Star Formation: Answering Fundamental Questions During the Spitzer Warm Mission Phase

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Abstract.
Through existing studies of star-forming regions, Spitzer has created rich databases which have already profoundly influenced our ability to understand the star and planet formation process on micro and macro scales. However, it is essential to note that Spitzer observations to date have focused largely on deep observations of regions of recent star formation associated directly with well-known molecular clouds located within 500 pc. What has **not** been done is to explore to sufficient depth or breadth a representative sample of the much larger regions surrounding the more massive of these molecular clouds. Also, while there have been targeted studies of specific distant star forming regions, in general, there has been little attention devoted to mapping and characterizing the stellar populations and star-forming histories of the surrounding giant molecular clouds (GMCs). As a result, we have yet to develop an understanding of the major physical processes that control star formation on the scale or spiral arms. Doing so will allow much better comparison of star-formation in our galaxy to the star-forming complexes that dominate the spiral arms of external galaxies.

The power of Spitzer in the Warm Mission for studies of star formation is its ability to carry out large-scale surveys unbiased by prior knowledge of ongoing star formation or the presence of molecular clouds. The Spitzer Warm Mission will provide two uniquely powerful capabilities that promise equally profound advances : high sensitivity and efficient coverage of many hundreds of square degrees, and angular resolution sufficient to resolve dense groups and clusters of YSOs and to identify contaminating background galaxies whose colors mimic those of young stars. In this contribution, we describe two major programs: a survey of the outer regions of selected nearby OB associations, and a study of distant GMCs and star formation on the scale of a spiral arm.

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1. INTRODUCTION

The sensitivity, angular resolution and wavelength coverage of the Spitzer Space Telescope have enabled fundamental contributions to the study of star formation during its first three years of operation. Among the most noteworthy are:

1. Providing a thorough census of forming stars in nearby (d < 500 pc) molecular

cloud complexes – from optically-obscured protostars, still enshrouded by their natal, collapsing cores, to optically revealed stars surrounded by circumstellar accretion disks, the birthplaces of planetary systems. As a result of these surveys, astronomers are now engaged in a panoply of research programs using both Spitzer and ground-based optical and radio telescopes to answer questions key to understanding the star and planet formation process:

   (a) How are initial conditions in protostellar cores (mass, density, temperature, turbulent speeds, rotation, infall rates) surrounding individual forming star-disk systems linked to outcome stellar properties?
   (b) Is there evidence for ongoing planet formation in circumstellar disks? If so, what is the relationship between the properties of forming planetary systems and the physical conditions of their parent disks?

2. Providing clear evidence that multiple star formation modes are manifest in nearby star-forming regions, ranging from young stars formed in isolation or in small aggregates of a few tens of stars, to clusters with 100 to 1000 stars. As a result, we are now armed with a database that promises over the next few years to uncover:
   (a) What conditions in parent molecular clouds lead to the observed outcome stellar populations (isolated/aggregate; cluster)?
   (b) How does environment influence star formation and disk evolution?
3. Providing a census of stars surrounded by circumstellar disks and spanning a wide range of masses (from brown dwarfs to stars as massive as 10 $M_\odot$) and ages from less than 1 Myr to 5-10 Myr. As a result, we now have in hand
   (a) An initial understanding of the range of timescales for the survival of accretion disks around stars of differing mass, and thus constraints on the timescales for completion of the initial phases of planet-building;
   (b) Evidence of disk evolution: (i) grain settling to the mid-plane – the first step in the planet-building process; (ii) evidence of grain growth and processing from analysis of mineralogical signatures; and (iii) evidence of major changes in the distribution of solid material within the disk, including evidence of large (multiple AU-sized) 'holes', which combined with other measurements suggest strongly that giant planet formation is underway in some systems.
4. Providing the first large-scale maps of the young stellar populations associated with a few selected giant molecular cloud complexes located both in the inner (Carina arm) and outer (Perseus arm) galaxy. As a result, we are beginning to see clearly the morphological relationships between multiple episodes of star formation in these complexes, and from these relationships to address questions essential to understanding large-scale star-formation processes in other galaxies:
   (a) What is the role of feedback from young stars in triggering, regulating and terminating star formation? Does formation of massive stars result in 'triggering' of star-forming episodes in nearby molecular material as a result of propagating HII regions?
   (b) How do the properties of stellar populations formed 'initially' in molecular clouds differ from YSOs formed as a result of 'triggering'?

Spitzer has clearly created rich databases which have already profoundly influenced our ability to understand the star and planet formation process on micro and macro scales, and have as well provided grist for a decade or more of follow-up analysis using complementary tools − ground-based radio and O/IR telescopes and next generation facilities in space (e.g. JWST and Herschel).

However, it is essential to note that Spitzer observations to date have focused largely on deep observations of regions of recent star formation associated directly with well-known molecular clouds located within 500 pc (e.g., Taurus-Auriga; Ophiuchus; NGC 1333 and IC 348; the Orion A and Orion B molecular clouds, as well as the Orion Nebula Cluster itself). In most cases, the IRAC integrations were chosen in order to detect and characterize young stars with masses at or in some cases well below the hydrogen-burning limit. What has not been done is to explore to sufficient depth or breadth is a representative sample of the much larger regions surrounding the more massive of these molecular clouds: larger T- and OB- associations comprised of multiple older generations of stars (some as old as 15 Myr) which have long since dispersed their natal material. As a result, we have little information regarding the likely sequence of star formation and the timescales associated with key events such as the dissipation of planet-building circumstellar disks.

Furthermore, while there have been studies of a small selection of more distant star-forming regions located at d $\sim$1-2 kpc from the Sun, these have tended to focus on small regions centered on known centers of active star formation. In general, there has been little attention devoted to mapping and characterizing the stellar populations and star-forming histories of the surrounding giant molecular clouds (GMCs). As a result, we have yet to develop an understanding of the major physical processes that control star formation on the scale of the large complexes that dominate the spiral arms of galaxies, or more globally on the scale of a spiral arm.

2. THE POWER OF SPITZER DURING ITS WARM MISSION PHASE

Despite restriction to the 3.6 and 4.5 μm IRAC channels, the Spitzer Warm Mission Phase will provide two uniquely powerful capabilities that promise equally profound advances − (i) sensitivity sufficient to detect infrared emission from dust around young stars and protostars, and hence to locate representatives of young stellar populations spanning areas of many hundreds of square degrees; and (ii) angular resolution sufficient to resolve dense groups and clusters of YSOs and to identify contaminating background galaxies whose colors mimic those of young stars. Together, these capabilities will enable us (i) to survey young stars in nearby OB associations in which episodes of star formation have continued for timescales approaching 15 Myr; and (ii) to conduct large-scale surveys of rich star formation complexes unbiased by the presence of already known ‘signposts’ of star formation for a representative sample of GMC complexes located at 1-2.5 kpc.

Carrying out these surveys will allow us to understand:

1. The number and spatial distribution of star-forming episodes in OB associations,

and how these episodes may be linked to the initial conditions in their parent molecular cloud complex;

2. The timescales for circumstellar disk evolution for stars spanning a wide range of masses and ages, including in particular, long-lived (t > 10 Myr) disks;
3. The properties of emerging stellar populations in rich, dense clusters and associations whose characteristics are far more similar to the star-forming complexes we observe in other galaxies than those of well-studied regions located within 0.5 kpc of the Sun;
4. The processes that initiate and sustain star-formation on the scale of a galactic spiral arm – an essential complement to extant Spitzer studies of targeted small regions or well-known GMCs;

We describe below two major programs aimed at addressing the above issues, outlining notional target regions, nominal sensitivity limits, corresponding survey times, along with a third program which offers the possibility of serendipitous discovery of variability patterns that may provide fundamental insight into the star and disk assembly processes.

Following a brief description of each of the proposed programs, we outline the potential 'legacy' value of the databases for follow-on ground- and space- based optical and radio observations, as well as the potential combined value of the Spitzer and ground-based programs. We also summarize the relative capabilities of the Spitzer Warm Mission and other planned space facilities (e.g. WISE; JWST) for carrying out aspects of the proposed science programs. Finally, we discuss the value of an ongoing archival research program, both during the Spitzer Warm Mission and beyond.

3. PROGRAM I. SURVEY OF SELECTED OB ASSOCIATIONS

3.1. Outline of a Possible Warm Mission Program

In large star-forming regions, molecular clouds and their associated newly-formed stellar populations are often found embedded within much larger OB associations which harbor evidence of multiple star-forming events which in some cases span up to 15 Myr. Exploiting the Spitzer Warm Mission's ability to carry out deep IRAC 3.6 and 4.5 μm observations offers the potential of identifying young stars surrounded by circumstellar disks and/or envelopes and located within large, nearby OB associations. Candidate regions and their characteristics are listed in Table 1.

TABLE 1. Candidate OB Associations for Spitzer Warm Mission Mapping

Associations	Distance	S-F age range (Myr)	Size (sq deg)	Time to Map (hrs)
Orion OB	0.5	0.1 - 12	100	500
Cyg OB1	0.8	1 - 10	50	250
Per OB1	2	1 - 20	225	1125

Extant studies of the proposed regions suggest each has harbored multiple episodes of star formation, in some cases spanning ages between 1 and 20 Myr.

The areas mapped range from 50 to 200 square degrees depending on the distance and extent of the association. We propose a survey depth of 12 μJy at 3.6μm and 17.8 μJy at 4.5μm. At a distance of 500 pc, these correspond approximately to a young stellar object of mass $\sim$ 0.08 $M_\odot$ at 5 Myr assuming an excess above photospheric emission of 1 mag at 3.6 μm and extinction A_v $\sim$10 mag. Assuming that we map a total of $\sim$2000 square degrees (sufficient to study a representative sample of OB associations) to the indicated sensitivity levels, an integration time of 2000 hours will be required.

The motivation for such large-scale surveys is well illustrated in Fig. 1, in which we present maps of the Orion Ia-d association. The green areas denote the largest portions of this region that have been mapped with Spitzer to date, the blue dots represent the known OB stars in the association, while the red areas represent the distribution of molecular gas to a limiting column density corresponding to A_v $\sim$5 mag. For reference (top), the mapped regions (left hand panel) are shown adjacent to the molecular map and an image of the well-known outline of the Orion constellation (which fairly well coincides with the extent of the OB association.) As the figure illustrates dramatically, current surveys with Spitzer have targeted the regions showing the highest column density of molecular gas and hence the youngest, most active star-forming regions. Regions with lower gas column density, small globules external to the cloud, and the older regions of the association which have dispersed their molecular gas have largely been ignored, even though they contain a plethora of B stars formed within the past 12-15 Myr, and presumably a large associated population of low mass young stars and substellar objects. As a result, we have no information regarding the distribution of the low mass population with ages 1-15 Myr, nor do we know what fraction of that population might still be surrounded by circumstellar accretion disks.

Figure 2 (a map of W5) further vivifies the importance of surveying well beyond the present boundaries of molecular cloud complexes and signposts of the most recent episodes of star formation. Here we see a significant population of young, low mass stars with excess emission indicative of circumstellar disks and/or envelopes extending well beyond the recently formed OB stars and associated dense molecular gas.

By carrying out the proposed survey of nearby OB associations we will provide

1. A complete survey, typically down to masses at least as low as 0.2 $M_\odot$, of the distribution of protostellar sources (forming star-disk systems still surrounded by infalling envelopes; Class I) and sources in which the envelopes have dissipated, but which are still surrounded by circumstellar accretion disks. This will provide a clear indication of the sequence of star formation (youngest dominated by Class I sources; older dominated by Class II sources) in these regions;
2. A complete catalog of stars still surrounded by circumstellar disks, including those located well away from the boundary of actively star forming molecular clouds, some in the vicinity of 10-15 Myr old B stars and presumably formed during earlier star-forming episodes within the larger association. Because studies of nearby moving groups (e.g. TW Hya) demonstrate some disks surrounding low mass stars can survive for ages as least as great as 10-15 Myr (see, e.g., Chen *et al.* [1]), it is almost certain that the proposed survey will locate a significant number of long-lived accretion disks. Understanding the range of disk lifetimes and the properties of older accretion disks can provide important information regarding the range of

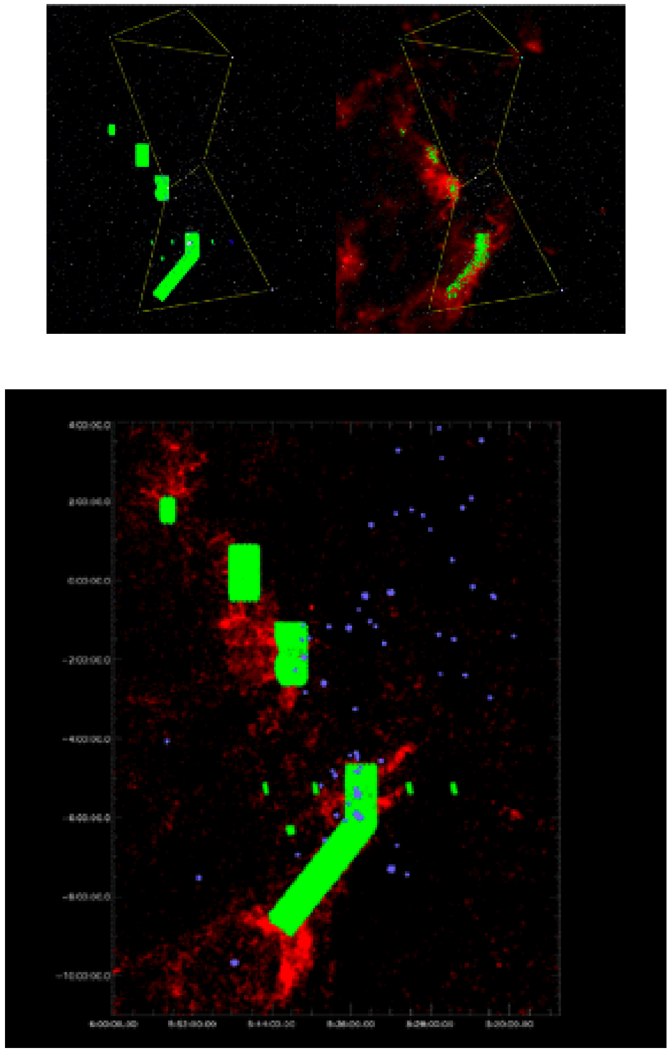

FIGURE 1. The top figure illustrates (LHS, bright green) most of the largest regions mapped with IRAC as part of GTO or GO programs carried out by Spitzer. The top RHS image represents a molecular line contour map (from the CfA CO surveyed) on which sources surrounded by disks and/or envelopes are superposed (green). The outlines of the Orion constellation and its signature bright stars are included for reference. The bottom figure depicts most of the regions mapped with IRAC as part of GTO or GO programs (bright green) overlaid on an extinction mass generated from the 2MASS database. Known OB stars with ages as great as 15 Myr are shown in blue, while the outlines of the molecular contour map shown in red (as in the top map). Note that the current surveys have been targeted largely at the main molecular clouds and signposts of recent ($t < 3$ Myr) or ongoing star-formation. The much more extensive regions of the Orion association in which star formation has proceeded for almost 15 Myr have yet to be surveyed.

times available for building planetary systems.

The proposed survey comprises three representative nearby OB associations to the limits needed to survey down to the hydrogen burning limit will require approximately 2000 hours of Spitzer time during the Warm Mission phase.

The Spitzer Warm Mission represents an ideal facility for carrying out this survey because:

1. It can provide a complete survey of protostars and stars surrounded by disks to below the hydrogen burning limit (at ages t $\sim$ 5 Myr) provided reddening is A_V<10 mag.
2. Its ability to survey large regions (100 sq deg or more) will for the first time enable study of the star-forming history of complex OB associations in which star-forming events have been spread out over time and space. Previous surveys have largely targeted well-known 'signposts' of recent star formation.

3.2. Complementary Ground-Based Observations Motivated by this Spitzer Warm Mission Program

The Spitzer Warm Mission survey of nearby OB associations will provide strong motivation for complementary ground-based observations, which, in combination with the Spitzer data, will add significantly to our understanding of star formation and disk evolution. For example:

1. Multi-epoch ground-based JHK imaging surveys will provide (i) via variability studies, a complete census of young, low mass stars formed throughout the star-forming history of the association, including those stars presently lacking circumstellar accretion disks (e.g., Carpenter *et al.* [2]); and (ii) via near-IR photometric measurements, a tool to weed-out heavily reddened background stars (A_V > 20 mag), and/or extragalactic interlopers of sizes near the limit of Spitzer's angular resolution $-$ in those cases, the IRAC colors mimic those of star-disk systems, but the JHK colors differ significantly from those of young stars surrounded by circumstellar disks. In combination with the Spitzer observations, these measurements will yield a complete census of the low mass stellar population spanning ages 1-15 Myr, and provide thereby the statistical basis for quantifying disk evolutionary timescales as a function of stellar mass $-$ essential input for constraining the timescales available for planet formation.
2. High resolution optical spectroscopic studies will provide (i) a map of the kinematic structure of the young stellar populations comprising the association; and (ii) quantitative measurements of disk accretion rates as a function of time and mass via measurements of Hα and Ca II triplet emission line profiles. The accretion rate measurements will help to quantify the rate of disk spreading as a function of age and mass, and provide the basis for identifying objects which lack excess infrared emission in the inner disk (0.1 to 1 AU) probed by IRAC and ground-based measurements, but are nevertheless still accreting gas through the inner disk regions. If so, such objects have the characteristics expected of disks in the process of building either terrestrial or Jovian mass planets. Choosing among these possibilities will require follow-up high resolution near- and mid-IR spectroscopy , as well as ground-based photometric studies with 8-10m class telescopes and facilities such as the SMT or ALMA.

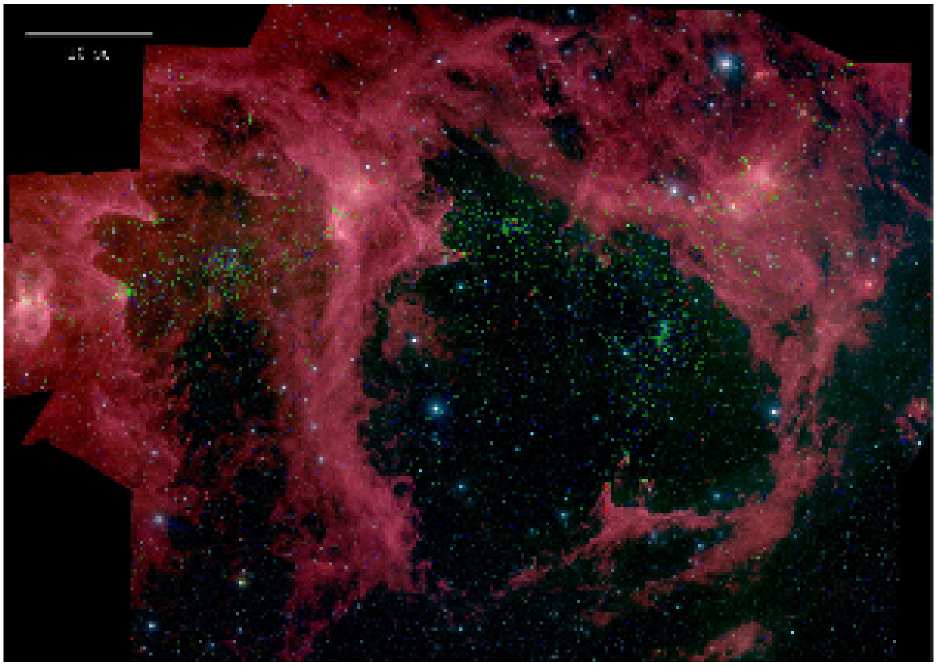

FIGURE 2. IRAC color composite (rgb = 8, 4.5, 3.6 μm) of W5, with the distribution of Spitzer-identified (IRAC only) young stars overlaid (Koenig *et al.* 2007, in prep). Green symbols are Class II, red are Class I, and blue are probably background galaxies. There is a rich population of young stars inside the cavity, not coincident with the molecular cloud material in the rim.

3.3. The Interplay of Spitzer Warm Mission Surveys and Theoretical Studies of Molecular Cloud Collapse

In combination with molecular line maps and numerical models of cloud collapse, these data will provide essential insight into the relationship between the outcome spatial distribution and kinematics of young stars comprising the association, and the initial conditions in their natal GMC.

Recent developments have suggested a new approach to understanding star formation that builds on the idea that molecular clouds are formed by swept-up, shocked gas. Instabilities in the post-shock gas can produce dense concentrations that can serve as the sites of star formation. To illustrate the idea, in Fig. 3 we show a recent simulation of colliding flows, demonstrating the formation of dense protostellar cores as a result of focusing instabilities along with rapid cooling (Heitsch et al. 2007 in preparation).

The simulations suggest that there are three qualitatively different “modes" of star formation: (1) “distributed" star formation, where initial instabilities are so strong that runaway growth of protostellar cores occurs before global cloud collapse; (2) filamentary formation, where perturbations are not strong enough to form stars before collapse into filaments; and (3) clustered star formation, which typically happens when gravity focuses material into dense regions, often at the ends of clouds.

As an example of how global collapse can explain cloud structure, in Fig. 4 we show the results of a (gas-only) simulation (Hartmann and Burkert [3]) which can

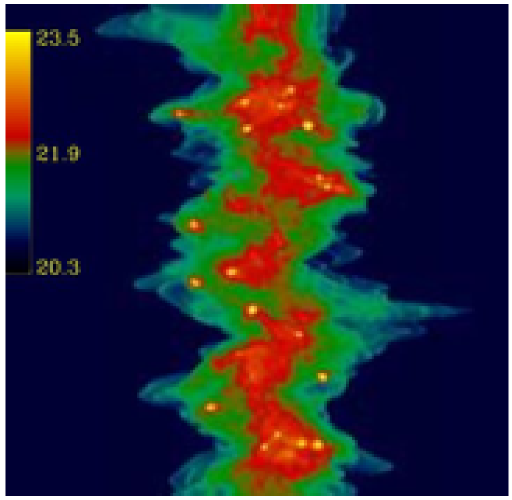

FIGURE 3. Edge-on view of instabilities developing from opposing uniform flows in the horizontal direction. Small, long-wavelength perturbations produce initial seeds which can grow initially through cooling and the ultimately through gravity. From Heitsch et al. 2007, in preparation.

reproduce the peculiar morphology of the Orion A cloud, including the integral-shaped filament, by global gravitational collapse of an initially elongated, rotating cloud. A dense concentration of material forms at the upper end, near the location where the present Orion Nebula Cluster of thousands of stars is situated.

These theoretical calculations make specific predictions about the relationship between cloud and stellar population morphology and kinematics. A warm Spitzer mission can help test these ideas and make advances in developing a more predictive theory of star formation in concert with kinematic studies.

4. PROGRAM II: DISTANT GMCS AND STAR FORMATION ON THE SCALE OF A SPIRAL ARM

4.1. Outline of a Possible Warm Mission Program

This program exploits the power of IRAC 3.6 and 4.5 μm colors to (a) select young stellar objects surrounded by disks or envelopes; and (b) map the extent of the UV radiation field within molecular clouds, and the relationship between forming stars and the boundaries of propagating HII regions and superbubbles. Potential targets would include:

1. Selected GMCs known to contain rich stellar populations, including dense clusters, comparable to those found in actively star-forming galaxies outside the Milky Way. These GMCs are located at distances between 1 and 2.5 kpc from the sun in the Perseus and Carina arms. The goal here is to understand how star formation in regions more typical of those that dominate external galaxies differs from that in well-observed molecular clouds located within 0.5 kpc of the Sun.

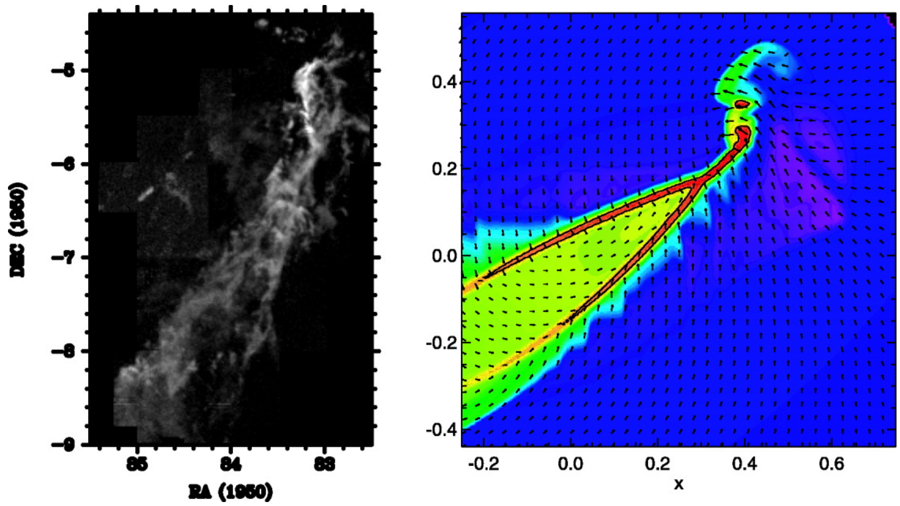

FIGURE 4. ^{13}CO map of Orion A (left) compared with the simple collapse model of Hartmann and Burkert [3]. Global collapse with rotation focuses material at the upper end into the integral-shaped filament, with a dense core which might fragment into a Orion Nebula-like cluster with higher resolution. Dense ridges are present at the lower (southernmost) end, which the Spitzer survey shows are locations of filamentary star formation.

2. A broad region (approximately 10 degrees in latitude and 30 degrees in longitude) of the Perseus arm (d$\sim$2-3 kpc). The target region will be selected solely from examination of the contours of molecular line maps of the outer Galaxy suggesting extinctions $A_V > 5$ mag. The proposed observations will provide the first detailed and objective survey of star formation on the scale of a spiral arm. The study is motivated not only by this overriding goal, but also by a surprising discovery from Spitzer surveys of star forming regions: that a large population of young stars (< 5 Myr) are found outside the confines of molecular clouds (Megeath et al. [5]). Depending on the number and spatial extent of this population, the proposed observations could alter significantly our understanding both of the sequence of star formation and the lifetime of molecular clouds.

Our observing strategy is predicated on the ability of IRAC 3.6 and 4.5 μm colors to locate protostars and young stars still surrounded by circumstellar disks based on the unique colors produced by heated dust located in the inner regions of circumstellar envelopes and disks. In Fig. 5, we present a histogram (from Hartmann *et al.* [4]) depicting the frequency distribution of 3.6 - 4.5 μm colors for well-studied stars in the nearby Taurus-Auriga complex for which (a) there is no evidence from IR or optical data for the presence of accretion disks (open histogram); and (b) those for which there is clear evidence of a disk (shaded histogram). The figure clearly demonstrates the ability of 3.6 - 4.5 μm colors to select stars surrounded by circumstellar disks from stellar objects with bare photospheres. This strategy is robust for objects obscured by $A_V < 30$ mag; typical extinctions in GMC complexes range from 5-20 mag, except in the densest, cluster-forming clumps. For more heavily reddened objects, deep ground-based (H and K-band) observations will be required to complement the Spitzer survey; several

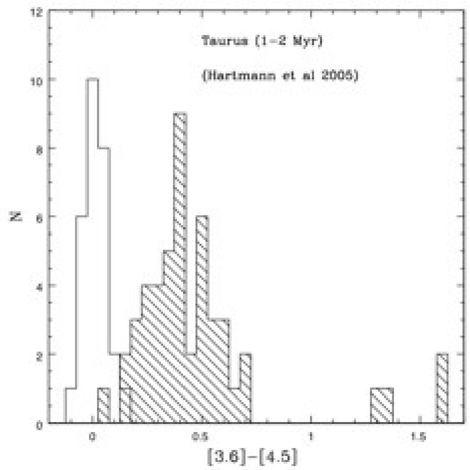

FIGURE 5. Histogram depicting stars surrounded by accretion disks (hatched region) and those known to lack accretion disks. After Hartmann *et al.* [4].

methods have been developed for identifying and classifying young stellar objects using combined near-IR and Spitzer 3.6 and 4.5 μm photometry (see, e.g., Hartmann et al. [6]). We note that although many galaxies, particularly AGN, have 3.6 - 4.5 μm colors similar to young stars surrounded by disks, they can typically be distinguished from young stars by their faintness, and/or because they will appear extended in 3.6 μm or even 2MASS (or deeper JHK) images.

Our strategy is to obtain four 12 second integrations for each of the $5'$x $5'$ frames for each position; with 10% overlap between frames; with these specifications the mapping speed is approximately 0.18 sq degrees per hour. Our integration times have been chosen to achieve 5-σ sensitivity limits of 12 μJy and 17.8 μJy at 3.6 μm and 4.5 μm respectively. At a distance of 2 kpc, these correspond to a 10σ detection of a young stellar object of mass $\sim$ 0.3 $M_\odot$ and age $\sim$5 Myr, assuming an excess above photospheric emission levels of 1 mag at 3.6μm, and cloud extinction A_v = 10 mag. In addition to locating stellar sources, the proposed survey will enable detection of the extent and boundaries of photodissociation regions diagnosed via strong PAH emission at 3.6 μm (see Fig. 6) and illuminate the possible role of propagating HII regions in triggering star-forming events.

By carrying out the proposed surveys, we will be able to detect recently formed stars in a wide range of environments as well as the outer boundaries of propagating HII regions. Together, these observations will allow us to

1. infer the distribution and sequence of star formation and study the role of triggering mechanisms such as colliding flows, or expanding superbubbles and HII regions;
2. relate the patterns and nature (isolated or cluster) of star forming events to the parent molecular cloud morphology and kinematics;
3. develop an understanding of star formation in a wide range of environments and an understanding of how star formation differs in these environments (e.g. molecular cloud density and turbulence; radiation fields from nearby star forming episodes);

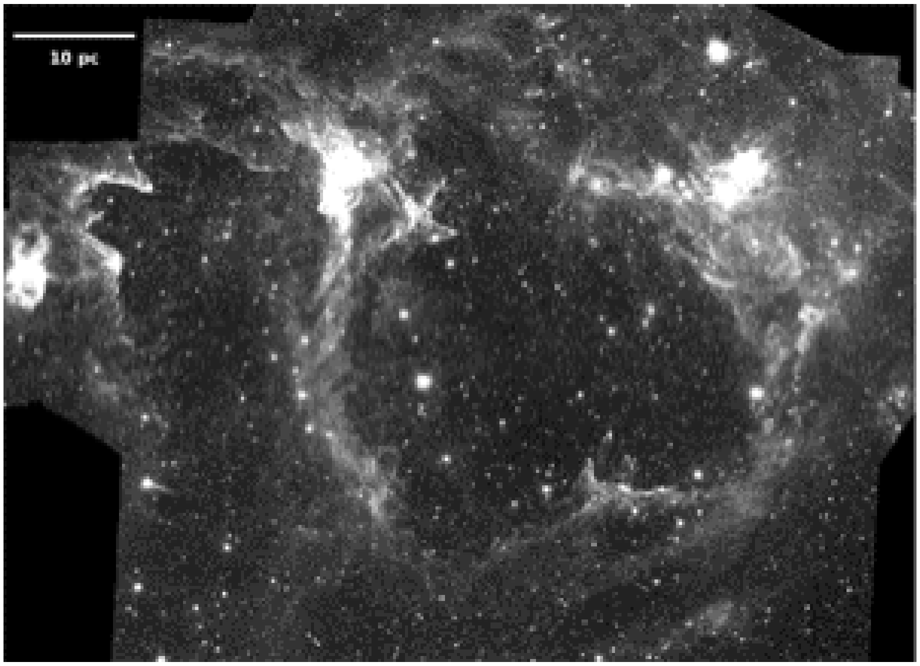

FIGURE 6. W5 mosaic at 3.6 μm (Koenig *et al.* 2007, in prep). The PAH emission lines in this bandpass clearly delineate the ionized/molecular gas boundary, or photodissociation region, powered by multiple O stars in this large HII region cavity.

4. infer the initial and environmental conditions that control the star formation process, from analysis of both Spitzer stellar and UV-radiation field tracers, and from extant molecular line maps.
5. understand the relative contributions to the Galactic disk from differing star-forming environments (small molecular clouds; GMCs; molecular clouds dominated by isolated star-formation; clouds dominated by cluster formation) from an unbiased survey of star-formation on the scale of a spiral arm.

We anticipate that a survey of selected GMCs in the Perseus and Carina arms will cover 300-500 square degrees and will require between 1600 and 3000 hours to cover to the desired depth.

An unbiased survey of the outer Galaxy would ideally cover ~300 sq degrees (see Fig. 7) selected using various molecular tracers and are characterized by relatively unconfused lines of sight. The total time to survey such a region to the indicated depths is ~1600 hours.

The Spitzer Warm Mission represents an ideal facility for carrying out this survey because:

1. Even with its restricted wavelength coverage, it has the ability to provide a complete census of protostars and young stars surrounded by accretion disks, in contrast to JHK ground-based surveys which miss a significant fraction of such sources (see Fig. 8).
2. Large areas can be probed at sufficiently fine ($1.7''$) angular resolution in times of

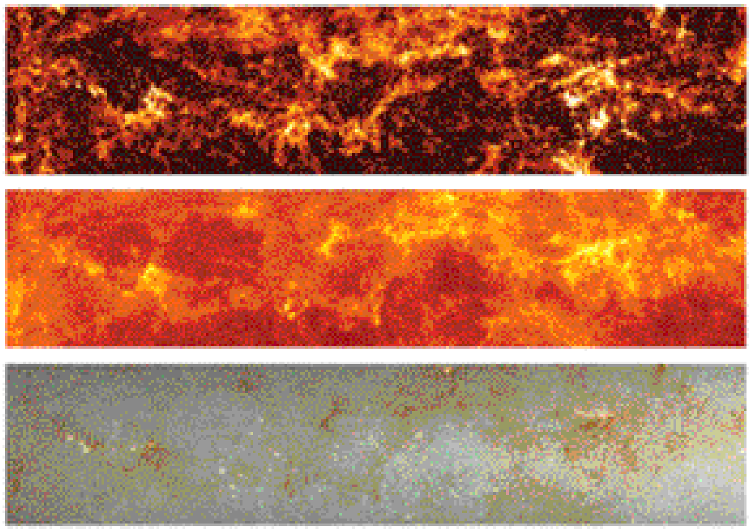

FIGURE 7. A map of the outer galaxy between 102.5 and 141.5 deg (longitude) and -3 to +5.4 latitude: representative of a region we propose for an unbiased $3.6-4.5\ \mu$m survey. Top panel is ^{12}CO J=1-0 from the FCRAO outer galaxy survey, middle panel is average J-K stellar colors from from 2MASS (a measure of extinction), bottom panel is three color JHK 2MASS surface density map.

a few hundred hours to sensitivities sufficient to detect 0.3 $M_\odot$, young ($t < 5$ Myr) stars surround by disks provided they are reddened by 10 magnitudes of extinction or less.

3. The angular resolution is sufficient to probe all but the densest regions of active star formation without suffering from significant source confusion.

4.2. Complementary Ground-Based Observations Motivated by this Spitzer Warm Mission Program

The Spitzer Warm Mission survey of distant GMCs will provide strong motivation for complementary ground- and space-based observations, which, in combination with the Spitzer data will add significantly to our understanding of star formation and disk evolution over the next decade. For example:

1. The proposed Spitzer survey will likely identify many hundreds of star-disk systems still surrounded by their natal protostellar cores and in various stages of assembly. Because we are probing rich star-forming regions known to be forming large numbers of intermediate and high mass stars, we expect that our sample will include protostars in the process of assembling not only large numbers of low mass stars, but a significant number of high mass stars as well. The Spitzer sample will

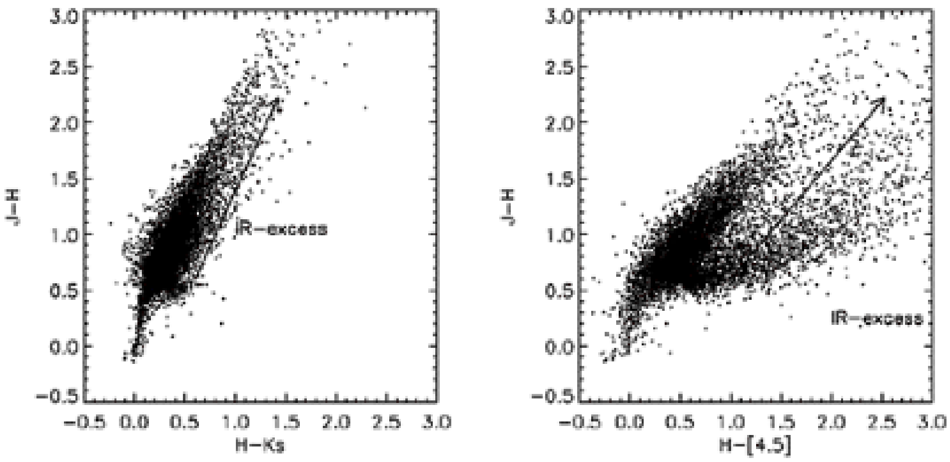

FIGURE 8. . Left panel: a J-H, H-K diagram depicting the location of stars survey in Orion A. The vector depicts the locus of reddened late-type stars. Objects that lie to the right of this vector have excess emission arising from warm dust in the inner regions of circumstellar accretion disks. Those to the left have colors consistent with pure photospheric emission. Right panel: a J-H, IRAC 3.6-4.5 μm color-color plot for the same region. Again, stars with disks lie to the right of the vector have colors indicative of the presence of circumstellar disks. Note the much larger fraction of detected disks manifest when 3.6 μm and 4.5 μm colors are used.

thus enable detailed study of the relationship between the physical properties of natal cores (size, mass, rotation, turbulent speeds, infall rates) and the mass of the forming star − thus providing a fundamental link between initial conditions and outcome stellar properties.

While Spitzer will provide the candidate target lists, follow-up observations with the CARMA, SMA, and ALMA interferometers will map the distribution of molecular gas and dust in the cloud core that feed the circumstellar environment. As an example, CARMA and ALMA will have the power to diagnose gas kinematics, temperature, density and chemistry in cores on scales extending from their outer radii (0.05 − 0.1 pc) to within 250 AU of the forming star-disk system for protostars located at a distance of 2.5 kpc. Ground-based O/IR telescopes will be able to probe infalling gas within 5-10 AU of the star-disk system using high resolution near- and mid- IR spectrographs to measure line profiles measured for a variety of gas tracers, yielding thereby temperature, density, and velocity along lines of sight through the core to the embedded star-disk system. These observations can yield complementary estimates of the infall rates characterizing cores surrounding stars of differing mass (and luminosity), thereby providing another essential link between initial conditions and outcome stellar properties.

2. While Spitzer will identify candidate protostars and young stars surrounded by accretion disks, a full picture of the young stellar population associated with these clouds will require tools to detect stars that no longer are surrounded by accretion disks. Spitzer will serve as a pathfinder to identify candidate regions for followup Chandra and XMM observations. Their ability to detect coronal X-ray emission

associated with young stars will enable identification of the cohort of stars that lack disks, i.e., those that cannot be distinguished from Spitzer IRAC observations. Chandra and XMM's ability to penetrate optically opaque GMC clouds will be particularly valuable in detecting heavily embedded young stars lacking disks.
Optical and near-IR surveys can also provide an important tool for detecting diskless stars via surveys aimed at locating stars that exhibit variability (typically driven by starspot-modulated light variations). Having a complete census of all recently formed stars will be essential to establishing both the full extent of star formation in the GMCs, as well as understanding the sequence and timescales for multiple star-forming events (see below).

3. Ground-based spectroscopic surveys (optical and near-IR) to provide spectral classification essential for placing young stars in HR diagrams and determining masses and ages. These measurements, combined with Spitzer-detected star-disk systems and space- and ground-based detections of diskless young stars will provide the basic information needed to quantify accretion disk lifetimes as a function of stellar mass. Moreover, the derived ages will provide the quantitative complement to the morphological information regarding the timing and sequencing of star-forming events.
4. Follow-up observations of targeted regions identified in Spitzer imaging surveys with JWST imaging and spectroscopy will enable deep studies of the stellar content, particularly of dense, source-confused forming clusters uncovered with the Spitzer survey. Such studies will enable studies of the initial mass function as well as the disk population in regions which find no analog in nearby star-forming complexes.

5. PROGRAM III: A SEARCH FOR VARIABILITY PATTERNS AMONG YSOS

5.1. Outline of a Possible Warm Mission Program

It would be of significant potential discovery value to select one of the nearby OB Associations (Orion I c-d is our preferred region) as a target for a systematic survey of variability patterns among YSOs. In particular, a 1 x 3 degree region centered on the Trapezium contains a thousand young stars that could be monitored photometrically. Monitoring observations, e.g., with 2MASS, have already identified variability time scales of days, months, and years (see, e.g., Carpenter *et al.* [2] or Grankin *et al.* [5]). The potential sources of variability include: rotational modulation by star spots, obscuration by remnant material in protostellar envelopes, and variability of accretion rates (and associated disk heating) in the inner disks. We propose to observe the Orion the inner regions of the Orion I c-d association to identify variability events, and to probe all time scales accessible with Spitzer to completely characterize the relevant time scales for disk variability. Since most stars in Orion have K< 14, high precision photometry is required on 0.5 mJy sources at 4.5 μm. In a 12 second integration, we can reach a signal to noise of 50 on the faintest cluster members.

The 1 x 3 degree region can be covered in 432 non-overlapping IRAC frames. Assuming 12 second frame times (an HDR mode), it would take about 3.5 hours to survey the entire region (based on Spot). The visibility window for Orion is about 44 days in duration, with windows in the early spring and fall each year. We would propose to survey the 1 x 3 degree region for one entire visibility window (44 days, or about 300 individual images at each point in the region), and then once per day for the next two visibility windows. The total survey would require of order 1300 hours.

The scientific return of the proposed survey is more difficult to quantify than the survey programs discussed above, simply because we currently know relatively little about the physical causes of variability among protostars and young stars surrounded by circumstellar disks. The proposed program offers the possibility of providing deeper insight into (i) the factors that control variability in the inner (0.1 to 1 AU) regions of circumstellar accretion disks, including stochastic processes associated with accretion and events driven by the interaction of orbiting giant planets and accreting material; (ii) variability during the protostellar infall/accretion phase and insight into the interactions between disk and envelope; and (iii) the relation between stellar rotation, age, and the presence/absence of accretion disks. We note that while ground-based surveys can contribute significantly to (iii), (i) and (ii) above require the sensitivity and rapid surveying power of Spitzer.

Spitzer can undertake this program based on its unique combination of sensitivity, area coverage, and photometric precision. Ground-based L-band surveys are generally limited to areas smaller than $\lesssim$ 0.03 deg and typically achieve 10% photometry at the sensitivity limit required to detect stars with masses near the hydrogen burning limit in nearby young clusters (e.g. Haisch, Lada, and Lada [6]). Therefore, the challenges of ground-based 3.5 μm observations prohibit for all practical purposes an extensive variability survey over large regions. While near-infrared (JHK) observations are more feasible in this context, mid-infrared observations are essential to probe variability from the disk. Spitzer on the other hand has demonstrated it can achieve the combination of coverage, sensitivity, and precision to probe variability in hundreds of young stars. These combined attributes are unlikely to be replicated in the foreseeable future.

6. COMPARISON WITH WISE AND JWST

The IR survey satellite WISE will be launched in late 2009, while JWST is expected to be launched in late 2013. Both include bands in the wavelength range that will be covered by Spitzer during its Warm Mission Phase. Hence, it is of some importance to examine the strengths of each of these missions for carrying out the programs proposed here.

WISE's 40 cm telescope will be able to image a 47$'$ FOV at wavelengths of 3.3, 4.7, 12, and 23 μm with typical image size of 6$''$ (FWHM). WISE will be an all-sky survey; as a polar orbiter, its sensitivity is a strong function of ecliptic latitude (as well as background). By contrast, JWST will be a pointed mission. JWST NIRCAM will have filters covering the 0.7 to 5 μm region and a detector/camera combination that will cover a 2.3$'$ x 4.5$'$ FOV and deliver images with FWHM $\sim$ 0.1$''$. JWST will also provide a mid-IR camera (MIRI) enabling imaging over the wavelength region between

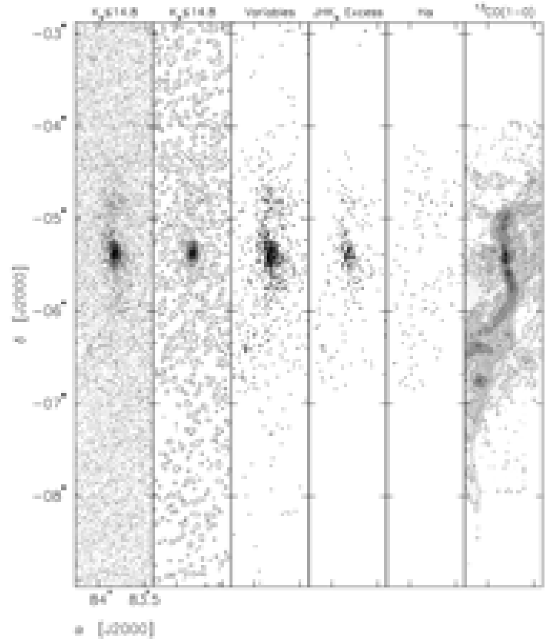

FIGURE 9. A plot depicting the variable stars found in the 2MASS survey of a region 1x3 degrees centered on the Orion Nebula Cluster. 1st panel: individual stars, K < 14.8 mag); 2nd panel: contour map of previous panel; 3rd panel: all variables found during the month-long survey period; 4th panel: stars showing excess emission at K-band; 5th panel: stars with Hα emission; and 6th panel 13CO contour map. Reprinted from Carpenter *et al.* [2].

5 and 27 μm and a FOV of 1.9$'$. For comparison, the Spitzer Warm Mission will provide imaging at 3.6 and 4.5 μm with image sizes (FWHM) of $\sim$ 1.7$''$ over a FOV of 5.5$'$. Of relevance to the surveys proposed in this are the times required by WISE, JWST, Keck and Spitzer to survey 1 square degree to fixed sensitivity in 1 hour, along with the angular resolution provided by each of the facilities. Figure 10 presents such a plot for a wavelength of 3.6 microns.

The plot reveals the enormous power of WISE to map 1 square degree to modest sensitivity in very short times (0.1), but at reduced angular resolution. By comparison, Spitzer can cover the same area to 10 times the sensitivity in only 1 hour, and to nearly 300 times the sensitivity of WISE in a few hundred hours. JWST can achieve much greater sensitivity that of Spitzer IRAC, but design constraints (primarily downlink data volume and slew/acquisition times) severely limit its ability to map large areas of sky. Also plotted on this graph is the sensitivity required by our proposed programs.

We conclude from this plot that

1. Surveys of the nature proposed here are impractical with JWST. Rather, JWST

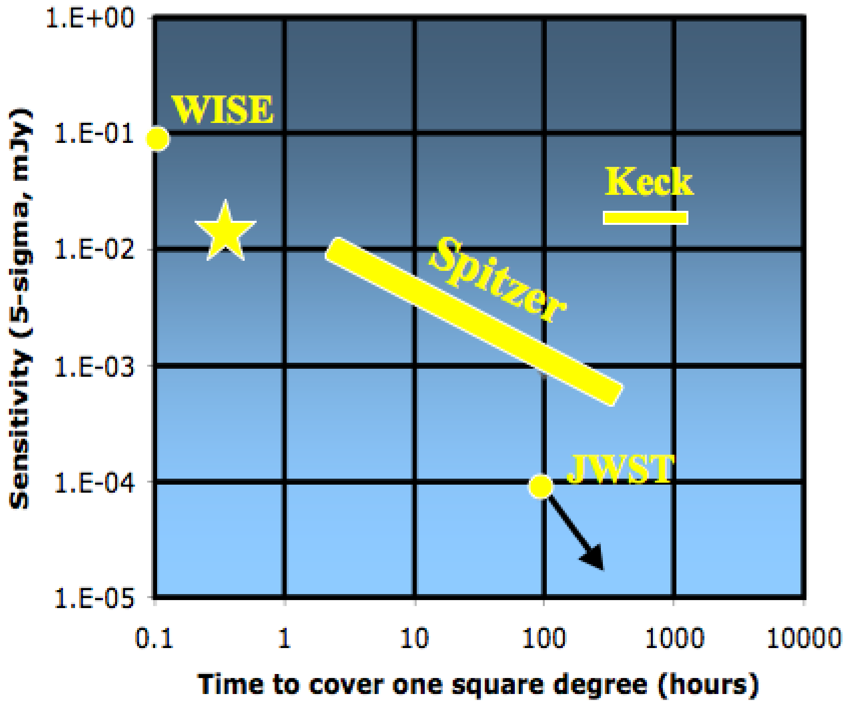

FIGURE 10. A comparison of the time to cover a one square degree field with WISE, Spitzer, JWST and Keck. The star (upper left) indicates the sensitivity limit required by the programs discussed here. Adapted from the Spitzer Science Center WISE memo, 3 April 2007.

pointings should be reserved for crowded regions, where its sensitivity provides overwhelming advantages, and for targets selected both from the Spitzer Warm Mission and the Spitzer archives that require higher sensitivity and/or higher angular resolution measurements at MIRI wavelengths

2. Surveys with Keck cannot reach the desired sensitivities in practical times – a natural consequence of working in the thermal regime with a warm telescope. Keck may be of value in making adaptive optics images of selected sources (e.g. protostars) where its angular resolution advantage (20 times Spitzer) can be brought to bear.
3. WISE lacks the sensitivity needed to survey significantly below the hydrogen-burning mass limit in nearby OB associations at ages up to >10 Myr needed to fully characterize the distributed population. For the more distant associations where source confusion is an issue, the lower angular resolution of WISE would compromise the ability to survey young clusters and embedded proto-clusters.
4. Spitzer (warm) hits a ‘sweet spot’ in both sensitivity and angular resolution that make it an ideal facility for carrying out the three science programs outlined here.

7. THE VALUE OF ARCHIVAL RESEARCH DURING THE SPITZER WARM MISSION ERA

Over the past three years, Legacy teams (C2D; FEPS; GLIMPSE), GTOs and GO teams have assembled databases of enormous value to addressing key problems in star formation. These programs include:

1. IRAC and MIPS surveys of nearby star-forming regions (e.g., Taurus-Auriga; NGC 1333 and IC 348) to sensitivities well below the hydrogen burning limit;
2. Pathfinder IRAC and MIPS surveys of the large scale star-forming processes operative in the inner galaxy;
3. IRS spectroscopic studies of large numbers of forming stars.

As a result, the Spitzer database contains IRAC, MIPS and in some cases, IRS data for hundreds of protostars unknown before the launch of Spitzer, thousands of young stellar objects surrounded by disks in various stages of evolution, and maps of large-scale star-forming events in the inner galaxy and near the galactic (clusters and associations) heretofore too obscured by intervening dust to enable detection or detailed study).

The database is so rich that neither the proposing teams or individuals nor archival researchers have begun to mine the data and carry out the ancillary observations at other wavelengths needed to enable full interpretation of key physical and chemical processes. To cite a few examples:

1. The compilation of protostars will provide a catalog for follow-up CARMA, ALMA, SMA, Herschel and in several years, ELT observations capable of probing the characteristics of protostellar cores and linking initial core conditions to outcome stellar properties;
2. The discovery of perhaps hundreds of 'transition disks' – disks which have developed inner opacity holes possibly associated with planet formation – demands follow-up high spectral resolution mid-IR and mm-wave observations aimed at diagnosing the gas content and kinematics of the circumstellar material orbiting parent suns – sine qua non for understanding whether planet formation is ongoing in these environments, what kinds of planets may be present, and where they were born.
3. The discovery of circumstellar debris disks surrounding relatively young stars is already providing the basis for adaptive optics observations aimed at understanding the distribution of material in these disks and how that distribution is linked to the presence of orbiting planets.

Together, further mining of the Spitzer databases combined with supporting complementary ground- and space-based data will provide the basis for a scientific legacy far exceeding the extraordinary results which have already emerged from the Spitzer mission. A good analog is the IRAS mission, which provided for nearly two decades a rich source both for discoveries emerging from the database itself as well as from complementary observations at other wavelengths.

8. CONCLUSIONS

Our proposed programs – and we suspect those of others – will no doubt aim to exploit the extraordinary ability of Spitzer during its warm mission phase to survey large areas at unprecedented sensitivity. In our major programs, we try to suggest the power of Spitzer to carry out large-scale surveys unbiased by prior knowledge of ongoing star formation or the presence of molecular clouds, and regions containing star forming complexes far more similar to those that dominate the appearance of external galaxies.

As we discuss above, Spitzer data alone will provide insight into (i) modes of star formation (isolated; aggregate; cluster); (ii) the sequence of star-formation over large regions of molecular clouds, as well as the role of 'triggers'; and (iii) the evolution of protostellar envelopes and circumstellar accretion disks. Moreover, we suggest a time domain study which is aimed at characterizing the variability characteristic of both protostars and the inner regions of accretion disks on timescales of hours, weeks, months and years – a program which may provide important insight into the accretion process.

The resulting databases will be incredibly rich – containing 1000s of protostars (including, we believe, those which will form very massive stars), and 10s of thousands of stars surrounded by circumstellar accretion disks in various stages of evolution.

These data not only promise new insights into the physical processes that initiate and propagate star formation, star formation in complexes analogous to those in other galaxies, and star-formation on the scale of a spiral arm, but as well represent critical pathfinder observations for follow-up with a variety of tools: complementary ground-based, Chandra and XMM imaging surveys; JWST imaging of targeted regions; AO-imaging of selected objects with large telescopes on the ground; high resolutions mid-IR and mm-wave spectroscopy of protostellar cores and clouds.

We believe that support of an archival research program aimed at mining both the extant database from the cold mission phase and the database that should emerge from the warm mission will yield enormous scientific return. The ideal program would be one that supports analysis not only of the Spitzer per se, but for the complementary data and theoretical studies that will enable deeper understanding of the fundamental physical processes at work in forming stars and planets.

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