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An Unbiased Survey of 500 Nearby Stars for Debris Disks: A JCMT Legacy Program

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ABSTRACT. We present the scientific motivation and observing plan for an upcoming detection survey for debris disks using the James Clerk Maxwell Telescope. The SCUBA-2 Unbiased Nearby Stars (SUNS) survey will observe 500 nearby main-sequence and subgiant stars (100 of each of the A, F, G, K, and M spectral classes) to the 850 μm extragalactic confusion limit to search for evidence of submillimeter excess, an indication of circumstellar material. The survey distance boundaries are 8.6, 16.5, 22, 25, and 45 pc for M, K, G, F, and A stars, respectively, and all targets lie between the declinations of $-40°$ to $80°$. In this survey, no star will be rejected based on its inherent properties: binarity, presence of planetary companions, spectral type, or age. The survey will commence in late 2007 and will be executed over 390 hr, reaching 90% completion within 2 years. This will be the first unbiased survey for debris disks since the *Infrared Astronomical Satellite*. We expect to detect ∼125 debris disks, including ∼50 cold disks not detectable in current shorter wavelength surveys. To fully exploit the order of magnitude increase in debris disks detected in the submillimeter, a substantial amount of complementary data will be required, especially at shorter wavelengths, to constrain the temperatures and masses of discovered disks. High-resolution studies will likely be required to resolve many of the disks. Therefore, these systems will be the focus of future observational studies using a variety of observatories, including *Herschel*, ALMA, and *JWST*, to characterize their physical properties. For nondetected systems, this survey will set constraints (upper limits) on the amount of circumstellar dust, of typically 200 times the Kuiper Belt mass, but as low as 10 times the Kuiper Belt mass for the nearest stars in the sample (≈2 pc).

1. INTRODUCTION

Debris disks are the dust disks found around many nearby main-sequence stars. The dust is short-lived and so must be continuously replenished by the destruction of comets and asteroids in these systems, deduced to lie in fairly narrow belts between 10 and 200 AU from the host stars. The *Infrared Astronomical Satellite* (*IRAS*) was the first and only large unbiased survey of debris disks, showing that they occur around ∼15% of nearby stars (Backman & Paresce 1993; Plets & Vynckier 1999; Aumann et al. 1984). There is evidence of a substantial population of disks too cold to have been detected by *IRAS* and only accessible to submillimeter observations (Lestrade et al. 2006; Wyatt et al. 2003) surrounding 5%–15% of stars. This is substantiated by the results of Rhee et al. (2007),

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who note that ~10% of stars show 70 μm dust emission in *Spitzer* MIPS (Multiband Imaging Spectrometer) maps, but below *IRAS* sensitivity (either due to low mass or cold dust), suggesting the overall frequency of disks may be as high as 25%. Based on an assumed disk incidence of 25%, our survey of 500 stars could yield as many as 125 disk detections, of which ≈50 could be cold disks. The survey is of sufficient size to measure the disk frequency across spectral type, and as a function of age and multiplicity.

Submillimeter observations have already been pivotal in studies of debris disks, having imaged or discovered 7 of the 14 resolved disks and constrained the mass and temperature, and hence radial extent, of many of the remainder. The submillimeter emission is both optically thin and sensitive to relatively large, cold grains, which dominate the masses of these disks. Hence, our survey will provide immediate mass estimates for detected disks. Constraining the temperature of newly identified disks will require complementary data in the mid- or far-IR. This will be particularly critical for warm disks, since the two potential submillimeter wavelengths observable through our survey (850 and 450 μm) will both lie longward of the peak of the spectral energy distribution (SED) and provide little constraint on the temperature.

The study of these disks is revolutionizing our understanding of planet formation. For the 14 disks that have been resolved, observed structures have even been used to infer the location of unseen planets (e.g., Wyatt 2003). Many more disks have been characterized by their SEDs, showing that they are the extrasolar equivalents of the Kuiper and asteroid belts of the solar system. The radial positions and masses of these belts, particularly when this information can be compared for stars of different ages, spectral types, multiplicity, or known planetary companions, provide vital constraints on planet formation processes and on how the resulting planetary systems subsequently evolve.

SCUBA-2 (Holland et al. 2006) is a new submillimeter camera arriving at the James Clerk Maxwell Telescope (JCMT) in late 2007. SCUBA-2 is expected to be, per pixel, 5 times as sensitive as its predecessor, SCUBA (Submillimeter Common-User Bolometric Array; Holland et al. 1999) at 850 μm. Its larger ($7' \times 7'$), fully sampled field of view makes it a premiere survey instrument, and seven comprehensive surveys have been planned to maximize the scientific output from the JCMT over the next 5 years (e.g., Gould Belt Legacy Survey, Ward-Thompson et al. 2007; Spectral Legacy Survey, Plume et al. 2007). Like its predecessor, it observes simultaneously at 850 and 450 μm, with resolutions of $15''$ and $7''$, respectively. Unlike its predecessor, SCUBA-2 will Nyquist sample the sky at 850 μm; at 450 μm, the array is undersampled by a factor of 2. The focal plane area coverage is provided by four "subarrays" at each wavelength, where each subarray is composed of 32×40 detectors (see Holland et al. 2006).

The SCUBA-2 Unbiased Nearby Stars (SUNS) survey will use 390 hr to observe 500 nearby stars (the 100 nearest M, K, G, F, and A stars) to the JCMT's extragalactic confusion limit at 850 μm to detect and map circumstellar dust. The survey is completely unbiased; no star will be rejected due to its intrinsic properties. The survey will determine the incidence of disks around nearby stars, constrain masses (and temperatures of disks detected in the far-IR), discover disks too cold to be detected in the far-IR, and provide limits on the presence of dust that are vital to targeted planet search missions, such as *Darwin* and the *Terrestrial Planet Finder* (*TPF*), as well as future instruments that will resolve disks in unprecedented detail (e.g., the Atacama Large Millimeter-submillimeter Array [ALMA], the *James Webb Space Telescope*, and the *Far-IR Interferometer* [*FIRI*; Ivison & Blain 2005]).

The mass sensitivity of the survey is a strong function of both distance and disk temperature. For disks of 70 K, the sensitivity ranges from 0.003 to 1.4 $M_{\rm lunar}$ ($M_{\rm lunar} = 1/81\ M_\oplus$) for the nearest (2 pc) and farthest (45 pc) stars. For lower disk temperatures of 40 K, the range is 0.005–2.7 $M_{\rm lunar}$. At the mean distance of the survey stars (15 pc), we will be sensitive to dust masses typically ~200 times the dust mass of the Kuiper Belt (≈$10^{-5}\ M_\oplus$), which is the mass of the disk around ϵ Eridani. Thus, while it will not be sensitive to present-day solar system analogs, it will detect such systems that are in a period of unusually high dust mass. We know that the Kuiper Belt is a factor of ≈100 times less massive than expected from the distribution of solids in the solar system (Morbidelli 2004). Thus, the Kuiper Belt used to be more massive. Equally, an episodic mode of dust creation could render the Kuiper Belt detectable in the future. The mass limit for undetected systems will also be useful for future planet search missions. Missions such as *Darwin* and *TPF* require a dust-free system, typically below 10 times that of the solar system, to limit the integration time required to detect Earth-like planets (Beichman et al. 2004).

The SUNS survey will provide a significant legacy for the field of extrasolar planetary system research. This field is rapidly evolving, and a variety of techniques are being developed to characterize the planetary systems of nearby stars. This survey will determine the dust and planetesimal content of these systems and so provide vital complementary information on the outcome of planet formation in them; for some techniques, the dust content even provides the limiting factor determining whether such techniques are going to work (e.g., *TPF*; Beichman et al. 2006b).

In this paper, we provide details about the SUNS survey, including the motivation for the survey in the context of our current understanding of debris disk systems (§ 2), advantages of the submillimeter compared to shorter wavelengths (§ 2.2), and the mass sensitivity of our survey (§ 2.3). Our science goals are described in § 3, and we describe the details of our target list in § 4, including ancillary targets, subset populations, and statistics. Plans for complementary data to the SUNS survey are described in § 5. We describe the data products in § 6 and summarize the survey in § 7.

TABLE 1
SUBMILLIMETER DEBRIS DISK SURVEYS

Reference	Targets	N_{star}	N_{disks}	%	850 μm, 1 σ rms (mJy)
Wyatt et al. 2003	Lindroos binaries	22	3	13	1.2
Holmes et al. 2003	Nearby bright stars	11	1	9	7
Liu et al. 2004	β Pic comoving groups	8	2	25	2
Carpenter et al. 2005	FEPS nearby stars	127	4	3	28
Greaves et al. 2005	Nearby G stars	13	2	15	1.5
Lestrade et al. 2006	M dwarfs	32	2	6	0.7

NOTES.—Flux limits at 850 μm were adjusted from other wavelengths through scaling of the fiducial 850 μm opacity of 1.7 cm^2 g^{-1} and the scaling relations $\kappa \propto (1/\lambda)$ and $F_\nu \propto \nu^{(2+\beta)}$, where $\beta = 0.7$.

2. MOTIVATION FOR THE SURVEY

2.1. Current Status of Debris Disk Studies

All of the approximately 200 known candidate debris disks were first discovered by their thermal emission, which is brighter than the photospheric emission of their host stars at far-IR and longer wavelengths (e.g., Mannings & Barlow 1998). The majority of these disks and disk candidates were discovered by *IRAS*, which provided the first and only large unbiased survey of nearby stars for excess thermal emission at 12–100 μm (with resolutions of 0.5′ to 2′). This survey showed that ~15% of nearby stars exhibit detectable excess emission (Backman & Paresce 1993), and the *IRAS* disk candidates have been the subject of intense follow-up observations from the ground at a range of wavelengths from optical to millimeter. Reanalyses of the *IRAS* and *Infrared Space Observatory* (*ISO*) databases have resulted in additions, and notably revisions, to the stars with identified infrared excess; for instance, Rhee et al. (2007) found 153 *IRAS* excess stars among *Hipparcos* dwarfs, 37 of which are newly identified. Forty-eight of their excess stars are among the 60 disk candidates identified by Moór et al. (2006) through a reanalysis of *IRAS* and *ISO* targets, 11 of which were previously unknown. Based on these analyses, Rhee et al. revised the fraction of nearby A stars with detected 60 μm excess to 20%.

Submillimeter observations have been pivotal in follow-up studies of these disks: imaging with SCUBA had mapped or discovered 7 of the 10 resolved disks at the time of its decommissioning in mid-2005 (e.g., Holland et al. 1998). Such images have also ruled out “disk candidate” stars that turned out to have nearby, unassociated background sources that fell within the relatively large *IRAS* beam sizes (e.g., Jayawardhana et al. 2002). Finally, photometric submillimeter observations of many disks have provided the best constraints on disk masses, as well as constraints on the SED and therefore the temperature and radial extent of the disks (e.g., Sheret et al. 2004).

Subsequent surveys have been more modest than *IRAS* in the number of stars surveyed, but have probed more deeply in sensitivity. For example, both the *ISO* and *Spitzer* strategies targeted several well-defined samples, each of which comprised at most 100 stars. The emerging picture is that the fraction of stars with detectable disks is a function of both stellar age (Rhee et al. 2007; Spangler et al. 2001), spectral type (Habing et al. 2001), and wavelength (Laureijs et al. 2002). Werner et al. (2006) summarized the early results from *Spitzer* surveys and targeted observations, including two Legacy surveys, The Formation and Evolution of Planetary Systems (FEPS; Meyer et al. 2004; Kim et al. 2005; Stauffer et al. 2005; Hines et al. 2006) and Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Uzpen et al. 2005). Surveys have also targeted stellar associations, such as the nearby ≈10 Myr old TW Hydrae association (Uchida et al. 2004; Low et al. 2005), Cep OB2 clusters (Sicilia-Aguilar et al. 2006), Orion OB1a and OB1b (Hernández et al. 2006), and the open clusters M47 (Gorlova et al. 2004) and the Pleiades (Gorlova et al. 2006; Stauffer et al. 2005). Projects to target nearby stars have concentrated on A stars (Rieke et al. 2005) and field FGK stars (Bryden et al. 2006; Beichman et al. 2006a), including selection by known planets (Beichman et al. 2005), metallicity (Beichman et al. 2006b), *IRAS* 60 μm excess (Chen et al. 2006), and age (Smith et al. 2006). Beichman et al. (2006b) concluded that there is no increased incidence of disks around stars of increased metallicity, in agreement with earlier results based on disks detected by *IRAS* (Greaves et al. 2006).

Evidence of a disk has been detected around the white dwarf at the center of the Helix Nebula (Su et al. 2007). *Spitzer* has also produced serendipitous detections of disks around individual stars, including HD 46190 (Sloan et al. 2004) and Be stars in the LMC (Kastner et al. 2006). Targeted observations toward the well-studied debris disks around Fomalhaut (Stauffer et al. 2005) and Vega (Su et al. 2005) have also been undertaken.

In general, few extensive ground-based searches have been made for excess emission. Recently, however, submillimeter surveys unbiased by previous far-IR detections have shown that there is a substantial population of disks that are only accessible in the submillimeter, since they are too cold to have been detected by *IRAS* (Lestrade et al. 2006; Wyatt et al. 2003). As Table 1 shows, while individual submillimeter surveys are typically small (10–20 stars), the detection rate in each is 5%–25%, indicating that this population is both real and as nu-

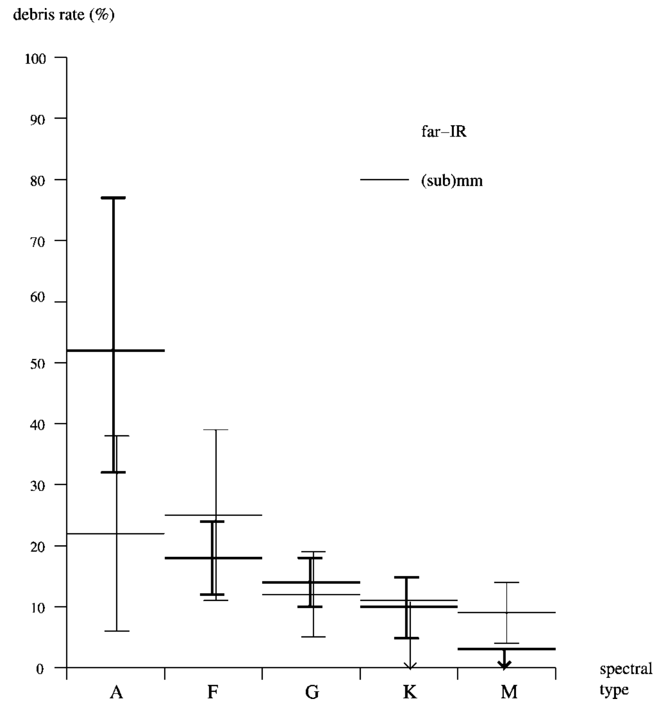

FIG. 1.—Frequency of debris disks as a function of spectral type based on existing data. The error bars are presently large for several spectral types. It is also evident that the submillimeter is the best wavelength range for searching for disks around later type stars. This is consistent with the detection of cold disks. The references for the data are N. Phillips et al. (2007, in preparation), Gautier et al. (2007), Su et al. (2006), Beichman et al. (2005, 2006a), Bryden et al. (2006), Lestrade et al. (2006), Najita & Williams (2005), Liu et al. (2004), Wyatt et al. (2003), and Holmes et al. (2003).

merous as the disks that were detected by *IRAS*. Statistics are currently too poor to ascertain whether the presence of such cold disks is favored around young, old, early- or late-type stars. Lestrade et al. (2006) derived a detection rate of 13^{+6}_{-8}% for M dwarfs between 20 and 200 Myr, based on the combined results of their survey and that of Liu et al. (2004).

The current debris disk detection rates are shown in Figure 1, which compares the detection rates in the far-IR to those in the submillimeter. The uncertainties in the disk frequencies are still large for several spectral types. Already, it is evident that the submillimeter is the favorable regime for detection of disks around low-mass stars.

2.2. Advantages of the Submillimeter to the Far-IR

To understand the origin and frequency of debris disks, we require an unbiased survey. In the past, large surveys for disks have been conducted at near-IR wavelengths (e.g., Mamajek et al. 2002; Haisch et al. 2001); however, these only sample warm dust in the inner ≈1 AU. In the far-IR, major surveys with *IRAS*, *ISO*, and *Spitzer* (e.g., Spangler et al. 2001; Decin et al. 2003; Werner et al. 2006, and references therein) sample the dust at ≈ 50–100 K (typically 40–100 AU radius), so these

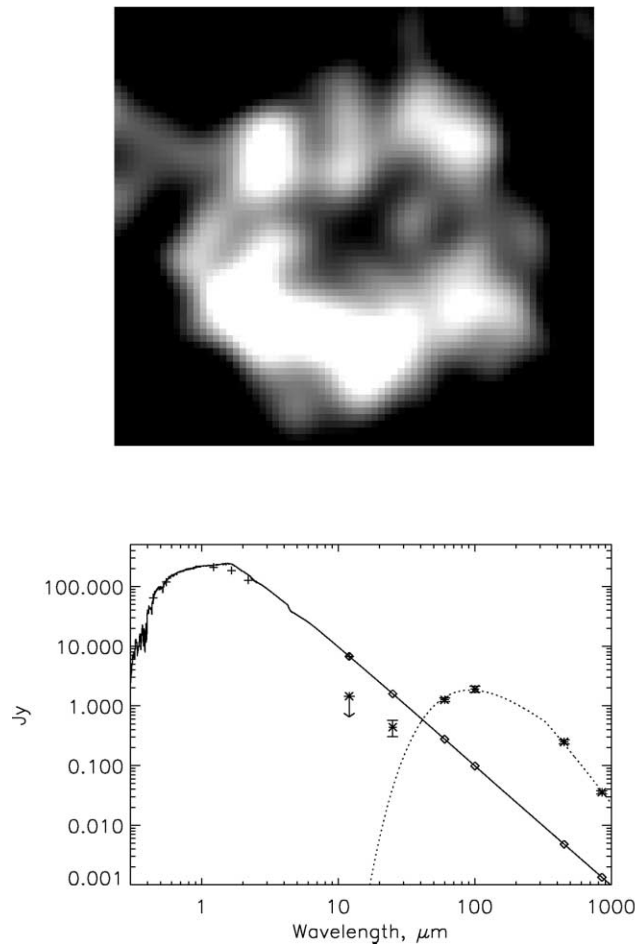

FIG. 2.—An 850 μm image of ϵ Eridani (Greaves et al. 2005) and the SEDs of the star (*solid line*) and gray-body fit to the dust (*dotted line*). Note the much greater disk-to-star contrast in the submillimeter compared to 60 μm, even for this midrange temperature of 55 K.

are also biased toward warm dust disks. Yet we know cool debris disks do exist; Figure 2 shows the SED of the bright nearby disk around ϵ Eridani, and Figure 3 shows the fitted temperatures of known debris disks versus stellar luminosity for stars of differing spectral classes. Disks around lower mass stars tend to be significantly cooler than their counterparts around A stars, with virtually all such disks exhibiting temperatures of <70 K. This is consistent with the findings of Wyatt et al. (2003) and Rhee et al. (2007) of a disk population below the sensitivities of *IRAS* observations.

To sample the cool dust, we must go to submillimeter wavelengths. However, the number of unbiased surveys conducted in the submillimeter is very limited (see Table 1). In most cases, once the submillimeter detections were made, only a few subsequent detailed analyses of far-IR data showed detections (Zuckerman 2001), indicating that the dust is indeed cool. A further point illustrated in Table 1 is that the percentage detection rate increases sharply with sensitivity, from 3% in the

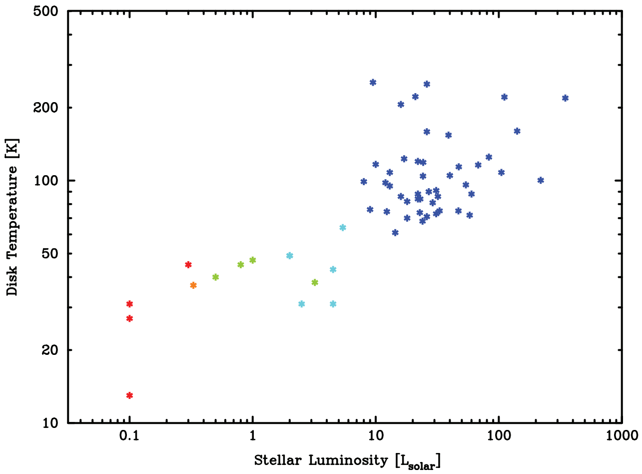

FIG. 3.—Observed temperatures of debris disks vs. stellar luminosities. The A stars (*dark blue*) are a sample of 46 detected at both 24 and 70 μm (Wyatt et al. 2007). The data for the F (*light blue*), G (*green*), K (*orange*), and M stars (*red*) are taken from (Lestrade et al. 2006 and references therein), with the addition of TWA 7 from Matthews et al. (2007).

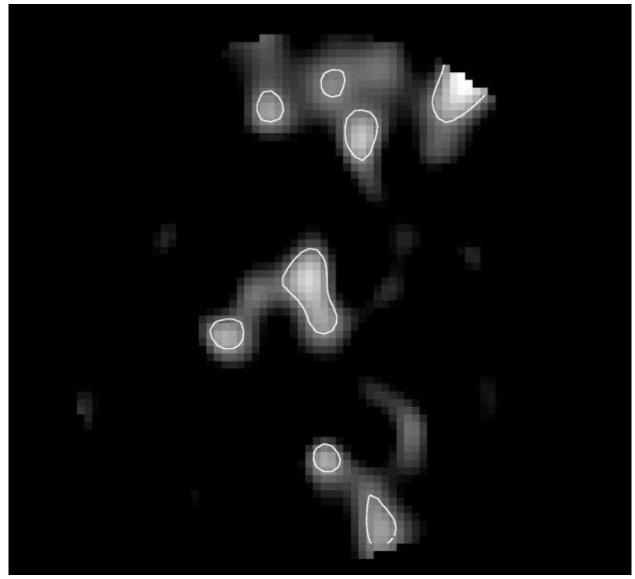

FIG. 4.—Example of disk extraction (Greaves et al. 2004b): disk detection toward τ Ceti with SCUBA at 850 μm. The rms in this map is 0.7 mJy (per smoothed 20″ beam). The faintest detected peaks are 2 mJy beam^{-1}. The disk is recognized by its elliptical shape centered about the star. This star is nearby, but the disk is in fact one of the smallest yet measured. In addition, this field is unusually rich in background sources.

least sensitive survey up to 10%–15% in deep searches (and higher in the β Pic group, perhaps because these stars are young). Extrapolating to still deeper surveys, we might expect a substantially higher detection rate of about 15%. In summary, there is growing evidence of a significant population of submillimeter-bright disks with $T \leq 40$ K. The final column in Table 1 shows depths reached thus far (where equivalent flux limits of other wavelengths have been corrected to 850 μm). The SUNS survey, with an rms sensitivity of 1 $\sigma = 0.7$ mJy, will be *40 times deeper* in flux than the only previous large-scale survey (Carpenter et al. 2005). This depth is equivalent to the observation of the disk around the 1 Gyr old star τ Ceti (Fig. 4).

Below, we discuss the effective limits on the submillimeter survey compared to the current generation of far-IR detectors on *Spitzer*.

2.2.1. *Photospheric Contributions*

For the nearby stars where photospheric emission dominates (Fig. 2), the dust detection limit of far-IR instruments is set by the accuracy with which a disk excess can be discriminated from photospheric contributions. The limits on the detectability of a disk are then dependent as well on the accuracy of synthetic stellar spectra, which are not well constrained by observations at these wavelengths. In this case, it is not possible to improve the detection limits, and in the case of *Spitzer*, detections are limited to >50% of the photospheric flux (Beichman et al. 2005). As the ϵ Eri SED shows, the excess flux over the photosphere is larger by a factor of 4 at 850 μm compared with 70 μm, and this contrast becomes much greater for cooler dust. Note that for the very bright A0 star Vega at only 8 pc, the photosphere is only 5 mJy. Therefore, assuming SCUBA-2 calibration to 10%, the largest photospheric error in the survey at 850 μm will be ± 0.5 mJy, so the calibration error will *always* be less than the confusion limit fluctuations of 0.7 mJy rms.

2.2.2. *Background Confusion Limit*

Background confusion is the absolute flux limit for any disk survey. For *Spitzer*, the confusion limit is 0.7 mJy beam^{-1} at 70 μm (the best wavelength for debris detection), but the photometric technique actually limits this to ≈2 mJy (Beichman et al. 2005), and often only 5 mJy is reached because of Galactic foregrounds. For 5 mJy at 70 μm and grain emissivity of $\beta = 0.7$, the SUNS survey is *intrinsically* more sensitive to dust cooler than 30 K. For far-IR limits of 2 mJy, single-temperature disks would be detectable down to 26 K, and for a range of β of 1.0 to 0.0, the limit lies between 26 and 43 K.

2.2.3. *Cirrus Confusion*

The 20″ beam of *Spitzer* at 70 μm and the bright and complex cirrus background are further limiting factors to the far-IR sensitivity. With SCUBA-2, we lose less than 20% of stars (i.e., those too far south), and importantly, with absolutely no additional bias due the cirrus background, which is not a factor in submillimeter observations.

2.2.4. *Extended Disks*

Submillimeter single-dish observations of debris disks are constrained by relatively poor resolution compared to optical observations. The beam size of the SUNS survey observations will be 15″, the JCMT's resolution at 850 μm. However, the potential does exist to follow up 850 μm detections with 450 μm observations with a substantially better resolution of 7″. Even out to a distance of approximately 30 pc, we might expect significant extended emission, based on the largest examples with ∼300 AU radii (i.e., 20″ across; Sheret et al. 2004), and so accurate photometry requires fully sampled maps to the same limiting sensitivity. Existing surveys are limited by the sparse pixel spacing of current instrumentation (e.g., Wyatt et al. 2003). SCUBA-2's Nyquist sampling will be a valuable new feature that is important if we are looking for relatively cool extended dust around nearby stars.

Our detections of new debris disks will provide some clear candidates for possible follow-up observations. Filling in the SED and thereby refining dust temperatures and spectral indices can be carried out in the short submillimeter and far-IR, and this prospect is imminent through the current *Akari* all-sky survey and in targeted observations with the *Herschel Space Observatory* using its photometric instruments SPIRE (the Spectral and Photometric Imaging Receiver; Griffin et al. 2006) and PACS (the Photodetector Array Camera and Spectrometer; Poglitsch et al. 2006).

2.3. Mass Sensitivity

While the SUNS survey data set will have a uniform flux sensitivity, the mass sensitivity of the survey is a function of three factors: the distance of the target, d, the temperature(s) of the material in the disks, T_d, and the opacity of the disks, κ_ν:

$$M_d = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_d)}. \quad (1)$$

At submillimeter wavelengths, in the Rayleigh-Jeans limit, the mass of the disk becomes a linear function of the temperature in the disk. This makes the mass relatively straightforward to estimate if the temperature can be constrained. The opacity in the disk is wavelength dependent ($\kappa_\nu \propto \lambda^{-1}$) and difficult to measure observationally, but the typical value adopted for debris disks at 850 μm is 1.7 cm^2 g^{-1}, based on a modified blackbody with $\beta = 1$ (Dent et al. 2000; Pollack et al. 1994).

Figure 5 shows the mass sensitivity of the SUNS survey as a function of temperature for circumstellar dust emission at several key distances in our survey. The mass of the closest known debris disk, ϵ Eridani, and the mass corresponding to 10 times that of the Kuiper Belt are also indicated. This mass sensitivity is for unresolved sources. For resolved sources, our mass sensitivity will be lower.

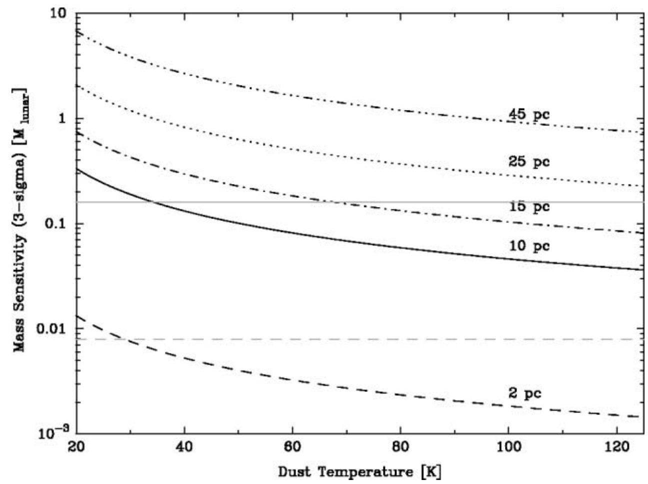

FIG. 5.—Disk mass sensitivity (3 σ) as a function of dust temperature for various limiting distances. The outer bound of the A stars sample is roughly 40 pc. The limits for F and G stars are ≈25 pc, and all the M stars lie within the 10 pc boundary. The horizontal lines show the mass of the ϵ Eridani disk (*solid line*) and 10 times the mass of the Kuiper Belt (*dashed line*). An opacity of 1.7 cm^2 g^{-1} is adopted.

For new disks, we will not immediately be able to constrain the disk temperature, unless measurements (even those resulting in nondetections) have been made in the mid- or far-IR (e.g., through *Spitzer*, *ISO*, or *IRAS*). For some cold disks (<50 K), additional 450 μm data will provide some temperature constraint, but for warmer disks, both submillimeter measurements will lie on the Rayleigh-Jeans tail of the SED, and shorter wavelength data will be essential.

3. SCIENCE GOALS

The outcome of this survey will be an order of magnitude improvement in the number of disks known in the submillimeter. These discoveries will provide a significant legacy for the planet formation community by achieving five key goals. The SUNS survey will

1. Determine unbiased statistics on the incidence of disks around nearby stars;
2. Constrain masses and temperatures of disks previously detected in the far-IR (e.g., by *IRAS*, *ISO*, *Spitzer*, *Akari*, and *Herschel*);
3. Discover numerous disks that are too cold to currently detect in the mid- and far-IR, for which complementary data at shorter wavelengths will be critical to constrain temperatures and hence masses;
4. Be the basis of source lists for future observing campaigns using instruments such as ALMA, *Herschel*, and *JWST*; and
5. Provide limits on the presence of dust around nearby stars, which are vital to future missions such as *TPF*.

Planet formation is thought to be largely complete by 10 Myr, so studying debris disks tells us where planetesimals remain after planet formation processes are complete. Such images may indicate locations where planets may be located within the systems. The majority of debris disks we detect will be the extrasolar counterparts to the Kuiper Belt. Thus, their temperatures, which will be determined through complementary far-IR data, tell us the sizes of the planetary systems that are clearing the inner regions of dust and planetesimals. Submillimeter fluxes also provide the most reliable method for measuring the mass of the disks (Zuckerman 2001).

We can thus address questions of what affects the extent of a planetary system and the mass of its planetesimal component. For example, do more massive stars form the most massive planetary systems? Are the disks truncated uniformly with spectral type, indicating that a universal process is at play, such as close stellar encounters in the cluster in which the star formed, or photoevaporation of the outer disk edge by a nearby massive star in such a cluster. It already appears that more massive stars host more massive disks (Greaves & Wyatt 2003), which are more readily detected (Habing et al. 2001). That said, a comparison of the disk masses around members of the nearby young TW Hydrae association suggests no correlation between disk mass and spectral type for these reasonably coeval disks (Matthews et al. 2007). In addition, comparisons of disk masses around low-mass stars of comparable age (e.g., AU Mic [Liu et al. 2004] and TWA 7 [Matthews et al. 2007]) reveal a difference of a factor of 10. Improved statistics are critical to reveal whether a genuine trend exists. Moreover, information about disk radii is scarce at present; the only reliable determinations are for the few disks that have submillimeter detections (Sheret et al. 2004), and these comprise a significantly biased data set.

With the SUNS survey data, it will be possible to test for planetary system evolution. Based on our understanding of the solar system's evolution, it is reasonable to expect that both the radius and mass of the belts will change with time. Within our own solar system, the outer planets may have migrated from the locations where they formed (Malhotra 1995), a scenario used to explain structure in some debris disks (Wyatt 2003). For example, Uranus and Neptune may have formed in between Jupiter and Saturn, until their orbits became unstable at a few hundred Myr (Thommes et al. 1999). The radius of the Kuiper Belt also may have been significantly different in the past. The period of late heavy bombardment in the inner solar system, and other evidence, such as the fact that the Kuiper Belt must have been more massive in the past (Morbidelli 2004), also indicates that the dust flux from the Kuiper Belt must have varied significantly with time. Thus, understanding the evolutionary changes in extrasolar systems will not only help place the evolution of the solar system in context, but could also help to illuminate Earth's own origins.

The survey will test the applicability of the solar system itself. One model for the origin of debris disks proposes that they flare into detectability when a system matures to the extent that a Pluto-sized object can form in its planetesimal belt (Kenyon & Bromley 2004). The new planet then perturbs the belt out of which it formed, initiating the collisional cascade that produces the copious amounts of dust that we see for a short amount of time. Since such Pluto analogs may take longer to form farther from the star, it can take up to 1 Gyr for those outer disks to become detectable. This model would mean that we could expect to detect disks at large distances around stars at late times (Rieke et al. 2005). Short bursts can also be produced when lunar-sized embryos are ejected from the inner planetary system. Such processes may explain the presence of dust around old stars, as well as the apparently episodic nature of the debris disk phenomenon (Rieke et al. 2005). Such disks would be cool and so may only be detectable at submillimeter wavelengths. Indeed, it can be shown that for several disks, the dust we are seeing must be transient (Su et al. 2005; Wyatt et al. 2007). An alternative view is that disks may be quasi-static in radii. These models say that dust mass (but not radius) does evolve with time, decaying through the collisional erosion of the belts (Dominik & Decin 2003), and such models can successfully explain the currently available statistics (Wyatt et al. 2007). Episodic periods of high dust mass are then provoked through the destruction of large planetesimals (Wyatt & Dent 2002) or a recent stellar flyby (Kalas et al. 2001). Our survey will confront these models with hard statistics.

The unbiased nature of the SUNS survey means that it will be possible to correlate disk parameters with other planet formation indicators. For example, we can assess whether the presence of a giant planet orbiting near the star, or a distant planetary companion detected with adaptive optics, affects the mass or size of an outer disk. Such planets may form and evolve independently from the planetesimals in the system's outer reaches. However, evolutionary processes that lead to planets migrating inward (e.g., massive gas disk, fast core growth) may be related to evolutionary processes further out, either promoting or inhibiting the presence of cold disks.

These are issues that can only be resolved with a large unbiased survey so that the variations of disk frequency with spectral type, binarity, and age can be untangled. The submillimeter is the ideal wave band in which to do this, since it is not limited to warm (40–100 K) disks (and so small planetary systems). The incidence and evolution of mass or radius of cold (<40 K) disks is completely unconstrained at present. Using the submillimeter also means that an estimate for the disk mass is obtained immediately, with more accurate limits on temperature and morphology possible once complementary data are obtained at shorter wavelengths. As Figure 6 shows, the SUNS survey will be particularly sensitive to disks around M stars, since the circumstellar dust is cold even at relatively close proximity (<100 AU) to the host stars.

For the nearest disks, the SCUBA-2 observations will result in resolved images. During its lifetime, SCUBA imaged 7 of the 14 resolved disks (Holland et al. 1998; Greaves et al. 1998,

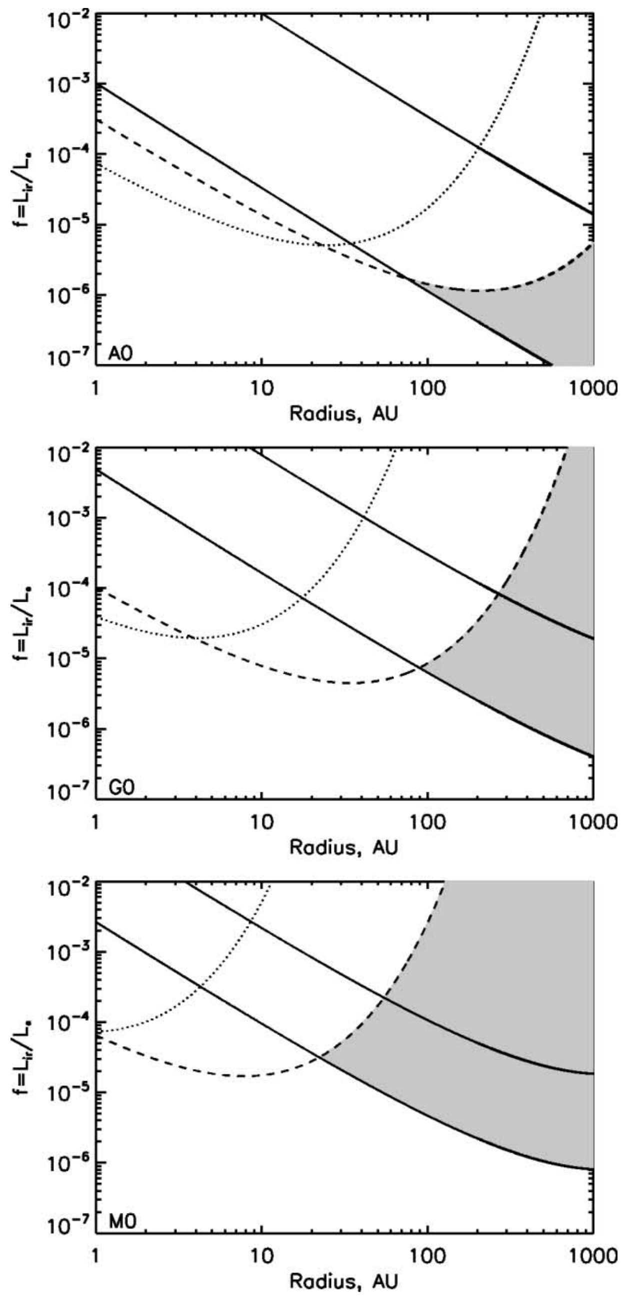

FIG. 6.—Parameter space in which the SCUBA-2 survey is uniquely sensitive (*shaded area*). In each case, this is the location of cold dust. The different lines show the limits of *Spitzer* 24 μm sensitivity (*dotted line*) assuming a limit of $F_{\rm disk}/F_* = 0.1$, and *Spitzer* 70 μm sensitivity (*dashed line*) assuming a limit of $F_{\rm disk}/F_* = 0.55$, based on Su et al. (2007). The solid lines are the SCUBA-2 3 σ limits for the closest and farthest stars in the samples, assumed to be 2.6–45.2 pc for A0, 3.6–24.8 pc for G0, and 1.8–8.6 pc for M0. For A0 stars, this space is relatively narrow (as shown by the shaded region). However, for M stars, the region is much more extensive and includes significantly smaller disks below the detection limits of *Spitzer* at 70 μm. This figure does not account for the fact that at these distances, the largest disks are going to be significantly resolved, and therefore we will not reach the 2 mJy limit (i.e., the SCUBA-2 limits are optimistic for disks larger than the beam size).

2004b; Sheret et al. 2004; Wyatt et al. 2005; Williams et al. 2004). Images allow the inner and outer radii of the disk to be determined directly, thereby confirming inferences about inner cavities. The morphology of disks can thereby reveal the presence of unseen planets (e.g., Wyatt 2003). The orbits, masses, and even the evolutionary histories of planets have been constrained in this way. Such images will thus be an extremely powerful tool for telling us about a region of parameter space that is unreachable with other techniques; planets perturbing debris disks are both small (Neptune size) and at large distances (tens of AU).

For disks that are not resolved, the information returned by SCUBA-2 will provide critical information, since it can confirm that the emission is star centered. Associations of excesses with stars are not always reliable from far-IR data alone, because of the relatively large beam size (e.g., Jayawardhana et al. 2002). For unresolved sources, SED fitting and radius estimation will indicate those objects that could be resolved with future observatories, at a range of wavelengths from optical to millimeter. Of particular importance will be ALMA follow-up, with our survey giving prior knowledge of the submillimeter disk flux and a good indication of angular size. These parameters can only be guessed at from far-IR data alone, so with these data, far less ALMA time will be spent observing sources that are ultimately too faint to detect, or performing observations using nonoptimal array configurations.

Wyatt et al. (2007) modeled the population of disks around A stars, fitting to the *Spitzer* statistics of Rieke et al. (2005) and Su et al. (2007) and yielding predictions for the outcome of the A star component of SUNS survey, excluding the cold disks that would not have been detected by *Spitzer*. They predict that 17 stars (of 100) would have detected disks at >2 mJy, and that >5 would be resolvable in 450 μm imaging. This study also concluded that the SUNS survey would be vital for constraining the distribution of disk radii and for determining the unknown population of disks that are too cold to detect with *Spitzer* (not included in the 17% of expected disks). Assuming the other spectral types have a similar submillimeter detectability, we could justify for the survey a prediction of 85 detections and 25 resolved disks, based on the model of the A star population. A cold-disk population not currently sampled by the *Spitzer* statistics would result in an elevated number of disk detections. We have estimated this value to be approximately 10% (50 disks), but deducing the true incidence of cold disks is in fact one of the principal drivers for this survey.

4. TARGET DETAILS

4.1. The Sample

The survey will cover 500 of the nearest stellar systems: 100 primaries of each of the spectral types A, F, G, K, and M observable from the JCMT. Subgiants are included for spectral types A, F, and G, while only dwarfs are included in the K and M targets. The aim is to obtain samples that are statistically robust and can be intercompared, while keeping the survey completely unbiased with regard to choice of star. This is a unique feature of our survey; no star will be rejected because of its intrinsic properties. The nature of the mass function of stars means that the five subsamples cover different volumes. The distance limits extend out to 45, 25, 22, 16.5, and 8.6 pc for A, F, G, K, and M stars, respectively. The uncertainties on the parallax for these stars are ± 1 pc for A, F, and G stars, and ± 0.1 pc for K and M stars. These volumes explored by this survey are similar to those being explored with *Spitzer*, and earlier with *ISO*, but the SCUBA-2 survey will be the first unbiased study. Further details on the selection of targets will be presented in a forthcoming paper (N. Phillips et al. 2007, in preparation).

The allocation of 390 hr includes 330 hr during the first 2 years of SCUBA-2 operations. Of this time, 270 hr has been allocated to weather band 3 ($0.08 < \tau_{225\ \mathrm{GHz}} < 0.12$), and 60 hr is available within band 2 ($0.05 < \tau_{225\ \mathrm{GHz}} < 0.08$) weather. (The lowest elevation stars are prioritized for the better conditions.) The number of targets that need close observing constraints (having low elevation and thus priority for upper band 2 conditions) is only 10% of the total number of targets. The remaining 60 hr is allocated beyond the first 2 years of operation in band 2 conditions; some follow-up may be possible in this period, although completion of the 850 μm survey will have priority.

Figure 7 shows that the targets are distributed across the sky; the furthest distance is 45 ± 1 pc, and there is no clustering of stars toward the Galactic plane. Observations at any time of the year will have suitable targets. The declination limits of $-40°$ to $+80°$ ensure that targets rise to at least 30° elevation.

We will image the total sample of 500 stars down to our adopted JCMT confusion limit of 0.7 mJy at 850 μm. In borderline band 2/3 conditions ($\tau_{225\ \mathrm{GHz}} = 0.08$) at an air mass of 1.15 (30° from zenith), this sensitivity requires an average of 45 minutes of observing per star. The priority is 850 μm observation, with 450 μm imaging being a bonus (giving first hints of disk substructure suitable for follow-up). In general, 450 μm observations will form a follow-up PI-driven project once the population of suitable detected disks is known. The practical strategy is to start with the nearest targets and work outward, while maintaining balance among the spectral types. Thus, the best resolved disks will be observed first, and these will have the highest priority for follow-up imaging.

Figure 5 shows the variation of mass sensitivity for disks of different temperatures, and also the limitations for several key distances in the survey, including the inner bound (2 pc) and the outer bound (45 pc), as well as the outer bounds of the M dwarf (8.6 pc) and G and F stars (22 and 25 pc, respectively). This figure shows that for unresolved disks, our sensitivity is sufficient to detect masses comparable to that of ϵ Eridani ($0.002\ M_{\oplus} = 0.16\ M_{\mathrm{lunar}}$) at most temperatures within 10 pc. The mass of ϵ Eridani lies in the midrange of dust masses for the handful of detected Sun-like systems (Greaves et al. 2004a).

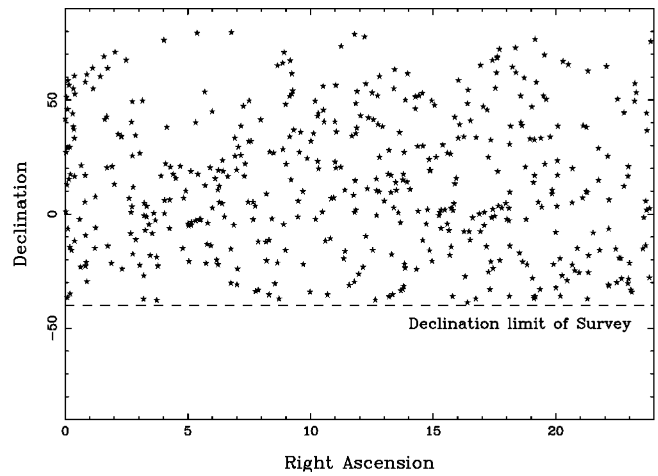

FIG. 7.—Distribution of target sources in the debris disk survey. The targets are all-sky. The declination limits are $-40 < \delta < +80$.

The detectable mass is of course modified by dust location, stellar heating, and resolution, but we note that 15 pc is a useful reference point, as it is the far end of planet search distances for *TPF*. At that distance, we will detect all unresolved systems with temperatures exceeding 70 K. Such limits mean that non-detections result in constraints on dust mass in these systems of typically 200 times the dust content of the solar system, but down to only approximately 4 times this for our nearest target, GJ 699, at 1.8 pc.

4.2. Ancillary Targets

In addition to the 500 primary targets of the survey, the large field of view of SCUBA-2 will enable us to image companions in multiple systems, and in some fields, to include other nearby stars, where they are present. In our target list, at least 240 stars are members of multiple systems of at least two members. This high fraction of multiple systems raises the total number of stars surveyed to well over 750. Very few of these systems require more than one SCUBA-2 subarray, since even wide binaries up to 1000 AU in separation will have an angular separation of <2′. In the case of binaries, their inclusion in the survey is based on the spectral type of the primary; exempting the secondary from the initial sample ensures that no bias is introduced due to the probabilities of disks in binary systems or the weighting of secondaries toward lower masses.

4.3. Subset Populations

The sample size for each of the spectral types was chosen so that we could statistically distinguish between detection rates of 5%, 10%, 25%, and 50% when the primary data set is divided into the following subcategories:

1. *Stellar type*.—With 100 stars each of A, F, G, K, and M. (Properties here and below are from the NASA NStars database).[19]

2. *Stellar age*.—With ~150 stars younger than 1 Gyr and ~350 stars aged 1–10 Gyr. The division corresponds approximately to the end of the heavy bombardment phase of the Earth, and this age split can readily be applied from the decline in X-ray activity, as measured by the *ROSAT* all-sky survey (Gaidos 1998). The 150 : 350 division arises from the proportions within each stellar type falling with this age bracket. This is ~100% of A stars (1 Gyr on the main sequence), 20% of F stars (lasting 5 Gyr), and 10% of G, K, and M stars (limited by the Galactic disk age of 10 Gyr).

3. *Stellar multiplicity*.—With ≈50% of target stars having another star as a companion.

4. *Presence of a planetary system*.—With ~20 examples within our volume known at the present time from radial velocity searches.

4.4. Statistics

The overall choice of sample size is driven by the aim of differentiating detection rates among the listed subgroups. The key is to have a sample size that is large enough that the smallest subgroup with the lowest detection rate can be distinguished from rates in other subgroups. The detection rate for X disks among Y stars is defined as $Z = (X + / - \sqrt{X})/Y$, as the uncertainty is Poissonian for small counts. In the simplest interpretation, we accept rates as differing if the upper bound of one Z value is below the lower bound of the comparison Z value. In practice, this means the survey size is driven by the smallest samples, which are one-tenth of the comparison group. The two cases are the planetary systems (~ 1 in 10 solar-type systems) and young Sun-like stars (20 among 200 of the G and K stars). Here we can distinguish observed detection rates Z for any pair of intrinsic detection rates among 10%, 25%, and 50%. The formal minimum required to do so is 163 stars, which is just met by our smallest group: the approximately 180 stars of late-F to mid-K potential planet hosts.

Detection rates do not need to be compared within every spectral type. For example, the effects of age on debris will be investigated for stars of Sun-like mass (i.e., both types G and K, rather than G and K separately). In fact, this approach is required, to allow us to establish robust distinctions (i.e., at the 2–3 σ level) between detection rates as a function of spectral type and age, due to the practical limits on sample size. For instance, with 200 stars per sample, a 15% difference in detection rate can be identified at the 3 σ level.

Results from the far-IR surveys with *IRAS*, *ISO*, and *Spitzer* show that these rates actually occur among subgroups of stars. For example, 10% is the global rate for Sun-like stars (Greaves & Wyatt 2003), 25% is the rate among Sun-like stars with known giant planets (Beichman et al. 2005), and 50% is the rate among more luminous A stars (Greaves & Wyatt 2003; Rieke et al. 2005). It is useful to note that 10% of disks exist even at the limited *IRAS* sensitivity, and so this a minimum frequency. However, we can also distinguish a 5% disk occurrence, should it occur among one of the less well studied subgroups. In the smallest subgroups of only 20 stars, we have evidence already for detection rates of 20%–25% (Greaves & Wyatt 2003; Beichman et al. 2005).

5. COMPLEMENTARY DATA

To make the most of the JCMT Legacy survey data set, it is essential that we ensure that the targets are selected based on accurate spectral classification. Although the targets are all very near the Sun, this proximity does not guarantee that the optical spectrum of each is well characterized. This is critical in order to exclude A/F giants and brown dwarfs, and also to ensure that the subcategories of the targets are accurately populated. Existing spectral surveys have observed nearly all of our stellar targets. Gray et al. (2006) have surveyed all spectral types earlier than M0 within 40 pc of the Sun, and M stars have been observed by the Palomar/Michigan State University survey (Reid et al. 2002 and references therein) and the ongoing study RECONS (Research Consortium on Nearby Stars; Henry et al. 2006 and references therein). For those that have not yet been observed spectroscopically, we have undertaken a small optical survey. We are using the 1.2 m telescope at the Dominion Astrophysical Observatory to obtain these spectra, with a resolution $R = \delta\lambda/\lambda \approx 3000$.

The SUNS survey is complementary to *Spitzer* programs searching for warmer debris disks at 24, 70, and 160 μm. Synergy with *Spitzer* data is important to the construction of the spectral energy distributions of the full disk population, even where *Spitzer* has failed to detect a disk in our targets. Due to the timescales of the missions, most complementary far-IR data for our survey targets are likely to come from *Akari* and the *Herschel Space Observatory*. *Akari* is currently doing an all-sky far-IR survey. A targeted *Herschel* debris disk survey is planned using guaranteed time on the *Herschel* photometric instruments PACS and SPIRE. In addition, other photometric observations are likely to be proposed during open time.

6. DATA PRODUCTS

The data products of the survey will include an archive of 500 single fields centered on the 500 target stars, publication-quality images of all the detected disks, and a catalog of the measured fluxes and flux limits at 850 and 450 μm. In addition, plots of the fitted SEDs for each disk and star combination will be made using optical and IR data, combined with the submillimeter fluxes.

It will be possible to systematically extract parameters from

[19] See http://nstars.nau.edu.

the data (see Sheret et al. 2004). These will also be included in the Legacy database of the survey and will include dust temperatures, masses, spectral indices, and characteristic disk radii (either inferred from temperature and spectral index, or measured where the disks are resolved). Systematic modeling will also yield masses of colliding bodies within the debris belts (up to specified sizes), and estimates of mass, location, and orbital direction for perturbing planets (where the disk structure is well resolved).

We have already developed additional tools for measuring disk sizes and fitting spectral energy distributions and will make these publicly available. For examples of development of public databases that we have already made available, see the Debris Disk Database page online.[20] Furthermore, our *Spitzer* contributors have developed tools using HIRES (High-resolution Image Restoration) techniques, specifically for the resolution-enhanced mapping of debris disks. These tools will be used in a unified analysis of the SCUBA-2/*Spitzer* database. *Herschel* data will be incorporated to our analysis where possible.

6.1. Ancillary Data Products

Some important ancillary data products will emerge from the survey. These will include a catalog of fluxes and positions of background sources not associated with the star, the majority of which will be distant, dusty galaxies of the kind discovered by Smail et al. (1997), and a list of fluxes for nearby stars where the photosphere is detected but there is no debris disk.

The extragalactic catalog is valuable for providing a large database of submillimeter galaxies (SMGs) that can be followed up with adaptive optics to measure optical/IR properties at very high spatial resolution. A unique aspect of these target fields is that the survey stars themselves will be available for guiding, and they are technically ideal, with magnitudes down to about $m_V = 12$ and offsets of up to about $5'$. Furthermore, the fields add up to 7 deg^2 of observed sky to the JCMT's 850 μm confusion limit, but is split 500 ways rather than in a few fields. Thus, the source counts provide a test for cosmological variance by comparison to the SCUBA-2 cosmology survey. Each 49 arcmin^2 survey field is well matched to the FOV of the *K*-band Multi-Object Spectrograph (KMOS) near-IR facility on *ESO*'s 8 m VLT (Sharples et al. 2004), allowing up to 24 SMGs to be targeted spectroscopically using deployable integral field units, which promises to yield the least biased spectroscopic redshift distribution to date.

The stellar photospheric data are valuable because the long-wavelength end of the Rayleigh-Jeans tail has never been measured. As an example, the A0 star Vega, at 8 pc, has a photosphere of about 5 mJy at 850 μm, and so the equivalent for a nondebris star can be detected with our survey at the 7 σ level. The science value is in observing the contribution of the photosphere to the SED of the star, a quantity that is poorly measured in the far-IR, especially for cooler stars (K and M) with deep molecular absorption bands. Measuring signals below the expected levels would show that the photosphere does not simply extrapolate as a blackbody, constraining stellar atmosphere models. At present, about 5% of stars are known to have far-IR signals 3 σ or more below the photospheric prediction (e.g., Habing et al. 2001).

7. SUMMARY

Many stars are surrounded by dusty cold debris disks. These are fed by asteroids and comets orbiting the stars. Studying the location, mass, and morphology of these disks provides crucial information about the outcome of planet formation in these systems. For the 14 disks that have been resolved at present, observed structures have even been used to suggest the location of unseen planets. Hundreds more stars have had their disks characterized from their SEDs, showing that these disks are the extrasolar equivalents of the Kuiper and asteroid belts in the solar system.

In this Legacy survey, we will use 390 hr of SCUBA-2 time on the JCMT to observe 500 nearby main-sequence stars to search for debris disk signatures. This will be the first unbiased survey since *IRAS*, as previous far-IR surveys have had to omit many stars. The crucial value of the submillimeter is that the stellar photospheric signal is irrelevant, and so any star can be examined. The output of our survey will be robust statistics on the incidence of debris disks, plus discovery of the underlying causes (in terms of the stellar environment and history). The nearer systems may also be resolved, contributing to planetary detection and planning for missions such as *TPF*/*Darwin*.

The data products will be unique, comprising deep and uniform searches for debris, without any bias toward particular stellar properties. This has never been done at any wavelength, and particularly not in the submillimeter, where a new cold population of disks is barely explored. The sample size of the SUNS survey exceeds that of the modest, unbiased G dwarf SCUBA survey (Greaves & Wyatt 2003) by 40-fold, while being substantially deeper. The SCUBA-2 sensitivity will approach the Kuiper Belt dust level for the closest solar analogs; a disk around these targets could actually be detected in our survey before the equivalent has been mapped around the Sun. The survey can never be done better until large far-IR telescopes fly in space, resolving the disk spatially from the stellar photosphere, a prospect considerably downstream of *JWST*.

The science legacy lies in answers to the five key outcomes:

1. Determining unbiased statistics on the incidence of disks around nearby stars;
2. Constraining masses and temperatures of disks previously detected in the mid- and far-IR (e.g., in *Spitzer* surveys);
3. Discovering numerous disks that are too cold to detect in the far-IR;

[20] See http://www.roe.ac.uk/ukatc/research/topics/dust/identification.html.

4. Being the basis of source lists for future observing campaigns using, e.g., ALMA and *JWST*; and
5. Providing limits on the presence of dust that are vital to future missions such as *Darwin*/*TPF*.

With these answers in hand, we will be able to understand for the first time the relation of debris disks—tracing planetesimals up to tens of km across in orbits at tens of AU—to the inner planetary systems detected by other methods. The results, especially when combined with shorter wavelength data to constrain temperature and mass, will test models of planet formation spanning the scale of our solar system (from inside Mercury's orbit to beyond Neptune's). The images of disks will be followed in the next decade by high-resolution imaging that may indicate perturbing planets, even following their orbital perturbations in real time. The results will be vital for the detection of extrasolar Earths with coronagraphs.

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