate suppressed condensate grain formation in L subdwarfs (Burgasser et al. 2003; Reiners & Basri 2006), peculiar Fe/Cr abundances (Sivarani et al. 2009), and enhanced collision-induced H2 absorption (Cushing et al. 2009), features that remain to be theoretically reproduced. L subdwarfs also display a break from the standard age/activity relations in low-mass stars (Reiners & Basri, 2006), a feature that has yet to be explained.

Upcoming large-scale surveys like Pan-STARRS and LSST will uncover millions of halo subdwarfs up to and beyond 1 Kpc, probing deep into the Galactic halo. With their large transverse velocities (v_t > 100 km/s) relative to the Sun, the majority of cool subdwarfs have proper motions easily detected and measured. With an estimated 2,000,000 objects to be identified over the entire sky, and the possible estimation of masses and metallicities based on broadband *gri* magnitudes alone, it will be possible to map out the full kinematics and metallicity distribution for an unprecedented number of halo stars. This will provide deep insights into the

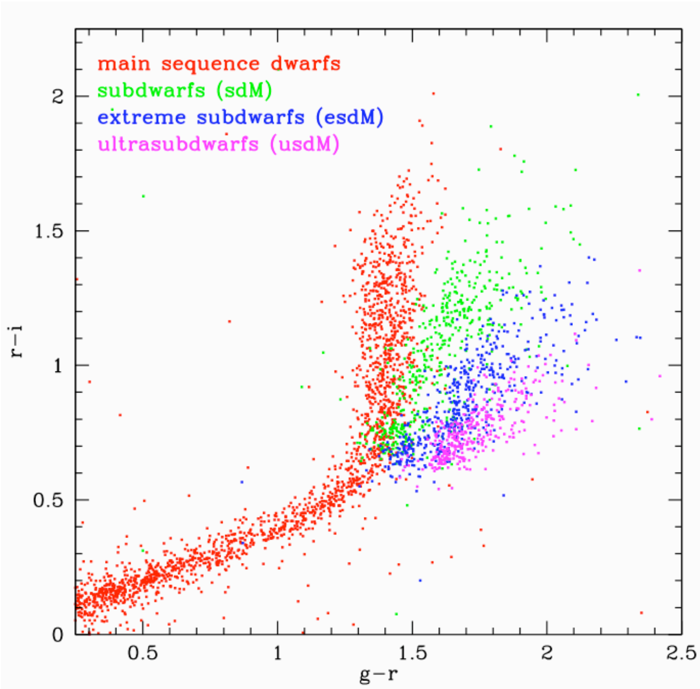

Figure 3—Distribution of cool subdwarfs in the *g-r / r-i* color-color diagram, from the Sloan Digital Sky Survey (SDSS). The four metallicity classes (dwarfs, subdwarfs, extreme subdwarfs, and ultrasubdwarfs) are represented in different colors. Subdwarfs are clearly segregated according to metallicity, spreading over what effectively represents a mass-metallicity grid.

early formation and evolution of the Galaxy. One important goal will be to build up a statistically significant sample of late-type M and L subdwarfs to make a robust measure of the halo mass function down to the substellar limit. It is as yet unknown whether the metal deficient halo environment is more or less efficient in the production of low-mass stars than is the Galactic disk. Measurement of the halo MF across the peak mass is essential to test theories of metal-dependency in star formation.

However, the physical properties of cool subdwarfs remain poorly characterized to date: their multiplicity function is not well known, mass-luminosity relationships have not been calibrated, and preliminary color-magnitude relationships appear to be significantly dependent on metallicity (Monet 1992, Jao et al. 2008). To use the full power of the huge halo sample to be assembled in coming years, sustained efforts are required to constrain the physical properties of the cool subdwarfs. It is particularly important to determine their metallicity scale, which so far has only been crudely estimated (Gizis & Reid 1997, Woolfe et al. 2009). High-resolution spectroscopy will be critical to perform a complete abundance analysis of those stars, and to constrain atmospheric models which currently provide poor fits to the low- and medium-resolution spectra. Parallax measurements for hundred of subdwarfs, spanning the full diversity of masses and metallicities, will be required to properly calibrate color-magnitude relationships, critical in calculating distances for stars in the entire sample.

Double Stars and the Mass Calibration

The mass-radius and mass-luminosity relationships for low-mass stars are still dependent on a relatively small number of astrometric doubles and eclipsing systems (Henry et al. 1999, Delfosse et al. 2000). More critically, no eclipsing system including a cool subdwarf has ever been identified, and only a handful of long period astrometric doubles have recently been found (Lepine et al. 2007a). A proper calibration of the masses of low-mass stars and brown dwarfs will require sustained efforts in the coming years in finding and monitoring appropriate systems.

The exploration of the time domain by various synoptic surveys will identify eclipsing doubles. Spectroscopic follow-up capabilities on large (10-meter) telescopes would allow us to use these systems to significantly improve mass radius relationships. High angular resolution surveys using LuckyCam, speckle, or AO systems (Law et at. 2006; Mason et al. 1999; Lloyd et al. 2006) will be required to identify astrometric doubles and monitor those systems in order to map out orbits and directly determine gravitational masses.

Summary of Needs

Deep, Very Wide Sky, Synoptic Surveys—Large, deep, near- and mid-infrared surveys that also provide astrometric measurements are crucial for identifying the coolest brown dwarfs and pushing the census of low-luminosity objects beyond the immediate Solar Neighborhood.

Near-Infrared Low-Resolution Spectroscopy—Efficient, low-resolution (R < 3000), NIR spectrographs on large (>=8 m) ground-based telescopes will be required to follow-up and confirm the onslaught of discoveries from the photometric and synoptic surveys.

Parallax Measurements—Without accurate trigonometric parallaxes, all of the basic derived parameters are uncertain. Even with LSST and PanSTARRS, we will still need additional facilities to measure distances to the coolest brown dwarfs (late L, T and Y dwarfs) further than 50 pc, and the cool subdwarfs. In addition, as discussed by the Henry et al. White Paper submission, we need to ensure that there is a next generation of trained astrometrists to tackle these problems.

Adaptive Optics Imaging— High angular resolution imaging programs (AO) will be needed to explore the multiplicity in the low-mass range, and identify/monitor astrometric doubles for mass calibrations. Such programs can be performed on 4-meter class telescopes.

Near-Infrared High-Resolution Spectroscopy—High-resolution (R~30,000) NIR spectrographs will be required to study atomic features that serve as age indicators and to measure radial velocities for kinematic studies.

Photometric Monitoring—Required for confirmation and follow-up of eclipsing systems. Can be performed on smaller 1-2 meter class telescopes.

.

References

Burgasser et al. 2002, ApJ , 564, 421
Burgasser et al. 2003, ApJ, 592, 1186
Carollo et al. 2007, Nature, 450, 1020
Cruz et al. 2007, AJ, 133, 439
Cruz et al. 2009, AJ, 137, 3345
Cushing et al. 2009, in press
Dawson & De Robertis 1988, AJ, 95, 1251
Delfosse et al. 2000, A&A, 364, 217
Eggen 1973, ApJ, 182, 821
Gizis 1997, AJ, 113, 806
Gizis & Reid 1997, AJ, 109, 1233
Gizis & Reid 1999, AJ, 117, 508
Jao et al. 2008, AJ, 136, 840
Henry et al. 1999, ApJ, 512, 864
Kirkpatrick, 2005, ARAA , 43, 195-245.
Kirkpatrick et al. 1999, ApJ, 519, 802-833
Law et al. 2006, MNRAS, 368, 1917
Laughlin et al. 1997, ApJ, 482, 420
Lepine 2005, AJ, 130, 1680
Lepine & Shara 2005, AJ, 129, 1483
Lepine et al. 2007a, ApJ, 668, 507
Lepine et al. 2007b, ApJ, 669, 1235

Lloyd et al. 2006, ApJ, 650, 131
Loebman et al. 2009,
Luyten. 1979, New Luyten Catalogue of Stars with Proper Motions Larger than 0.2” (Minneapolis: Univ. Minnesota Press)
Mason et al. 1999, AJ, 117, 1023
Monet et al. 1992, AJ, 103, 638
Reid et al. 2008, AJ*,* 136, 1290
Reiners & Basri 2006, AJ, 131, 1806
Sivarani et al. 2009, ApJ Letters, in press
West et al. 2006, 132, 2507
West et al. 2008, 135, 785
Woolfe et al. 2009, AJ, in press
Zuckerman & Song 2004, ARAA, 42, 685