Brown Dwarfs: Discovery and Detailed Studies

Perhaps the best way to summarize the advances under the current Origins grant is offered by our publication list[1] (§0.1). We now summarize the highlights of the past three years:

Observational Results. We obtained the optical and IR spectra of Gliese 229B (Figure 2; [OKM+97]) and identified (in addition to the prominent CH_4 and H_2O) Cs I and CO features – as expected in theoretical models. Our optical-IR spectrum showed that most of the refractory metals have condensed out of the atmosphere and the presence of Cs I and CO shows evidence for disequilibrium chemistry (as in Jupiter; see [Noll, Geballe & Marley 1997]). In [GBK+98] we report orbital evidence for Gliese 229B. The HST measured optical magnitudes provide additional evidence for the absence of dust in the atmosphere of this cool object ($T_{eff} \sim 900$ K).

Oppenheimer, as a part of his thesis project, completed the tip-tilt optical (R, I and z) coronagraphic and direct IR (JK) imaging survey of all stars accessible to the Palomar telescope and within 8 pc of the Sun. This extensive survey (100 nights at the Palomar 60-inch and 50 nights at the Palomar 200-inch) took five years to complete (1994-1999). Oppenheimer surveyed 163 stars and identified six new stellar binaries but only one brown dwarf: Gliese 229B. The luminosity of brown dwarfs depend on their masses and ages and in order to interpret the results of the survey we have carried out an extensive Monte Carlo analysis. The result of this analysis is summarized in Figure 1. An extensive paper that contains all the observational details of the 8-pc sample and the Monte Carlo analysis and will be submitted within this month.

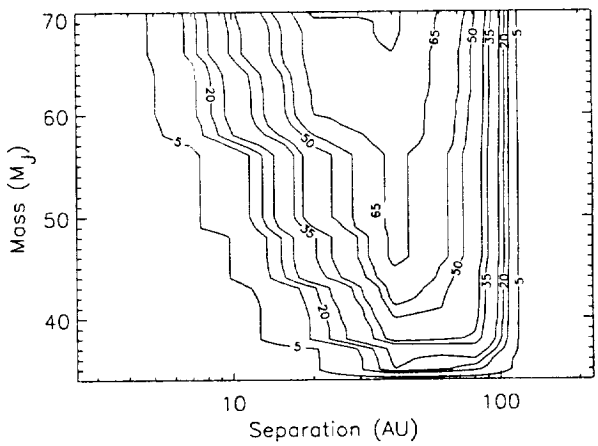

Figure 1: *Sensitivity of our tip-tilt coronagraphic optical (z-band) imaging survey of stars within 8-pc distance of the Sun. The contour levels show the percentage of detectable brown dwarfs of mass (y-axis) and orbital separation (x-axis). The sensitivity falls at small orbital separation due to scattered light and that at large separation is limited by the field of view[s] of the optical camera. The sensitivity of our direct imaging JK band survey is very similar.*

Our conclusion is that warm brown dwarfs are rare (~1% incidence), as companions in the orbital period range beyond ~30-50 AU. The Palomar survey poses no constraint for brown dwarfs in planetary orbits similar to those of the outer planets. We have just

[1] We use the notation [ABC99] to refer to our publications listed in §2.1

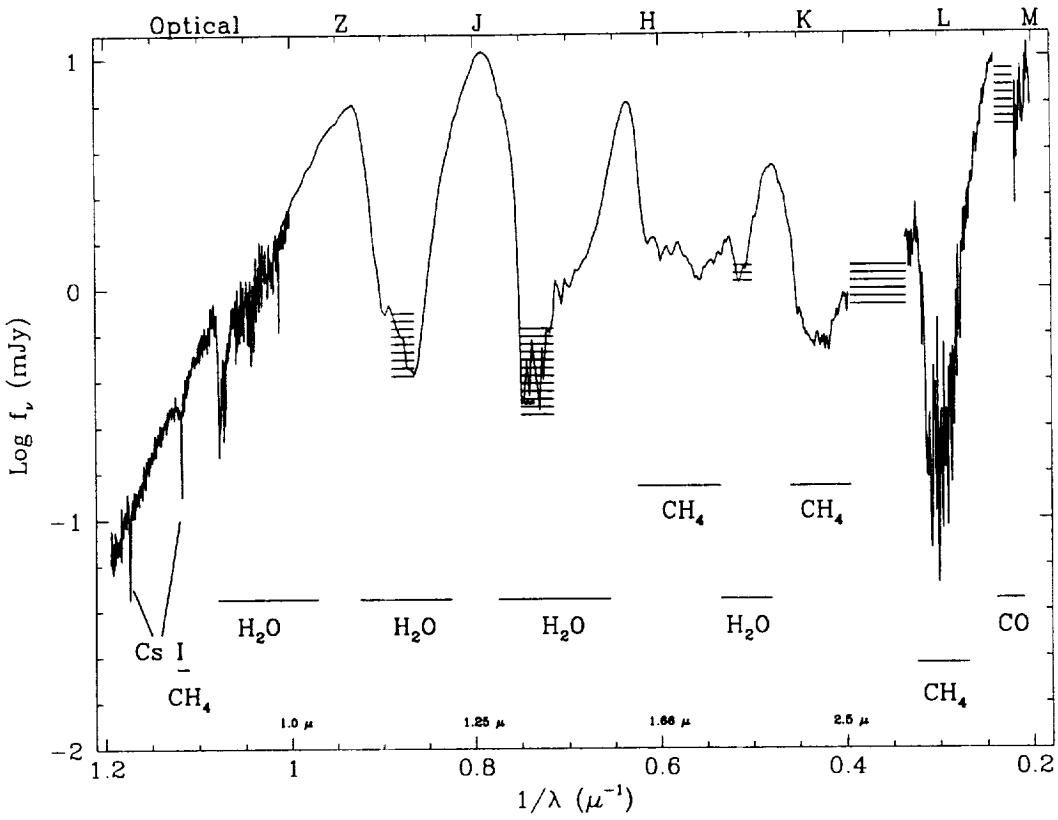

Figure 2: *Keck spectrum of Gliese 229B obtained with LRIS and NIRC spectrographs on the Keck telescope.*

started a program of imaging nearby stars with the newly commissioned AO system at Palomar and Keck and have already found a brown dwarf candidate [MKK+00].

Interferometry. The Palomar Testbed Interferometer (PTI) is now routinely operational [C+99]. The primary purpose of the interferometer is to develop and refine modes for the Keck interferometer. However, we have used the interferometer in the standard amplitude mode for observations of stars; see §0.1.

We were able to limit any bright companion to 51 Pegasi on a 4-milliarcsecond scale and thus settle a minor controversy that 51 Pegasi was a face-on stellar binary [B+98]. Our PTI observations of FU Ori probed the disk around this object on milliarcsecond scales [M+98].

We are now developing phase referencing and two-color interferometry – techniques of central interest to the Origins program (and key to the success of the Keck Interferometer) – and the initial results are exciting.

Graduate Students and Post-doctoral Fellows. This grant was used to support graduate student Oppenheimer, whose thesis was the detailed study of Gliese 229B and the extensive 8-pc sample described above. The grant also supported research expenses of post-doctoral fellow Koresko. Oppenheimer graduated last summer and is now a Hubble fellow at U. C. Berkeley while Koresko has obtained a staff position at JPL (working on the Keck Interferometer).

The PI has strongly encouraged his students to work on hardware projects and technique development. Oppenheimer was one of the three members of the core team of the Palomar AO system. In addition, Op-

penheimer contributed to three original technique papers [SB98, RBB+98, BMD+00]. Oppenheimer was supported briefly as a postdoctoral fellow during which period he initiated a program of spectroscopy of cool white dwarfs [HBH+00]. In the atmosphere of such white dwarfs collision induced absorption from H_2 provides a significant source of opacity, as is the case in Gliese 229B. As a result, both these classes of objects possess blue IR colors despite their low effective temperatures.

The PI has a policy of encouraging postdocs to undertake independent research in addition to research tied to a specific grant. Koresko had a fruitful stay as evidenced by his collaborative research with Caltech astronomers on a variety of subjects: surfaces of asteroids, disks around young stars, exo-zodiacal dust disks and magnetic fields of pre-main sequence stars [KHC+97, MK98, KBK98, JVK99, K98, K00].

0.1 Publications Related to the Origins Brown Dwarf Grant during the period 1997–2000

[K97][2] "Brown dwarfs: a possible missing link between stars and planets" by S. R. Kulkarni, *Science*, **276**, 1350, (1997).

[OBN+97] "Lithium in Very Low-Mass Stars in the Pleiades" by B. R. Oppenheimer, G. Basri, T. Nakajima, S. R. Kulkarni, *Astron. Journal*, **113**, 296, (1997).

[GBK+98] "WFPC2 Observations of Brown Dwarf Gliese 229B: Optical Colors and Orbital Motion" by D. A. Golimowski, C. J. Burrows, S. R. Kulkarni, B. R. Oppenheimer, R. A. Brukardt, *Astron. J.*, **115**, 2579, (1998).

[OKM+98] "The Spectrum of the Brown Dwarf Gliese 229B" by B. R. Oppenheimer, S. R. Kulkarni, K. Matthews, M. H. van Kerkwijk, *Astrophys. J.*, **502**, 932, (1998).

[KKB98] "Keck Speckle Imaging of the White Dwarf G29-38: No Brown Dwarf Companion Detected" by M. J. Kuchner, C. D. Koresko, M. E. Brown, *Astrophys. J. Lett.*, **508**, L81 (1998).

[OKS00] "Brown Dwarfs" by B. R. Oppenheimer, S. R. Kulkarni, J. R. Stauffer, in *Protostars and Planets IV*, V. Mannings, A. Boss, S. Russell, eds. (Tucson: University of Arizona Press),(2000).

[MKK+00] "The Discovery of a Companion to the Very Cool Dwarf Gliese 569B with the Keck Adaptive Optics Facility" by E.L. Martin, C.D. Koresko, S.R. Kulkarni, B.F. Lane, P.L. Wizinowich, *Astrophys. J. Lett.*, **529**, 37, (2000).

[ODH+00] "Companion detection limits with adaptive optics coronagraphy" by B. R. Oppenheimer, R. G. Dekany, T. L. Hayward, B. Brandl, M. Troy, E. E. Bloemhof in *Adaptive Optical Systems Technology*, P. L. Wizinowich, ed. Proceedings of SPIE, Vol. 4007, in press, (2000).

Other Observational Papers

[KHC+97] "A Multiresoulution Infrared Imaging Study of LkHa 198" by C. D. Koresko, P. M. Harvey, J. C. Christou, R. Q. Fugate, W. Li, *Astrophys. J.* , **485**, 213, (1997).

[MK98] "Detection of Water Ice on the Centaur 1997 CU26" by M. E. Brown, C. D. Koresko, *Astrophys. J. Lett.*,**505**, L65, (1998).

[MKB98] "Detection of Water Ice on Nereid" by M. E. Brown, C. D. Koresko, G. A. Blake, *Astrophys. J. Lett.*, **508**, L175, (1998)

[KBK98] "An 11.6 Micron Keck Search for Exo-Zodiacal Dust" by M. J. Kuchner, M. E. Brown, C. D. Koresko, PASP, **110**, 1336, (1998).

[K98] "A Circumstellar Disk in a Young Binary Star" by C. D. Koresko, *Astrophys. J. Lett.*, **507**, L145, (1998).

[2]The list includes only papers published or submitted to professional journals and refereed review articles. No conference proceedingsa are included with the exception of those submitted to SPIE. It is expected that technical papers submitted to SPIE Conference Proceedings are final references.

[JVK99] "Measuring the Magnetic Field on the Classical T Tauri Star BP Tauri" by C. M. Johns-Krull, J. A. Valenti, C. D. Koresko, *Astrophys. J.*, **516**, 900, (1999).

[KOO] "A Third Star in the T Tauri System" by C.D. Koresko, *Astrophys. J. Lett.*, **531**, L147, (2000).

[HBH+00] "Infrared Spectrum of an Extremely Cool White Dwarf Star" by S. T. Hodgkin, B. R. Oppenheimer, N. C. Hambly, R. F. Jameson, S. J. Smartt, I. A. Steele, *Nature*, **403**, 57.,(2000).

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