FROM MOLECULAR CORES TO PLANET-FORMING DISKS: A SIRTF LEGACY PROGRAM

NEAL J. EVANS II
The University of Texas at Austin, Department of Astronomy, 1 University Station C1400, Austin, Texas
78712–0259
nje@astro.as.utexas.edu

LORI E. ALLEN
Smithsonian Astrophysical Observatory, 60 Garden St. MS42, Cambridge, MA 02138
leallen@cfa.harvard.edu

GEOFFREY A. BLAKE
Division of Geological and Planetary Sciences 150-21, California Institute of Technology, Pasadena, CA 91125
gab@gps.caltech.edu

A. C. A. BOOGERT
Division of Physics, Mathematics, & Astronomy 105-24, California Institute of Technology , Pasadena CA 91125
acab@astro.caltech.edu

TYLER BOURKE
Smithsonian Astrophysical Observatory, 60 Garden St. MS42, Cambridge, MA 02138	
tbourke@cfa.harvard.edu

PAUL M. HARVEY
The University of Texas at Austin, Department of Astronomy, 1 University Station C1400, Austin, Texas
78712–0259
pmh@astro.as.utexas.edu

J. E. KESSLER
Division of Chemistry & Chemical Engineering, California Institute of Technology, Pasadena, CA 91125
kessler@its.caltech.edu

DAVID W. KOERNER
Northern Arizona University, Department of Physics and Astronomy, Box 6010, Flagstaff, AZ 86011-6010
koerner@physics.nau.edu

CHANG WON LEE
Taeduk Radio Astronomy Observatory, Korea Astronomy Observatory, 36-1 Hwaam-dong, Yusung-gu,
Taejon 305-348, Korea
cwl@trao.re.kr

LEE G. MUNDY
Astronomy Department, University of Maryland, College Park, MD 20742
lgm@astro.umd.edu

PHILIP C. MYERS
Smithsonian Astrophysical Observatory, 60 Garden St. MS42, Cambridge, MA 02138
pmyers@cfa.harvard.edu

DEBORAH L. PADGETT
SIRTF Science Center, MC 220-6, Pasadena, CA 91125
dlp@ipac.caltech.edu

K. PONTOPPIDAN
Leiden Observatory, Postbus 9513, 2300 RA Leiden, Netherlands
pontopp@strw.leidenuniv.nl

ANNEILA I. SARGENT
Division of Physics, Mathematics, & Astronomy 105-24, California Institute of Technology , Pasadena CA 91125
afs@astro.caltech.edu

KARL R. STAPELFELDT
MS 183-900, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109
krs@exoplanet.jpl.nasa.gov

EWINE F. VAN DISHOECK
Leiden Observatory, Postbus 9513, 2300 RA Leiden, Netherlands
Crucial steps in the formation of stars and planets can be studied only at mid-infrared to far-infrared wavelengths, where SIRTF provides an unprecedented improvement in sensitivity. We will use all three SIRTF instruments (IRAC, MIPS, and IRS) to observe sources that span the evolutionary sequence from molecular cores to protoplanetary disks, encompassing a wide range of cloud masses, stellar masses, and star-forming environments. In addition to targeting about 150 known compact cores, we will survey with IRAC and MIPS (3.6 to 70 μm) the entire areas of five of the nearest large molecular clouds for new candidate protostars and substellar objects as faint as 0.001 solar luminosities. We will also observe with IRAC and MIPS about 190 systems likely to be in the early stages of planetary system formation (ages up to about 10 Myr), probing the evolution of the circumstellar dust, the raw material for planetary cores. Candidate planet-forming disks as small as 0.1 lunar masses will be detectable. Spectroscopy with IRS of new objects found in the surveys and of a select group of known objects will add vital information on the changing chemical and physical conditions in the disks and envelopes. The resulting data products will include catalogs of thousands of previously unknown sources, multiwavelength maps of about 20 square degrees of molecular clouds, photometry of about 190 known young stars, spectra of at least 170 sources, ancillary data from ground-based telescopes, and new tools for analysis and modeling. These products will constitute the foundations for many follow-up studies with ground-based telescopes, as well as with SIRTF itself and other space missions such as SIM, JWST, Herschel, and TPF/Darwin.

Subject headings: surveys: infrared — stars: formation — planetary systems: formation — planetary systems: protoplanetary disks — ISM: dust, extinction — ISM: clouds

1. INTRODUCTION

Stars and planets form in a closely coupled process that is generally accessible to study only at relatively long wavelengths, from infrared to radio. Observational studies of this process have generally suffered from one or more of the following problems: biased samples, inadequate sensitivity, inadequate spatial resolution, or incomplete data across the wavelength ranges of interest. The Space Infrared Telescope Facility (SIRTF) offers a singular opportunity for a major advance in this area of research. The SIRTF mission has been described by Gallagher, Irace, & Werner (2002).

Our Legacy program, “From Molecular Cores to Planet-forming Disks,” uses 400 hours of SIRTF observations to study the process of star and planet formation from the earliest stages of molecular cores to the epoch of planet-forming disks. This program, hereafter referred to simply as “Cores to Disks” or c2d, is closely coordinated with the Legacy program on “Formation and Evolution of Planetary Systems” or FEPS, which carries the age sequence to later times. Our program uses all three SIRTF instruments: the InfraRed Array Camera or IRAC, covering 3.6 to 8 μm (Fazio et al. 1998); the Multiband Imaging Photometer for SIRTF or MIPS, covering 24 to 160 μm (Engelbracht et al. 2000); and the InfraRed Spectrometer, or IRS, supplying spectroscopy from 5.3 to 40 μm with resolving power \( R = 60 - 120 \) and from 10 to 37 μm with \( R = 600 \) (Houck et al. 2000).

The observational programs, described in greater detail in the individual sections, include unbiased mapping of 5 large nearby molecular clouds and about 150 compact molecular cores (§2), photometry of about 190 stars with ages up to about 10 Myr (§3), and spectroscopy of at least 170 objects in a wide range of evolutionary states (§4). In these sections, we discuss the scientific questions, the sample selection, the planned observations, and the expected results. The data products are summarized in §5. We also describe ancillary data, which are part of the c2d data products, and complementary data, which are being obtained by us or others to provide a more complete picture. The SIRTF and ancillary data will be available to the broader community from the SIRTF Science Center (SSC), via their Infrared Sky Archive (IRSA). Complementary data products will be made available, as far as possible, through either IRSA or public web sites. Further information on the program can be found at the c2d website: http://peggysue.as.utexas.edu/SIRTF/.

2. A SURVEY OF NEARBY MOLECULAR CLOUDS AND CORES

2.1. Scientific Questions

The SIRTF mission offers an unprecedented opportunity to determine the stellar content of the nearest star-forming molecular clouds, the distributions of their youngest stars and substellar objects, and the properties of their circumstellar envelopes and disks. Just as IRAS and ISO revealed many properties of isolated and clustered star-forming regions, SIRTF will yield new insights into how stars and brown dwarfs are born. Among the specific questions that our program will address are the following.
1. In large cloud complexes, how are the youngest stars and substellar objects distributed, in position and mass? The IRAC and MIPS maps of large complexes will reveal the reddest, and presumably youngest, associated objects. Is their distribution “bimodal” between singles and clusters, or is there a more continuous distribution of multiplicity? Is the distribution of young stars better correlated with line-of-sight extinction, the supply of dense gas, or with proximity to other young stars, a measure of triggering or cooperative star formation? Do the answers to these questions depend on the mass of the object – for example, can brown dwarfs form in isolation, as can ordinary low-mass stars, or do they require proximity to stars, as expected if they originate primarily in circumstellar disks or in small stellar groups?

2. What is the incidence of circumstellar disks in complexes and in isolated cores? The excess emission over that of a stellar photosphere at near- and mid-infrared wavelengths indicates the presence of a circumstellar disk, the birthplace of planets. To improve understanding of the factors that influence disk dissipation and survival, our sample includes a wide range of complex and isolated star-forming regions. This comparison will differ from past studies of disk incidence in its greater sensitivity to faint objects, in its unbiased coverage of large cloud areas, and in its inclusion of isolated cores not in complexes.

3. Do “starless” isolated cores harbor faint protostars? Starless or “pre-protostellar” cores have no pointlike infrared emission according to ground-based near-infrared observations and far-infrared observations by the IRAS and ISO satellites. These cores are prime targets for studies of the initial conditions of isolated star formation, and some such cores have associated internal motions suggestive of the early stages of star formation. SIRTF’s sensitivity will allow detection of extremely young protostars and proto-brown-dwarfs missed by earlier observations. Identification of such objects would stimulate more detailed studies and so would advance our understanding of the earliest stage of star formation.

4. What are the statistical lifetimes of various stages? Our survey covers a large area and will catalog a large number of young and embedded systems. These data will allow the first unbiased statistical studies of the complete stellar content of five large clouds. In addition, systems that are statistically rare and systems in rapid phases of evolution will be present in the sample. We may, for example, find systems in the short-lived phase in which the first hydrostatic core forms, a crucial, but so far unobserved stage of star formation (Boss & Yorke 1995).

5. Do isolated cores with associated stars preferentially harbor single stars or small stellar groups? Observations by IRAS and ISO led to the idea of “one core, one star”: an isolated core or globule tends to form a single star or an unresolved binary, as opposed to a small group of 3 to 10 members. In large molecular clouds, many isolated IRAS point sources are accompanied by groups of near-infrared sources that constitute the more evolved members of a small stellar group (e.g., Hodapp 1994). SIRTF will be much more sensitive to faint emission from nearby sources than was IRAS and ISO, allowing us to test whether truly isolated star formation occurs.

6. What is the density structure of individual cores? Some isolated starless cores have a density structure similar to that of a pressure-bounded isothermal sphere, according to observations of their submillimeter dust emission and of their near-infrared absorption of background starlight. These cores have a single local maximum of density and tend to make single stars. Line profiles toward these cores usually indicate low levels of turbulence. In contrast, cores in cluster-forming regions appear to have more complex density structure, and their spectral lines indicate more turbulent conditions. Deep IRAC imaging of such cores will reveal their detailed structure through mapping the extinction of background stars. This structure will be compared with that of isolated cores to improve understanding of the initial conditions for stellar groups.

2.2. Sample Selection

Our sample of the nearest star-forming molecular clouds covers a range of cloud “types” broad enough to encompass all modes of star formation and sufficient in number to allow robust statistical conclusions. To ensure a wide variety of star-forming conditions, we target five large complexes known to be forming stars in isolation, in groups, and in clusters, and 156 small, isolated cores – 110 starless and 46 with associated IRAS sources.

The five large clouds selected for mapping, listed in Table 1, satisfy the following criteria: they contain a substantial mass of molecular gas; they are actively forming stars; they are within 350 pc; and they can be mapped in a reasonable amount of time. Table 1 gives for each target region the distance, the area to be mapped with IRAC, and the full time for IRAC and MIPS observations, including off-cloud comparison fields. Although the distance criterion excludes some important star-forming regions, such as the Orion clouds, it was imposed to ensure that our SIRTF observations would be sensitive to brown dwarfs. The Perseus cloud is the most distant cloud at 320 pc (de Zeeuw et al. 1999), though previous distance estimates range from 220 pc (Cernis 1990) to 350 pc (Herbig & Jones 1983). The Taurus molecular cloud satisfies most criteria but is too large to be mapped within the time allocated.

The selected complexes span a wide range of conditions. The most quiescent and least opaque are Lupus and Chamaeleon II, whose young stars are isolated or in sparse groups, and whose gas has low extinction and narrow lines. The most turbulent complexes are Perseus, Ophiuchus, and Serpens, with more densely clustered stars. The guaranteed time observers (GTOs) will observe smaller regions in many of these clouds. Our goal is to provide complete and unbiased coverage down to a set $A_V$ limit.

Selection of the compact molecular cores proceeded in three steps: selection of a large sample with inclusive criteria; classification into cores with and without known internal luminosity sources (“stars”); and reduction of the sample to eliminate objects being observed by GTOs and to fit within the allowed time. The latter requirement resulted in removing cores with less robust evidence for dense gas and dust. The initial criteria for selection of the isolated dense core sample were that the distance is less than 400 pc, that the size is not too large (typically less than 5'), and that the core has been mapped in a dense gas tracer, typically NH$_3$ (Jijina, Myers & Adams 1999), CS (Lee, Myers & Tafalla 2001), and/or N$_2$H$^+$ (Lee et
To determine whether a core has an associated “star,” meaning a central luminosity source at any evolutionary stage, we used the catalog of Lee & Myers (1999). For embedded sources (Class 0 and Class I), they searched the IRAS database and required the following to be true. The projected position of the IRAS source on the sky should fall within the contour of least extinction defining the optical extent of the core. The source should be detected in at least two wavebands. The detected flux densities ($F$) should be greater in the longer wavelength band. However, sources with $F_{100 \mu m} < F_{60 \mu m}$ or $F_{125 \mu m} < F_{25 \mu m}$ were included as long as $F_{60 \mu m} > F_{25 \mu m} > F_{12 \mu m}$. To select pre-main-sequence stars from the IRAS catalog the color-color criteria of Weintraub (1990) was used by Lee & Myers (1999), which requires $-2.00 < \log(\nu_{12} F_{12}/\nu_{25} F_{25})/\log(\nu_{12}/\nu_{25}) < 1.35$ and $-1.75 < \log(\nu_{25} F_{25}/\nu_6 F_6)/\log(\nu_{25}/\nu_6) < 2.20$. The Herbig & Bell (1988) catalog of pre-main-sequence stars was also searched. Other cores with stars were identified on a core by core basis from the literature; e.g., IRAM 04191+1522 was not detected by IRAS, but was identified by its dust continuum emission (André, Motte & Bacmann 1999) and found to have a central source. This candidate target list was cross-checked against the GTO lists and the area to be mapped by us in the 5 large molecular clouds to remove overlap. In order to fit the time allocation, the list was further reduced by eliminating cores not detected at all in CS and $N_2H^+$, or detected, but not mapped, in a dense gas tracer and detected only weakly in millimeter or submillimeter continuum.

### 2.3. Planned Observations and Expected Results

The molecular cloud complexes and isolated cores will be observed with both IRAC and MIPS at all wavelengths from 3.6 to 160 $\mu m$, but we expect the 160 $\mu m$ detector to be saturated toward these regions. Because most of the molecular clouds in our sample are at low ecliptic latitude ($-40^\circ \leq \beta \leq 40^\circ$), all observations will be made at two epochs separated by 3 to 6 hours in order to identify faint asteroids. One set of observations will be made in the high dynamic range mode of IRAC to minimize saturation on bright sources.

The boundaries for four of the five large cloud maps were defined using optical extinction maps from Cambresy (1999) (see Figures 1 to 4). A $^{13}$CO map (Padoan et al. 1999, Figure 5) was used to define the Perseus molecular cloud. The SIRTF map of Perseus will include nearly all of the area mapped in $^{13}$CO; this region corresponds to an $A_V \sim 2$ as inferred from maps of near-infrared colors (Carpenter, pers. comm.) generated using the 2MASS Point Source Catalog (Cutri et al. 2001). For the other clouds, an $A_V$ level was chosen so that each map could cover a continuous area of high extinction within the allocated time. In most cases, $A_V = 2$ or 3 defined the cloud edge. However, the Serpens cloud boundary was limited to $A_V = 6$ because lower levels merge into unrelated extinction in the Galactic plane.

Several factors shaped the detailed observing strategy for the large clouds. In Ophiuchus and Perseus, some regions will saturate the MIPS 70 $\mu m$ detector. Each saturated region was quarantined by limiting it to a single SIRTF Astronomical Observation Request (AOR) so that the data in the surrounding regions would not be adversely affected. Point sources will also saturate; the after-image may leave a trail in the direction of the MIPS scans. In order to obtain usable data in such regions, MIPS will scan in the opposite direction for the second epoch observations. Additionally, many of our cloud maps overlap designated GTO regions. Therefore, unnecessary duplicate observations had to be avoided. Another factor considered in the observation planning was cloud orientation. The sky orientation of SIRTF maps for high ecliptic latitude targets, such as Chamaeleon II and Serpens, rotates rapidly. In order to eliminate the possibility of gaps in the maps due to this rotation, the overlap between adjacent AORs was increased, or the observations were constrained to specific position angles.

We also plan observations of off-cloud positions in order to sample properly the background source counts. In the selection of these off-positions, we implemented three criteria. First, in order to sample the stellar density gradient as a function of galactic latitude, we chose off-cloud positions at different heights above the galactic plane. Next, we required that $A_V < 0.5$ in the off-cloud regions, based on the optical extinction maps of Cambresy (1999). Finally, the off-cloud regions were required to have little or no molecular emission ($^{12}$CO), based on the maps of Dame et al. (2001). The off-cloud regions are mostly $15^\circ \times 15^\circ$. Using a Galactic model (Wainscoat et al. 1992), we have predicted the stellar background counts for each field (Table 2) and have chosen the size of the off-cloud region so that we will detect at least 100 background stellar sources at 3.6 $\mu m$. The counts in these off-cloud regions are often much greater than 100 — e.g., at $b = 2^\circ$ (for Serpens), we expect more than 10$^5$ background stellar sources in the $15^\circ \times 15^\circ$ region.

The cloud maps will be made using slightly overlapping IRAC frames and MIPS scan legs. The IRAC cloud maps will employ 2 dithers with an exposure time of 12 seconds in 2 epochs (24 sec total). Since each cloud will be mapped twice, one map will be made in IRAC’s high dynamic range mode (HDR), which uses exposure times of 12 and 0.6 seconds, the shorter exposure time enabling photometry of bright point sources that might be saturated in the 12 second frames. Isolated clouds will be observed with the same parameters as large cloud complexes; expected sensitivities of the IRAC molecular cloud observations are given in Table 3.

The cloud area mapped with MIPS will be at least 20% larger than that mapped by IRAC because of the efficiency of MIPS scan mapping and the instrument-limited choice of scan lengths. Using the MIPS fast scan mode, we will obtain 15 sec exposures at each epoch and achieve the sensitivities given in Table 3. MIPS observations of isolated
clouds will be made in large-source photometry mode. At 24 \( \mu \)m, an integration time of 3 sec (for a total time, including 2 epochs, of 72 sec) will be used. At 70 \( \mu \)m, isolated clouds that contain no IRAS sources, or IRAS sources fainter than 2 Jy at 60\( \mu \)m will be observed in the large-source, coarse-scale mode, with an integration time of 3 sec (for a total time, including 2 epochs, of 36 sec). Clouds that contain IRAS sources with 2 < \( S_\nu \) (60\( \mu \)m) < 10 Jy, will be observed at 70 \( \mu \)m in the large-source super-resolution mode (fine scale), with an integration time of 3 sec (for a total time, including 2 epochs, of 48 seconds).

The 3\( \sigma \) limits from Table 3 for the scan maps yield a limit on \( L_{bol} \) from 3.6 to 70 \( \mu \)m of about \( 10^{-3} \) \( L_\odot \) at 350 pc. Figure 6 shows (clockwise from upper left) the survey detection limits against typical spectral energy distributions for a heavily embedded protostar, a less embedded protostar with a disk, a brown dwarf with a disk of 4.5 \( M_{Jup} \), and an embedded brown dwarf. Our simulations indicate that disks as small as 1 \( M_{Earth} \) could be detected, even when buried behind \( A_V \approx 100 \) mag of extinction. The IRAC bands would detect a 1 Myr old, 5 \( M_{Jup} \) brown dwarf at 350 pc, based on models by Burrows et al. (1997). The five large molecular complexes contain about 750 known stars and IRAS point sources. Based on recent estimates of the initial mass function in the field and in young clusters (Meyer et al. 2000, Luhman et al. 2000), we expect to identify several thousand new substellar objects. These must be distinguished from a large number of background stars (Table 2) and galaxies (e.g., Lagache et al. 2003) by color criteria (Fig. 6) and follow-up observations.

2.4. Ancillary and Complementary Data

To extend the data base to longer wavelengths, where the dust emission becomes optically thin and a good tracer of mass, we are obtaining ancillary data at millimeter wavelengths, using Bolocam for those clouds accessible from the Caltech Submillimeter Observatory (Perseus, Ophiuchus, and Serpens). In addition, we are obtaining complementary data for the southern clouds (Lupus and Chamaeleon) and isolated cores using the Sest Imaging Bolometer Array (SIMBA) on the Swedish-ESO Submillimeter Telescope (SEST). Further complementary data on the northern clouds in molecular lines and dust extinction and emission are being obtained by the COMPLETE\(^1\) team, who also plan to make the data public.

Complementary data on the isolated cores are also being taken with the Submillimetre Common User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) and MAMBO on the 30-m telescope of IRAM. Complementary spectral line data to extend the CS \( J = 2 \rightarrow 1 \) and \( N_2H^+ \ J = 1 \rightarrow 0 \) observations of Lee et al. (2001) and Caselli et al. (2002) are being obtained with the 32 element SEQUOIA focal-plane array on the Five College Radio Astronomy Observatory (FCRAO) 14-m telescope. These complementary data, which will be made available to the community through our c2d website, provide information on the existence and distribution of cloud material around objects detected at shorter wavelengths. Such information will be valuable for establishing the association of specific SIRTF sources with the cloud, for comparison of the material and stellar distributions, and for completing the overall picture of how star formation proceeds in clouds.

Complementary gas and dust observations on smaller scales are being acquired with the BIMA millimeter wavelength array. A mapping survey of 21 embedded cores, mostly in the Perseus complex in the \( \lambda = 2.7 \) mm continuum and \(^{13}\)CO and \(^{18}\)O \( J = 1 \rightarrow 0 \) lines, has been completed. The observed cores include well-known young embedded systems such as NGC 1333 IRAS4, NGC 1333 IRAS7, and B5 IRS1, as well as ammonia cores without known embedded sources. The maps have a resolution of 2\( '' \) and a field of view of 100\( '' \). This combination of resolution and field of view will allow detailed comparisons of the gas, dust, and IRAC-derived stellar distributions. The typical continuum sensitivity of 1 mJy/beam will permit detection of circumstellar disks down to a mass of 0.01 \( M_\odot \). The molecular data will also provide velocity structure information, which can be used to look at the correlation between turbulent/systematic velocity fields and stellar binarity and the stellar spatial distribution.

In addition, as complementary data, the large clouds and many northern cores are being imaged at shorter (R, i, and z) wavelengths to limiting magnitudes of 24.5, 22, and 22, respectively. The photometry at these wavelengths will be very valuable for identifying young objects, discriminating against background and foreground stars, and extending the coverage of the spectral energy distribution. Extended objects will also be resolved, and young reflection nebulae (and contaminating) background galaxies will be identified. Data will be obtained primarily with the CFH12K and Megacam cameras at the Canada-France-Hawaii Telescope. Southern targets (such as Chamaeleon) will be imaged in similar bands with WFI at ESO, La Silla.

3. THE EVOLUTION OF DISKS UP TO 10 MYR

3.1. Scientific Questions

Disks around pre-main sequence stars are the likely sites of planet formation. As such, they have been targets of extensive research over the past two decades. Surveys of continuum emission at infrared and millimeter wavelengths have established that 50\% of all classical T Tauri stars (cTTs) (ages < 3 Myr) have disks with typical masses of \( 10^{-3} \rightarrow 10^{-1} \) \( M_\odot \), sufficient to form a planetary system like our own (see Beckwith & Sargent 1996, Beckwith 1999 for reviews). Disk sizes, as revealed by millimeter interferometry and \( HST \) images, range from 100 to 1000 AU in diameter. Much less is known about the occurrence and properties of disks in later stages of evolution. Evidence suggests that disk dispersal is marked by the termination of viscous accretion onto the star, dissipation of circumstellar gas, and the coagulation of grains into larger particles. During this process, disks are thought to evolve from an early opaque stage to one in which they are optically thin to both stellar radiation and their own thermal infrared emission. Examples of such “debris disks” are found in association with nearby stars at ages up to about 1 Gyr and contain relatively small amounts of dust (less than a few lunar masses). Analyses of timescales for grain dispersal have led to the conclusion that the dust is

\(^1\) http://cfa-www.harvard.edu/~agoeman/research8.html
maintained by replenishment from asteroid collisions and cometary passages. The evolutionary transition between massive protoplanetary disks and tenuous debris disks appears to take place early in a star’s life, perhaps within the first 10 Myr (Strom et al. 1989). However, the timescales and synchronization of dispersal processes are largely unknown.

Unprecedented sensitivity at critical wavelengths will enable SIRTF to address key questions in the early evolution of circumstellar disks. Weak-line T Tauri stars (wTTs) represent a strategically important sample for this purpose. These young pre-main sequence objects are characterized primarily by reduced signatures of protostellar accretion. In addition, they lack evidence for outflows and display diminished or absent near-infrared excess emission in contrast with their cTTs counterparts. IRAS and ISO detected far-infrared excesses in only a small fraction of wTTs, but these early efforts lacked the sensitivity needed to detect the masses of material associated with nearby debris disks at the distances of the nearest star-forming clouds. Consequently, it remains unclear whether wTTs are the evolutionary descendants of classical T Tauri stars or simply represent a population of stars without disks altogether. SIRTF studies of the wTTs population will bridge this gap in understanding and address the following key scientific questions:

1. What is the frequency of debris disks in the low-mass stellar population at ages of less than 5 Myr? Our program will establish the general presence or absence of disks in the wTTs sample together with the evolutionary implications of either possibility.

2. On what timescale does the metamorphosis from protorealm to debris disk occur? By comparing cTTs and wTTs disk properties with those of the disks around young main-sequence stars in clusters, we can infer their evolutionary progress and synchronization. For example, grain-growth models predict a rapid transition from the opaque to translucent states, but the replenishment of small grains by planetesimal collisions may lead to a longer transition. The dispersion in disk properties within a coeval sample of stars will also provide a sensitive indicator of the diversity of evolutionary pathways for a forming planetary system.

3. Do most disks develop inner holes or gaps during the dissipation process? This aspect of disk structural evolution is observable through the signature of the spectral energy distribution, and our observations will indicate whether disk dissipation and planetesimal formation proceeds at an equal pace throughout the disk, or at an accelerated pace in the inner disk region.

3.2. Sample Selection

The selection of wTTs targets was driven by three considerations. First, targets were sought that were associated with the large molecular clouds being mapped. The proper motion dispersion for wTTs at 140 pc distance is sufficient for the stars to move several degrees away from their natal clouds on a timescale of 10 Myr (Hartmann et al. 1991), so targets were restricted to a zone within 5° from the cloud boundaries. Second, nearby wTTs targets were chosen because they allow the best sensitivity to dust excess. For this reason, only targets associated with clouds closer than 160 pc were considered. Third, we required that stars show evidence of young age: high levels of chromospheric activity as traced by X-ray emission detected by ROSAT, and strong Li I 6707 Å absorption at levels exceeding those of Pleiades stars of the same spectral type.

On the basis of these criteria, we selected 190 targets associated with the Chamaeleon, Lupus, Ophiuchus, and Taurus clouds2. These are distributed as follows: 30 stars from Chamaeleon (Covino et al. 1997), 60 from Lupus (Wichmann et al. 1999), 40 from Ophiuchus (Martín et al. 1998), and 60 from Taurus (Wichmann et al. 2000). A few additional stars were selected from the catalog of Herbig & Bell (1988). Spectral types in the overall sample range from G5 to M5. Thirty of the targets fall within the boundaries of the large cloud maps, leaving 160 to be measured separately. With the observing strategy outlined below, these 160 targets require 50 hours.

3.3. Planned Observations and Expected Results

We will search for excess infrared emission in our wTTs sample by means of photometric measurements at wavelengths3 of 3.6, 4.5, 5.8, 8.0, 24, and 70 μm. At each target, single 5′ × 5′ fields will be imaged with the IRAC and MIPS cameras. The IRAC observations consist of a single 0.6 second and two 12 second exposures. This sequence is designed to detect the stellar photospheres at S/N > 50 in all four IRAC bands. At 24 μm, the MIPS observation strategy will detect the stellar photosphere at a S/N level of 20. For the typical target, 2 photometry cycles with a 3 second exposure time are required to reach this sensitivity; actual exposure time will be tailored to the expected photospheric brightness of each star. At 70 μm, robust detection of a stellar photosphere would be prohibitively time-consuming and probably impossible due to cirrus and extragalactic confusion. Consequently, we have aimed to achieve a more modest goal: S/N level greater than 5 for the detection of a β Pictoris-like debris disk characterized by a fractional luminosity of ~ 0.001 and 70 μm flux density ten times the stellar photosphere. For the typical target, 2 photometry cycles with the 10 sec exposure time are needed to achieve this. As at 24 μm, the planned exposure time is tailored to the brightness of the individual star.

The presence of infrared excess in an individual source can be readily determined by comparing its colors to those of SIRTF standard stars. To measure absolute levels of the excess, we will compare the observed flux densities to those of model photospheres appropriate to each object’s spectral type, normalized to match available 2MASS photometry. Figure 7 shows how the survey sensitivity compares to the emission from various stars surrounded by a debris disk. The survey will readily detect disks like that around β Pic, even if they have evacuated inner holes with radii as large as 30 AU. Disks an order of magnitude more tenuous

---

2 Although the Taurus molecular cloud is not mapped by c2d, parts of the region are being mapped by SIRTF Guaranteed Time Observers and will be available for comparison.

3 While highly desirable, 160 μm photometry of our target sample is impractical due to the high sky backgrounds in the regions surrounding molecular clouds.
will still be detected if their inner edge is at a radius of 5 AU. Fitting of model spectral energy distributions to the SIRTF measurements will allow the disk optical depth, inner radius, and radial density/temperature profiles to be constrained.

3.4. Ancillary and Complementary Data

Two ground-based observing programs are being carried out in support of the c2d weak-line T Tauri star study. The first is ancillary echelle spectroscopy using the 4-m telescopes at KPNO and CTIO. These spectra provide uniform measurements of spectral type, metallicity, lithium abundance, and chromospheric activity in the entire target sample, directly supporting the determinations of infrared excess and stellar age. The second is an adaptive optics (AO) search for source multiplicity using the ESO Adonis instrument (Hogerheijde et al. 2003). The presence of companion stars has been shown to have a strong effect on the frequency of circumstellar disks (Jensen, Mathieu, and Fuller 1996); by understanding multiplicity in our sample, its effect on the disk properties can be isolated.

4. THE EVOLUTION OF THE BUILDING BLOCKS OF PLANETS

4.1. Scientific Questions

Spectroscopy complements imaging and is essential to understand the physical and chemical state and evolution of gas and dust surrounding young stellar objects. The mid-infrared wavelength range encompassed by SIRTF is particularly rich in diagnostic features, each of which probes different aspects of the star- and planet-formation process (see Table 4). Indeed, bands of solid-state material and the fundamental lines of the most abundant molecule, H$_2$, can be studied only in the mid-infrared. In the 75 hour c2d IRS program, high signal-to-noise spectra will be obtained over the full 5–40 μm range [high resolution ($R \approx 600$) over the 10–37 μm range] for all phases of star- and planet-formation up to ages of ~5 Myr for at least 170 sources. The MIPS-SED mode at 50–100 μm will also be used in the second year of the program to characterize the longer wavelength silicate and ice features of a disk subsample. Previous spectroscopic studies, e.g., with ISO, only had the sensitivity to probe high- or intermediate-mass young stellar objects. SIRTF will permit the first comprehensive mid-infrared spectroscopic survey of solar-type young stars.

The IRS spectra can be used to address the following questions:

1. What do spectroscopic diagnostics tell us about the different stages of early stellar evolution? As chronicled in Table 4 and Figure 8, there are many mid-infrared spectroscopic features that are potentially diagnostic for distinct physical and chemical states of young circumstellar environments. A classification based on these features would complement the current classification scheme (Lada & Wilking 1984) based on spectral energy distributions. Prime diagnostics in the earliest embedded stages are the solid CO$_2$ bending mode at 15 μm, the [S I] 25 μm line and other atomic lines, the PAH features, and the H$_2$ lines. The shape of the 15 μm solid CO$_2$ band seen in absorption toward protostars is particularly sensitive to the thermal history of the envelope, and changes in its profile have allowed young high-mass protostars to be put in an evolutionary sequence (Gerakines et al. 1999). The [S I] 25 μm and H$_2$ lines probe the presence and properties of shocks, whereas the PAH features signal the importance of ultraviolet radiation. Together, they allow us to trace the relative importance of these two processes for clearing the envelope. A particularly exciting prospect is mid-infrared spectroscopy of disks as they are being unveiled.

In the later evolutionary stages, changes in silicate features become the main diagnostics. Indeed, one of the major results from the SWS instrument on ISO is that solid-state evolution of grain minerals occurs in disks around pre-main sequence stars (Meeus et al. 2001). Some objects show only amorphous dust emission, whereas others have clear signatures of crystalline silicates and/or PAHs. These variations may be related to the processes of grain coagulation, settling and destruction in the circumstellar disk, i.e., its evolution.

2. How does the chemical composition of dust and ices change from molecular clouds to planetary bodies? In the embedded phase a reservoir of volatile and solid materials is delivered to the disk from the surrounding cloud core. The composition of the ices in the embedded phase can be probed by absorption spectroscopy, whereas that of the silicates in the pre-main sequence phase requires emission studies. The low IRS resolving power below 10 μm does not allow detection of minor ice species, but the major ice components can be traced. Many ices may survive the accretion shock and will be incorporated into icy grain mantles in the outer reaches of planetary systems, perhaps to be delivered to inner planets intact. Indeed, remarkable similarities are found between the composition of interstellar ices and comets and between the crystalline silicates and PAHs seen in some disks and those in comet Hale-Bopp (Malfait et al. 1998). An inventory of the material present at each stage of low-mass envelope and disk evolution as a function of stellar luminosity, mass, and environment will be a major goal of the spectroscopy program. The resulting spectra will form a powerful data base to compare with spectra of Kuiper-Belt objects, comets and asteroids obtained in other SIRTF programs and to clarify the links between interstellar, circumstellar, and solar-system material.

3. How does the size distribution of dust grains evolve in circumstellar environments? Observational and theoretical evidence points to a great deal of activity in dust grain evolution during the gas-rich disk phase, suggesting that grain growth to a km-sized population of planetesimals may occur at this stage. The silicate emission widely observed from gas-rich disks arises from small (~0.5 μm) grains, while the underlying continuum stems from larger particles. Further, the overall excess shortward of 200 μm scales approximately as the ratio of the disk (dust) photosphere to the gas scale height (Chiang et al. 2001). The low noise IRS spectra automatically cover the lowest pure rotational emission lines of H$_2$ at 28 and 17 μm, which may be detectable if the gas and dust temperatures are sufficiently different. Successful detection of these lines would permit an independent assessment of the dust coagulation and gas dissipation time scales, processes of great importance for planet formation.

It is important to note that the spectral energy distri-
butions (SEDs) themselves do not give a unique answer to
grain growth because of the degeneracy between disk mass
and grain size distribution in radiative transfer models, es-
pecially if the physical size of the disk is uncertain (Chi-
ang et al. 2001). However, the combination of SEDs with
complementary spatially resolved infrared and millimeter-
wave images of disks does resolve the parameter correla-
tion, making it possible to constrain the relative settling
of the dust versus the gas in gas-rich disks and the earliest
stages of planetesimal formation up to roughly millimeter
sizes. Our c2d program will provide hundreds of objects
for more detailed follow-up.

4. What is the spectral evolution of substellar objects?
Do they form as stars do, or do they form as companions
to stars? A clue that they form as stars do is the existence
of a disk around many young substellar objects (Natta &
Testi 2001; Apai et al. 2002; Liu et al. 2003). Another
important question is whether their atmospheres are dusty
at later times. Atmospheric spectra are predicted to show
significant changes with age and mass (e.g., Burrows et
al. 1997). Apart from limited photometry, nearly nothing
is known observationally about the mid-infrared spectra
of brown dwarfs, young or old. The young brown dwarfs
and super-Jupiters discovered in the IRAC and MIPS sur-
veys (~100 expected) therefore form a critical second look
population for study with the IRS.

4.2. Sample Selection

The IRS observations are divided into two sets with
roughly equal time, the first being observations of known
embedded and pre-main-sequence stars and the second
consisting of follow-up spectroscopy of sources discovered
in the IRAC and MIPS mapping surveys. The source list
for the first-look program was restricted primarily to low-
mass young stars, defined as having masses \( M \lesssim 2 \ M_\odot \)
with ages younger than \( \sim 5 \) Myr, for minimal overlap with
existing infrared spectroscopy. Within these criteria the
selection contains a broad representative sample of young
stars with ages down to 0.01 Myr and masses down to the
hydrogen burning limit or even less, if possible. Figure
9 shows the distribution of sources over luminosity, and
Figure 10 shows the distribution over age.

The initial selection of sources to be observed with the
IRS was constrained to the cloud regions scheduled to
be mapped by IRAC. A large list of Class 0, I and II
sources was compiled, primarily from the existing near-
and mid-infrared surveys of the mapped clouds (Persi et
al. 2000, Bontemps et al. 2001). All overlays with GTO
high spectral resolution IRS targets were removed. The
SIMBAD database was searched for additional observa-
tions and modeling of every source remaining in the list.
All available photometric points were collected and typi-
cal parameters such as bolometric luminosity,SED Clas,
effective temperature, and optical extinction were entered
into a concise database from which the final selection could
be made. Stars with no measured mid-infrared fluxes were
dropped first. The availability of sensitive ISO-CAM sur-
veys covering part of the mapped regions ensured that the
fainter end of the luminosity function is well represented.

Most sources with \( 5 - 25 \ \mu \)m fluxes less than 200 mJy
were also discarded in the first look IRS sample due to
time limitations; some fainter sources of special interest,
such as a few stars known to have an edge-on disk, were re-
tained. Stellar ages of the Class II sources were calculated
by fitting the extinction-corrected temperature and bolo-
metric luminosity from the database to the evolutionary
tracks by Siess et al. (2000), assuming solar abundances.
Stars with a calculated age of more than 5 Myr were sub-
sequently discarded since systems of this age and older are
covered in the FEPS Legacy spectrophotometry program,
although largely at low spectral resolution. The flux limit to
be achieved in the first-look survey corresponds to a typi-
cal source luminosity of 0.1 L_\odot and mass of 0.1 M_\odot in
the Ophiuchus, Chameleon, Serpens and Lupus clouds at an
age of 1 Myr.

Care was taken at this point to verify that all stellar ages
and masses within the limits of the full database were rep-
resented in the final sample. For completeness and com-
parison purposes, a few sources were added such as back-
ground stars and certain Herbig Ae stars that were well
characterized by the ISO-SWS. The final source list for the
first-look survey consists of about 170 unique targets, of
which about 10% belong to Class 0, 20% to Class I and the
rest to Class II. A roughly equal amount of time is reserved
to the spectroscopic follow-up of interesting sources found
in the imaging and photometry surveys, complementary
MIPS-SED observations of selected first-look IRS sources,
and spectral mapping of one cloud core.

4.3. Planned Observations and Expected Results

All first-look targets will be observed using the IRS star-
ing mode in each of its four modules, except for those
sources that are part of various GTO programs involving
the low resolution modules. For those stars, only the high
resolution 10-37 \mu m spectra will be acquired as part of the
c2d IRS effort. Whenever possible, cluster observations
will be used to reduce the slewing and peak-up overheads.
Specifically, the moderate precision cluster mode will be
used in conjunction with the blue filter on the peak-up
array.

The integration times for the short-high and long-high
modules were fixed such that theoretical S/N ratios of at
least 100 and 50 are obtained for sources brighter and
fainter than 500 mJy, respectively. The spectra to be
taken using the short-low modules always reach theoretical
S/N ratios of >100. In contrast to the scheduled GTO ob-
servations of large numbers of young stars, typically with
the low resolution IRS modules, the c2d IRS program fo-
cuses on long integration times in the high resolution mod-
ules, ensuring high dynamic range even on weak sources.
Instrumental fringing may limit these S/N ratios, so the
c2d IRS team is leading the development of defringing
tools for SIRTF, as described below. In order to evalu-
ate the pointing performance of the spacecraft and assess
the defringing software before beginning the full survey,
the c2d IRS validation program will include cluster mode
observations of stars with widely varying brightness.

While most of the objects will be observed in the IRS
stare mode only, the northwestern Serpens molecular core
will be imaged over more than 4 square arcminutes to a
1\sigma sensitivity of 2 mJy using the low resolution IRS spe-
ctral mapping mode. This core contains several deeply-
embedded sources and possesses a complex physical struc-
ture with infall, outflow, and formation of the envelope
and disk all occurring within 30″ to 60″ (≈ 0.05 – 0.1 pc) of the central star. Because the continuum is weak off-source, emission lines can be detected even at \( R = 60 \) – 120, and every SIRTF pixel may have an interesting spectrum, ranging from those characterized by deep ice absorption bands toward the protostars themselves to silicate emission from nearby disk sources or strong ionized lines at the heads of shocks. At some positions, the “continuum” emission may even be entirely due to lines or PAHs, which could significantly affect the interpretation and classification of objects.

The targeted dynamic range of 50–100 on the continuum in the IRS stare observations is driven by the scientific questions outlined above, especially the desire to study the thermal history of the envelope through the 15 μm CO₂ bending mode profiles and to search for gas phase emission and absorption features in all phases of star formation. Even at \( R = 600 \), however, minor grain mantle components will be difficult to detect, and little or no kinematic information will be gleaned from the gas-phase lines. In addition, no information will be available on features shortward of 5 μm.

### 4.4. Complementary Data

As a complementary ground-based program, we have therefore initiated flux-limited surveys in the atmospheric L-band and M-band windows using the VLT-ISAAC and Keck NIRSPEC (McLean et al. 1998) instruments in order to examine the fundamental stretching vibrations of the H₂O and CO molecules, respectively. The excellent sensitivity of these spectrometers has enabled the first high spectral resolution \( (R = 10,000 – 25,000) \) CO observations of low-mass protostars, revealing both gaseous and solid CO (Pontoppidan et al. 2003). Embedded sources in Taurus and Ophiuchus show a blend of gas-phase CO absorption and emission profiles that are related to the simultaneous infall and outflow velocity fields in protostars (see Pontoppidan et al. 2002). Studies of edge-on disk sources have been particularly revealing of the solid state components and velocity fields in accretion disk surface layers and mid-plane (Boogert, Hogerheijde, & Blake 2002, Thi et al. 2002). In older Class II disk systems, particularly Herbig Ae stars, emission from CO and atomic hydrogen lines is observed and likely arises from the inner disk in or near the dust sublimation radius (see also Dullemond et al. 2001, Brittain & Rettig 2002).

A subset of IRS targets with known infrared ice absorption features is being characterized, using the CSO and OVRO facilities. Observations of C¹8O and HCO⁺ lines as well as millimeter continuum emission are used to derive the distribution and physical conditions (temperature, density, and column density) of material along the line of sight. This information is crucial in locating the ices and understanding ice evolution indicators (ice column, absorption band profile), as well as in properly interpreting the spectral energy distribution (Boogert et al. 2002).

### 4.5. Analysis Tools

The c2d-IRS team will enhance the IRS pipeline data delivered by the SSC in several ways. The most important improvement will be in the defringing of the IRS spectra, because laboratory experiments indeed show the presence of fringes. Special software derived from the ISO-SWS experience is being written for defringing both 1-D and 2-D spectra (Lahuis & Boogert 2002). The in-flight fringe characteristics (complexity and amplitude) are presently unknown, however, which is one of the reasons why two independent defringing approaches, each with its own merits, are being exploited. The first uses a robust method of iteratively fitting sine functions; the second algorithm minimizes fringe residuals by correcting the flat field to best match the data. In parallel, a “complete” fringe model is being developed, applying basic optical theory and incorporating the geometry and optical properties of the IRS detectors. The routines are written in IDL and the resulting modules are compatible with the SMART package, developed by the IRS instrument team for their data reduction and management (see http://www.astro.cornell.edu/SIRTF/). The 1-D pre-launch modules have been delivered to the SSC for use by the community. Other improvements to the pipeline data will come from monitoring of the data quality and calibration over time.

### 5. DATA PRODUCTS

The source samples and observations are summarized in Table 5. The data products (summarized in Table 6) include the following categories of observations and analyses: SIRTF mapping observations together with an associated source catalog and ancillary mapping of the same regions at millimeter wavelengths; SIRTF photometry and NOAO optical spectroscopy of associated weak-line T Tauri stars; and IRS spectroscopy of a sample of objects at all stages of early evolution. These data can be used by the community to address far more than just the principal science areas listed above. We describe the particulars of these products below in hopes that other researchers will easily recognize their utility across a broader range of scientific studies. SIRTF and ancillary products will be made available to the SIRTF Science Center for community access through the Infrared Sky Archive (IRSA). Because the complementary data are being obtained by many researchers operating under many different guidelines about archiving, the availability of those data will be handled on a case by case basis. We hope to make most of the complementary data accessible eventually, either through IRSA or through our web sites.

#### 5.1. Clouds and Cores

We will examine and, where necessary, enhance the basic calibrated data (BCD) delivered by the pipeline at the SIRTF Science Center. We will provide to IRSA the enhanced calibrated data (ECD) for all the fields incorporated in our IRAC and MIPS imaging studies of nearby star-forming regions. In addition, we will provide mosaicked maps of the clouds and cores; these products are referred to in Table 6 as mosaics. A band-merged catalog of sources contained within these images will also be compiled and provided to IRSA. The catalog will include cross-identifications with known pre-main sequence objects, foreground stars, and transient sources (for example, asteroids in the field of view). This resource should allow the community easy access to SIRTF photometry of
any individual objects that fall within our field of view, as well as the capability to carry out statistical studies of color- or magnitude-selected samples with the help of the IRSA search engine. As noted in Table 6, all of our large clouds except Cham II include “cut-outs,” regions observed by GTOs. Because data on these regions will not be available to us until 12 months after they are observed, delivery of full mosaics and catalogs for those clouds will depend on the observation date of those cut-outs.

5.2. Data Products for weak-line T Tauri Stars

IRAC and MIPS images of weak-line T Tauri stars will be processed in the same manner as the images of isolated cloud cores and extended molecular clouds and the results provided to IRSA. The c2d team will also deliver the following: 1) enhanced calibrated data (ECD) consisting of images in six SIRTF bands; 2) a catalog of the sample which includes cross-identifications with objects in the literature and spectral energy distributions including both SIRTF and published measurements; 3) new high-resolution optical spectra for the sample, together with properties such as equivalent widths of lithium and Hα, and with radial velocities and identification of any double-lined spectroscopic binaries; and 4) a list of positions and fluxes for serendipitous sources. Archival researchers will be able to access SIRTF photometry, band-merged with other relevant photometric measurements for any individual source of interest, or to view selected properties of the entire sample with the help of IRSA.

5.3. IRS Data Products

The data products will consist of best-effort reduced and defringed spectra, together with an identification of the spectral features where possible. Results from our complementary VLT, Keck, and CSO/SEST programs will be made available through publications in refereed journals. The reduced spectra will appear on the c2d web site at the time of the final data delivery from our program.

The most important improvement the c2d-IRS team will make to the IRS pipeline data is defringing of the spectra. Special software has been written for this purpose (Section 4.4). Other improvements to the pipeline data will come from monitoring the data quality and calibration over time. The 1-D pre-launch modules have been delivered to the SSC for use by the community. Other improvements to the pipeline data will come from monitoring of the data quality and calibration over time.

5.4. Modeling Tools

Simple modeling tools that fit the photometric data of individual sources with emission from protostellar cores and circumstellar disks will be available to help identify the nature of catalogued sources (http://wits.ipac.caltech.edu/). Simple analysis programs for modeling SEDs from disks are being developed for our team based on the formalism by Dullemond et al. (2001) and will be made available through the c2d website.

6. SUMMARY

The c2d program will provide a legacy for future research on star and planet formation. By selecting samples with attention to coverage of the relevant parameters, we hope to provide a data base for unbiased statistical studies of the formation of stars and substellar objects. Ancillary and complementary data from other wavelength regimes will complete the picture. Analysis and modeling tools will assist researchers in getting the most out of the data base. The source lists may be found on the c2d web page, noted in the introduction, by following the link to “source list.” Table 5 summarizes the samples (columns) and observations (rows) to be collected, and Table 6 lists the data products and anticipated delivery dates. Of course, source lists, observations, data products, and delivery dates may be modified if in-flight performance differs from what was predicted.

We anticipate extensive follow-up studies of these samples with SIRTF itself and with future missions such as SIM, Herschel, SOFIJA, JWST, and TPF/Darwin, as well as with ground-based instruments such as SMA, CARMA, and ALMA.

This research has made use of NASA’s Astrophysics Data System, the SIMBAD database, operated at CDS, Strasbourg, France, and the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We thank L. Cambrésy and P. Padoan for supplying electronic versions of data. This material is based upon work supported by the National Aeronautics and Space Administration under Contract No. 1224608 issued by the Jet Propulsion Laboratory. The Leiden SIRTF legacy team is supported by a Spinoza grant from the Netherlands Foundation for Scientific Research (NWO) and by a grant from the Netherlands Research School for Astronomy (NOVA). CWL is partially supported by grant R01-2000-000-00025-0 from the Basic Research Program of the Korea Science and Engineering Foundation.

REFERENCES

André, P., Motte, F., & Bacmann, A. 1999, ApJL, 513, 57
Apai, D. et al. 2002, ApJ, 573, L115
Beckwith, S. V. W. 1999, NATO ASIC Proc. 540: The Origin of Stars and Planetary Systems, 579
Beckwith, S. V. W. & Sargent, A. I. 1996, Nature, 383, 139
Bontemps, S. et al. 2001, A&A, 372, 173
Boogert, A.C.A., Hogerheijde, M.R., Blake, G.A. 2002, ApJ, 568, 761
Boogert, A. C. A., Hogerheijde, M. R., Ceccarelli, C., Tielens, A. G. G. M., van Dishoeck, E. F., Blake, G. A., Latter, W. B., & Motte, F. 2002, ApJ, 570, 708
Boss, A. P., & Yorke, H. 1995, ApJ, 439, L55
Brittain, S. D., Rettig, T. 2002, Nature, 418, 57
Burrows, A., Marley, M., Hubbard, W. B., Lunine, J. I., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D., and Sharp, C. 1997 ApJ, 491, 856
Cambrésy, L. 1999, A&A, 345, 965
Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M., 2002, ApJ, 572, 238
Černis, K. 1990, Ap&SS, 166, 315
Chiang, E. I. et al. 2001, ApJ, 547, 1077
Covino et al. 1997, A&A 328 187
Crovisier, J. et al. 1997, Science 275, 1904
Evans et al.
Cutri, R.M., Skrutskie, M.F., Van Dyk, S., Chester, T., Evans, T., Fowler, J., Gizis, J., Howard, E., Huchra, J., Jarrett, T., Kopan, E.L., Kirkpatrick, J.D., Light, R.M, Marsh, K.A., McCannon, H., Schneider, S., Stiening, R., Sykes, M., Weinberg, M., Wheaton, W.A., Wheelock, S., 2001, “Explanatory Supplement to the 2MASS Second Incremental Data Release,” http://www.ipac.caltech.edu/2mass/

Dame, T. M., Hartmann, D., Thaddeus, P., 2001, ApJ, 547, 792

de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354

Dullemond, C.P., Dominik, C., Natta, A. 2001, ApJ, 560, 957

Engelbracht, C. W., Young, E. T., Rieke, G. H., lis, G. R., Beeman, J. W., & Haller, E. E. 2000, Experimental Astronomy, 10, 403

Fazio, G. G. et al. 1999, Proc. SPIE, 3354, 1024

Gerakines, P.A. et al. 1999, ApJ 522, 357

Gibb, E. et al. 2000, ApJ, 536, 347

Hartmann, L., Stauffer, J.R., Kenyon, S.J., and Jones, B.F. 1991, AJ, 101 1050

Herbig, G.H., & Bell, K.R. 1988, in Third Catalog of Emission-Line Stars of Orion Population, Lick Obs. Bull., 1111

Herbig, G. H., & Jones, B. F. 1983, AJ, 88, 1040

Hodapp, K. 1994, ApJS, 94, 615

Hogerheijde, M. R., Ménard, F., Duchêne, G., Koerner, D., Padgett, D., Sargent, A. I., Stapelfeldt, K. R., van Dishoeck, E. F., 2003, in prep.

Houck, J., van Cleve, J., Brandl, B., Charmandaris, V., Devost, D., & Uchida, K. 2000, ISO beyond the peaks: The 2nd ISO workshop on analytical spectroscopy. Eds. A. Salama, M.F.Kessler, K. Leech & B. Schulz. ESA-SP 456., 456, 357

Jijina, J., Myers, P.C., & Adams, F.C. 1999 ApJS, 125, 161J

Jensen, E.L., Mathieu, R.D., and Fuller, G.A. 1996 Ap.J. 458312

Lada, C.J., Wilking, B.A. 1984, ApJ 287, 610

Lagache, G., Dole, H., & Puget, J.-L. 2003, MNRAS, 338, 555

Lahuis, F., Boogert, A.C.A. 2002, in ‘Chemistry as a diagnostic of star formation’, proceedings of the Waterloo conference, eds. M. Fich et al., in press

Lee, C.W., & Myers, P.C. 1999, ApJS, 123, 233

Lee, C.W., Myers, P.C. & Tafalla, M. 2001, ApJS, 136, 703

Liu, M. C., Najita, J., & Tokunaga, A. T. 2003, ApJ, 585, 372

Luhman, K. L., Rieke, G. H., Young, E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJ, 540, 1016

Malfait, K. et al. 1999, A&A, 332, L25

Martin, E. et al. 1998, M.N.R.A.S. 300 733

McLean, I.S. et al. 1998, SPIE vol. 3354, pp. 566-578

Meeks, G., Waters, L.B.F.M., Bouwman, J., van den Ancker, M.E., Waenkens, C., Malfait, K. 2001. A&A, 365, 476

Meyer, M. R., Adams, F. C., Hilenbrand, L. A., Carpenter, J. M., & Larson, R. B. 2000, Protostars and Planets IV, 121

Natta, A., Testi, L. 2001, A&A, 376, L22.

Padoan, P., Bally, J., Billawala, Y., Juvela, M., Nordlund, Å. 1999 ApJ, 525, 318

Persi, P. et al. 2000, A&A 357, 219

Pontoppidan, K. M., Schöier, F. L., van Dishoeck, E. F., & Dartois, E. 2002, A&A 393, 585

Pontoppidan, K. M., et al. 2003, A&A, submitted

Siess, L., Dufour, E., Forestini, M. 2000, A&A, 358, 593

Strom, K.M., Strom, S.E., Edwards, S., Cabrit, S., and Skrutskie, M.F. 1989. AJ 97 1451

Thi, W. F., Pontoppidan, K. M., van Dishoeck, E. F., Dartois, E., & d’Hendecourt, L. 2002, A&A, 394, L27

van den Ancker, M.E., Wesselius, P.R., Tielen, A.G.G.M. 2000a, A&A, 355, 194

van den Ancker, M.E., Bouwman, J., Wesselius, P.R., Waters, L.B.F.M., Dougherty, S.M., van Dishoeck, E.F. 2000b, A&A, 357, 325

Wainscoat, R.J., Cohen, M., Volk, K., Walker, H.J., & Schwartz, D.E. 1992, ApJS, 83, 111

Weintraub, D.A. 1990, ApJS, 74, 575

Wichmann et al. 1999, M.N.R.A.S. 307 909

Wichmann et al. 2000, A&A 359 181

### Table 1

| Cloud      | Distance (pc) | Area a  | Time b  |
|------------|---------------|---------|---------|
| Perseus    | 320           | 3.8     | 52.7    |
| Ophiuchus  | 125           | 8.0     | 78.1    |
| Lupus      | 125           | 2.4     | 46.6    |
| Serpens    | 310           | 0.8     | 12.9    |
| Chamaeleon II | 200     | 1.1     | 15.2    |

a Area mapped with IRAC; MIPS will cover a larger area.

b Time for full maps with IRAC and MIPS, including off-cloud comparison fields, using SPOT6.2.
Fig. 1.— The observations for Chamaeleon II are outlined on this optical extinction map (Cambrésy 1999). The contour shows $A_V = 2$ and was used in planning.

| $\lambda$          | Cham II | Lupus  | Ophiuchus | Perseus | Serpens |
|--------------------|---------|--------|-----------|---------|---------|
| L(3.6 $\mu$m)     | 400     | 7000   | 900       | 110     | $10^4$  |
| N(10.2 $\mu$m)    | 20      | 300    | 45        | 10      | 600     |
| 25 $\mu$m          | 1       | 8      | 1         | 1       | 15      |

$^a$ Expected background counts are from the model of Wainscoat et al. (1992) and are for a $5' \times 5'$ observing area. The wavelength bands do not exactly correspond to the SIRTF bands.
Fig. 2.— We planned observations of Lupus I, III, and IV based on the $A_V = 2$ contour (for III and IV) and the $A_V = 3$ contour (for Lupus I). The optical extinction map is from Cambrésy (1999)
Fig. 3.— The planned observations for Rho Ophiuchus are outlined around the $A_V = 3$ contour (Cambrésy 1999).

### Table 3

**Sensitivities of Cloud Survey**

| $\lambda$ (μm) | Sensitivity$^a$ (mJy) | Sensitivity$^b$ (mag) | Saturation (Jy) | Saturation (mag) |
|---------------|------------------------|-----------------------|-----------------|-----------------|
| 3.6           | 0.015                  | 18.0                  | 0.040           | 9.4             |
| 4.5           | 0.019                  | 17.3                  | 0.031           | 9.3             |
| 5.8           | 0.060                  | 15.6                  | 0.093           | 7.6             |
| 8.0           | 0.083                  | 14.6                  | 0.077           | 7.1             |
| 24            | 0.83                   | 9.8                   | 0.206           | 3.9             |
| 70            | 5.2                    | 5.7                   | 0.258           | 1.5             |

$^a$Sensitivities are 3 $\sigma$ for 24 sec total time.

$^b$Magnitudes based on power-law interpolation and extrapolation of zero-point fluxes from standard bands to the *SIRTF* wavelengths.
Fig. 4.— The planned observations for Serpens are outlined around the $A_V = 6$ contour (Cambrésy 1999).
Fig. 5.—Observations of Perseus in $^{13}$CO (in grayscale) were primarily used in the SIRTF planning for this molecular cloud (Padoan et al. 1999). However, we also used maps of near-infrared colors from the 2MASS Point Source Catalog (Cutri et al. 2001) to provide constraints similar to those for the other clouds; the outlined region in this figure corresponds to $A_V \sim 2$.

Table 4

| $\lambda$ (µm) | Species            | Diagnostic                | $\lambda$ (µm) | Species     | Diagnostic                |
|----------------|-------------------|---------------------------|----------------|---------------------------|
| 6.0            | H$_2$O ice        | Bulk of ice               | 12.8           | [Ne II]     | Radiation field, shocks |
| 6.2            | PAH               | UV radiation, carbon. material | 15.2          | CO$_2$ ice  | Thermal history          |
| 6.8            | Unid. ice         | Processed ices (UV/cosmic ray) | 15.6          | [Ne III]    | Radiation field          |
| 6.9            | H$_2$S(5)         | Photon vs shock heating   | 17.0           | H$_2$S(1)   | Mass and T warm gas     |
| 7.7            | CH$_4$ ice        | Building organics, solar system | 18.5          | (Mg,Fe)SiO$_3$ | Cryst. pyroxenes     |
| 7.7            | PAH               | UV radiation, carbon. material | 23.0          | FeO         | Oxides                 |
| 8.0            | H$_2$S(4)         | Photon- vs shock-heating  | 25.2           | [S I]       | Shocks                 |
| 8.6            | PAH               | UV radiation, carbon. material | 27.5          | Mg$_2$SiO$_4$ | Cryst. silicates, heating |
| 9.7            | Amorp. sil.       | Bulk of dust              | 28.2           | H$_2$S(0)   | Mass and T warm gas     |
| 9.7            | H$_2$S(3)         | Photon vs shock heating   | 33.5           | Mg$_2$SiO$_4$ | Cryst. silicates (enstatite) |
| 11.3           | Mg$_2$SiO$_4$     | Cryst. silicates, heating | 35.8           | Mg$_2$SiO$_3$ | Cryst. pyroxenes     |
| 11.3           | PAH               | UV radiation, carbon. material | 61            | cryst. H$_2$O | Cryst. ices, heating   |
| 12.2           | H$_2$S(2)         | T warm gas, ortho/para ratio | 70            | cryst. sil. | Cryst. silicates, heating |

Table 4:  
Selected mid-infrared spectral features
Fig. 6.— Flux density distributions for sources at 300 pc. Clockwise from upper left, a deeply embedded 0.1 L⊙ protostar, a lightly embedded 0.1 L⊙ star with a 30 AU circumstellar disk, a 10 Myr old, 0.007 L⊙ brown dwarf with a 4.5 M_Jup disk, and a young 0.003 L⊙ brown dwarf with a 1 M_Jup envelope (Chiang et al. 2000, pers. comm.). The lower curve in the lower left panel shows a background giant star with the same temperature, and with the same extinction, as the brown dwarf. The stars represent our 3σ IRAC and MIPS sensitivity limits.
Fig. 7.— Flux density distributions for model debris disks around stars of various spectral types in nearby star-forming regions. Model properties are based on observations of debris disks around A stars, with 0.1 $M_{\text{Moon}}$ of 30 µm-sized dust grains in a zone extending from 30 to 60 AU radius. Horizontal bars mark 5σ sensitivity levels for our survey and for IRAS and ISO.
Fig. 8.— ISO-SWS mid-infrared spectra of newly-formed stars in different stages of formation. From top to bottom – in a rough evolutionary sequence – the spectra change from dominated by solid-state absorption features (ices and amorphous silicates) to gas emission lines and PAH features to amorphous silicate emission and eventually crystalline silicate features (labeled “F”). Note the similarity of the spectra of mature disks with that of comet Hale-Bopp. ISO was able to obtain such spectra only for massive young stars; SIRTF has the capability to study these features for sun-like objects. Based on van den Ancker et al. (2000a,b), Gibb et al. 2000, Crovisier et al. 1997, and Malfait et al. (1998).
Fig. 9.— Distribution of luminosity over the sample for the first-look IRS observations. Stellar luminosities are calculated from fits to SEDs compiled from the literature (about 80% of sample is included in this plot).
Fig. 10.— Distribution of ages over the sample for the first-look IRS observations. Note that age information is quite incomplete and only one-quarter of the sample is represented in this plot.
## Table 5

**Summary of Samples and Observations**

| Item          | Clouds | Cores | Disks | IRS Targets | Comments |
|---------------|--------|-------|-------|-------------|----------|
| Number        | 5      | 156   | 190   | 170+        | First Look\(^a\) |
| Area (sq.deg) | 16     | 1     |       |             |          |
| IRAC          | map    | map   | phot  |             | 3.6–8 \(\mu\)m |
| Sens. 3.6 \(\mu\)m | 0.015 | 0.015 | 0.015 |             | (mJy, 3\(\sigma\)) |
| Sens. 4.5 \(\mu\)m | 0.019 | 0.019 | 0.019 |             | (mJy, 3\(\sigma\)) |
| Sens. 5.8 \(\mu\)m | 0.060 | 0.060 | 0.060 |             | (mJy, 3\(\sigma\)) |
| Sens. 8.0 \(\mu\)m | 0.083 | 0.083 | 0.083 |             | (mJy, 3\(\sigma\)) |
| MIPS          | map    | map   | phot  |             | 24, 70 \(\mu\)m |
| Sens. 24 \(\mu\)m | 0.83  | 0.53  | varies\(^b\) |             | (mJy, 3\(\sigma\)) |
| Sens. 70 \(\mu\)m | 5.2   | 4.7   | varies\(^b\) |             | (mJy, 3\(\sigma\)) |
| IRS Signal/Noise | select\(^c\) | select\(^c\) | ⋯     | L, H\(^d\) | 50–100 On continuum |
| Complementary | yes    | yes   | yes   |             | Ancillary as noted |
| Visible images | map    | select\(^c\) | ⋯     | ⋯          | R, i, z images |
| Visible spectra | ⋯      | ⋯     | 190   |             | Ancillary |
| NIR AO        | ⋯      | ⋯     | select\(^c\) | ⋯          | Adaptive optics |
| MIR spectra   | select\(^c\) | select\(^c\) | ⋯     | select\(^c\) | Continuum maps |
| mm/submm\(^e\) | map    | map   | ⋯     | select\(^c\) | Continuum maps |
| mm interf.\(^f\) | select\(^c\) | ⋯     | ⋯     | select\(^c\) | Spectral maps |
| mm spectra    | map    | map   | ⋯     | select\(^c\) |          |

\(^a\) A roughly similar number of spectral sources will be observed in second look mode, based on the results of the continuum surveys.

\(^b\) Adjusted to achieve a certain signal/noise depending on the star.

\(^c\) Selected objects or regions within this sample will be observed in the indicated mode; the coverage is not complete. For example, 129 of the IRS targets are toward the large clouds.

\(^d\) Spectra will be taken with both low resolving power \((R \approx 60 – 120)\) and high resolving power \((R \approx 600)\) modules.

\(^e\) Large-scale maps made with bolometer arrays (Bolocam, SIMBA, SCUBA, MAMBO). Maps of three clouds (Perseus, Ophiuchus, and Serpens) are ancillary data.

\(^f\) Small-scale maps of selected regions made with interferometers (BIMA, OVRO).
Table 6

**ANTICIPATED DATA PRODUCTS AND DELIVERY DATES**

| Date   | Product                                                                 | If Observed By |
|--------|-------------------------------------------------------------------------|----------------|
| L + 9  | Sampler: validation observations, all modes                            | L + 6          |
|        | Ancillary NOAO optical spectroscopy of wTTs                            | ...            |
|        | Catalog of IRAC/MIPS results for wTTs                                  | L + 6          |
| L + 15 | Initial band-merged, cross-id catalog for wTTs                         | L + 12         |
|        | Initial band-merged, cross-id catalog for cores                        | L + 12         |
|        | ECDs for cores, cloud areas                                           | L + 12         |
|        | Spectra, cataloged features, first-look targets                        | L + 12         |
| L + 21 | Final band-merged, cross-id catalog for wTTs                           | L + 15         |
|        | Final band-merged, cross-id catalog for cores                          | L + 15         |
|        | Mosaics for cores                                                      | L + 15         |
|        | Mosaic for Cham II                                                     | L + 15         |
|        | Defringed spectra, cataloged features, first-look                      | L + 15         |
| L + 27 | Mosaics for Clouds                                                     | L + 9<sup>d</sup> |
|        | Final, band-merged, cross-id catalog for clouds                        | L + 9<sup>d</sup> |
|        | Ancillary submm cloud maps                                             | L + 9<sup>d</sup> |
|        | Catalog of small extended sources                                      | L + 9<sup>d</sup> |
|        | Catalog of transient sources                                           | L + 9<sup>d</sup> |
|        | Defringed spectra, cataloged features, second-look                      | L + 24         |
| L + 31 | Mosaics for any delayed clouds                                         | L + 12<sup>d</sup> |
|        | Updated catalogs for any delayed clouds                                | L + 12<sup>d</sup> |
|        | Defringed spectra, cataloged features, second-look                      | L + 28         |
|        | Complementary data, where possible                                     | ...            |

<sup>a</sup>The products and delivery dates are based on assuming that the spacecraft and all instruments function normally and that the data pipeline runs smoothly. If any of those assumptions are wrong, products may be delayed or even eliminated.

<sup>b</sup>The dates are all given in months after Launch.

<sup>c</sup>Products will be available on sources observed by this date.

<sup>d</sup>All large clouds except Cham II have “cut-outs,” areas observed by GTOs; these areas will not be available to us until 12 months after they are observed. Delivery of our final cloud images and catalogs depends on the observation date of these cut-outs.