Stellar Astronomy in the Warm Spitzer Era

Gillian R. Knapp[*], Peter R. Allen[†], Željko Ivezić[**], Massimo Marengo[‡], Fergal Mullally[§] and Paula Szkody[**]

[*]*Department of Astrophysical Science, Princeton University, Princeton NJ 08544*
[†]*Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802*
[**]*Department of Astronomy, University of Washington, Seattle, WA 98195*
[‡]*Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138*
[§]*Department of Astronomy, University of Texas, Austin, TX 78712, and Department of Astrophysical Science, Princeton University, Princeton NJ 08544*

Abstract. We consider the impact on the study of normal stars of large-scale pointed and mapping observations at 3.6μm and 4.5 μm with the *Spitzer* IRAC imager. Deep observations at these wavelengths are particularly sensitive to very cool stellar and substellar objects, both as companions to other stars and in the field. A wide-angle survey can be expected to detect 50 – 100 cool T dwarfs and up to 5 "Y" dwarfs in the field, and AGB stars throughout the Galactic halo. Pointed observations of white dwarfs at these wavelengths will be sensitive to unresolved cool companions and to circumstellar dust disk remnants of planetary system objects. The cumulative photometry of normal stars in the imaging fields will be invaluable for understanding stellar colors and atmospheres.

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INTRODUCTION AND OVERVIEW

This paper discusses science from IRAC 3.6μm and 4.5μm photometry of stars in the Galaxy and Local Group made possible by large surveys using IRAC on *Spitzer* in the post-cryogen era. As a strawman we consider that the "Warm Spitzer" observations, and the post-cryogen mission, may fall into three broad categories: (1) One or two very large surveys, perhaps consisting of a shallow survey over a wide area accompanied by embedded deeper surveys over smaller areas, to acquire data to support a very wide range of science investigations of interest to the entire astronomical community. What strategies would be optimal for stellar science, i.e. depth, cadence, region(s) of sky covered, existence of data sets at other wavelengths? (2) moderate-sized (PI team) pointed surveys of individual classes of rare objects: (3) reduction of the imaging data from the accumulated *Spitzer* mission, to provide photometric catalogues of serendipitous objects (stars in particular of course) found in the fields of the observed targets.

We consider four main science topics: (1) searches for brown dwarfs, in particular those cooler than any found to date: (2) a survey of white dwarfs to detect low luminosity companions and circumstellar dust and to provide infrared data to extend the spectral energy distribution coverage and investigate atmospheric models: (3) studies of AGB stars in the Galactic halo and: (4) stellar photometry from IRAC imaging to extend the available broad-band photometry for normal stars and contribute to measures of gravity, metallicity and effective temperature.

WIDE AREA SURVEYS: CONSIDERATIONS FOR STELLAR ASTRONOMY

With the exception of studies of the stellar content of clusters, streams etc., we could think of no particular rationale for a large *ab initio* filled area as far as stellar science goes - in principle a wide-area survey designed for stellar astronomy could consist of a large number of individual $5' \times 5'$ patches of sky. Of greater importance is a uniform sensitivity limit, very accurate photometric calibration, a large total area, and wide coverage in Galactic latitude. Thus in principle the areas to be observed could be driven by ease of scheduling. However, there are two strong arguments for a contiguous area: calibration, and the existence of data at other wavelengths.

Calibration

Accurate photometric calibration is probably the single hardest problem facing observational astronomy. As Worthey and Lee (2007) put it: "Perhaps the reason no-one has done this exercise (stellar effective temperatures from multiple broad-band colors) before is that photometric systems are such a mess". The problem can be separated into two parts: accurate *internal* calibration, in which the relative measurements of all sources with a given instrument through a given filter are accurate with respect to each other across the entire survey area, and accurate *external* calibration, in which the instrumental quantities are accurately converted to physical units, so that they can be used with observations at other wavelengths to construct broad-band spectral energy distributions (SEDs). There has been enormous progress in this area of late, with both 2MASS and SDSS employing multiple dithered or overlap observations to ensure end-to-end internal calibration of their surveys to better than 2% (Skrutskie et al. 2006; Padmanabhan et al. 2007). Therefore, the *Spitzer* 3.6/4.5 μm wide area survey needs to be done in such a way as to ensure consistent calibration across its area. One way or the other, this will be done with multiple exposures, thereby enabling a second type of science, that of time variability. The appropriate observing pattern is to spread the observations over the entire six years of the warm mission, with a consistent flux limit across the whole survey area at all times (in case the warm mission were to terminate early), sensitivity built up by multiple passes of the entire survey area, and an observing cadence analogous to that proposed for LSST (Ivezić 2006), i.e. with a roughly logarithmic distribution of Δt, the time interval between any pair of observations. This would optimize the ability to find photometric variability on a wide range of time scales, and to find secular position variability (i.e. proper motions).

Observations at Other Wavelengths

Since *Spitzer* will not observe the whole sky during the warm mission, all science will be optimized if the *Spitzer* surveys cover areas with data at as many other wavelengths as possible. USNO-B, 2MASS, IRAS, Akari, GALEX and ROSAT cover the whole sky, and large-area surveys covering part of the sky include UKIDSS, FIRST and SDSS. We highlight two surveys here: the SDSS southern equatorial survey and a planned *Subaru* very deep optical and near-infrared survey over several hundred square degrees.

The SDSS southern stripe is a 2.5° wide stripe along the celestial equator between right ascensions 20^h to 4^h, about 300 square degrees in all, which has been observed multiple times by the SDSS mosaic telescope in the u, g, r, i, and z bands over almost ten years. Co-added, the survey depth is about 24^m (AB), and there is a wealth of variability and proper motion information. There are about 500 spectra per square degree and deep surveys available in the near-infrared (UKIDSS), the ultraviolet (GALEX), and the radio (FIRST). The Atacama Cosmology Telescope (ACT) will image this region at 1 mm wavelength in 2007-2009 at a resolution of about 1 arcminute. While *Spitzer* is not affected by limits on sky coverage, regions near the celestial equator can be observed by most ground-based telescopes and naturally cover a range of Galactic and Ecliptic latitudes.

The second complementary survey is only at present in the planning stages. A group including the National Astronomical Observatory of Japan and Princeton University is planning a multiband optical survey with *Subaru* over several hundred square degrees in the g(27.3), r(26.8), i(26.4), z(25.8) and y(25.3) filters - the numbers in parentheses are the 5σ limiting (point source) magnitudes. The region to be surveyed is not yet decided, but since its primary driver is extragalactic science it will be at high latitudes. This region will also be surveyed by ACT, and is the only current survey whose sensitivity to very cool substellar objects will approach that of *Spitzer*.

Catalogues

We consider a most important aspect of the warm mission to be the production of catalogues from all *Spitzer* imaging, including that acquired during the cryogenic mission, exploiting the measurement of objects in the large IRAC field of view. This archive should be searchable both for objects of particular properties and for objects matched with those discovered at other wavelengths. A position query of this data base would then return the *Spitzer* flux densities and uncertainties plus the epoch of observation, or upper limits and the epoch of observation, or a notation that this position had not been observed by *Spitzer*. This facility would have particular use in several of the stellar programs discussed below. As examples: (1) it would provide a large archive of the colors of normal stars. These would be useful for identifying infrared excesses, for defining colors which could help identify chemically peculiar stars, and for input to determinations of temperature, metallicity, and gravity based on multiband observations and model atmospheres; (2) it could provide earlier epoch measurements to help identify proper motion pairs, including very low temperature wide pairs and companions; (3) it could help verify the existence of single-band sources, for example possible very cool dwarfs found only at 4.5μm by *WISE* (Mainzer et al. 2006), as pointed out by Stauffer et al. (2007); and (4) there may be rare objects in these fields.

The general usefulness of the *Spitzer* "Point Source Catalogue" and "Extended Source Catalogue" would be greatly enhanced if the data base were to return not only the IRAC and MIPS photometry and *Spitzer* spectroscopy, but also matches, positions and photometric data from other catalogues. This effort will integrate into the National Virtual Observatory to provide a comprehensive UV to mid-infrared photometric catalogue for all of the sky observed by *Spitzer* during the cryogenic and warm missions.

T AND Y DWARFS

Expected Flux Densities, Colors, Numbers

The Warm *Spitzer* Mission has the potential of finding several tens of brown dwarfs with temperatures less than 1000 K, i.e. cool T dwarfs and the as-yet-undiscovered "Y" dwarfs.

Recent deep large-area surveys at optical and near-infrared wavelengths, primarily 2MASS and SDSS, have led to the discovery of many field L and T dwarfs, allowing the definition of these two spectral types and the measurement of their effective temperatures (Kirkpatrick et al. 1999, 2000; Burgasser et al. 2002; Geballe et al. 2002; Golimowski et al. 2004). The stellar- substellar boundary appears to occur at spectral type about L5, $T_{eff} \sim 1700$ K), and the spectral transition between L and T at $T_{eff} \sim 1300$ K, although exactly what happens at this transition is still uncertain because of the complicating effects of close binaries on the observations (Liu et al. 2007). Spectroscopically, the L/T transition is defined by the onset of CH_4 absorption in the *H* and *K* bands, although absorption in the methane fundamental at 3.3μm is seen as early as spectral type L5 (Noll et al. 2000).

T dwarfs as cool as 700 K have been observed (Golimowski et al. 2004; Warren et al. 2007). The next spectral type cooler than T9, dubbed "Y", remains to be discovered (unless you count Jupiter and recently directly detected extrasolar planets). These objects will have effective temperatures less than 600 K and NH_3 absorption bands. Their discovery in the field, should this prove to happen, will be invaluable for their study uncontaminated by the light of a nearby/primary star.

Finding the very faint T dwarfs has proved challenging both for SDSS (where the objects are often detected only in the *z* band) and in 2MASS, where the *JHK* colors are degenerate with those of main sequence stars over much of the T dwarf temperature range. The discovery of very cool T and Y dwarfs in the field will require a sensitive, wide area survey in at least two bands where they can be expected to be detected. Further, the two bands should be selected to produce a T/Y dwarf color which is very different from that of any other astronomical objects. In addition to the upcoming *WISE* mission (see below) there are two surveys which will meet these criteria: deep mapping in the near-infrared, and a *Spitzer* survey in IRAC bands 1 and 2.

UKIDSS is a set of surveys in *JHK* which is reaching several magnitudes deeper than 2MASS (Lawrence et al. 2007) and has already led to the discovery of very cool

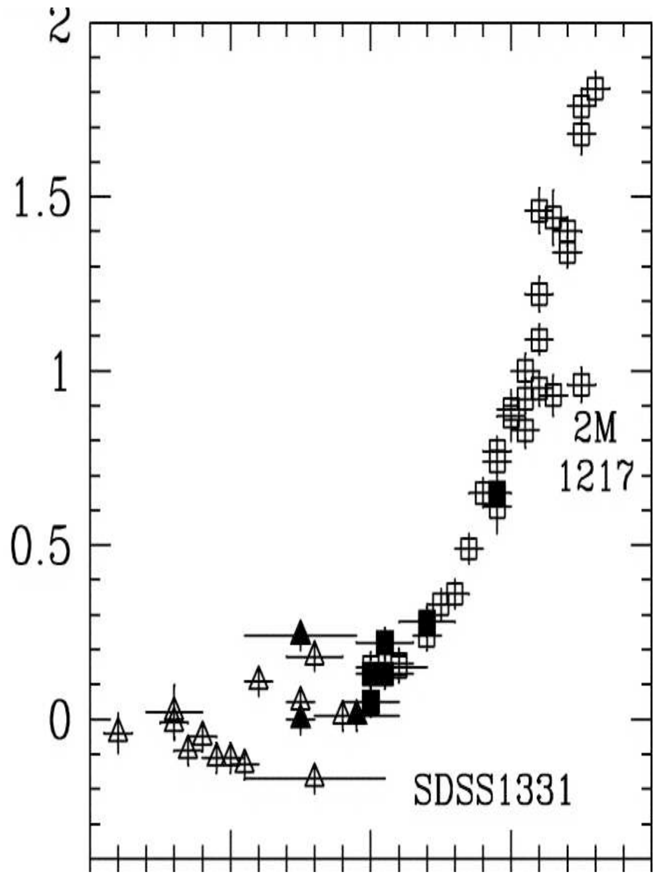

FIGURE 1. [3.6] - [4.5] color vs spectral type for L and T dwarfs, from Leggett et al. (2007a). The horizontal axis is spectral type between L0 and T9.

T dwarfs (Kendall et al. 2007; Warren et al. 2007; Lodieu et al. 2007). The proposed *Subaru* survey described in the previous section will reach 25.8 in z and 25.3 in y (AB magnitudes). A medium sensitivity *Spitzer* survey would be orders of magnitude more sensitive than UKIDSS for very cool T dwarfs.

The *Spitzer* instrumentation is almost ideal for this work. Bands 1 and 2 cover the sky at different times, so that asteroids can be eliminated by proper motion. The [3.6] - [4.5] colors of M and L dwarfs are close to zero, while towards later spectral types the colors rapidly become redder, with values of about 2 for the latest T dwarfs observed (Patten et al. 2006; Leggett et al. 2007a; Stern et al. 2007); see Figure 1. The reasons for this behavior are twofold. First, the emission peak moves through these bands for objects cooler than about 3000 K. Second, the 3.5μm band contains the CH_4 fundamental at 3.3μm, which greatly suppresses the 3.6μm flux towards lower temperatures. Although the CO fundamental is at 4.6μm and therefore affects the 4.5μm band, it becomes increasingly weak with decreasing temperature and does not have a strong effect on the colors. (CO is weakly present in very cool objects with methane-dominated atmospheres due to vertical mixing and non-equilibrium chemistry, which can be probed with larger samples (cf. Mainzer et al. 2007).

The colors measured by IRAC (Patten et al. 2006; Leggett et al. 2007a) are in qualitative agreement with those predicted by models (Burrows, Sudarsky and Lunine 2003; Jones et al. 2005; Burrows, Sudarsky and Hubeny 2006; Marley et al. 2007; Saumon et al. 2007). Figure 2 shows a plot of the predicted 3.5μm flux density at 10 pc vs. [3.6] - [4.5] for dwarfs of effective temperature below 1200 K (the 3.6μm flux is selected because the objects are far fainter at 3.6μm, so it is the sensitivity of this band, fortunately the more sensitive of the two because of lower backgrounds, that limits our ability to detect and characterize T and Y dwarfs). Comparison with the data of Patten et al. (2006) shows that present observations have probed only the bluest objects, to [3.6] - [4.5] $\sim$ 2. While the quantities plotted in Figure 2 are somewhat schematic (gravity, metallicity and weather all affect the colors, Leggett et al. 2007b) the important point from Figure 2 is that the dwarfs continue to get redder in the [3.5] - [4.5] color with decreasing temperature and therefore if they are detected at both bands, they will not be confused with faint stars. Neither will they be confused with highly redshifted galaxies, whose spectra, containing roughly equal contributions from the almost single age turnoff, red giant and AGB stars are basically flat at the *Spitzer* wavelengths over a wide range of redshift.

Also plotted in Figure 2 are the 5σ depths for the “shallow” and “moderate” surveys (Stauffer et al. 2007), showing that the shallow survey can detect almost all T dwarfs in the survey area in the presently-known effective temperature range.

Serendipity and Confirmation

As pointed out by Stauffer et al. (2007) T and Y dwarfs are much brighter at 4.5μm and will therefore produce a lot of 4.5μm single-band detections by both *Spitzer* and *WISE*. Since *WISE* is an all sky survey, any such object found by *WISE* can be compared with *Spitzer* 4.5 μm data. For this and many other reasons, it will be very useful to have an archive of all fully-reduced *Spitzer* data, i.e. catalogues derived from all images ever observed. *Spitzer* will also be able to confirm faint single-band 4.5μm detections by *WISE*.

Of the data sets at other wavelengths; the existing 2MASS, UKIDSS and deep SDSS surveys, and the upcoming or proposed VISTA and *Subaru* surveys: only the last will rival *Spitzer* in sensitivity. Its magnitude limits of 25.8 and 25.3 in z and y will allow the detection of dwarfs to essentially the same depth as will the moderate *Spitzer* survey, as illustrated in Figure 2, i.e. down to objects as cool as 400 K at a distance of 10 pc. Thus inasmuch as possible, the *Spitzer* survey should be carried out in the same part of the sky as the proposed *Subaru* survey.

How many T and Y dwarfs can *Spitzer* be expected to detect? Since these objects cool with time, the answer depends on both the initial mass function and its possible variations with time, and on the star formation history. Models by Burrows et al. (2001, 2003, 2006), together with mass-function fits to the existing counts of cool dwarfs (Allen 2005) indicates that the “wide” survey (Table 1 of Stauffer et al. 2007) will find up to 100 T dwarfs, many of them very cool, and 1-5 Y dwarfs. If they are detected in both IRAC bands, these objects will have unique colors, but the selection efficiency

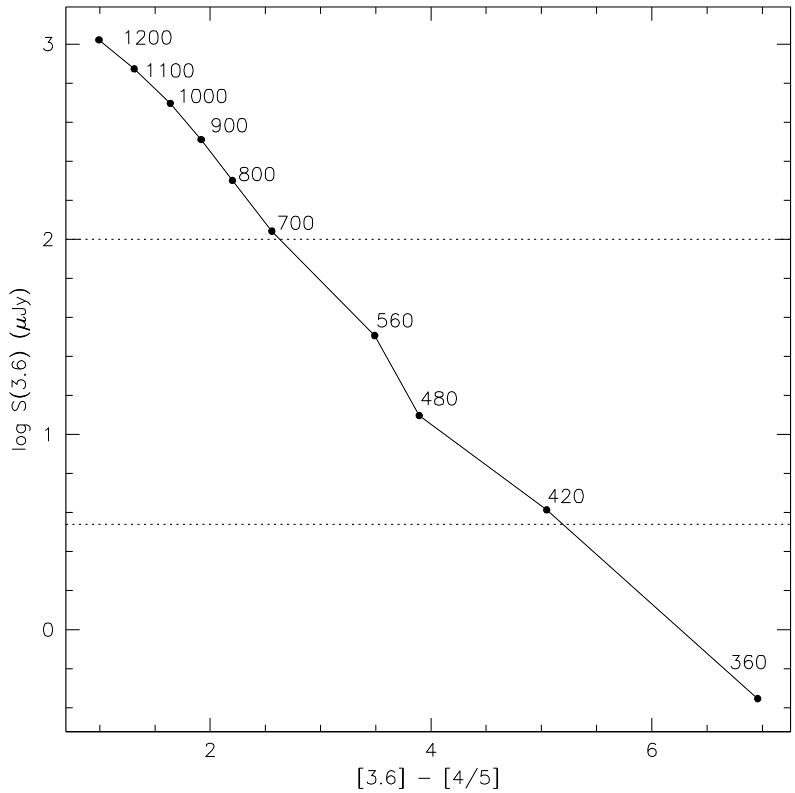

FIGURE 2. Model flux density in IRAC band 1 at a distance of 10 pc versus [3.6] - [4.5], from the models of Burrows et al. (2003) and Burrows at al. (2006). The points are labelled by the effective temperature of the model. The horizontal lines show the 5σ sensitivities of the "shallow" and "moderate" surveys from Stauffer et al. (2007).

for follow-up can be greatly enhanced by the inclusion of J and K photometry using methods developed by Marengo et al. (2006a) and, as mentioned above, by very deep optical imaging.

Resolved Companion Searches

Spitzer has already led to the discovery of resolved T dwarf companions to nearby stars, most notably of the T7.5 companion to HD 3651, which has a planetary system (Luhman et al. 2007). *Spitzer* is unsurpassed by any current project for this sort of discovery because of its great sensitivity to very cool objects, its good spatial resolution, and the fact that the parent stars are so much fainter at the *Spitzer* wavelengths than at shorter wavelengths (Marengo et al. 2006b). A survey of the 1000 nearest stars would sample stars within about 20 pc to separations of about 600 AU and greater for the most distant stars (this estimate is based on an assumed ability to reliably detect a cool companion as close as 20″ to the primary star) and could detect companions as cool as about 400 K in modest amounts of observing time (about one hour total observing time per star). Ideally, the exposure would be built up over the six-year timescale of the warm mission, to allow the identification of faint companions by common proper motion. The above estimate of 1000 stars mostly comprises M dwarfs, so the star list could be modified to more uniformly sample the spectral type range, the metallicity range, the present or absence of massive planetary systems, etc.

Unresolved Companion Searches: White Dwarfs

Cool companions can also be detected when they are too close to their primary to be spatially resolved by searching for color excesses at long wavelengths. Given the huge luminosity contrast between main sequence stars (even late M stars) and T dwarfs, plus the fact that the long-wavelength colors of normal stars are not well characterized (see below) such searches are too difficult for current technology. The exception is the search for cool companions to white dwarfs, whose low luminosities and blue colors ensure that cool companions are brighter then the star in the infrared and can be found as measurable infrared excesses. Indeed, the first known object of spectral type L was discovered as a companion to the nearby white dwarf GD 165 (Zuckerman and Becklin 1988), and large numbers of dM/WD pairs are known (Silvestri et al. 2006). Currently, only a small handful of L/T dwarf companions is known (Zuckerman and Becklin 1988; Farihi and Christopher 2004; Farihi et al. 2005; Maxted et al. 2006).

A search for cool companions to white dwarfs offers, as well as the opportunity to discover more ultracool dwarfs, the opportunity to measure the mass function at the bottom of the main sequence and, perhaps, to identify the coolest, lowest mass main sequence star. This transpires because white dwarfs are old, and substellar companions may have faded below detectability (Burrows et al. 2001). There are some 20,000 white dwarfs known at present, and the number is rising rapidly, including the discovery of many new nearby white dwarfs (Bergeron et al. 1995; McCook and Sion 1999; Eisenstein et al. 2006; Subasavage et al. 2007). Several searches for cool companions have recently been made by matching known white dwarfs with infrared surveys, in particular 2MASS (e.g. Wachter et al. 2003), but unfortunately 2MASS is not quite sensitive enough to detect substellar companions around most known white dwarfs. A targeted search with well-controlled exposure times of a sample of 100-200 carefully selected white dwarfs - nearby, with decent photometric or trigonometric distances, with well-determined masses, ages and temperatures, and known from optical and 2MASS photometry not to have companions of spectral type M8 or earlier could answer this question, while a sample twice as large would also allow the investigation of metallicity effects. The search could also possibly find extremely cool brown dwarfs - late T and perhaps even Y, may yield resolved ultracool companions, and would also be of enormous interest for studies of fossil planetary systems around WDs (see below).

Unresolved Companion Searches: Cataclysmic Variables

Cataclysmic variables (CVs) are interacting binaries whose primary is a white dwarf and secondary a low mass donor star. Mass accretion onto the white dwarf causes sporadic huge increases in luminosity due to a short-lived phase of nuclear burning of material accreted to the white dwarf from the circumstellar disk produced by Roche-lobe overflow from the secondary. Until recently, most known CVs were discovered while in their high state, but recent surveys, especially the SDSS, have discovered hundreds of CVs in their low state, where the spectroscopic signature of the low-mass M stars companion can almost always be discerned (e.g. Szkody et al. 2006).

Quite apart from their interest as variable stars, as possible nova and supernova precursors, and as laboratories for studying accretion under extreme conditions, including very high magnetic fields, CVs can also be used to study the properties of their low-mass secondaries. Star formation and stellar evolution theory predict that a fair number of CV secondaries should be substellar, so that observations of CVs allow the measurement of masses (via measures of the orbital parameters of these binaries), luminosities (via measurements of the infrared excess), and radii (since the secondary is experiencing Roche lobe overflow) for low-mass stars and substellar objects. Indeed, recent *Spitzer*-IRAC observations have discovered infrared excesses from several short-period CVs, and substellar masses are inferred for some companions from radial velocity measurements (Harrison et al. 2003; Howell et al. 2006a,b; Littlefair et al. 2006; Brinkworth et al. 2007). There is some question (Howell et al. 2006a) as to whether the infrared excesses are due to dust or to a substellar companion, but this can be answered by deeper near-infrared photometry and spectroscopy, with *Spitzer* observations providing the candidates.

WHITE DWARFS

As well as the search for unresolved companions described above, 3.6μm and 4.5μm observations of large samples of white dwarfs will allow the investigation of two other important areas: a search for circumstellar dust disks (see Figure 3), and the investigation of model atmospheres.

Circumstellar Dust

White dwarfs come in two main flavors, DA and DB (the analogues of main sequence A and B stars, with H and He lines respectively). Some DA stars have long been known to have in addition absorption lines of heavy elements, especially Ca. This has been hard to explain, since the heavy-element settling times are much shorter than the evolutionary timescales (Fontaine and Michaud 1979). While metals can be radiatively levitated in the atmospheres of hot white dwarfs (Chayer et al. 1995), metal lines are also seen in cooler white dwarfs. Recent accretion is therefore suggested, but the interstellar medium is, over almost all of its volume, of too low density for sufficient accretion. A natural possibility is then the accretion of left-over planetary system objects - comets or

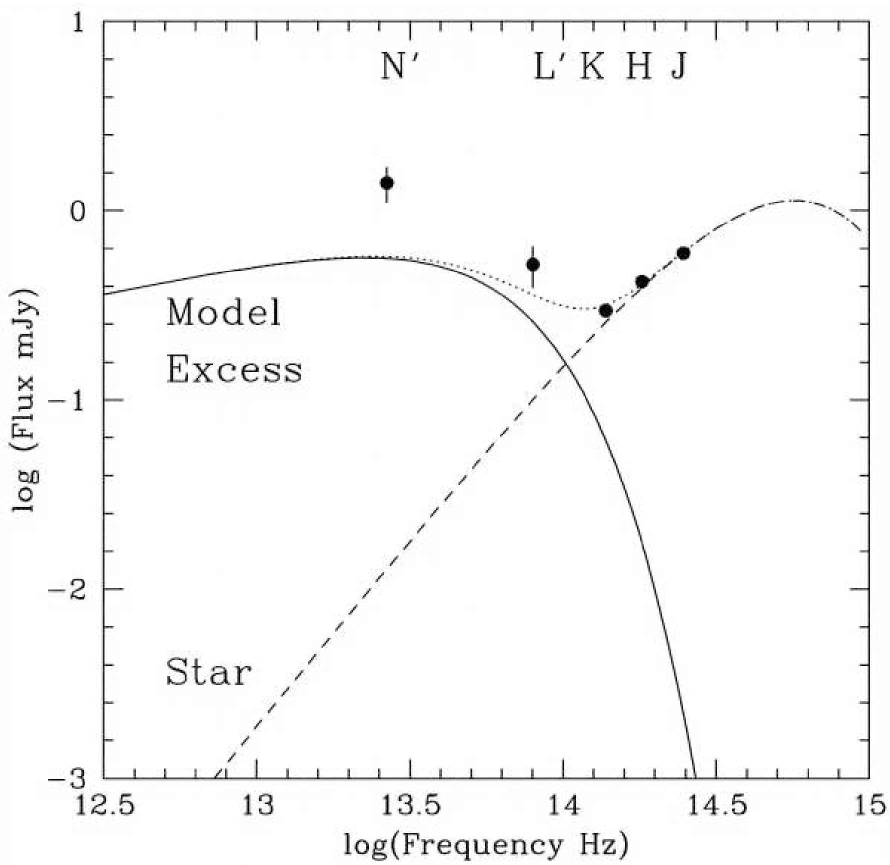

FIGURE 3. Spectral energy distribution of the white dwarf GD 362, showing the excess due to circumstellar dust (Becklin et al. 2005). The *Spitzer* spectrum of this feature shows strong silicate emission (Jura et al. 2007).

asteroids (Alcock et al. 1986; Jura 2006). This phenomenon can give new and quite different insights into planetary systems. These white dwarfs must have an asteroid system not dissimilar to that of the Solar System - well outside the radius of an AGB star and well within the orbits of the giant planets. This suggestion, that these DAZ stars might be temporary phenomena, in that they are accreting comets from a left-over planetary system, has very likely been confirmed by the discovery of dust disks around a small number of cool white dwarfs (Zuckerman and Becklin 1987; Becklin et al. 2005; Jura et al. 2007; Mullally et al. 2007; von Hippel et al. 2007). At the same time, Gänsicke et al. (2006) have found several hotter white dwarfs showing double-peaked emission lines of Ca, showing the presence of metal rich gas disks around these stars. These exciting discoveries provide new information on planetary systems, the type of stars they form around, and how they survive the rigors of stellar evolution. The currently known number of white dwarfs with circumstellar disks is small, but judicious observing campaigns will likely discover many more – about 25% of DA white dwarfs have CaII absorption (Zuckerman et al. 2003), and about 14% of DAZ white dwarfs have detectable circumstellar disks (Kilic and Redfield 2007).

A large 3.5μm and 4.5 μm search for dusty disks around nearby white dwarfs is clearly called for, focussing for this purpose on DAZ and DZ white dwarfs. The spectroscopic data set for white dwarfs has improved enormously in recent years, with some 10,000 good spectra extant, the discovery of hundreds of WDs with metal lines, the characterization of some 150 DZ white dwarfs (Dufour et al. 2006, 2007), and the development of white dwarf models to the point of deriving reliable masses and surface temperatures. The two short IRAC bands are especially well suited to this work. Unlike the situation for debris disks around main-sequence stars, where the bulk of the dust is far enough from the stars to be too cool for detection at these relatively short wavelengths (see Marengo et al. 2006b for a discussion of sensitivity limits), the dust disks around white dwarfs are close enough to the star to have temperatures close to 1000 K and therefore emit strongly in the near-infrared (suggesting that the dust is produced by the tidal destruction of asteroids or comets, Jura et al. 2007; Zuckerman et al. 2007).

White Dwarf Atmospheres

The *Spitzer* observations which have led to the above discoveries have also shown that the observed WD colors at IRAC wavelengths often do not agree well with the predictions of model atmospheres, with, in particular, flux deficits observed for cool ($<$ 7000 K) white dwarfs (Kilic et al. 2006; Mullally et al. 2007). It is well known that ultracool ($<$ 4000 K) white dwarfs (Gates et al. 2004; Harris et al. 2007) have flux deficits in the optical red and near infrared bands due to collisionally-induced H_2 absorption, and presumably similar molecular processes are producing the longer-wavelength deficits in somewhat warmer stars. Understanding this is important not only for searches for flux enhancements due to cool companions or dusty disks, but for the modeling of white dwarf cooling, age-dating of white dwarfs, and the chronology of star formation in the local Galactic disk and halo (Harris et al. 2006).

A Strawman Observing Project on White Dwarfs

All of the above discoveries (ultracool companions, dust disks and flux deficits) are based on observations of fewer than 200 white dwarfs, including the *Spitzer* survey of 124 white dwarfs at 4.6μm and 8 μm of Mullally et al. (2007). For a sample of white dwarfs and cataclysmic variables within 30 pc, the required sensitivity to detect a 500 K companion is about 1.8 μJy, which can be achieved in both bands for 200 objects in 400 hours, and will also find very low mass disks. A further 50 hours of observing will reach 4μJy for 500 stars. All observations should be repeats, to verify the reality of the detections. The white dwarfs can be selected from the spectroscopic surveys which include ultracool white dwarfs (Gates et al. 2004; Harris et al. 2007), about 150 DZ WDs (Dufour et al. 2007), about 200 DQ WDs (Halford et al. 2005), as well as large samples of magnetic WDs, normal DA and DB WDs, and cataclysmic variables. Using 2MASS and the SDSS z band data, where available, white dwarfs with M dwarf companions can be rejected.

During the discussions at this meeting, it was apparent that there is a lot of interest in this search for infrared excess emission due to circumstellar dust disks around white dwarfs (see e.g. the paper by M. Jura, this volume). The exact moment at which the cryogen will run out is not known, and there needs to be an observational program ready to go when that event happens and the system verification checks have been carried out. A program to begin imaging white dwarfs is ideal – there are large numbers of them all over the sky and therefore targets available at any time, the observing priority and strategy are reasonably easy to work out for each star, the observations are simple, and the science is exciting and of interest to many areas of current astronomical research. We encourage the development of this survey to provide the plan for the initial *Warm Spitzer* observations.

AGB STARS

Spitzer's sensitivity is sufficient to detect AGB stars throughout the Galaxy and the Local Group in all the IRAC bands. In particular, the sensitivity is enough to detect the color excesses (with respect to flux densities at shorter wavelengths from 2MASS, for example) due to mass loss rates as low as a few $\times 10^{-8}$ $M_\odot$ yr^{-1}.

Spitzer Galactic plane surveys (GLIMPSE, Benjamin et al. 2005) and surveys of the Magellanic Clouds (Meixner et al. 2006, Groenewegen et al. 2007) will discover very large numbers of AGB stars. In addition, we believe it to be worth while to carry out searches for mass-losing AGB stars in loose halo structures such as the Sagittarius stream and in the distant halo.

Any star which leaves the red clump/horizontal branch with more than about 0.6 $M_\odot$ can become an AGB star, but as the mass decreases the amount of time spent on the AGB, and the amount of fuel burned there, decreases, so that AGB stars are extremely rare in old populations, in Galactic globular clusters for example. Nevertheless, there are some hundred distant carbon AGB stars found at high Galactic latitudes, some with significant infrared excesses indicating mass loss (Liebert et al. 2000; Ibata et al. 2001; Mauron et al. 2007; Downes et al. 2007).

The halo AGB stars can be found in two ways, via their large infrared excesses, and via variability (typical periods are 1-3 years), in wide-angle surveys. In addition, the chemistry, i.e. whether the star has "normal" abundances with more oxygen than carbon, or is a carbon star, with carbon more abundant than oxygen, can be determined from the infrared colors. Figures 4-6 show a series of color-color diagrams combining JHK and IRAC photometry. The JHK photometry is from 2MASS, and the IRAC colors are derived by convolving ISO SWS spectra with the IRAC filters for a sample of AGB stars and supergiants (Marengo et al. 2007). Some scatter will be present because of variability (cf. Smith et al. 2006), since these observations were taken at different times. Also shown in Figures 4-6 are data from the *Spitzer First Look Survey*, containing both Galactic stars and extragalactic objects.

AGB stars of all types are redder than main sequence stars in the near-IR colors in all diagrams, especially in J-K, even for AGB stars with little circumstellar dust ([3.6] - [4.5] $<$ 0.5). AGB stars with thick circumstellar envelopes are easily separated from galaxies by color. In addition, the oxygen and carbon-rich stars partly separate, in that

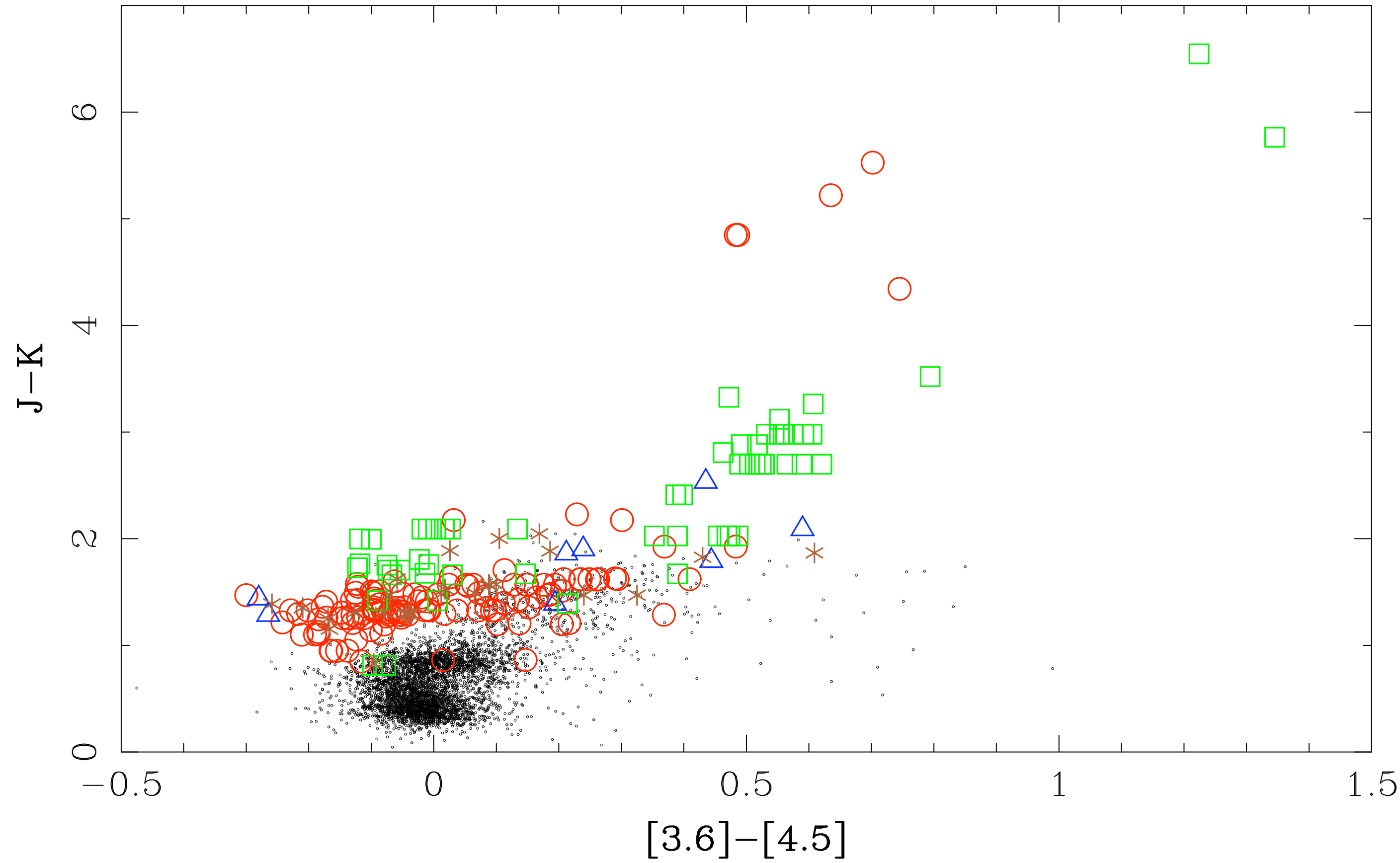

FIGURE 4. J-K versus [3.6] - [4.5] color for a sample of AGB stars. Oxygen rich stars are red circles, Carbon stars are green squares, S stars are blue triangles and supergiants are shown by brown asterisks. The data are from 2MASS and synthesized for the IRAC bands from ISO SWS spectra. The black dots show sources from the IRAC First Look Survey.

dust-poor carbon stars have slightly redder near-infrared colors than do oxygen stars, while for stars with larger infrared excesses the oxygen-rich stars have redder near-IR colors than do the carbon stars.

Any wide-angle survey at high latitudes, such as the shallow survey over 400 square degrees, will detect 100-200 distant halo AGB stars, and more will be found in the fields around targeted sources. These objects are invaluable for probing the structure and formation history of the very distant Milky Way.

THE COLORS OF NORMAL STARS

The GALEX, SDSS and 2MASS surveys provide precision photometry of millions of stars. The 2MASS limit of 14^m at K_s together with an assumed Rayleigh-Jeans spectral index gives a desired 5σ depth of 0.61 mJy at 3.6μm and 0.39 Jy at 4.5 μm. This is achievable with the “shallow” survey in Table 1 of Stauffer et al. (2007). The expected stellar density to this limit is about 5000 per square degree at high Galactic latitudes,

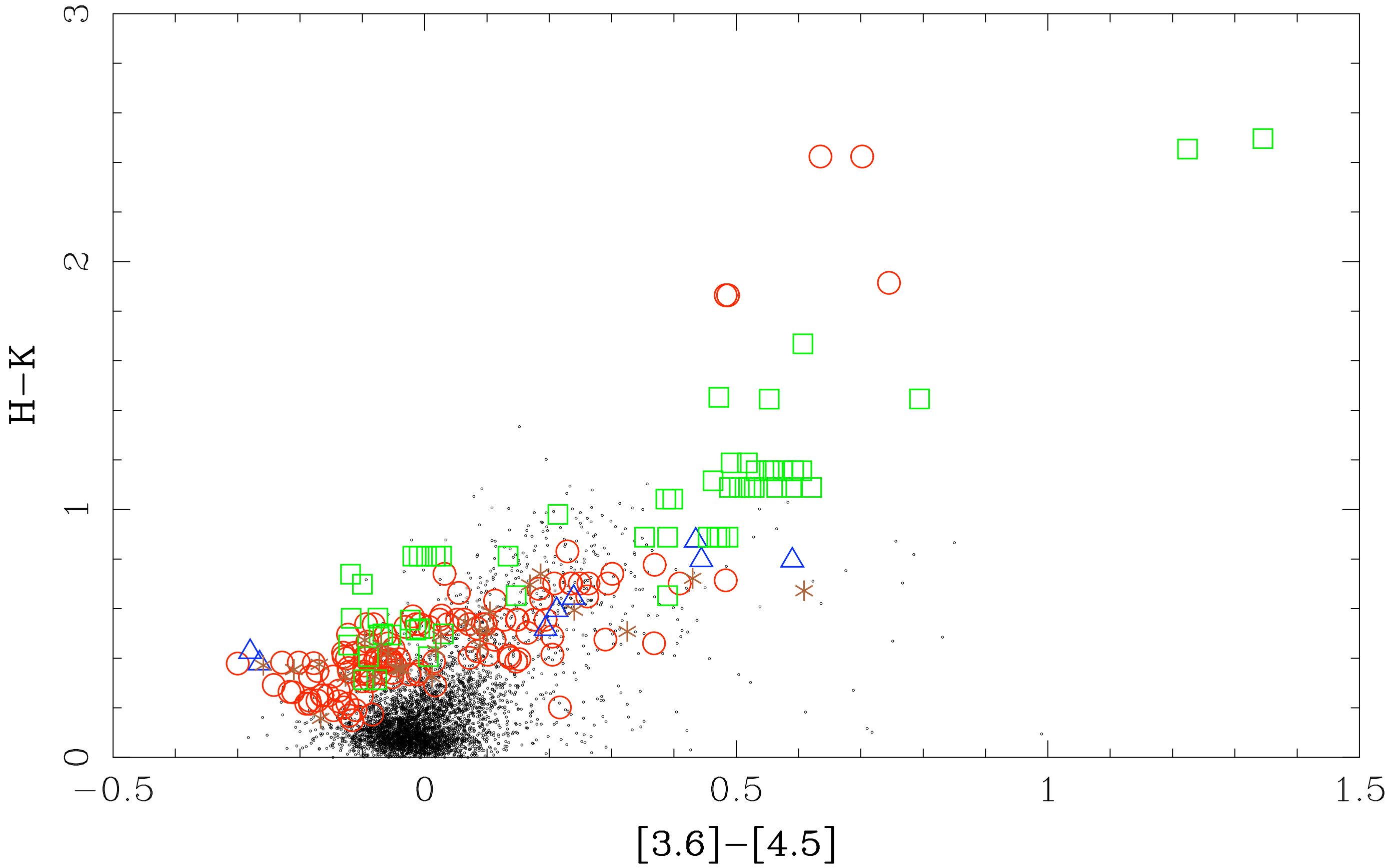

FIGURE 5. H-K versus [3.6] - [4.5] color for a sample of AGB stars. Oxygen rich stars are red circles, Carbon stars are green squares, S stars are blue triangles and supergiants are shown by brown asterisks. The data are from 2MASS and synthesized for the IRAC bands from ISO SWS spectra. The black dots show sources from the IRAC First Look Survey.

so that data added by *Spitzer* during its warm mission will produce precision 12-band photometry between 0.14 and 4.5μm for 50,000 - 100,000 stars as a byproduct, and these can reliably be separated from galaxies and quasars by color and image size at optical wavelengths.

While data from each of these four surveys are expected to be extremely well calibrated internally, some of the challenge in exploiting the data will be on consistency between surveys. Here, the stellar data play a vital rôle and will likely provide fundamental broad-band calibration across this wavelength range for all other classes of object as well. A huge effort is underway at present to make multiband stellar photometry internally consistent using synthetic magnitudes calculated from stellar spectral libraries, both observed and synthesized (e.g. Cohen et al. 2003; Coelho et al. 2005; Martins and Coelho 2007; Worthey and Lee 2007; Davenport et al. 2007; Lee et al. 2007, and many others), and this work is driven by the need to understand both stellar populations and galaxy colors. These efforts use compilations of data from the literature, and demonstrate that different stellar colors have sensitivities to stellar effective temperature, metallicity, gravity, chemical peculiarity and even α element enhancement. For exam-

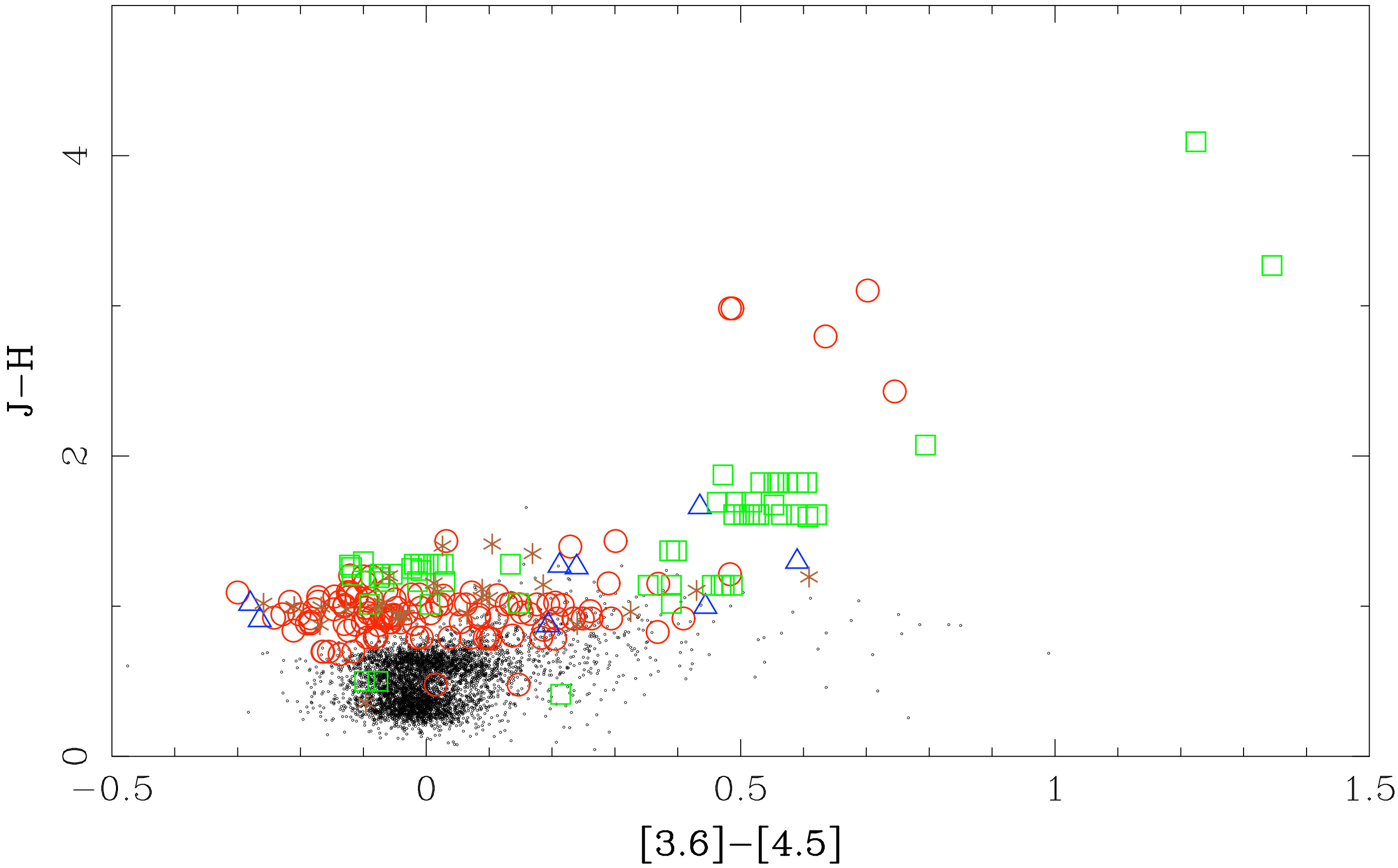

FIGURE 6. J-H versus [3.6] - [4.5] color for a sample of AGB stars. Oxygen rich stars are red circles, Carbon stars are green squares, S stars are blue triangles and supergiants are shown by brown asterisks. The data are from 2MASS and synthesized for the IRAC bands from ISO SWS spectra. The black dots show sources from the IRAC First Look Survey.

ple, V-I is weakly sensitive to α element abundance, V-K is an excellent indicator of effective temperature, J-K is degenerate with temperature for M dwarfs but depends on metallicity while H-K does not, and so on. These findings are based on small samples of bright stars for which high-dispersion spectroscopy yields accurate element abundances but whose photometry is heterogeneous. Major efforts are now underway to use moderate resolution spectroscopy to derive stellar parameters for these very large numbers of stars with well calibrated photometry (e.g. Re Fiorentin et al. 2007).

What will *Spitzer* add to this effort? It extends the longest wavelength by almost a factor of two, into a spectral region sensitive to spectral lines of common molecules, especially those containing carbon. At present only very crude metallicity values are available for the cooler stars (spectral types K, M and later). These stars are so cool that their flux densities are negligible at UV and blue wavelengths, and the *Spitzer* observations will thus provide wavelength coverage equal to that available for bluer stars. This effort can extend reliable measures of basic stellar parameters to much cooler stars than are accessible by optical photometry alone, including the most numerous stars, the M dwarfs. The likely science outcomes include: more reliable effective temperatures for cool stars, photometric identification of chemically peculiar cool stars (giant and especially dwarf carbon stars, cool subdwarfs, extremely low metallicity stars etc.) and the characterization of the broad-band colors of normal stars of all spectral types which will greatly aid in the identification of excess emission at wavelengths from 2- 5 μm due to cool companions and circumstellar dust.

SUMMARY

The advances in stellar astronomy that can be achieved by the Warm Spitzer Mission include:

(a) The discovery of 50-100 very cool T dwarfs ($<$ 1000 K) and possibly up to 5 Y dwarfs from large, wide angle surveys. The location in the sky is to first order irrelevant, since these objects are nearby enough to be isotropic, so this project can piggy back on any general purpose survey that is sensitive enough.

(b) The discovery of tens of resolved companions to nearby stars, which will provide important ancillary information: distance, metallicity and age, as well as information on the relative frequencies of planetary and substellar companions, the dependence of the presence of companions on stellar age and metallicity, and, perhaps, indirect information on the formation of brown dwarfs and planets.

(c) Three important areas can be investigated with the same pointed survey of white dwarfs: the detection of unresolved L, T and Y companions via their infrared excesses, and the determination of the luminosity function and lowest luminosity star at the bottom of the main sequence: the detection of dust disks possibly produced by remaining planetary system members: and the characterization of the broad-band SEDs to 4.5μm, useful for white dwarf models atmospheres and for white dwarf cosmochronology.

(d) The combination of *Spitzer* and near-infrared colors will identify several tens of distant, high-latitude AGB stares in the Galactic halo and allow their mass loss rates and, with some uncertainty, chemical composition, to be determined.

(e) Accurate broad-band photometry of tens of thousands of normal stars of all spectral types between 0.15μm and 4.5μm and the relation of these colors to metallicity, effective temperature, gravity and other chemical properties (carbon excess, α-element variation, etc.) These spectra will form a calibration set for use in all multi-wavelength astronomy surveys.

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