Mem. S.A.It. Vol. 84, 1005
© SAIt 2013
Memorie della

The fundamental importance of brown dwarf binaries

Q. M. Konopacky*

Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada, e-mail: konopacky@dunlap.utoronto.ca

Abstract. Binary and multiple stellar systems have long been used to study the formation and fundamental properties of stars. With the first discovery of brown dwarf binary systems in 1999, these constraints could be extended into the substellar regime. In the subsequent 14 years, over 100 very low mass (VLM) binaries have been discovered, both amongst the field population and in young clusters. In this proceedings, I review the surveys that discovered this important population. Specifically, these surveys have shown that there seems to be a dearth of wide VLM binaries in the field, and a preference for nearly equal mass components, while in young clusters, a larger range of separations and mass ratios have been found. I also discuss long-term monitoring programs that have constrained the masses of these objects, and how the assumed coevality of VLM binaries has been important for understanding the atmospheric physics of the L/T transition. Finally, I will discuss how additional measurements of the radii, temperatures, and rotational properties of VLM binaries have been, and will continue to be, essential for our understanding of substellar objects.

Key words. stars: brown dwarfs – stars: binaries: general – stars: fundamental parameters

1. Introduction

Multiplicity has long been used as a powerful constraint on the star formation process. With the initial discoveries of brown dwarfs in the mid-1990s (e.g., Zuckerman & Becklin 1992; Nakajima et al. 1995; Rebolo et al. 1995; Kirkpatrick et al. 1997), determining whether brown dwarfs existed as part of multiple systems was an immediate goal. Brown dwarfs in multiple systems help illuminate the physics of the star formation process in the low mass regime, and the statistics of their multiplicity can elucidate their evolution.

Discoveries of the first binary brown dwarfs occurred shortly after the initial identification of brown dwarfs. Martín et al. (1998) announced the discovery of a binary brown dwarf in the Pleiades, CFHT-Pl-18AB, a 0.″33 visual binary resolved with NICMOS on the Hubble Space Telescope (HST). Shortly thereafter, the first spectroscopic binary brown dwarf, PPL 15AB, was announced by Basri & Martín (1999). Discovered using HIRES on the W.M. Keck I 10-m telescope, this binary is also a Pleiades member. The first field binary brown dwarf was announced the same year by Martín et al. (1999), DENIS-P J1228.2-1547AB, also a resolved system identified with NICMOS. These initial discoveries set the stage for the

Send offprint requests to: Q.M. Konopacky
* Dunlop Fellow

large scale surveys that followed in the next five years.

2. Multiplicity properties of brown dwarfs

2.1. Surveys

A number of large scale surveys have formed the basis for our current understanding of the multiplicity properties of brown dwarfs. The largest of these were the HST surveys, which combined targeted around 250 very low mass (VLM) objects with resolution up to ~0.″05 (e.g., Bouy et al. 2003; Gizis et al. 2003; Burgasser et al. 2003, 2006; Reid et al. 2006, 2008). The rough physical separation range probed by these surveys was ~1 - 100 AU. These surveys were complemented by ground-based adaptive optics (AO) surveys on 8-10 meter telescopes, which are sensitive to a similar range of separations (e.g., Close et al. 2003; Siegler et al. 2005; Kraus et al. 2008; Kraus & Hillenbrand 2012; Dupuy & Liu 2012; Duchêne et al. 2013). In particular, laser guide star AO is ideally suited to targeting VLM objects, as they are often too faint in the optical for typical natural guide star AO systems (Liu & Leggett 2005). These surveys, combined with other discoveries of individual objects using high resolution techniques, have identified over 70 VLM binaries.

To offer a complete census of the multiplicity properties of brown dwarfs, surveys probing closer and wider separations than the HST surveys have been performed. Spectroscopic surveys using both near-infrared and optical high resolution spectrographs have found more than 10 new brown dwarf binaries (e.g., Reid et al. 2002; Guenther & Wuchterl 2003; Joergens 2008; Blake et al. 2010). Meanwhile, large scale, all-sky surveys have been very successful at finding very wide brown dwarf binaries (separations generally ≳100 AU, e.g., Billères et al. 2005; Allers 2006; Radigan et al. 2009; Luhman et al. 2009), as well as brown dwarf companions to higher mass stars (e.g., Burningham et al. 2009; Day-Jones et al. 2011; Faherty et al. 2011; Luhman et al. 2012). Tens of these types of systems have been discovered.

Another method for discovering brown dwarf binaries has been through the use of spectroscopic blends. It has been shown that the spectra of some VLM objects are a poor match to an individual spectral type template, but a very good match to a combination two spectral templates (e.g., Burgasser 2007; Burgasser et al. 2008, 2010, 2012; Gelino & Burgasser 2010; Geißler et al. 2011). Though they must be followed up with high spatial or high spectral resolution observations for confirmation, this method of determining candidate brown dwarf binaries has successfully yielded more than 30 new discoveries.

Recently, a promising new technique for detecting brown dwarf binaries has been microlensing. Choi et al. (2013) announced the discovery of two closely separated very low mass binaries, closer than could be probed by imaging techniques. These new discoveries highlight a promising method of discovering binaries in currently unexplored regions of parameter space.

2.2. Statistics

With all of these surveys, the binary frequency amongst VLM objects has now been significantly probed. Initial visual binary surveys noted that the multiple systems they were finding tended to be fairly tightly separated (semi-major axis $a \lesssim 20$ AU). Additionally, it was noted that the binaries tended to have mass ratios very close to 1. In a summary of the state of the field as of 2006, Burgasser et al. (2007) noted a seeming lower limit of the binding energy for field VLM binaries (see their Figure 6, adapted from Close et al. 2003). They also noted that the overall multiplicity fraction was somewhere between 10-30%. However, they cautioned that the statistics at that time were incomplete for very tight ($a \lesssim 1$ AU) and very wide ($a \gtrsim 100$ AU) systems.

Since then, those areas of incompleteness have been filled in by many of the spectroscopic and all-sky surveys discussed in Section 2.1, and in general those statistics have held. For example, Blake et al. (2010) determined a binary frequency of very tight systems of $2.5^{+8.6}_{-1.6}$%, in spite of earlier speculations that perhaps there were numerous very tight VLM binaries. Further, it has remained true that the frequency of wide binary brown dwarfs is quite small, of order 1% or less (e.g., Kraus & Hillenbrand 2012). The number of wide substellar companions to higher mass stars has also remained small, of order $\lesssim 3\%$ (e.g., Metchev & Hillenbrand 2009).

Surveys of young star clusters have revealed slightly different trends from the field population. VLM objects in young clusters have been shown to have slightly wider separations and lower mass ratios. In a recent survey of the Hyades, Duchêne et al. (2013) found several VLM binaries with lower mass ratios than typically seen amongst field objects. Combining this information with other surveys of young VLM objects (e.g., Martín et al. 2003; Konopacky et al. 2007; Kraus & Hillenbrand 2012), they conclude that the differences seen in the properties of young versus old binaries might be explained by the original field surveys having missed lower mass ratio systems. Indeed, a recent study by Pope et al. (2013) was able to recover additional VLM binaries in archival HST data using improved image processing techniques. Further studies are needed to determine whether it is possible that there is a missing population of lower mass ratio/wider VLM binaries in the field.

The overall multiplicity of VLM objects can be compared to that of field objects. Figure 1, from Raghavan et al. (2010), shows the overall multiplicity rate as a function of spectral type from O stars though L and T type objects. The multiplicity fraction declines from almost 100% at the highest masses down to the ~20% level seen in brown dwarfs. Interestingly, Duchêne & Kraus (2013) point out that the multiplicity fraction of objects separated by between 1 and 10 AU is basically constant from the VLM objects all the way to objects of about 1.5 $M_{\odot}$. Determining the reason for the decline in multiplicity as a function of mass is an active area of research and will shed light on the star formation process in general.

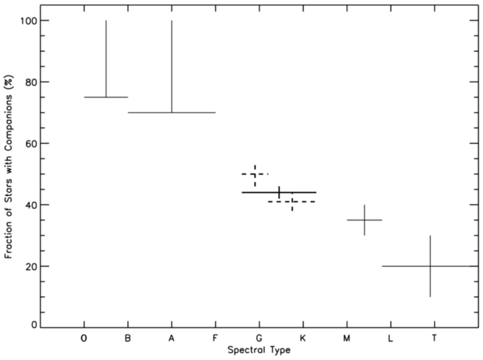

Fig. 1. From Raghavan et al. (2010), the multiplicity of stars as a function of spectral type. Raghavan et al. (2010) were able to improve on previous surveys for a comprehensive look at multiplicity across the entire stellar and substellar regime. Credits: Figure 12, Raghavan et al., ApJS, 190, 1, 2010, 1. Reproduced by permission of the AAS.

3. Measuring fundamental parameters

Brown dwarfs in binary systems have been the primary sample used to measure and constrain fundamental parameters for substellar objects. Empirical measurements of fundamental parameters are essential for feedback into substellar atmosphere and evolutionary models. These include parameters such as metallicity, age, mass, radius, temperature, and rotation. Binaries offer the best, and sometimes only, means of achieving these empirical measurements. Some of the work being done in this critical area is highlighted below.

3.1. Metallicity and age

There has been considerable progress made in identifying brown dwarf companions to higher mass objects that can be used to constrain properties like metallicity and age. While there has been progress in measuring the metallicities for late-type objects directly (e.g., Rojas-Ayala et al. 2012), it is often easier and more precise to determine them for higher mass stars. There is a long history of comparative literature for higher mass objects, and as such brown dwarf companions to objects with known metallicity can serve as standards of comparison for other brown dwarfs.

The same is true for age estimates. In general it is quite difficult to determine the age of a field brown dwarf, although there are some diagnostics that point to youth (e.g., Kirkpatrick et al. 2006). Again, it is often easier to determine an age for a higher mass star than it is for a brown dwarfs.

Many studies have undertaken identifying brown dwarf companions that can serve as standards for the rest of the field. The works of, for example, Luhman et al. (2007), Luhman et al. (2012), Day-Jones et al. (2011), Deacon et al. (2012), Gomes et al. (2013), among others, have found a number of these objects, primarily through large scale surveys. Their identification has provided valuable insight into the evolution of spectral morphology as a function of age and metallicity.

3.2. Atmospheric properties

Binary brown dwarfs have been used to characterize atmsopheric features of substellar objects. In particular, they played an essential role in ascertaining the properties of objects in the L/T transition region. It was noted in objects of spectral type early T that there was a significant "brightening" of their flux at the *J*-band compared to objects of slightly earlier spectral type (e.g., Dahn et al. 2002). This feature, known as the "*J*-band bump", is shown in Figure 2 and was attributed to perhaps patchy or dispersing clouds in the transition region (e.g., Knapp et al. 2004). Alternatively, it was suggested that the brightening could be due in part to unresolved binarity, making the objects appear brighter than expected (e.g., Liu et al. 2006).

Using binaries straddling the L/T transition region, a number of studies were able to show that the object of later spectral type in the co-eval systems were brighter at the *J*-band than the object of earlier spectral type (e.g., Burgasser et al. 2006, 2013; Looper et al. 2008; Stumpf et al. 2010). Due to these discoveries, it was confirmed that the *J*-band brightening was in fact a real atmospheric feature. This has been further confirmed by new measurements of the parallax of brown dwarfs (e.g., Faherty

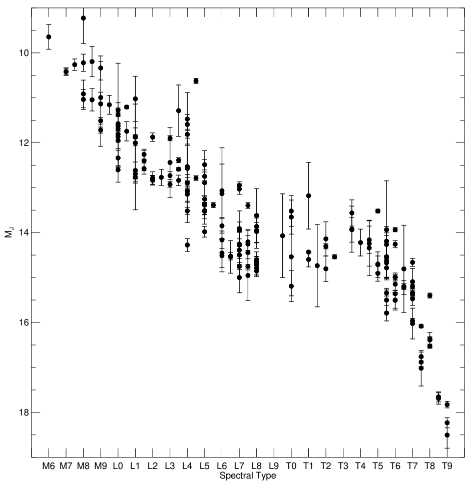

Fig. 2. *J*-band magnitude as a function of spectral type, based on data from Faherty et al. (2012). The flattening and then increase in brightness around spectral type T0 is referred to as the "*J*-band bump", and was demonstrated through observations of binaries to be intrinsic to the atmospheres of L/T transition objects.

et al. 2012). As a result of these measurements, new models of clouds at the L/T transitions (e.g., Marley et al. 2010) and observations of the variability of L/T transition objects (e.g., Radigan et al. 2012) have vastly improved our understanding of this complex transition.

3.3. Masses and orbital parameters

The most fundamental parameter that determines the evolution of an object is its mass, and yet it is among the most difficult to measure. Binaries offer an opportunity to measure the masses of objects empirically through monitoring of their orbits. Monitoring programs of brown dwarf binaries started nearly as soon as they were discovered. The first orbital solutions were determined by Basri & Martín (1999) for the spectroscopic binary PPL 15, Lane et al. (2001) for the tight visual M-type binary GJ 569Bab, and Bouy et al. (2004) for the visual L-type binary 2MASSW J0746425+2000321AB (Figure 3). The first orbital solution and mass for a T dwarf binary was derived by Liu et al. (2008) for the visual binary 2MASS J15344984-2952274AB. Since these initial works, many more dynamical masses have been determined through monitoring programs, now providing a sample of tens that can be used to constrain models (e.g., Ireland et al. 2008; Dupuy et al. 2009, 2010; Dupuy & Liu 2011; Konopacky et al. 2010). The majority of this sample consists of visual binaries for which only total system masses have been derived, and component masses are inferred from other properties, such as luminosity. However, more spectroscopic binaries have been discovered in recent years (e.g., Joergens 2008; Blake et al. 2010), providing mass ratios rather than system masses. In some cases astrometry and spectroscopy have been combined to yield empirical component masses (Konopacky et al. 2010).

The feedback into atmosphere and evolutionary models from these measurements has been extensive. Generally the comparison to the models requires some estimate of either age, luminosity, or effective temperature. Of these, luminosity is the easiest to measure, and hence very commonly used. Age and temperature generally require the use of a model or other empirical indicators, some of which are more robust if the binary happens to orbit a higher mass star as described above (e.g., Dupuy et al. 2009). In general, it has been shown that there is a disconnection between evolutionary and atmosphere models in terms of predictions. More direct measurements of effective temperature would shed light on this topic. This requires the discovery and monitoring of more brown dwarf eclipsing binaries. Thus far, only one such system is known (Stassun et al. 2006), and the wealth of information obtained from this one system stresses the importance of discovering more objects like it. Future surveys will hopefully accomplish this goal. Such discoveries will also provide direct radii measurements for these objects, a fundamental parameter for which there is a significant dearth of information presently. With additional radius measurements, the mass-radius relationship for brown dwarfs can be constrained.

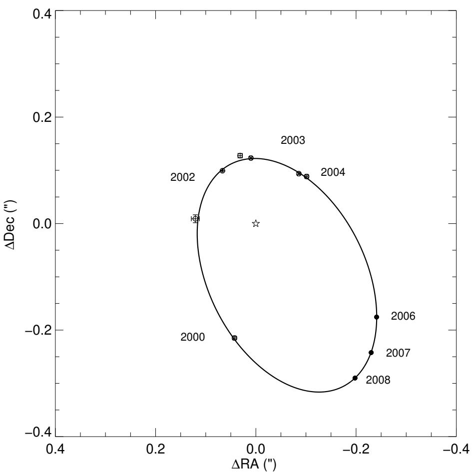

Fig. 3. From Konopacky et al. (2010), the visual orbit of the L-type binary 2MASSW J0746425+2000321AB, based on data from Bouy et al. (2004) and additional data from the W.M. Keck II 10 meter telescope. This system was among the first to have a dynamical mass determination, and futher monitoring has refined the total system mass such that the uncertainty is of order 1%. Credits: Figure 5, Konopacky et al., ApJ, 711, 2, 2010, 1087. Reproduced by permission of the AAS.

In addition to yielding dynamical mass measurements, the orbital solutions for binaries provide other interesting parameters. Among the most illuminating is the eccentricity distribution. Larger samples of VLM binary orbits have provided a glimpse of this distribution (e.g., Dupuy & Liu 2011), which has been shown to be not only a bit different from higher mass objects (e.g., Duchêne & Kraus 2013), but also inconsistent with expected distributions such as thermal or flat. This may provide insight into the formation of brown dwarf binaries as compared to higher mass binaries, or perhaps their subsequent dynamical evolution.

3.4. Rotational properties

Recent work has shown that the rotational properties of brown dwarf binaries can yield interesting insight into their formation and dynamical evolution. When coupled with an es-

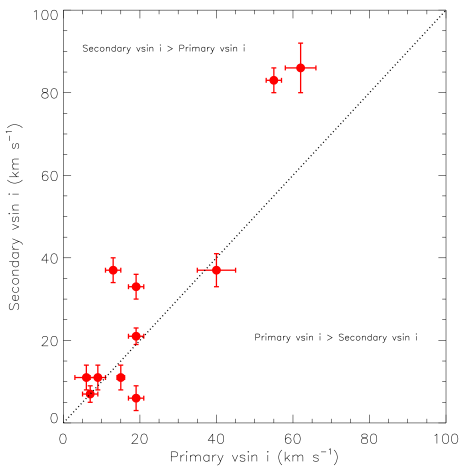

Fig. 4. From Konopacky et al. (2012), $v \sin i$ measurements for components of a set of visual brown dwarf binaries, plotted with respect to each other. For about half of the sample, the $v\sin i$ measurements are significantly different from each other. This is either due to their true rotation speed being different, or their rotation axes not being aligned. Most likely, the systems in this sample represent both possibilities. Credits: Figure 4, Konopacky et al., ApJ, 750, 1, 2012, 79. Reproduced by permission of the AAS.

timate of the inclination of the object, the rotational period and rotational velocity offer another means of obtaining radii (e.g., Harding et al. 2013). Furthermore, recent measurements of a larger sample of brown dwarf binary rotational velocities have shown that in many cases the velocities of the components are quite different from one another (Konopacky et al. 2012, Figure 4). This is either due to intrinsic properties influencing their rotational evolution, subsequent dynamical evolution due perhaps to the influence of a tertiary companion, or something else entirely. Rotational velocity has also recently been coupled with linear polarization measurements to yield insight into the atmospheric properties of these objects (Miles-Páez et al. 2013)

4. Summary

In summary, brown dwarfs in binary systems have been incredibly important for advancing our understanding of substellar objects. The statistics of their multiplicity have yielded insight into their formation compared to higher mass objects. The empirical measurements of fundamental parameters have expanded our understanding of their evolution and atmospheres. At the "Brown Dwarfs Come of Age" conference, 20 presentations involved brown dwarf binaries of some kind, demonstrating that this is still an active, evolving field of research. New discoveries in the next 18 years will greatly enhance our understanding of this fascinating class of objects.

Acknowledgements. I would like to thank Antonio Magazzù and Eduardo Martín for spearheading a stimulating conference. I would like to acknowledge funding through the Dunlap Fellowship Program at the Dunlap Institute for Astronomy & Astrophysics, University of Toronto. The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto.

References

Allers, K. N. 2006, Ph.D. Thesis, The University of Texas at Austin
Basri, G., & Martín, E. L. 1999, AJ, 118, 2460
Billères, M., Delfosse, X., Beuzit, J.-L., et al. 2005, A&A, 440, L55
Blake, C. H., Charbonneau, D., & White, R. J. 2010, ApJ, 723, 684
Bouy, H., Brandner, W., Martín, E. L., et al. 2003, AJ, 126, 1526
Bouy, H., Duchêne, G., Köhler, R., et al. 2004, A&A, 423, 341
Burgasser, A. J. 2007, AJ, 134, 1330
Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., et al. 2003, ApJ, 586, 512
Burgasser, A. J., Kirkpatrick, J. D., Cruz, K. L., et al. 2006, ApJS, 166, 585
Burgasser, A. J., Reid, I. N., Siegler, N., et al. 2007, in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil eds., (University of Arizona Press, Tucson), 427, 427
Burgasser, A. J., Liu, M. C., Ireland, M. J., Cruz, K. L., & Dupuy, T. J. 2008, ApJ, 681, 579
Burgasser, A. J., Cruz, K. L., Cushing, M., et al. 2010, ApJ, 710, 1142

Burgasser, A. J., Luk, C., Dhital, S., et al. 2012, ApJ, 757, 110
Burgasser, A. J., Sheppard, S. S., & Luhman, K. L. 2013, arXiv:1303.7283
Burningham, B., Pinfield, D. J., Leggett, S. K., et al. 2009, MNRAS, 395, 1237
Choi, J.-Y., Han, C., Udalski, A., et al. 2013, ApJ, 768, 129
Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, ApJ, 587, 407
Dahn, C. C., Harris, H. C., Vrba, F. J., et al. 2002, AJ, 124, 1170
Day-Jones, A. C., Pinfield, D. J., Ruiz, M. T., et al. 2011, MNRAS, 410, 705
Deacon, N. R., Liu, M. C., Magnier, E. A., et al. 2012, ApJ, 755, 94
Duchêne, G., Bouvier, J., Moraux, E., et al. 2013, arXiv:1306.4122
Duchêne, G., & Kraus, A. 2013, arXiv:1303.3028
Dupuy, T. J., Liu, M. C., & Ireland, M. J. 2009, ApJ, 692, 729
Dupuy, T. J., Liu, M. C., Bowler, B. P., et al. 2010, ApJ, 721, 1725
Dupuy, T. J., & Liu, M. C. 2011, ApJ, 733, 122
Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19
Faherty, J. K., Burgasser, A. J., Bochanski, J. J., et al. 2011, AJ, 141, 71
Faherty, J. K., Burgasser, A. J., Walter, F. M., et al. 2012, ApJ, 752, 56
Geißler, K., Metchev, S., Kirkpatrick, J. D., Berriman, G. B., & Looper, D. 2011, ApJ, 732, 56
Gelino, C. R., & Burgasser, A. J. 2010, AJ, 140, 110
Gizis, J. E., Reid, I. N., Knapp, G. R., et al. 2003, AJ, 125, 3302
Gomes, J. I., Pinfield, D. J., Marocco, F., et al. 2013, MNRAS, 431, 2745
Guenther, E. W., & Wuchterl, G. 2003, A&A, 401, 677
Harding, L. K., Hallinan, G., Konopacky, Q. M., et al. 2013, A&A, 554, A113
Ireland, M. J., Kraus, A., Martinache, F., Lloyd, J. P., & Tuthill, P. G. 2008, ApJ, 678, 463
Joergens, V. 2008, A&A, 492, 545
Kirkpatrick, J. D., Beichman, C. A., & Skrutskie, M. F. 1997, ApJ, 476, 311
Kirkpatrick, J. D., Barman, T. S., Burgasser, A. J., et al. 2006, ApJ, 639, 1120
Knapp, G. R., Leggett, S. K., Fan, X., et al. 2004, AJ, 127, 3553
Konopacky, Q. M., Ghez, A. M., Rice, E. L., & Duchêne, G. 2007, ApJ, 663, 394
Konopacky, Q. M., Ghez, A. M., Barman, T. S., et al. 2010, ApJ, 711, 1087
Konopacky, Q. M., Ghez, A. M., Fabrycky, D. C., et al. 2012, ApJ, 750, 79
Kraus, A. L., Ireland, M. J., Martinache, F., & Lloyd, J. P. 2008, ApJ, 679, 762
Kraus, A. L., & Hillenbrand, L. A. 2012, ApJ, 757, 141
Lane, B. F., Zapatero Osorio, M. R., et al. 2001, ApJ, 560, 390
Liu, M. C., & Leggett, S. K. 2005, ApJ, 634, 616
Liu, M. C., Leggett, S. K., Golimowski, D. A., et al. 2006, ApJ, 647, 1393
Liu, M. C., Dupuy, T. J., & Ireland, M. J. 2008, ApJ, 689, 436
Looper, D. L., Gelino, C. R., Burgasser, A. J., & Kirkpatrick, J. D. 2008, ApJ, 685, 1183
Luhman, K. L., Patten, B. M., Marengo, M., et al. 2007, ApJ, 654, 570
Luhman, K. L., Mamajek, E. E., Allen, P. R., Muench, A. A., & Finkbeiner, D. P. 2009, ApJ, 691, 1265
Luhman, K. L., Loutrel, N. P., McCurdy, N. S., et al. 2012, ApJ, 760, 152
Martín, E. L., Basri, G., Brandner, W., et al. 1998, ApJ, 509, L113
Martín, E. L., Brandner, W., & Basri, G. 1999, Science, 283, 1718
Martín, E. L., Barrado y Navascués, D., Baraffe, I., Bouy, H., & Dahm, S. 2003, ApJ, 594, 525
Marley, M. S., Saumon, D., & Goldblatt, C. 2010, ApJ, 723, L117
Metchev, S. A., & Hillenbrand, L. A. 2009, ApJS, 181, 62
Miles-Páez, P. A., Rosa Zapatero Osorio, M., Pallé, E., & Peña Ramírez, K. 2013, arXiv:1306.6314
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, Nature, 378, 463
Pope, B., Martinache, F., & Tuthill, P. 2013, ApJ, 767, 110
Radigan, J., Lafrenière, D., Jayawardhana, R., & Doyon, R. 2009, ApJ, 698, 405

Radigan, J., Jayawardhana, R., Lafrenière, D., et al. 2012, ApJ, 750, 105
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, Nature, 377, 129
Reid, I. N., Kirkpatrick, J. D., Liebert, J., et al. 2002, AJ, 124, 519
Reid, I. N., Lewitus, E., Allen, P. R., Cruz, K. L., & Burgasser, A. J. 2006, AJ, 132, 891
Reid, I. N., Cruz, K. L., Burgasser, A. J., & Liu, M. C. 2008, AJ, 135, 580
Rojas-Ayala, B., Covey, K. R., Muirhead, P. S., & Lloyd, J. P. 2012, ApJ, 748, 93
Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L., & Reid, I. N. 2005, ApJ, 621, 1023
Stassun, K. G., Mathieu, R. D., & Valenti, J. A. 2006, Nature, 440, 311
Stumpf, M. B., Brandner, W., Bouy, H., Henning, T., & Hippler, S. 2010, A&A, 516, A37
Zuckerman, B., & Becklin, E. E. 1992, ApJ, 386, 260