Ultracool Dwarf Science from Widefield Multi-Epoch Surveys

N.R. Deacon1, D.J. Pinfield2, P.W. Lucas2, Michael C. Liu1, M.S. Bessell3, B. Burningham2, M.C. Cushing4, A.C. Day-Jones5, S. Dhital6, N.M. Law7, A.K. Mainzer4 and Z.H. Zhang2

1Institute for Astronomy, University of Hawai‘i, 2680 Woodlawn Drive, Honolulu, Hawai‘i, 96822-1839, USA
2Centre for Astrophysics Research, University of Hertfordshire, Hatfield, AL10 9AB, UK
3Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Rd, ACT 2611, Australia
4Jet Propulsion Laboratory, M/S 264-765, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
5Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
6Department of Physics & Astronomy, Vanderbilt University, Nashville, TN 37235, USA
7Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street Room 101, Toronto, Ontario, M5S 3H4, Canada

Abstract. Widefield surveys have always provided a rich hunting ground for the coolest stars and brown dwarfs. The single epoch surveys at the beginning of this century greatly expanded the parameter space for ultracool dwarfs. Here we outline the science possible from new multi-epoch surveys which add extra depth and open the time domain to study.

1. Introduction

Widefield multi-epoch surveys have been a crucial discovery tool for ultracool dwarfs. Photographic plate data was used by Luyten (1979) to identify nearby cool stars by their proper motion. As technology evolved these plates were digitised (Hambly et al. 2001, Monet et al. 2003) leading to more discoveries of cool nearby stars.

The study of brown dwarfs did not begin with widefield digital infrared and red optical surveys, but datasets such as 2MASS (Skrutskie et al. 2006) and SDSS (York et al. 2000) massively expanded the sample of brown dwarfs. Works such as Chiu et al. (2006), Reid et al. (2008) and Burgasser et al. (2004) provided large samples and ob-
jects from these surveys were used to define the new L and T spectral classes (Kirkpatrick et al. 1999, Burgasser et al. 2006).

Now a new generation of widefield surveys are expanding into relatively unexplored regions, identifying extremely cool objects, finding nearby brown dwarfs by their trigonometric parallax and opening the time domain to the search for variability. Here we outline the leading surveys currently in operation and those about to come online.

2. Current Surveys

2.1. The UKIRT Deep Infrared Sky Survey

Of the five UKIDSS surveys (Lawrence et al. 2007), three are contributing significantly to the study of substellar objects: the Galactic Clusters Survey (GCS), the Large Area Survey (LAS) and the Galactic Plane Survey (GPS). The first of these has is targeting 10 clusters, and totalling over 1400 sq degs to a depth of $K = 18.7$. Four of these will have two epochs to allow proper motion selection of members for robust IMF determination (Pleiades, Alpha Per, Praesepe and Hyades). Results already published for several clusters are painting a picture of the substellar IMF that is broadly consistent with previous studies. For an IMF of the form $\psi(M) \propto M^{-\alpha}$, a value of $\alpha = 0.6$ appears to be common (e.g. Lodieu et al. 2007, Lodieu et al. 2009).

The LAS search for field brown dwarfs has now resulted in the discovery of over 100 T dwarfs, making it the single largest contributor to the known sample of these objects, has now provided the most precise measurement of the space density of T6-T8 dwarfs to-date (Burningham et al. 2010), revealing a significant dearth of these objects compared to what would be expected given the initial mass function observed in young clusters. The origin of this discrepancy is not clear, but possibilities include a variant substellar initial mass function over the lifetime of the Galaxy or problems with the evolutionary models used to predict the space density. In addition to studies of the IMF, the LAS sample is producing additional results from searches for benchmark systems (e.g. Day-Jones et al. 2010; Zhang et al. 2010) and the search for halo T dwarfs (e.g. Murray et al. in prep.)

Despite the challenges associated with searching for T dwarfs in the Galactic plane, the GPS is also beginning to deliver very cold objects. The discovery of the extremely cool T10 dwarf UGPS J0722-0540 at a distance of just 4.1pc (Lucas et al. 2010), means that UKIDSS T dwarfs are now on the threshold of probing the sub-500K regime, where water clouds may start to be seen in the photosphere. Over the next few years the synergy of the UKIDSS data set with the WISE survey will likely reveal even cooler atmospheres, and possibly the first observation of water clouds beyond the Solar System.

2.2. VISTA public surveys

The Visible and Infrared Survey Telescope for Astronomy (VISTA) is a UK built 4 metre class, near-infrared survey telescope located at the ESO site on Cerro Paranal, Chile. VISTA’s wide field camera has sixteen 2048x2048 Raytheon arrays with quantum efficiency >90%. It produces tiles with dimensions of 1.5x1.0 degrees, compiled from 6 dithered pawprints. The image scale is 0.34 arcsec per pixel. During its first 5 years of operation VISTA is mainly dedicated to performing six public surveys, which
began taking data in late 2009. These surveys include: UltraVISTA, the smallest of the surveys covering only 0.73 square degrees to a depth of $J = 26.6$. VIDEO (Vista Deep Extragalactic observations), VMC (Vista Magellanic Cloud Survey), VVV (Vista Variables in the Via Lactea), a synoptic survey of the Galactic plane, VIKING (Vista Kilo-Degree Infrared Galaxy Survey) and the largest, VHS (Vista Hemisphere Survey), which will image the rest of the southern hemisphere.

The last two of these surveys will likely be the source of most brown dwarf discoveries from the VISTA surveys. With their large sky coverage in several filters, these surveys will probe deeper than any other near-infrared survey, for example VIKING alone will cover three times the volume of the UKIDSS Large Area Survey, providing data in the $Z, Y, J, H$ and $K_{s}$ filters. Both VIKING and VHS will have optical counterparts provided respectively from the ESO KIDS (Kilo degree survey) and DES (Dark Energy Survey), such that combining these surveys, and data from WISE, Skymapper and Pan-STARRS, will provide a powerful tool for the identification of brown dwarfs. There is the potential to increase the number of T dwarfs known by an order of magnitude. In addition this will allow the identification of many brown dwarfs that could be used as benchmark objects as well as objects that are cooler than those presently known. These discoveries will be able to test and help calibrate existing ultracool models and measurement of the mass function to new precision. However, a very efficient follow-up strategy will be required to classify the large number of brown dwarf candidates, many of which will be challenging targets for ground-based spectroscopy.

### 2.3. The WISE All-Sky Survey

One of the two primary science objectives for the Wide-field Infrared Survey Explorer (WISE) is to find the coldest brown dwarfs, which represent the final link between the lowest mass stars and the giant planets in our own solar system. WISE is a NASA Medium-class Explorer mission designed to survey the entire sky in four infrared wavelengths, 3.4, 4.6, 12 and 22 microns (Wright et al. 2010; Liu et al. 2008; Mainzer et al. 2005). WISE consists of a 40 cm telescope that images all four bands simultaneously every 11 seconds. It covers nearly every part of the sky a minimum of eight times, ensuring high source reliability, with more coverage at the ecliptic poles. Astrometric errors are less than 0.5 arcsec with respect to 2MASS (Wright et al. 2010). The preliminary estimated SNR=5 point source sensitivity on the ecliptic is 0.08, 0.1, 0.8 and 5 mJy in the four bands (assuming eight exposures per band; Wright et al. 2010). Sensitivity improves away from the ecliptic due to denser coverage and lower zodiacal background. WISE’s two shortest wavelength bands, centered at 3.4 and 4.6 m (W1 and W2, respectively), were specifically designed to optimize sensitivity to the coolest types of brown dwarfs (Kirkpatrick et al. in prep). In particular, BDs cooler than ~1500 K exhibit strong absorption due to the nu-3 band of CH$_{4}$ centered at 3.3 microns, with the onset of methane absorption at this wavelength beginning at ~1700 K (Noll & Marley 2000). The as-measured sensitivities of 0.08 and 0.1 mJy in W1 and W2 allow WISE to detect a 300 K BD out to a distance of ~8 pc, according to models by Marley et al. (2002) and Saumon & Marley (2008). While the W1 and W2 bands are superficially similar to the Spitzer/IRAC bands 1 and 2 (which were also designed to isolate cool BDs; Fazio et al. 1998), the WISE W1 band is wider to improve discrimination between normal stars and ultra-cool BDs (Wright et al. 2010). This results in a systematically larger W1-W2 color compared to $[3.6]-[4.5]$. Currently, only about two dozen objects with spectral types later than T7 are known, and four objects are known
to have type T9 or later (Warren et al. 2007; Delorme et al. 2008, Burningham et al. 2008, and Lucas et al. 2010). New spectral indices for typing these late-type T dwarfs have been developed as the CH4 absorption band depths may not continue to increase in the NIR with temperatures lower than those of T8/T9 dwarfs (Burningham et al. 2010), but spectral anchors have yet to be defined. We have recently reported the discovery of WISEPC J0458+64 (Mainzer et al. 2010) an object which is consistent with an extremely late T dwarf. The best-fitting model has an effective temperature of 600 K, log g=5.0, [Fe/H]=0, and evidence for the presence of vertical mixing in its atmosphere. As this remarkably cool object was found easily in some of the first WISE data, WISE is likely to find many more similar objects, as well as cooler ones, inevitably producing abundant candidates for the elusive Y class brown dwarfs. Scaling from the Spitzer sample of 4.5 micron selected ultra-cool BD candidates (Eisenhardt et al. 2010), we expect to find hundreds of new ultra-cool brown dwarfs with WISE. We compute that for most likely initial mass functions, WISE has a better than 50% chance of detecting a cool BD which may actually be closer to our Sun than Proxima Centauri (Wright et al. 2010).

2.4. Surveys with Pan-STARRS 1

The Pan-STARRS project (Panoramic Survey Telescope and Rapid Response System; Kaiser et al. 2002), led by the University of Hawai’i’s Institute for Astronomy, is developing a unique optical survey instrument consisting of four co-aligned wide-field telescopes based in the Hawaiian Island (http://panstarrs.ifa.hawaii.edu). As a pathfinder for the full system, the project has successfully completed a single telescope system, called Pan-STARRS 1 (PS1), on the summit of Haleakala on the Hawaiian island of Maui. PS1 is a full-scale version of one of the four Pan-STARRS telescopes, with a 1.8-m primary mirror which images a 7-degree field-of-view on a 1.4-Gigapixel camera. The large étendue of PS1 allows for rapid surveying of the observable sky, obtaining ≈2500 sq. degs and 1.5 Tb of raw data each night.

The PS1 3.5-year science survey mission officially began in May 2010 and is carrying out a suite of pre-defined surveys, spanning the nearest asteroids to the cosmological horizon. Of greatest interest to ultracool dwarf research is the Pan-STARRS 1 3π survey, the largest of the PS1 surveys, amounting to 56% of the observing time. The Pan-STARRS 1 3π survey will monitor three quarters of the sky (30,000 sq. degs north of declination −30°) in g, r, i, z and y with six epochs per filter spread over three years and two observations per epoch to detect solar system objects. The survey goes to depths roughly similar to SDSS in the bluest bands and is significantly more sensitive in the far-red, with the novel y-band filter (0.95-1.03 μm) providing the greatest gains for ultracool dwarf science. The 5σ single-epoch limits are grizy = 23.2, 22.5, 22.2, 21.2, 19.8 mag (AB system).

The Pan-STARRS 1 3π cadence will allow objects to be selected based on their proper motions and parallaxes without a priori colour selection (Magnier et al. 2008). This will allow a complete survey of the ultracool dwarf population within 30 pc down to the mid/late T regime, as well as discovery of low-mass objects with extreme properties that might otherwise have gone undetected. The resulting catalog unprecedented in its volume, sample size, and completeness will address several key areas, including: (1) the luminosity function of nearby ultracool objects with the first volume-limited sample of brown dwarfs; (2) rigorous tests of theoretical models of brown dwarf atmospheres
and evolution using densely populated color-magnitude diagrams; and (3) exploring the physics of ultracool objects over a wide range of metallicities and gravities.

As of this writing, Pan-STARRS 1 is just completing its first pass of the sky. With these first epoch data, we have been carrying out a proper motion survey for nearby L and T dwarfs by combining them with 2MASS. The survey spans a ≈10 year baseline and is most sensitive to objects with proper motions from ≈0.2–2.0″/yr. So far this has resulted in the discovery of a number of interesting ultracool dwarfs, including bright T dwarfs not previously identified in 2MASS (Deacon et al., in prep.).

In addition, the Pan-STARRS 1 Medium Deep Fields is repeatedly observing a set of high-galactic latitude fields to search for supernovae and other transients (100 sq. degs in total). This survey is also suitable for the stellar/substellar variability studies, with the potential to find around 300 low-mass eclipsing binaries, 10 brown-dwarf EBs, and about a dozen transiting brown dwarfs around low-mass stars within 100 pc (Dupuy & Liu 2009).

2.5. The Stromlo Southern Sky Survey

SkyMapper is a 1.3m telescope with a 5.7 sq degree field of view covered with 32 2Kx4K E2V CCds that will carry out a 6-color, multi-epoch survey of the southern sky (including the galactic plane) - The Stromlo Southern Sky Survey. We aim to provide star and galaxy photometry to better than 3% global accuracy and astrometry to better than 50 mas. The sampling will be 4 hr, 1 day, 1 week, 1month and 1 yr, although not in all filters. It will take five years to complete the survey. Some time is reserved for non-survey work. The photometric system of u (like Stromgren), v (like DDO38), griz (SDSS) is designed to maximize precision in the derivation of stellar astrophysical quantities. We also have available an Halpha filter for limited use. We expect 6 epoch limiting magnitudes of 22.9, 22.9, 22.8, 22.8, 21.9, 21.2 in u,v,g,r,i,z, respectively. The data will be supplied to the community after science verification without a proprietary period. Young M dwarfs will be surveyed using Halpha, r and i. L and T dwarfs (high-z QSO contaminants) will be surveyed using i-z. VISTA photometry will also be cross-referenced and proper motions derived from our different epoch SkyMapper observations as well as through comparison with earlier epoch catalog positions. Follow-up spectroscopy will be carried out on the ANU 2.3m telescope and AAO 3.9m telescopes.

2.6. The Palomar Transient Factory

The Palomar Transient Factory (PTF; Law et al. 2009) is a new fully-automated, wide-field survey conducting a systematic exploration of the optical transient sky. The transient survey is performed using a new 8.1 square degree camera installed on the 48 inch Samuel Oschin telescope at Palomar Observatory; colors and light curves for detected transients are obtained with the automated Palomar 60 inch telescope. With an exposure of 60 s the survey reaches a depth of m~21.3 and m~20.6 (5σ, median seeing). Cadences range between 10 minutes and 5 days, with a 3-day-cadence r-band supernova search making up the largest fraction of the survey. The survey covers 8000 square degrees, and fields are observed between tens and hundreds of times. PTF provides automatic, real-time transient classification and follow-up, as well as a database including every source detected in each frame. As of Nov 22 2010, PTF had discovered and spectroscopically classified 910 supernovae. The wide-area, many epoch dataset is being used for a wide variety of cool star science, including the activity / rotation / age...
relation, proper motion surveys, and a search for transiting planets around 100,000 M and L dwarfs.

3. Future Surveys

3.1. The Large Synoptic Survey Telescope

The Large Synoptic Sky Survey (LSST) will cover the 20000 square degrees of the Southern sky, with ~1000 total visits in the \textit{ugrizy} bands over 10 years. The faintness limit will be $z \sim 23.3$ mags for each visit and $z \sim 26.2$ mags for the total survey \citep{LSST2009}. LSST’s depth, all-sky coverage, and 1000 epochs provide an large and unique dataset for studying the ultracool dwarfs (UCDs; specifically of M, L, T, and the hypothetical Y spectral classes).

LSST will allow for a census of the ultracool dwarfs (UCDs) in the solar neighborhood, with M0, L6, and T9 dwarfs detectable to $\sim 10$ kpc, 200 pc, and 25 pc, respectively. In terms of absolute numbers, Galactic simulations predict >347,000 M, 35000 L, 2300 L, and $\sim 18$ Y dwarfs in the LSST fields \citep{LSST2009}. In addition, we will have accurate proper motions and parallaxes (see Figure 1). This will allow us not only to measure the mass function, luminosity function, and velocity distribution of UCDs but also complete the census of nearby moving groups and associations (also see chapter on Juvenile UCD session).

The Southern sky is very rich in large, nearby open clusters, like the Orion Nebula, NGC 3532, IC 2602/IC 2391, and Blanco 1. Detecting and characterizing brown dwarfs in these clusters, which have known ages, will allow us to constrain the theoretical brown dwarf cooling curves \citep[e.g.][]{Chabrier2000}. As most known brown dwarfs are in the field with very uncertain ages, they cannot be used to constrain the cooling curves. Similarly, LSST will detect a large number of UCD eclipsing binaries that will serve as benchmarks to constrain our stellar evolutionary models. Based on LSST data, 77 M and 2 L dwarfs EBs will be characterized, with perhaps ten times as many UCD EB candidates \citep[J. Pepper et al. in prep.]{Pepper2021}.

4. Combining survey data

As mentioned previously surveys often complement each other by providing information in different wavelengths or providing additional epochs for proper motion measurement. Works such as \cite{Burgasser2004} use infrared colours in combination with legacy optical data \citep{Monet2003} to select ultracool dwarfs while UKIDSS studies such as \cite{Burningham2010} make use of SDSS data. Examples of using widefield surveys in combination for proper motions include \cite{Sheppard2009} and \cite{Deacon2009}. The new generation of surveys can also be used together and with legacy data increase their science yield.

4.1. Ultracool Subdwarf Binaries Discovered from Large Area Surveys

Ultracool subdwarfs (UCSDs; \cite[e.g.,][]{Burgasser2009}) are metal-poor, halo counterpart of ultracool dwarfs. They have not been understood well both observationally and theoretically due to the limited number of known UCSDs, especially benchmarks \citep[e.g.,][]{Pinfield2006}. The number of known UCSDs is increasing benefit from current
Figure 1. The distance at which stars of a given spectral type will be detected in LSST. The red (lighter grey in black and white) strip shows the distance for the brightness limits of $r = 16$ and $r = 21$ where proper motions greater than 1.5 mas yr$^{-1}$ and parallaxes greater than 4.5 mas will be measured, with a 5$\sigma$ significance. The solid blue (darker grey in black and white) shows the single epoch faintness limit, where proper motions greater than 7.5 mas yr$^{-1}$ and parallaxes greater than 22 mas will be measured. The hashed blue shows the limits of the entire 10 year survey, extending up to $r = 28$. The depth as well as the proper motion and parallax accuracies are unprecedented.
optical and NIR large area surveys (SDSS, York et al. 2000; 2MASS, Skrutskie et al. 2006; UKIDSS, Lawrence et al. 2007). This makes it possible to identify UCSDs in wide binary systems. I selected a sample of objects with proper motions larger than 100 mas/yr from the SDSS and USNO-B proper motion catalog (Munn et al. 2004). Around one thousand M subdwarfs are confirmed with SDSS spectra. Starting with this subdwarf sample, I identified two extreme UCSDs (esdM6+esdK2, esdM6+esdM1) and six M subdwarfs (including an sdM1+WD system) in binary systems based on their common proper motions (Zhang et al. in preparation). The esdM6+esdK2 binary is the most exciting system with very high proper motions (444±3mas/yr). Distances for both components are estimated, and both consistent with 180±30 parsec. It is one of the widest ultracool systems (16740±2790AU), with a separation of 93″ at this distance. It’s galactic velocity ($U = -325.3\text{km/s}$; $V = -259.5\text{km/s}$; $W = 8.4\text{km/s}$) consistent with halo population. This is the first halo subdwarf benchmark in wide binary system. We have obtained optical spectra of both components and will do further analysis on them. This research indicated that the wide cool subdwarf binary fraction is similar to that of ultracool dwarfs ($>0.01$; e.g., Zhang et al. 2010; Faherty et al. 2010). It indicates that a large number of benchmarks are potentially identifiable, sampling the broad range in mass, age and metallicity need to adequately calibrate both atmospheric and evolutionary models.

5. Summary

Widefield surveys will continue to play a leading role in the discovery and study of ultracool dwarfs. From the widefield infrared surveys with UKIDSS, VISTA and WISE, to multi-epoch optical surveys with Skymapper, Pan-STARRS, PTF and in the future LSST, such surveys will identify the coolest objects, large samples for population studies and many interesting variable sources. A summary of the surveys discussed in this paper can be found in Figure 2.

Acknowledgments. The authors would like to thank the University of Washington for hosting Cool Stars 16, Local and Scientific Organising Committees and our SOC contact Andrew West.

References

Burgasser, A. J., Geballe, T. R., Leggett, S. K., Kirkpatrick, J. D., & Golimowski, D. A. 2006, The Astrophysical Journal, 637, 1067. URL http://stacks.iop.org/0004-637X/637/i=2/a=1067

Burgasser, A. J., McElwain, M. W., Kirkpatrick, J. D., Cruz, K. L., Tinney, C. G., & Reid, I. N. 2004, The Astronomical Journal, 127, 2856. URL http://stacks.iop.org/1538-3881/127/i=5/a=2856

Burgasser, A. J., Witte, S., Helling, C., Sanderson, R. E., Bochanski, J. J., & Hauschildt, P. H. 2009, The Astrophysical Journal, 697, 148. URL http://stacks.iop.org/0004-637X/697/i=1/a=148?key=crossref.9a4368db154dc9074ea61a3e8b8877e4

Burningham, B., Pinfield, D. J., Leggett, S. K., Tamura, M., Lucas, P. W., Homeier, D., Day-Jones, a., Jones, H. R. a., Clarke, J. R. a., Ishii, M., Kuzuhara, M., Lodieu, N., Zapatero Osorio, M. R., Venemans, B. P., Mortlock, D. J., Barrado y Navascués, D., Martin, E. L., & Magazzù, a. 2008, Monthly Notices of the Royal Astronomical Society, 391, 320. URL http://doi.wiley.com/10.1111/j.1365-2966.2008.13885.x

Burningham, B., Pinfield, D. J., Lucas, P. W., Leggett, S. K., Deacon, N. R., Tamura, M., Tinney, C. G., Lodieu, N., Zhang, Z. H., Huelamo, N., Jones, H. R. a., Murray, D. N.,
Ultracool dwarf science from widefield multi-epoch surveys

Mortlock, D. J., Patel, M., Navascses, D. B. Y., Osorio, M. R. Z., Ishii, M., Kuzuhara, M., & Smart, R. L. 2010, Monthly Notices of the Royal Astronomical Society, 23. URL http://arxiv.org/abs/1004.1912

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, The Astrophysical Journal, 542, 464. URL http://stacks.iop.org/0004-637X/542/i=1/a=464

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, The Astrophysical Journal, 542, 464. URL http://stacks.iop.org/0004-637X/542/i=1/a=464

Deacon, N. R., Hambly, N. C., King, R. R., & McCaughrean, M. J. 2009, Monthly Notices of the Royal Astronomical Society, 394, 857. URL http://blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2008.14371.x

Delorme, P., Delbosse, X., Albert, L., Artigau, E., Forveille, T., Reylé, C., Allard, F., Homeier, D., Robin, A. C., Willott, C. J., Liu, M. C., & Dupuy, T. J. 2008, Astronomy, 971, 961

Dupuy, T. J., & Liu, M. C. 2009, The Astrophysical Journal, 704, 1519. URL http://stacks.iop.org/0004-637X/704/i=2/a=1519?key=crossref.7c3265fd6df02624f3b1023d21b543

Eisenhardt, P. R. M., Griffith, R. L., Stern, D., Wright, E. L., Ashby, M. L. N., Brown, M. J. I., Bussmann, R. S., Dey, A., Ghez, a. M., Glikman, E., Gonzalez, A. H., Kirkpatrick, J. D., Konopacky, Q., Mainzer, A., Vollbach, D., & Wright, S. a. 2010, The Astronomical Journal, 139, 2455. URL http://stacks.iop.org/1538-3881/139/i=6/a=2455?key=crossref.91cb592e93c56d4de9f4fd8370491dbc

Law, N. M., Kulkarni, S. R., Dekany, R. G., Ofek, E. O., Quimby, R. M., Nugent, P. E., Surace, J., Grillmair, C. C., Bloom, J. S., Kasliwal, M. M., Bildsten, L., Brown, T., Chen, Y., Ciardi, D., Croner, E., Djorgovski, S. G., van Eyken, J., Filippenko, A. V., Fox, D. B., Gal-Yam, A., Hale, D., Hamam, N., Helou, G., Henning, J., Howell, D. A., Jacobsen, J., Laher, R., Mattingly, S., McKenna, D., Pickles, A., Poznanski, D., Rahmer, G., Rau, A., Rosing, W., Shara, M., Smith, R., Starr, D., Sullivan, M., Velur, V., Walters, R., & Zolkower, J. 2009, Publications of the Astronomical Society of the Pacific, 121, 1395. URL http://www.journals.uchicago.edu/doi/abs/10.1086/648598

Lawrence, A., Warren, S. J., Almaini, O., Edge, A. C., Hambly, N. C., Jameson, R. F., Lucas, P., Casali, M., Adamson, A., Dye, S., Emerson, J. P., Foucaud, S., Hewett, P., Hirst, P., Hodgkin, S. T., Irwin, M. J., Lodieu, N., McMahon, R. G., Simpson, C., Smail, I., Mortlock, D., & Folger, M.
2007. Monthly Notices of the Royal Astronomical Society, 379, 1599. URL http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2007.12040.x

Liu, F., Cutri, R., Greanias, G., Duval, V., Eisenhardt, P., Elwell, J., Heinrichsen, I., Howard, J., Irace, W., Mainzer, A., Razzaghi, A., Royer, D., & Wright, E. L. 2008, SPIE, 7017, 16

Lodieu, N., Dobbie, P. D., Deacon, N. R., Hodgkin, S. T., Hambley, N. C., & Jameson, R. F. 2007. Monthly Notices of the Royal Astronomical Society, 380, 712. URL http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2007.12106.x

Lodieu, N., Zapatero Osorio, M. R., Rebolo, R., Martín, E. L., & Hambley, N. C. 2009, Astronomy and Astrophysics, 505, 1115. URL http://www.aanda.org/10.1051/0004-6361/200911966

LSST Science Collaborations, T. 2009. URL http://arxiv.org/abs/0912.0201

Lucas, P. W., Tinney, C. G., Burningham, B., Leggett, S. K., Pinfield, D. J., Smart, R., Jones, H. R. a., Marocco, F., Barber, R. J., Yurchenko, S. N., Tennyson, J., Ishii, M., Tamura, M., Day-Jones, A. C., Adamson, A., Allard, F., & Homeier, D. 2010. Monthly Notices of the Royal Astronomical Society: Letters, 40. URL http://doi.wiley.com/10.1111/j.1745-3933.2010.00927.x

Luyten, W. J. 1979, LHS catalogue. A catalogue of stars with proper motions exceeding 0′5 annually (Minneapolis: University of Minnesota)

Magnier, E. A., Liu, M., Monet, D. G., & Chambers, K. C. 2008, Proceedings of the International Astronomical Union, 3. URL http://www.journals.cambridge.org/abstract_S1743921308020139

Mainzer, A., Cushing, M. C., Skrutskie, M., Gelino, C. R., & Davy, J. 2010, ApJ in press, arXiv:1011.2279v1

Mainzer, A. K., Eisenhardt, P., Wright, E. L., Liu, F.-C., Irace, W., Heinrichsen, I., Cutri, R., & Duval, V. 2005, SPIE, 5899, 262

Marley, M. S., Seager, S., Saumon, D., Lodders, K., Ackerman, A. S., Freedman, R. S., & Fan, X. 2002, The Astrophysical Journal, 568, 335. URL http://stacks.iop.org/0004-637X/568/i=1/a=335

Monet, D. G., Levine, S. E., Canzian, B., Ablres, H. D., Bird, A. R., Dahn, C. C., Guetter, H. H., Harris, H. C., Henden, A., Leggett, S. K., Levison, H. F., Lugmihul, C. B., Martini, J., Monet, A. K. B., Munn, J. A., Pier, J. R., Rhodes, A. R., Riepe, B., Sell, S., Stone, R. C., Vrba, F. J., Walker, R. L., Westerhout, G., Brucato, R. J., Reid, I. N., Schoening, W., Hartley, M., Read, M. A., & Triton, S. B. 2003, The Astronomical Journal, 125, 984. URL http://stacks.iop.org/1538-3881/125/i=2/a=984

Sheppard, S. S., Cushing, M. C., Skrutskie, M., Weingb, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., Huchra, J., Liebert, J., Lonsdale, C., Monet, D. G., Price, S., Seitzer, P., Jarrett, T., Kirkpatrick, J. D., Gizis, J. E., Howard, E., Evans, T., Fowler, J., Fullmer, L., Hurt, R., Light, R., Kopan, E. L., Marsh, K. A., McCallon, H. L., Tam, R., Van Dyk, S., & Wheelock, S. 2006. The Astronomical Journal, 131, 1163. URL http://stacks.iop.org/1538-3881/131/i=2/a=1163
Warren, S. J., Mortlock, D. J., Leggett, S. K., Pinfield, D. J., Homeier, D., Dye, S., Jameson, R. F., Lodieu, N., Lucas, P. W., Adamson, a. J., Allard, F., Barrado y Navascués, D., Casali, M., Chiu, K., Hambly, N. C., Hewett, P. C., Hirst, P., Irwin, M. J., Lawrence, a., Liu, M. C., Martín, E. L., Smart, R. L., Valdivielso, L., & Venemans, B. P. 2007, Monthly Notices of the Royal Astronomical Society, 381, 1400. URL http://doi.wiley.com/10.1111/j.1365-2966.2007.12348.x

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., Ressler, M. E., Cutri, R. M., Jarrett, T., Kirkpatrick, J. D., Padgett, D., McMillan, R. S., Skrutskie, M., Stanford, S. a., Cohen, M., Walker, R. G., Mather, J. C., Leisawitz, D., Gautier, T. N., McLean, I., Benford, D., Lonsdale, C. J., Blain, A., Mendez, B., Irace, W. R., Duval, V., Liu, F., Roey, D., Heinrichsen, I., Howard, J., Shannon, M., Kendall, M., Walsh, A. L., Larsen, M., Cardon, J. G., Schick, S., Schwalm, M., Abid, M., Fabinsky, B., Naes, L., & Tsai, C.-W. 2010, The Astronomical Journal, 140, 1868. URL http://stacks.iop.org/1538-3881/140/i=6/a=1868?key=crossref.7bc383db470f437aa42190755268583

York, D. G., Adelman, J., Anderson, Jr., J. E., Anderson, S. F., Annis, J., Bahcall, N. A., Bakken, J. A., Barkhouse, R., Bastian, S., Berman, E., Boroski, W. N., Bracker, S., Briggs, C., Briggs, J. W., Bruin, J., Brinkmann, J., Brucato, J., Burles, S., Carey, L., Carr, M. A., Castand, F. J., Chen, B., Colestock, P. L., Connolly, A. J., Crocker, J. H., Csabai, I., Czarapata, P. C., Davis, J. E., Doi, M., Dombeck, T., Eisenstein, D., Ellman, N., Elms, B. R., Evans, M. L., Fan, X., Federwitz, G. R., Fiscelli, L., Friedman, S., Frieman, J. A., Fukugita, M., Gillespie, B., Gunn, J. E., Gurbani, V. K. de Haas, E., Haldeman, M., Harris, F. H., Hayes, J., Heckman, T. M., Hennessy, G. S., Hindsley, R. B., Holm, S., Holmgren, D. J., Huang, C.-h., Hull, C., Husby, D., Ichikawa, S.-i., Ichikawa, T., Ivezic, v., Kent, S., Kim, R. S. J., Kinney, E., Klaene, M., Kleinman, A. N., Kleinman, S., Knapp, G. R., Korienek, J., Kron, R. G., Kunszt, P. Z., Lamb, D. Q., Lee, B., Leger, R. F., Lim, I., Lindenmeyer, C., Long, D. C., Loomis, C., Loveday, J., Lucinio, R., Lupton, R. H., MacKinnon, B., Manner, E. J., Mantsch, P. M., Margon, B., McGehee, P., McKay, T. A., Meiksin, A., Merelli, A., Monet, D. G., Munn, J. A., Narayan, V. K., Nash, T., Neilsen, E., Neswold, R., Newberg, H. J., Nichol, R. C., Nicinski, T., Nonino, M., Okada, N., Okamura, S., Ostriker, J. P., Owen, R., Pauls, A. G., Peoples, J., Peterson, R. L., Pettravich, D., Pier, J. R., Pope, A., Pordes, R., Prosapio, A., Rechenmacher, R., Quinn, T. R., Richards, G. T., Richardson, M. W., Rivetta, C. H., Rockosi, C. M., Ruthmankof, K., Sandford, D., Schlegel, D. J., Schneider, D. P., Sekiguchi, M., Serre, G., Shimazu, K., Stetson, W. A., Smee, S., Smith, M. A., Snedden, S., Stone, R., Stoughton, C., Strauss, M. A., Stubbs, C., Strauss, M. A., Szalay, A. S., Szapudi, I., Szokoly, G. P., Thakar, A. R., Tremonti, C., Tucker, D. L., Uomoto, A., Van der Berk, D., Vogele, M. S., Waddell, P., Wang, S.-i., Watanabe, M., Weinberg, D. H., Yanny, B., & Yasuda, N. 2000, The Astronomical Journal, 120, 1579. URL http://stacks.iop.org/1538-3881/120/i=3/a=1579

Zhang, Z. H., Pinfield, D. J., Day-Jones, a. C., Burningham, B., Jones, H. R. a., Yu, S., Jenkins, J. S., Han, Z., Gámez-Ortiz, M. C., Gallardo, J., García-Pérez, a. E., Weights, D., Tinney, C. G., & Pokorny, R. S. 2010, Monthly Notices of the Royal Astronomical Society, 1834. 1817. URL http://blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2010.16394.x
Figure 2. A summary of the surveys discussed in this paper.

| Survey      | Filters     | Depth (Single Epoch) | Area (sq.deg.) | Epochs | Dates      | Public Release |
|-------------|-------------|----------------------|----------------|--------|------------|----------------|
| UKIDSS LAS  | Y,J,H,K     | Y=20                 | 3700           | 2(3000sq.deg.) | 2005-2012 | 2014           |
| Pan-STARRS  | g,r,i,z,y   | y=19.8(AB, 5σ)       | 33000          | 6 per filter | 2010-2013 | 2014           |
| VISTA VHS   | J,H, partial Z,Y,K | J=20.2(AB, 5σ) | 19000          | 1      | 2010-2017 | 2011-          |
| Stromlo SSS | u,v,g,r,i,z | z=20.6(AB, 5σ)       | 22000          | 6 per filter | 2010-2015 | After calibration |
| WISE        | 3.4, 4.6, 12, 22 μm | σ=0.1 mJy in 4.6μm | All Sky        | 1      | 2010       | 2011-2012      |
| PTF         | g,R         | r=21                 | 8000           | 300+   | 2009-      | 2012           |
| LSST        | u,g,r,i,z,y | z=23.3(AB)           | 20000          | 1000 total | 2018-2028 | 2018-          |