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Mining the Next Generation of Surveys for Cool Star Science

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Abstract. A number of major new and near future survey facilities are set to have a large impact on cool star science. With increased sky coverage and sensitivity over a wide wavelength range and in the time domain, a variety of new populations will be discovered. We discuss the capabilities of these new surveys and some of the science they will facilitate in the coming years.

1. Introduction

Cool star science will benefit greatly in the near future from a variety of major new surveys that are just commencing, or about to start in the next few years. These surveys will have a large and broad impact both on cool star science, and the way cool star science is done. They will provide the community with multi-band wide-field imaging across much of the sky, as well as the ability to do time-domain studies of cool stars. This will allow extensive study of a large range of cool star phenomena, from very hot and violent coronal/flare activity, to extremely cool brown dwarfs with temperatures approaching the planetary regime. Time domain data will reveal information about cool stars in multiple systems and their fundamental properties (via the transit method), as well as the variability intrinsic to individual cool stars. Proper motion and parallax will become increasingly powerful discovery tools in some time domain surveys.

In this paper we summarize the contents of a splinter session, designed to educate the larger community about the survey resources soon to become widely available, and how these will change the field of cool stars.

2. Optical surveys: Opening the Variability Domain

The advent of the first digital wide-field sky surveys, most notably the Sloan Digital Sky Survey (SDSS), the Two Micron All Sky Survey (2MASS), and the

Deep Near Infrared Survey of the Southern Sky (DENIS), has demonstrated a fundamental leap in our ability to identify and characterize low-mass stars and brown dwarfs (e.g. Kirkpatrick 2005; West et al. 2004, 2006, Covey et al. this conference). New wide-field surveys at optical wavelengths should give a similar gain in science opportunities. Perhaps most notably, the etendue of optical imagers have entered a regime where most of the entire sky can be monitored repeatedly. The intrinsic *multi-epoch* character of new optical surveys means that variability will become a powerful new tool, both temporal and astrometric.

For many science programs, the volume of a survey is a key metric. Larger volumes encompass larger numbers of objects and also increase the probability of finding rare objects of special interest. In this regard, the volume scales linearly in exposure time t when surveying more angular area, whereas going deeper in flux sensitivity over a fixed area increases the volume as $t^{3/4}$. For these science programs, a wide shallow survey is preferred. Also for a given population of objects, a wide survey tends to find objects at closer distances; these will be brighter and hence easier to study in detail. For many decades, our ability to catalog low-mass objects in optical bands over the entire sky has relied on photographic surveys; this epoch is coming to an end.

2.1. The WASP Project and SuperWASP

The WASP Project has progressed rapidly from imaging of Na I D tails in comets with CoCAM (Cremonese et al. 1997), via a single camera prototype (WASP0, which operated for a few months in 2000 and 2002), to two multi-camera SuperWASP instruments. The first of these, SuperWASP-North (SW-N), became operational on La Palma in 2004 and construction of SuperWASP-South (SW-S) started in August 2005. The first remotely operated night for SW-S was 2006 May 05 and since then over 600,000 images have been obtained.

The SuperWASP instruments (Pollacco et al. 2006) operate robotically and consist of an enclosure with roll-off roof, GPS, weather station and a fork mount with 8 cameras. Each camera consists of a Canon 200mm f/1.8 lens and an Andor 2048^2 pixel CCD (giving 13.7 arcsec/pixel and a 7.8° field of view). Two 30 s exposures are taken in a strip at constant declination and 5 & 30 s exposures are taken in all-sky mode. Combined with the 4s readout and the fast slewing, this gives an excellent duty cycle.

After pipeline processing, the data is ingested into the SuperWASP archive at Leicester. The current contents from the 5 month 2004 SW-N season has $\sim 12.8\times10^9$ data points on $\sim 6.7\times10^6$ objects with $V \sim$8–15. Many objects have > 4000 data points on > 100 nights, ideal for looking at long-term variations, activity cycles, spot evolution etc on cool stars. The archive cross-matches SuperWASP objects with the GCVS, ROSAT & USNO-B1 catalogues, allowing many cool star science projects to be undertaken. An example of this is the matching of SuperWASP objects with ROSAT sources to identify new active stars and binaries (Norton et al. 2007 submitted). As a by-product of the extrasolar transit search (Collier Cameron et al. 2006), many EA-type and low amplitude W UMa binaries have been discovered and searches are underway for brown dwarf and low-mass binaries (Pinfield et al. 2005; Street et al. this conference). Other cool star work undertaken with SW data includes examining the origins of rapid rotators in clusters and magnetic activity cycles on close binaries.

2.2. Pan-STARRS and the Extended Solar Neighborhood

The Pan-STARRS project, led by the University of Hawaii, is developing a unique optical survey instrument consisting of four co-aligned wide-field telescopes. Each telescope has a 1.8-meter diameter primary meter and a 7 degree^2 field-of-view, imaged with a well-sampled 1.4 Gigapixel camera. This instrument is planned to be completed on Mauna Kea in the 2010 timeframe. As a pathfinder for the PS4 system, the Pan-STARRS project has built a single telescope system (called PS1) on the summit of Haleakala on the Hawaiian island of Maui, consisting of a full-scale version of one of the four PS4 telescopes. PS1 will be used for a 3.5-year survey mission, beginning after the complete system is commissioned in late 2007.

The 3π Survey will be one of the major observing projects of the PS1 mission. This survey will cover the 3π steradians north of Declination $-30°$ with many repeated visits. Each point on the sky will be observed 12 times in each of the 5 filters ($grizy$), with a faint 5-σ limit in the range 20.6 – 23.7 mag depending on the filter. The survey cadence is designed to enhance the detection of high-proper motion stars and the measurement of the stellar parallaxes.

The contents of the solar neighborhood are poorly known, despite several millennia of intensive scrutiny. Simple estimates suggest that $\sim$60% of stars are missing from the cataloged sample within 25 pc (Henry et al. 1997). Even the existing census is highly heterogeneous, representing a compilation of objects identified from a mix of techniques (parallaxes, proper motions, photometry and spectroscopy) with varying sensitivities and angular coverage. The incompleteness of the solar neighborhood has been amply demonstrated with the continuing discoveries of nearby low-mass objects, e.g. the binary T dwarf ϵ Ind Bab (McCaughrean et al. 2004) and the high proper-motion M dwarf SO 025300.5+165258 (Teegarden et al. 2003), both within 5 pc.

The PS1 3π Survey will result in an unprecedented census of very low-mass stars and brown dwarfs. Its high-accuracy CCD-based photometry (1%) and astrometry (10 mas), combined with the very wide field and depth will result in more than an order of magnitude improvement over all other comparable optical surveys. The sensitivity of the PS1 far-red z (8700 Å) and y (9900 Å) bands will make the 3π Survey particularly valuable for studies of ultracool objects. For instance, the PS1 detectors have a quantum efficiency (QE) of around 30% at 1 μm, more than an order of magnitude better than SDSS (see Figure 1).

Previous surveys have been very successful at using optical and/or near-IR color selection to identify and classify ultracool objects (late-M, L, and T dwarfs; Kirkpatrick 2005). The PS1 3π Survey will provide a new dimension for identification of these objects by adding parallaxes and proper motions. Multiple samples of ultracool objects will be produced from the 3π Survey data, include parallax-selected and proper-motion selected samples. The coolest brown dwarfs (T dwarfs and the as-yet-undiscovered Y dwarfs; see Section 3) can be uniquely identified by their steeply rising flux in the far-red optical ($\lambda \sim 0.8 - 1.0$ μm) due to the pressure-broadened K I doublet. The large volume probed by the PS1 survey also indicates that illuminating classes of rare low-mass objects can

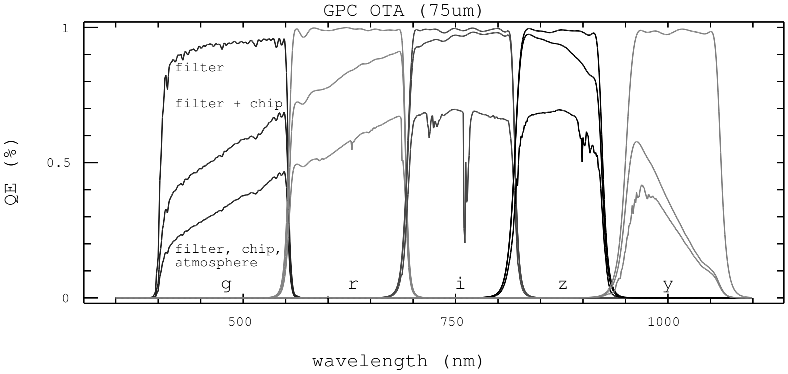

Figure 1. PS1 filter profiles. The top curves represent the transmission of each filter alone. The middle curve includes the measured quantum efficiency of the 75 μm thick detectors. The bottom curve includes the effect of the atmosphere and two mirror reflections.

be identified to probe a wide range of physical parameters, e.g., halo objects, very young objects in nearby moving groups and the field, eclipsing objects (e.g., Dupuy & Liu, this conference), and "benchmark" objects associated with stars and/or stellar clusters of known age and metallicity.

The 3π Survey parallax-selected sample will produce the first volume-limited low-mass census of the extended solar neighborhood ($d < 50$ pc). Every object in this sample will be reliably identified as low-luminosity and nearby by having detected parallaxes. Combined with J-band 2MASS photometry, every object will have estimated spectral typing based on colors and absolute magnitudes in 4 filters. We estimate that the 3π Survey Parallax sample will consist of $\sim$ 2000 L0-L5 dwarfs, 300 L5-L9 dwarfs, and $\sim$ 200 T0-T6 dwarfs, all with measured parallaxes. The 3π Survey parallax observations will generate a volume-limited sample of low-mass objects, out to 100 pc for the late-M's and early-L's and out to 10–30 pc for T dwarfs. Finally, the availability of proper-motion and parallax data opens the door to serendipitous discovery of nearby low-mass objects with unanticipated physical properties.

3. Infrared surveys

3.1. The near infrared

With large scale infrared surveys moving from small ~1m telescopes (e.g. 2MASS) to larger ~4m facilities like the Wide Field Camera (WFCAM) on the UK infrared Telescope (UKIRT), the Wide-field Infrared Camera (WirCam) on the Canada-France Hawaii Telescope (CFHT) and the Visible and Infrared Survey Telescope for Astronomy (VISTA), our view of the infrared sky is set to improve greatly in the coming years.

The creation of large databases from these facilities (e.g. UKIDSS the UKIRT Infrared Deep Sky Survey, and the VISTA public surveys) that combine with deep optical surveys (e.g. the SDSS, and the CFHT Legacy Survey) will provide the astronomical community with access to these major resources via on-line query tools, and there is great potential for the community to fully exploit these surveys for cool star science.

UKIDSS is the forerunner in the near infrared, and plans to cover 7000 sq degs of sky with five sub-surveys using combinations of Z, Y, J, H, K filters (see Hewett et al. 2006). The largest of these sub-surveys is the Large Area Survey (LAS), set to cover 4000 sq degs in Y, J, H and K. The LAS will uncover new populations of L and T dwarfs and expand greatly on our knowledge of the low-$T_{\rm eff}$ extremes of cool stars. It is also anticipated that the LAS will probe new $T_{\rm eff}$ ranges cooler even than the T dwarfs previously found in 2MASS and SDSS.

Approximately ∼50,000–100,000 early L dwarfs, 2,000–9,000 late L dwarfs, 400–1400 early T dwarfs, and 600–2,000 late T dwarfs should be uncovered in the field by the LAS, dependent on the substellar initial mass function (IMF) and birth rate (see Deacon & Hambly 2006), thus harbouring the potential to revolutionise our knowledge of these corner stones of the star formation process.

New spectral characteristics could become manifest for new even lower $T_{\rm eff}$ populations (e.g. ammonia absorption and water clouds; Burrows et al. 2003), which would warrant a new spectral class. This class has been pre-emptively christened Y, and the hunt for the first Y dwarfs is at the forefront of LAS exploitation. However, the number of LAS Y dwarfs depends on the actual $T_{\rm eff}$ of the T-Y transition, with 25-100, 14–27, 4–6 and ∼1 Y dwarfs expected if the T-Y transitions occurs at 750K, 700K, 600K and 500K respectively. These numbers will be complemented in the short term by discoveries from a slightly deeper but much smaller CFHT WirCAM survey, and significantly built upon in the longer term by the public VISTA Hemisphere Survey.

Analysis of the UKIDSS LAS first data release (190 sq degs; see Warren et al. 2007) has so far yielded 5 new late T dwarfs that have been spectroscopically confirmed with GNIRS on Gemini South (see Figure 1 left hand plot; see also Lodieu et al. in prep.; Warren et al. in prep.). Four of these have spectral types (estimated from flux ratios and template fitting) from T5-T7.5. One of these (labeled ULAS 0034 here) may be even later than T8. Warren et al. (in prep.) use synthetic spectra and the well-studied dwarf 2MASS J04151954-0935066 to show that the preferred atmospheric parameters for ULAS 0034 are $T_{\rm eff} \approx 650$ K with log g/[m/H] of 4.5/0.0 or 5.0/+0.3. The range in age and mass is then 0.5–3 Gyr and 15–30 $\rm M_{Jupiter}$ (see also Leggett et al. this conference).

Looking to the future, maximum exploitation of all the new populations of field L and T dwarfs would require spectroscopic determination of their properties. Such calibration could be facilitated by the discovery and spectroscopic study of large numbers of benchmark brown dwarfs – L and T dwarfs with properties that are well constrained independently. Two major resources for such benchmarks exist in open clusters and as wide companions to age calibrating primaries such as high mass white dwarfs (see also Day-Jones et al. this conference) and subgiant stars (see Pinfield et al. 2006).

Open clusters are also being targeted by the new surveys, with the UKIDSS Galactic Cluster Survey covering a total of 1400 sq degs, and the WirCam large programs pushing down into the ∼Jupiter mass regime through a combination of broad-band and CH_4 filters. The primary goal is to extend our knowledge of the low-mass extremes of the cluster mass functions, but a large number of young benchmark brown dwarfs will also be identified. Figure 12 of Pinfield

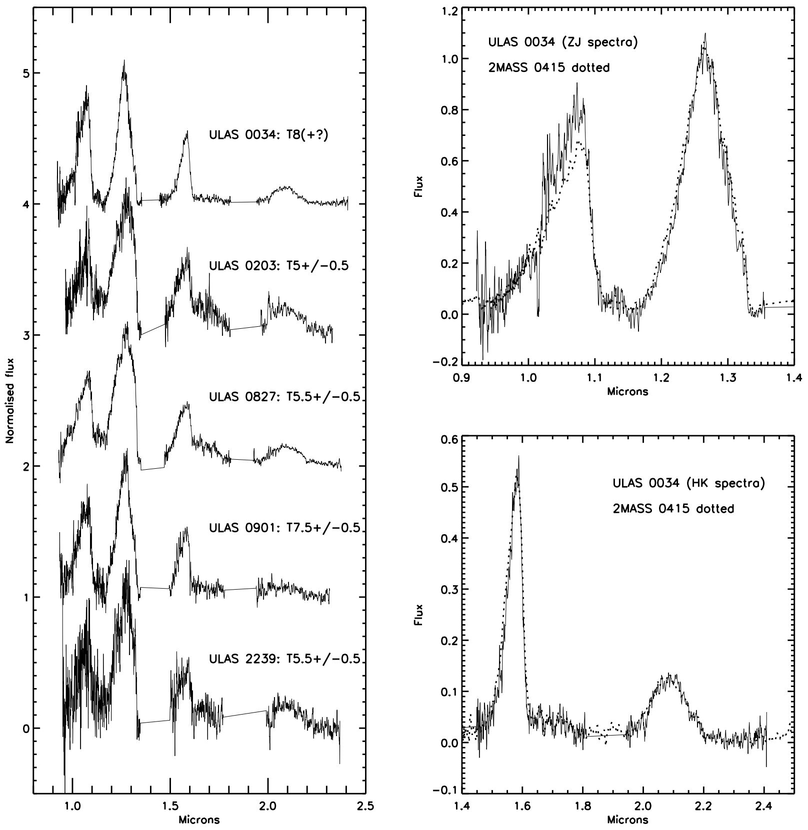

Figure 2. The left plot shows GNIRS spectra of five new late T dwarfs discovered in the UKIDSS LAS. Spectral types are indicated next to the spectra. The two right hand plots show zoomed in regions (ZJ and HK) of ULAS 0034, which is our latest LAS discovery.

et al. (2006) shows the results of a simulation of the number of benchmark brown dwarfs in wide binaries that could be expected from the UKIDSS LAS and even larger near infrared surveys such as the VISTA public surveys (the region covered by the clusters is also indicated). By studying large numbers of benchmark brown dwarfs, it may become possible to spectroscopically calibrate the properties of the new L and T dwarf field populations, and thus revolutionise our knowledge of the low-mass and substellar IMF and formation history.

3.2. WISE

The Wide-field Infrared Survey Explorer (WISE) is a NASA Medium Explorer mission scheduled to launch in November 2009. It is an all-sky survey in four bands 3.3, 4.7, 12, and 23 μm. In the two shortest wavelength bands, WISE will reach sensitivities half a million times deeper than the Diffuse Infrared

Background Experiment (DIRBE) on-board the Cosmic Background Explorer (COBE). In the two longest wavelength bands, WISE reaches sensitivities 500 times better than the Infrared Astronomical Satellite (IRAS).

WISE consists of a 40-cm telescope and re-imaging optics, a scan mirror which stabilizes the line of sight while the spacecraft sweeps the sky, two HgCdTe and two Si:As 1024×1024 arrays, and a two-stage solid hydrogen cryostat to cool the focal planes and optics. The resulting resolution is ∼6 arcsec full width at half maximum (although the 23 μm band is diffraction limited to 12 arcsec). WISE will orbit in a circular, 500-km high, Sun-synchronous, polar orbit around the Earth for a seven-month mission. The sky-pointing instrument has an 11-second data-taking exposure cycle synchronized with the orbit. Generous overlap is produced between orbits so that >99% of the sky will have eight or more separate, repeat exposures. The first data products will be released to the public six months after the beginning of science operations.

A WISE search for cool brown dwarfs will rely largely on the two short-wavelength bands, which have been optimized for this task. The first channel samples the very strong methane absorption band at 3.3 μm and the second measures the relatively opacity-free portion of the brown dwarf atmosphere near 4.7 μm. Cool brown dwarfs will thus have very red, perhaps uniquely red, [3.3 μm] - [4.7 μm] colors (Burrows et al. 2003). Such red colors for known L and T dwarfs have been confirmed through observations by the Infrared Array Camera (IRAC) on the Spitzer Space Telescope (Patten et al. 2006).

Extrapolating various forms to the mass function (log-normal from Chabrier 2002 and power laws of $\alpha = 0.7, 1.0, 1.3$ from Reid et al. 1999) to very cool temperatures, assuming that the lower limit for star formation is 10 Jupiter masses, and that the star formation rate has been constant over the last 10 Gyr, we can predict the number of brown dwarfs WISE is expected to image. WISE could detect 700–1300 $T_{\rm eff}$ <750K brown dwarfs, 200–300 with $T_{\rm eff}$ <500K, and even 5–20 with $T_{\rm eff}$ <300 K. Statistically, there is a reasonable chance WISE will uncover a cool brown dwarf closer to the Sun than Proxima Centauri.

4. Other surveys

As well as the optical and infrared, major surveys over a wide range of other wavelengths are also becoming available for cool star science. The Second XMM-Newton Serendipitous Source Catalogue (2XMM) is the largest catalogue of X-ray sources ever produced, with 0.2–12 keV fluxes, spectra, and light curves available over 400 sq degs. The Galaxy Evolution Explorer (GALEX) will offer the opportunity to study the sky at ultraviolet wavelengths (130-300nm), and is conducting several first-of-a-kind sky surveys, including an ultraviolet all-sky survey. GALEX will probe the causes of star formation during a period when most of the stars and elements we see today had their origins. Sky Surveys with the new generation of synoptic radio telescopes, such as the Allen Telescope Array (ATA) and the Square Kilometre Array (SKA), will also be amenable to spectral and temporal analysis, capable of, for example, detecting and studying coherent emission from ultracool dwarfs (Bourke et al. this conference).

Indeed, the longer term potential for high spatial resolution studies (e.g. using NIRCam on JWST; Horner et al. this conference), and even inteferometric surface imaging (using the Stellar Imager; see Carpenter, this conference) of stellar populations identified and studied by these surveys is extremely exciting.

5. Future prospects

As a guide for the reader, we present a summary table of new and near future surveys, and their expected/known operational start date.

Survey (operational)	Sky coverage	Depth	Cadence
Galex (Apr 2003)	All sky	U=22	Some rapid, mostly once
SuperWASP (N&S) (2006)	All sky	R=15	∼40/night over >100 nights
Pan-STARRS (2007)	Dec>-30	$grizy$=20.6–23.7	12 epochs in 3.5y
SkyMapper (mid 2007)	Southern	uv_sgriz=22.9,22.7,22.9 22.6,22.0,21.5	6 epochs: hrs-yrs
LSST (2012)	Southern	$ugrizy$= 26.5 (AB), 24.5 in u	>300 epochs in ∼3yr
UKIDSS LAS (May 2005)	4000sd	$YJHK$= 20.2, 19.6, 18.8, 18.2	2 J epochs in 5yr
VISTA (VHS) (end 2007)	Southern	$ZYJK_s$= 21.9, 21.2, 20.2, 18.1	Once
WirCam shallow (2006)	180sd	J ∼21	Once
WirCam deep (2006)	∼10sd	$YJHK, CH_4$, J ∼22	Once
WISE (end 2009)	All sky	$LMNQ$ = 17.9, 15.0, 11.5, 8.6	Once

Table 1. Summary of survey sensitivities.

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