

2MASS Data Mining and the M, L, and T Dwarf Archives

J. Davy Kirkpatrick

*Infrared Processing and Analysis Center, California Institute of
Technology, Pasadena, CA 91125, USA*

Abstract. Studies of brown dwarfs as a distinct galactic population have been largely pioneered by dedicated, vast-area surveys at deep optical and near-infrared wavebands. The Two Micron All Sky Survey has, because of its full-sky coverage and depth, been the most successful at providing new targets for further study. The author briefly reviews some of the ways in which 2MASS data have been used by brown dwarf researchers. One of the by-products – namely the 2MASS Team’s follow-up spectroscopy of brown dwarf candidates – is potentially valuable as a scientific resource itself and is also being released to the public.

1. Introduction

The Two Micron All Sky Survey (2MASS) has, along with the Sloan Digital Sky Survey (SDSS) and to a lesser extent the Deep Near-infrared Survey (DENIS), provided a treasure trove of information with which to study brown dwarfs both in the field and in nearby open clusters. As an illustration, Table 1 contains a breakdown of the number of known nearby L and T dwarfs so far discovered by each. In addition to providing a discovery tool for field brown dwarfs, 2MASS data in particular have also been used in a variety of other ways to study substellar objects. The 2MASS mission is briefly overviewed in §2 and some of its contributions to brown dwarf science are highlighted in §3.

Table 1. Numbers of L and T Dwarfs Currently Known

Survey	No. of	No. of
	L Dwarf Discoveries	T Dwarf Discoveries
2MASS	155	18
SDSS	72	11
DENIS	9	0
Others	9	3

Furthermore, Keck Observatory follow-up of 2MASS-selected brown dwarf candidates has resulted in a wealth of high-quality spectroscopic information which the author is releasing to the general public for the first time. In tandem

with the Keck data, the author is also releasing libraries of other dwarf spectra that he and his collaborators have amassed over the period 1989-2002. These libraries are being paired with the 2MASS final release dataset to produce tables of uniform spectral types and near-infrared photometry for all dwarf spectral types from K5 through T8. These libraries are further described in §4.

2. Brief Overview of 2MASS

The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center at the California Institute of Technology. As the name implies, the purpose of the survey was to image the entire celestial sphere at near-infrared wavelengths. Twin 1.3-meter telescopes were built. One was placed in North America on Mt. Hopkins in southern Arizona, USA, and the second in South America on Cerro Tololo, Chile. Twin three-channel cameras were also built, one for each telescope, to observe the sky simultaneously at J, H, and K_s bands using NICMOS 256×256 detectors. The scale was $2''/\text{pixel}$ for a field of view of $8'.5 \times 8'.5$.

The scanning mode for 2MASS was designed to build up strips of sky $8'.5$ wide in Right Ascension and 6° long in Declination. As the telescope tracked the sky in RA, it would move at a set rate in Dec. The secondary mirror moved at the same rate in Dec but in the opposite direction. This motion would freeze an image of the sky on the detectors for a 1.3-second integration. After the integration, the secondary mirror would flip back to its starting position and freeze a new image of the sky onto the detectors for another 1.3-second integration. Because the telescope continues to move at a constant rate in Dec while the secondary is swinging back, this new image is offset in Dec from the first, in this case by about one-sixth of a frame. A sequence of 274 such frames would be coadded to give a 6° -long 2MASS scan where each spot on the sky is viewed in six consecutive frames for a total integration time of 7.8 seconds. In regions of high galactic latitude, resulting SNR=10 limits of $J \approx 16.3$, $H \approx 15.3$, and $K_s \approx 14.9$ mag were reached.

By the time these proceedings go to press, 2MASS will have publicly released catalogs and images of the entire sky. Details of the release as well as more information on the 2MASS project itself can be found at the URL <http://ipac.caltech.edu/2MASS>.

3. Brown Dwarf Research Enabled by 2MASS

3.1. Science by the 2MASS Team

Initial 2MASS studies of brown dwarfs concentrated on the search and characterization of L dwarfs (Kirkpatrick et al. 1999, 2000; Reid et al. 1999) and T dwarfs (Burgasser 2001). Today our team has several other focuses including the search for M and L dwarfs within ~ 25 parsecs of the Sun (see contributions by Cruz and by Wilson), completing a census of 2MASS-detected T dwarfs (see contribution by Burgasser), the search for widely separated M, L, and T dwarf companions to nearby stars (see contribution by Gizis), parallax follow-up of confirmed L and T dwarfs from both the northern and southern hemispheres

(see contributions by Harris and by Tinney), and the analysis of the entire sample for purposes of refining global properties of brown dwarfs in the solar vicinity (see contribution by Liebert).

3.2. Science by the Community

Whereas the 2MASS team itself has concentrated on brown dwarfs in the field, the larger astronomical community has found 2MASS to be a useful tool in the study of nearby open clusters and star forming regions. Both Martín et al. (2001) and Briceño et al. (2002) have used 2MASS photometry to search for lower mass members of the Taurus star forming region. Luhman et al. (2000) have used 2MASS to probe the initial mass function in Taurus as compared to other star forming regions of differing star and gas densities. In the Pleiades, Adams et al. (2001) have used 2MASS data to determine the extent of the cluster and the rate of evaporation of its lower mass members. In MBM12, Wolk et al. (2000) and Luhman (2001) have used 2MASS to refine the general census of the cluster. In σ Orionis, Oliveira et al. (2002) have used 2MASS data to search for disks.

3.3. Observational Follow-up of 2MASS Discoveries

Another avenue of study has been in-depth follow-up of brown dwarfs and low-mass stars initially selected via 2MASS photometry. Koerner et al. (1999) acquired conventional deep near-infrared imaging around late-M and L dwarfs to search for cooler companions and to study the frequency and separation ranges of low-mass binaries. Potter et al. (2002) and Close et al. (2002) have used adaptive optics to probe even smaller separations. High-resolution spectroscopic studies for detailed analysis have been obtained by McLean et al. (2000, 2001) and Nakajima et al. (2001). 2MASS brown dwarfs have also been scrutinized for photometric variability by Bailer-Jones & Mundt (1999, 2001), and photometry in other bands – mainly V , R , I , z , L , and M – has been obtained by Dahn et al. (2002), Dobbie et al. (2002), Stephens et al. (2001), and Leggett et al. (2001).

3.4. Theoretical Follow-up of 2MASS Discoveries

Other investigators have used 2MASS discoveries to refine their flux modelling and to derive physical parameters for L and T dwarfs. Burrows et al. (2000) and Schweitzer et al. (2002) have fit their models to low-resolution optical and near-infrared spectra to derive a temperature scale for L and T dwarfs. Leggett et al. (2001) have obtained wide wavelength coverage to compare the observed spectral energy distributions to models and to better estimate bolometric luminosities. Geballe et al. (2001) have obtained new observations of the 2MASS discovery Gliese 570D to determine a theoretically derived temperature for this very cool T dwarf. High resolution spectroscopic observations have also been compared to theory by Schweitzer et al. (2001) to check the validity of the predictions.

Discovery Name	Discovery Reference	2MASS J mag	2MASS H mag	2MASS Ks mag	2MASS J-Ks	2MASS J-H	2MASS H-Ks	Spectral Type*
Finder Chart	Paper	---	---	---	---	---	---	Ascii Data
GJ 1001B = LHS 102B	Goldman et al. (1999)	13.10 \pm 0.03	12.05 \pm 0.02	11.40 \pm 0.03	1.70 \pm 0.04	1.05 \pm 0.04	0.65 \pm 0.04	L5 V
2MASSW J0015447+351603	Kirkpatrick et al. (2000)	13.82 \pm 0.04	12.81 \pm 0.03	12.24 \pm 0.03	1.58 \pm 0.05	1.00 \pm 0.05	0.57 \pm 0.05	L2 V
SDSS J001911.65+003017.8	Hawley et al. (2002)	14.92 \pm 0.05	14.18 \pm 0.06	13.57 \pm 0.05	1.35 \pm 0.07	0.74 \pm 0.08	0.61 \pm 0.08	[L1 V]
2MASS J0028394+150141	Kirkpatrick et al. (2000)	16.49 \pm 0.14	15.33 \pm 0.10	14.62 \pm 0.13	1.87 \pm 0.19	1.16 \pm 0.17	0.71 \pm 0.16	L4.5 V
2MASSW J0030300-145033	Kirkpatrick et al. (2000)	16.79 \pm 0.16	15.36 \pm 0.09	14.38 \pm 0.08	2.41 \pm 0.18	1.44 \pm 0.18	0.98 \pm 0.12	L7 V
2MASSW J0030438+313932	Kirkpatrick et al. (1999)	15.49 \pm 0.06	14.58 \pm 0.06	13.99 \pm 0.06	1.50 \pm 0.08	0.91 \pm 0.08	0.59 \pm 0.08	L2 V
EROS-MP J0032	Goldman et al. (1999)	14.79 \pm 0.03	13.87 \pm 0.03	13.26 \pm 0.04	1.53 \pm 0.05	0.92 \pm 0.05	0.61 \pm 0.05	[L0:V]
SDSSp J003259.36+141036.6	Geballe et al. (2002)	16.77 \pm 0.17	15.67 \pm 0.16	14.96 \pm 0.12	1.81 \pm 0.21	1.10 \pm 0.23	0.71 \pm 0.20	[L8?V]
SDSS J003524.44+144739.8	Hawley et al. (2002)	16.95 \pm 0.18	16.26 \pm 0.19	>15.69	<1.26	0.69 \pm 0.26	<0.57	[L0 V]
2MASSW J0036159+182110	Reid et al. (2000)	12.44 \pm 0.04	11.58 \pm 0.03	11.03 \pm 0.03	1.41 \pm 0.05	0.86 \pm 0.05	0.55 \pm 0.04	L3.5 V
SDSS J003843.99+134339.5	Hawley et al. (2002)	15.91 \pm 0.07	15.21 \pm 0.08	14.76 \pm 0.10	1.15 \pm 0.13	0.71 \pm 0.11	0.45 \pm 0.13	[L1 V]
SDSS J004154.54+134135.5	Hawley et al. (2002)	14.59 \pm 0.03	13.80 \pm 0.04	13.36 \pm 0.04	1.23 \pm 0.05	0.79 \pm 0.05	0.44 \pm 0.06	[L0 V]
SDSS J004221.15+145923.9	Hawley et al. (2002)	16.68 \pm 0.16	16.09 \pm 0.18	15.58 \pm 0.20	1.10 \pm 0.26	0.59 \pm 0.24	0.51 \pm 0.27	[L1 V]
2MASSW J0051107-154417	Kirkpatrick et al. (2000)	15.23 \pm 0.05	14.15 \pm 0.04	13.42 \pm 0.05	1.81 \pm 0.07	1.08 \pm 0.07	0.72 \pm 0.06	L3.5 V

Figure 1. A portion of the L dwarf archive as it currently appears.

4. The M, L, and T Dwarf Archives

As they become known, discoveries of L and T dwarfs are served to the community through publications and databases such as SIMBAD. Although such services are valuable, they fail to present data in a consistent, homogeneous way since authors do not always present findings on the same photometric system or spectral classification system. 2MASS has covered the entire sky relatively deeply, so almost all L and T dwarfs – even if discovered by other surveys – will be present in the 2MASS images and catalogs. Furthermore, the 2MASS team has acquired optical spectra of many of these same objects on a uniform classification system. Hence, it *is* possible to present a vast collection of L and T dwarfs with homogeneous photometry and spectral types.

The author has also obtained many spectra of late-K through late-M dwarfs, late-type giants, and assorted other stellar spectra in the same wavelength regime (roughly 6000-10000Å) as that used for optical L and T dwarf classification. Because of their potential usefulness to the astronomical community at large, these data will now be served to the public. A portion of the archive is shown in Figure 1. The URL for the archives is <http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/>.

These databases will be disseminated under the aegis of the On-line Archive Science Information Services (OASIS), a data fusion and visualization applet accessible through the NASA/IPAC Infrared Science Archive (IRSA). OASIS is evolving as a portal to data services deployed as part of the National Virtual

Observatory (NVO). Its utility lies in the fact that providers of small to moderate sized data sets can enable community access to their data without having to learn NVO standards and protocols.

4.1. Summary of the Archives

Table 2 gives a breakdown of data contained in the main archives. The lists of 245 L and 32 T dwarfs represent a complete collection of all such objects known in the solar vicinity. The lists of 529 K and M dwarfs, 43 late-type giants, and 19 M subdwarfs are not meant to be complete collections in any magnitude- or volume-limited sense but will nonetheless contain a wealth of data on many familiar objects.

Table 2. Summary of the Archives

Type of Object	No. of Objects	No. w/ 2MASS Photometry	No. w/ Optical Spectra
late-K dwarfs	23	23	23
M dwarfs	506	506	506
L dwarfs	245	242	114
T dwarfs	32	29	17
late-type giants	43	43	43
M subdwarfs	19	19	19

In addition to uniform photometry, uniform spectra, and uniform spectral types, the archives will also contain positional information, finder charts, and published references for each object. Other subsets will also be provided, such as a list of bright late-K through late-T dwarfs to observe as spectral standards, a subset of high-SNR spectra with which to compare unclassified spectra if standards were not obtained at the telescope¹, and subsets of ultracool dwarfs with measured trigonometric parallaxes and absolute magnitudes.

4.2. Science Already Enabled by the Archives

Although the archives have existed (in partial states of completeness) for less than a month, a couple of interesting scientific discoveries have already been made using the information provided there.

First, in checking the L dwarf archive against areas of sky that 2MASS imaged more than once, the late-L dwarf 2MASSW J1515008+484742 (discovered by J. Wilson, priv. comm.) was found to be moving with a high proper motion of $1''.7/\text{yr}$ (R. Cutri, priv. comm.). For an implied spectrophotometric distance of 12 pc, this translates into a tangential velocity (v_{tan}) of ~ 100 km/s. This is comparable in size to two of the estimated v_{tan} values in the Gizis et al. (2000)

¹The author **strongly** recommends the acquisition of spectral standards for each telescope/instrument combination, rather than relying on comparison to other researchers' data with different telescopes/instruments or comparing to uncalibrated spectral ratios.

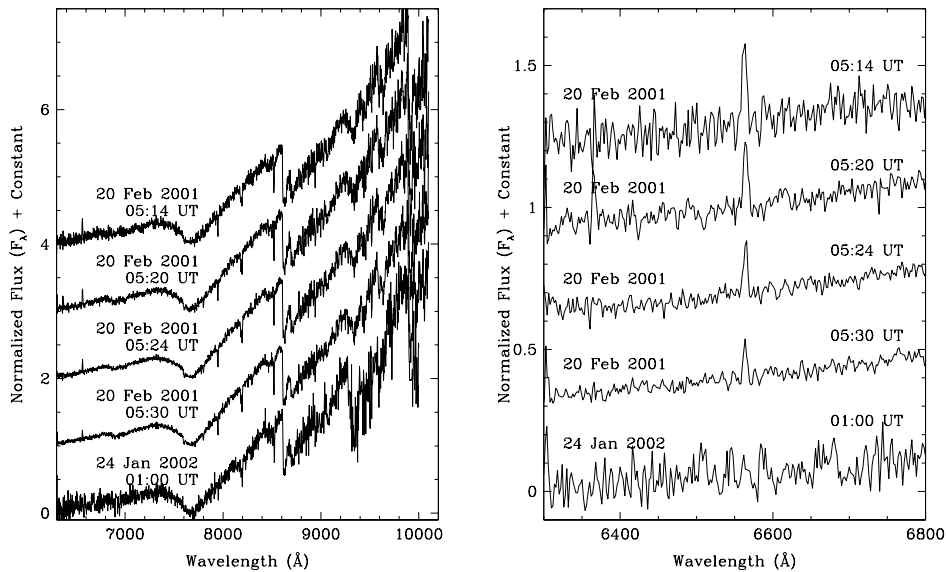


Figure 2. In the left figure is shown the sequence of four Keck spectra at the top and the single CTIO spectrum at the bottom. The four Keck spectra show an $H\alpha$ line (6563 \AA) that weakens with time, indicating a decaying flare event. The right figure shows the same five spectra, this time zoomed in on the $H\alpha$ line for clarity. Each spectrum has been normalized to one at 8250 \AA and offset by integral (for the left plot) or half integral (for the right) steps to separate it from neighbor spectra. No correction for telluric absorption has been applied, which is why the lower-altitude CTIO spectrum exhibits more 9300-\AA water than the Keck spectra.

bright L dwarf sample though larger than any of the v_{tan} measures for L and T dwarfs in Dahn et al. (2002).

Second, during compilation of the archives it was noticed that the L5 dwarf 2MASS J0144353-071614 was discovered independently by K. Cruz (priv. comm.) and by the author and C. Tinney (priv. comm.). The spectrum by Cruz – taken at Cerro Tololo Interamerican Observatory on 24 Jan 2002 – shows no measurable $H\alpha$ emission (pseudo equivalent width $pEW < 3 \text{ \AA}$). The author’s Keck spectrum, taken in collaboration with J. Liebert to confirm L dwarf candidates on Tinney’s southern L dwarf parallax program, shows an $H\alpha$ line that is abnormally strong ($pEW \approx 13 \text{ \AA}$) when compared to other mid-L dwarfs in the literature (Gizis et al. 2000; Kirkpatrick et al. 2000).

This information resulted in a re-analysis of the original Keck spectrum, which was a coaddition of four separate exposures. In looking at the individual exposures, it became obvious that the dwarf was caught declining after a flare event, with the individual $H\alpha$ lines showing pEW values of 23, 16, 12, and 6 \AA , respectively. The decline of the flare is shown graphically in Figure 2. Because Gizis (2002) has cast doubt on the flare event ascribed by Hall (2002)

in the L5 dwarf 2MASSI J1315309-264951, this new observation becomes the only confirmed flare in an object this cool. As Mullan & MacDonald (2001) describe, such a magnetically active object may be proof that it is, in fact, a star and not a brown dwarf. The lack of a lithium detection in the Keck spectrum ($pEW < 1 \text{ \AA}$) lends some weak support of this argument. If this is indeed a hydrogen-burning object, it must be one of the very lowest mass stars.

Acknowledgments: The author would like to thank John Wilson, Roc Cutri, Kelle Cruz, Chris Tinney, and James Liebert for permission to use data prior to publication. The author would also like to thank Patrick Lowrance and Adam Burgasser for proofreading the manuscript. This publication makes use of data products from 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This paper has also made use of the Archive of M, L, and T Dwarfs maintained at <http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/>. The author wishes to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct our spectroscopic follow-up observations from this mountain.

References

- Adams, J. D., Stauffer, J. R., Monet, D. G., Skrutskie, M. F., & Beichman, C. A. 2001, *AJ*, 121, 2053.
- Bailer-Jones, C. A. L. & Mundt, R. 1999, *A&A*, 348, 800.
- Bailer-Jones, C. A. L. & Mundt, R. 2001, *A&A*, 367, 218.
- Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, *ApJ*, in press.
- Burgasser, A. J. 2001, PhD Thesis, California Institute of Technology.
- Burrows, A., Marley, M. S., & Sharp, C. M. 2000, *ApJ*, 531, 438.
- Close, L. M., Siegler, N., Potter, D., Brandner, W., & Liebert, J. 2002, *ApJL*, 567, 53.
- Dahn, C. C., Harris, H. C., Vrba, F. J., Guetter, H. H., Canzian, B., Henden, A. A., Levine, S. E., Luginbuhl, C. B., Monet, A. K. B., Monet, D. G., Pier, J. R., Stone, R. C., Walker, R. L., Burgasser, A. J., Gizis, J. E., Kirkpatrick, J. D., Liebert, J., & Reid, I. N. 2002, *AJ*, in press.
- Dobbie, P. D., Kenyon, F., Jameson, R. F., Hodgkin, S. T., Hambly, N. C., & Hawkins, M. R. S. 2002, *MNRAS*, 329, 543.
- Geballe, T. R., Saumon, D., Leggett, S. K., Knapp, G. R., Marley, M. S., & Lodders, K. 2001, *ApJ*, 556, 373.
- Gizis, J. E. 2002, *ApJ*, in press.
- Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000, *AJ*, 120, 1085.
- Hall, P. B. 2002, *ApJL*, 564, 89.

- Kirkpatrick, J. D., Reid, I. N., Liebert, J., Cutri, R. M., Nelson, B., Beichman, C. A., Dahn, C. C., Monet, D. G., Gizis, J. E., & Skrutskie, M. F. 1999, *ApJ*, 519, 802.
- Kirkpatrick, J. D., Reid, I. N., Liebert, J., Gizis, J. E., Burgasser, A. J., Monet, D. G., Dahn, C. C., Nelson, B., & Williams, R. J. 2000, *AJ*, 120, 447.
- Koerner, D. W., Kirkpatrick, J. D., McElwain, M. W., Bonaventura, N. R. 1999, *ApJL*, 522, 65.
- Leggett, S. K., Allard, F., Geballe, T. R., Hauschildt, P. H., & Schweitzer, A. 2001, *ApJ*, 548, 908.
- Luhman, K. L. 2001, *ApJ*, 560, 287.
- Luhman, K. L. 2000, *ApJ*, 544, 1044.
- Martín, E. L., Dougados, C., Magnier, E., Ménard, F., Magazzù, A., Cuillandre, J.-C., & Delfosse, X. 2001, *ApJL*, 561, 195.
- McLean, I. S., Prato, L., Kim, S. S., Wilcox, M. K., Kirkpatrick, J. D., & Burgasser, A. J. 2001, *ApJL*, 561, 115.
- McLean, I. S., Wilcox, M. K., Becklin, E. E., Figer, D. F., Gilbert, A. M., Graham, J. R., Larkin, J. E., Levenson, N. A., Teplitz, H. I., & Kirkpatrick, J. D. 2000, *ApJL*, 533, 45.
- Mullan, D. J., & MacDonald, J. 2001, *ApJ*, 559, 353.
- Nakajima, T., Tsuji, T., & Yanagisawa, K. 2001, *ApJL*, 561, 119.
- Oliveira, J. M., Jeffries, R. D., Kenyon, M. J., Thompson, S. A., & Naylor, T. 2002, *A&A*, L22.
- Potter, D., Martín, E. L., Cushing, M. C., Baudoz, P., Brandner, W., Guyon, O., & Neuhäuser, R. 2002, *ApJL*, 567, 133.
- Reid, I. N., Kirkpatrick, J. D., Liebert, J., Burrows, A., Gizis, J. E., Burgasser, A., Dahn, C. C., Monet, D. G., Cutri, R., Beichman, C. A., & Skrutskie, M. F. 1999, *ApJ*, 521, 613.
- Schweitzer, A., Gizis, J. E., Hauschildt, P. H., Allard, F., & Reid, I. N. 2001, *ApJ*, 555, 368.
- Schweitzer, A., Gizis, J. E., Hauschildt, P. H., Allard, F., Howard, E. M., & Kirkpatrick, J. D. 2002, *ApJ*, 566, 435.
- Stephens, D. C., Marley, M. S., Noll, K. S., & Chanover, N. 2001, *ApJL*, 566, 97.
- Wolk, J., Cover, R. T., Jayawardhana, R., & Hearty, T. J. 2000, in “From Darkness to Light: Origin and Evolution of Young Stellar Clusters,” ed. T. Montmerle & Ph. André, *ASP Conf. Ser.* 243, p. 687.