Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy’s Evolution (SAGE)

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Abstract:
The recycling of matter between the interstellar medium (ISM) and stars drives the evolution of a galaxy’s visible matter. To understand this recycling, we propose to study the physical processes of the ISM, the formation of new stars and the injection of mass by evolved stars and their relationships on the galaxy-wide scale of the Large Magellanic Cloud (LMC). Due to its proximity, favorable viewing angle, multi-wavelength information, and measured tidal interactions with the Milky Way (MW) and Small Magellanic Cloud (SMC), the LMC is uniquely suited for surveying the agents of a galaxy’s evolution (SAGE), the ISM and stars. Our uniform and unbiased survey of the LMC (7x7 degrees) in all IRAC and MIPS bands will have much better wavelength
coverage, up to ~1000 times better point source sensitivity and ~11 times better angular resolution than previous IR surveys. Full and uniform coverage of the LMC is necessary to study the galaxy as a system, to develop a template for more distant galaxies and to create an archival data set (rights waived) that promises a lasting legacy to match current LMC surveys at other wavelengths. SAGE will reveal over 6 million sources including ~150,000 evolved stars, ~50,000 young stellar objects and the diffuse ISM with column densities $>1.2\times10^{21} \text{H/cm}^2$. In contrast to the MW and SMC, the diffuse IR emission in the LMC can be unambiguously associated with individual gas/dust clouds, thereby permitting unique studies of dust processes in the ISM. SAGE’s complete census of newly formed stars with masses $>1−3 \text{M}_{\odot}$ will reveal whether tidally−triggered star formation events in the LMC are sustained or short−lived. SAGE’s complete census of evolved stars with mass loss rates $>1\times10^{-8} \text{M}_{\odot}/\text{yr}$ will quantitatively measure the rate at which evolved stars inject mass into the ISM. SAGE will be the crucial link between Spitzer’s survey of individual IR sources in the MW (GLIMPSE) and its surveys of galaxies (e.g., SINGS) and a stepping stone to the deep surveys (e.g., GOODS & SWIRE).
1 Science Justification

The interstellar medium (ISM) plays a central role in the evolution of galaxies as the birthsite of new stars and the repository of old stellar ejecta. The formation of new stars slowly consumes the ISM, locking it up for millions to billions of years. As these stars age, the winds from low mass, asymptotic giant branch (AGB) stars and high mass, red supergiants (RSGs), and supernova explosions inject nucleosynthetic products of stellar interiors into the ISM, slowly increasing its metallicity. This constant recycling and associated enrichment drives the evolution of a galaxy’s visible matter and changes its emission characteristics. To understand this recycling, we have to study the physical processes of the ISM, the formation of new stars, and the injection of mass by evolved stars, and their relationships on a galaxy-wide scale.

Among the nearby galaxies, the Large Magellanic Cloud (LMC) is the best astrophysical laboratory for studies of the lifecycle of the ISM, because its proximity (~50 kpc, Feast 1999) and its favorable viewing angle (35°, van der Marel & Cioni 2001) permits studies of the resolved stellar populations and ISM clouds. The ISM in the Milky Way (MW) and in the Small Magellanic Cloud (SMC) is confused in infrared (IR) images due to crowding along the line of sight. In contrast, all LMC features are at approximately the same distance from the Sun, and there is typically only one cloud along a given line of sight, so their relative masses and luminosities are directly measurable. The LMC also offers a rare glimpse into the physical processes in an environment with spatially varying sub-solar metallicity (Z~0.3-0.5 Z⊙) that is similar to the mean metallicity of the ISM during the epoch of peak star formation in the Universe (z~1.5, Madau et al. 1996; Pei et al. 1999). The dust-to-gas mass ratio has real spatial variations and is ~2-4 times lower than the solar neighborhood (Gordon et al. 2003), resulting in substantially higher ambient UV fields than the solar neighborhood. In comparison to the SMC, the LMC is better surveyed in depth and coverage revealing structures on all scales and a global asymmetry that varies with wavelength (Fig. 1). The ISM gas that fuels star formation (Fukui et al. 1999; Staveley-Smith 2003), the stellar components that trace the history of star formation (Harris & Zaritsky 1999; Van Dyk et al. 1999; Nikolaev & Weinberg 2000), and the dust (Schwering 1989; Egan, Van Dyk & Price 2001) have all been mapped at a variety of wavelengths by the members of our team (Fig. 1). From the perspective of galaxy evolution, the LMC is uniquely suited to study how the agents of evolution, the ISM and stars, interact as a whole in a galaxy that has undergone tidal interactions with other galaxies, the MW and SMC (Zaritsky & Harris 2004; Bekki & Chiba 2005).

Spitzer IRAC and MIPS images will provide key insights into this life cycle because the IR emission from dust grains is an effective tracer of the ISM, star formation, and stellar mass-loss. Here, we propose a uniform survey of the LMC (7x7 degrees) in all the IRAC (3.5, 4.5, 5.8, and 8.0 μm) and MIPS (24, 70, and 160 μm) bands (Fig. 1) that will survey the agents of a galaxy’s evolution (SAGE). Full and uniform coverage of the LMC is necessary to understand the galaxy as a complete system, to develop a template for more distant galaxies, and to create an archival data set that promises a lasting legacy to match current LMC surveys at other wavelengths (Fig. 1). With much improved wavelength coverage, up to ~1000 times better point source sensitivity and ~11 times better angular resolution than the MSX and IRAS surveys (Fig. 2), SAGE will reveal over 6 million sources including ~150,000 mass-losing evolved stars and ~50,000 young stellar objects (YSOs). Our analysis of this survey will provide a quantum leap in our knowledge.
of the ISM, current star formation, and evolved star mass-loss that will fundamentally constrain galaxy evolution theories. SAGE will extend the Spitzer science legacy by linking the IR properties of galaxies from SINGS (PI: Kennicutt) to the individual IR sources in the MW from GLIMPSE (PI: Churchwell).

**Figure 1:** Examples of the many existing LMC surveys: HI (Staveley-Smith et al. 2003), CO (Fukui et al. 1999), IRAS 100 µm, Hα (Gaustad et al. 2001) with 1 epoch of MIPS coverage overlaid, and stellar density (Harris & Zaritsky 1999) with 1 epoch of IRAC coverage overlaid. The need for complete coverage of the LMC is clear from these images: structure is seen at all scales, and the structure is asymmetric and varies tremendously with wavelength over the whole galaxy. Examples of the expected data quality are demonstrated by the Spitzer observations. Top: LMC-survey-test strip with all 4 IRAC bands using the same depth planned for our survey (PI, Hora). Bottom: The star formation region Henize 206 in IRAC bands 3.6 & 4.5 µm in blue, 5.6 µm in cyan, 8 µm in green and MIPS 24 µm band in red (Gorijan et al. 2004).

**Interstellar Medium in the LMC:**
SAGE will be sensitive to faint, diffuse ISM dust emission corresponding to column densities >$1.2 \times 10^{21}$ H cm$^{-2}$ ($A_v=0.2$ mag). The angular resolution is sufficient to separate the stars from the ISM and to distinguish the major cloud populations: HII regions, photodissociation regions, molecular clouds, atomic clouds and diffuse medium. The full and uniform coverage of the LMC is necessary to sample the full range of physical conditions in the ISM. The combination of SAGE with existing multi-wavelength, high-resolution data on the LMC will allow us to determine the interrelationship of the different phases of the ISM and their relationship to stellar sources of UV radiation and kinetic energy. In particular, we will address two key questions:
1) **What are the properties and abundance of dust in different parts of the LMC?** UV extinction measurements have indicated that the dust properties in the LMC vary spatially (Gordon et al. 2003). Most of the dust mass is in the largest grains, which will be traced by the MIPS 70-160 µm images. We will compare these images to the H I and CO data, make regional correlations between the dust and gas, and thereby map out the dust-to-gas ratio across the galaxy. In addition to the amount of dust, the grain size distribution can be measured using the color ratios (IRAC 3.6, 5.8 and 8 µm tracing PAH, MIPS24 tracing small grains, and MIPS 70+160 tracing larger grains). Theoretical studies as well as studies of elemental depletion in the ISM suggest that shocks are the main drivers of the grain size distribution. We will measure the IR colors for a wide range of environments (gas phases, star clusters, supernova remnants, and with distance from center), to trace spatial variations of grain properties. In particular, variations in the properties of the smallest grains, as traced by PAH emission, are of fundamental importance to the thermodynamics of the ISM because small grains are very efficient in heating the gas through the photoelectric effect (Bakes & Tielens 1994). ISO (Madden 2000) and Spitzer (Houck et al. 2004; Engelbracht et al. 2005) observations have shown that low-metallicity galaxies have weak or absent PAH emission. The absence of PAH and small grains will have profound influence on the gas heating and the existence of cold and warm phases in the ISM (Wolfire et al. 1995).

2) **What is the structure of the ISM in the LMC?** On scales of a few to several hundred pc, the ISM is organized into clouds and shells (Fig. 1), as revealed by Hα and H I studies. At Spitzer’s angular resolution and sensitivity, we will be able to separate shells and individual supernova remnants, and to measure their dust content and properties. In addition, we will search for secondary generations of triggered star formation, such as observed in the MSX observations of a large shell in the LMC (Cohen et al. 2003). These large-scale features represent the connection between generations of stars. Comparing to radio continuum images that trace the emission from cosmic rays, we will also determine whether the radio/far-IR correlation, which was found to be very tight for integrated galaxy fluxes (Helou et al. 1985), applies on scales smaller than the cosmic-ray diffusion path length.

**Galaxy-wide Star Formation in the LMC:**

Star formation in the LMC appears to be a stochastic process, in which stars form in clumps, clusters and supershells (e.g. Panagia et al. 2000; Walborn et al. 1999). The star formation may be self-propagating through the energetic feedback of stellar winds and supernovae (e.g. Oey & Massey 1995; Efremov & Elmegreen 1998) but this stellar feedback also acts to eventually squelch star formation by dissipating the local ISM (Yamaguchi et al. 2001;Israel et al. 2003). The CO survey of the LMC (Fukui et al. 1999) has uncovered 261 giant molecular clouds (GMCs) with similar masses and radii to MW GMCs. Current optical and near-IR observations reveal that one-third of the LMC GMCs are forming populous young star clusters that may become Superstar clusters (such as 30 Dor) while an equally large fraction exhibit no massive star formation (Fukui et al. 1999). This contrast in star formation activity may indicate a phase of deeply embedded star formation in the latter and emphasizes the need for a complete census of star formation that only Spitzer's longer IR wavelengths can bring.

SAGE will provide a comprehensive picture of the current star formation activity which is traced by the IRAC (3.5, 4.5, 5.8, and 8.0 µm) and MIPS (24, 70, and 160 µm) bands. Our expected point source sensitivity, which has been verified by an LMC-survey-test strip (Fig. 1 & 2), will
reveal ~50,000 HII regions and YSOs on physical size scales of ~0.5 pc (IRAC) to ~1.5-9 pc (MIPS). The 358 known HII region complexes will be imaged at higher resolution than previous IR surveys (see Henize 206 in Fig. 1; Gorjian et al. 2004). For the first time, tens of thousands of lower mass (>1-3 M⊙) Class 0, I and II YSOs in small Taurus-like clusters (~12 stars, Fig. 2) will be observed and studied. FU Orionis systems, detectable by their variability, will be revealed by our 2 epochs of photometry. Analyzing SAGE’s point source catalog in the context of the CO, HI and stellar population surveys, we will address two outstanding issues:

1) **What is the galaxy-wide star formation rate of the LMC and how do the details vary on a scale of a few pc?** We will provide a direct measurement of the current state of star formation in the LMC by comparing the star forming regions’ IR intensities to the CO and HI gas emission. Our census of star formation on all scales in the LMC will provide a detailed mapping of the star formation rate and the range of stellar masses formed. This map will be compared to other measures of star formation, such as Hα or UV emission. In addition, the statistical properties of star-forming regions in the LMC will be compared directly to those in the inner MW, as revealed by GLIMPSE, providing an interesting comparison of star formation processes in two significantly different environments.

![Figure 2: Spitzer color-magnitude diagrams will define populations of key sources throughout the LMC: YSOs (1-30 M⊙), HII regions, Taurus-like clusters, O-rich and C-rich AGB stars, RSGs and main sequence O stars. Symbols, as noted in the legend, represent template/model photometry of Cohen (1993) and Whitney et al. (2004). SAGE’s sensitivity limit (solid line) falls x1000 below the MSX limit (dashed line) and the lower limit to AGB mass loss, >10⁻⁸ M⊙ yr⁻¹ (dotted line). The smallest points on the left CMD are real IRAC photometry points extracted from the LMC-survey-test strip map of the LMC bar (see Figure 1) and are near the expected sensitivity limit even in this most crowded region of the LMC. The (yellow) filled circle and star represent a subregion of Taurus containing ~12 stars, placed at the distance of the LMC.](image)

2) **Do tidally-triggered star formation events sustain themselves by propagating through the ISM, or are they short-lived?** As satellites of the MW, the LMC and SMC suffer periodic tidal-force episodes (Gardiner and Noguchi 1996). An optical analysis of the SMC (Harris &
Zaritsky 2004; Zaritsky & Harris 2004) has shown at least two distinct star formation events coincident with its past perigalactic passages providing a direct measurement of interaction-induced star formation. Our Spitzer map of the current star formation rate will be compared with the map of the recent star formation history of the LMC (Harris & Zaritsky 2005) to determine if the star formation, which was triggered during the last LMC perigalacticon, ~400 Myr ago, has propagated through the ISM or has fizzled out.

**Stellar Mass Loss Return to the LMC:**
High mass loss during the AGB and RSG phases leads to the formation of circumstellar envelopes that are observable via their dust emission in all IRAC and MIPS bands. SAGE will be sensitive to all mass losing evolved stars (mass-loss rates $>10^{-8} \text{M}_\odot \text{yr}^{-1}$) across the entire LMC; a dramatic improvement upon the MSX survey, which detected only the most luminous evolved stars (Fig. 2), and the ISO mini-survey, which was limited in scope to a 0.5 square degree region and a limit of ~10 mag at 8 µm (Loup et al. 1999). By revealing the circumstellar dust shells of ~150,000 evolved stars, SAGE will provide an unprecedented view of how evolved star mass loss shapes the surrounding ISM. In particular, we will address two major questions.

1) **What is the mass budget of material injected into the ISM by evolved stellar winds?** We will quantify the contributions of mass loss from the numerous lower luminosity AGB stars, the IR bright stars at the tip of the AGB, and the rare RSGs and LBVs. Present estimates disagree on the relative contributions from these different stellar classes to the injected mass budget of a galaxy (Tielens 2001). By combining the IRAC and MIPS photometry with existing 2MASS and optical photometry, we will construct the spectral energy distribution (SED) of each evolved star. Because these stars vary on a ~1 yr timescale, our two epochs of photometry, separated by ~3 months are crucial to constrain the expected variability of Spitzer photometry. Following the general approach outlined by Alard et al. (2001), we will use dust radiative transfer codes to relate these SEDs to mass-loss rates, assuming 10 km s$^{-1}$ expansion velocities (see van Loon et al. 1999). We will initially derive mass-loss rates based on a range of possible dust compositions from spectra of bright LMC AGB stars available in the literature (van Loon et al. 1999), but we will propose for cycle3 and 4 IRS observations of representative samples of LMC stars to improve the estimates. Our LMC map of calculated mass loss rates will provide a basis for tying mass-loss-rate return to the parent stellar population, its metallicity and its star formation history (e.g. Holtzman et al. 1999; Olsen 1999; Harris & Zaritsky 2005).

2) **How does stellar mass loss rate depend on stellar parameters: luminosity, effective temperature, period, composition (carbon- or oxygen-rich), metallicity?** Stellar mass loss can drive the late stages of stellar evolution yet the mechanism for mass loss remains poorly understood. Van Loon et al. (1999) found that mass loss rate increased for redder stars and for higher luminosity stars as expected since pulsation at the top of the AGB is expected to play a key role in mass loss for the most luminous stars. With mass-loss rates derived for the complete population of evolved stars in the LMC, we can approach such correlations from a statistical basis that will delineate the mass-loss process for each segment of the stellar population. Luminosities and effective temperatures will be derived from the SEDs. Periods will be derived from the MACHO light curve database, with variability indications supplemented by our two epochs of Spitzer observations. The Spitzer colors (Fig. 2) and near-IR colors (Cioni & Habing 2003) can differentiate between the Carbon-rich (C-rich) and oxygen-rich (O-rich) AGB stars. The ratio of these populations should vary with regional metallicity because the amount of 3rd dredge-up necessary to transform an O-rich to C-rich AGB star is smaller in lower metallicity
stars making the conversion more efficient (Costa & Frogel 1996; Schultheis et al. 2004).

**Larger Astronomical Impact, a Legacy for the community:** Our proposed survey offers a data set that connects a survey of the MW (GLIMPSE; Benjamin et al. 2003) and a survey of galaxies (SINGS Legacy; Kennicutt et al. 2003). SAGE is complementary to the survey of the SMC, but the greater structural complexity of the SMC, and poorer multi-wavelength coverage of the SMC would render the science goals proposed here more difficult to achieve for the SMC. Knowledge gained from SAGE about star formation and mass loss in the LMC will fundamentally constrain semi-empirical modeling of galaxies, and be used to interpret deep Spitzer surveys, e.g. GOODS (Dickinson et al. 2003) and SWIRE (Lonsdale et al. 2003). In short, without the SAGE survey, there would be a missing link in our understanding of galaxies. Our imaging survey is a base for future cycle spectroscopic investigation with Spitzer of star forming regions, mass losing stars, and the ISM. This, in turn, is a precursor for future work in the LMC with SOFIA, Herschel, Astro-F, the James Webb Space Telescope (JWST), and the Atacama Large Millimeter Array (ALMA). In comparison with other wavelengths, existing mid- and far-IR surveys of the LMC lag in both angular resolution and sensitivity. SAGE offers a service to the community by closing the gap. The community will mine the SAGE database to study classes of objects that are not part of our investigation, e.g. planetary nebulae, supernova remnants, main sequence massive stars, compact clusters and serendipitous discoveries that lead to new science.

## 2 Technical Plan

SAGE will be a uniform, unbiased survey of the LMC (~7x7 square degrees), in all the IRAC (3.6, 4.5, 5.8 and 8 µm) and MIPS (24, 70 and 160 µm) bands (Fig. 1). The angular resolutions of 2 arcseconds (0.5 pc at the distance to the LMC) in the IRAC bands, and 6 (1.5 pc), 18 (4.5 pc) and 40 (10 pc) arcseconds in the MIPS bands will be 11 times better than the angular resolution of the MSX and IRAS surveys. The science-driven point source sensitivity of 5.1, 7.2, 41 and 44 µJy in the IRAC 3.6, 4.5, 5.8 and 8 µm bands, respectively, and 0.31, 10 and 60 mJy in the MIPS 24, 70 and 160 µm bands, respectively, will improve upon these previous surveys by a factor of ~1000 and with better wavelength coverage (Fig. 2). The most efficient strategy is to map the entire LMC with a 7x7 array of 1.1x1.1 degree tiles of IRAC HDR exposures, and a 19x2 array of 4x0.4 degree tiles of MIPS fast scans (Fig. 1). To minimize artifacts that limit sensitivity, we will map the LMC at two epochs, separated by ~3 months, which will provide a ~90 degree roll angle difference. This strategy has proven to be the most effective way of removing artifacts in the SINGS project and is recommended by the SSC and IRAC and MIPS instrument teams. These two epochs will be critical for measurements of source variability expected for evolved stars and some YSOs. The observing strategy is designed to maximize the science return and observatory efficiency, while minimizing observing artifacts, and requires 511 total hours (291 IRAC, 220 MIPS). Below we expand on the reasoning for this approach and our proposed data products.

**Full and Uniform Coverage:** The science of SAGE requires full and uniform coverage. The coverage must extend to the IR edge of the LMC and beyond to provide adequate background in both scientific terms, to measure the background and Galactic foreground source populations, and in data reduction terms for the Ge:Ga MIPS arrays which require off-source background for accurate photometric measurements. Proper source identification in the LMC needs to be done over the whole galaxy because the different types of IR sources, e.g. AGB stars and YSOs, have
different spatial distributions in the LMC which can be used to improve the source identification (e.g. Egan et al. 2001; Cioni et al 2000). Our strategy for full coverage will duplicate ~3% of the LMC which is currently covered by GTO and GO MIPS & IRAC programs. Mapping strategies that carefully avoid these small regions without many time constraints would increase the total time request by ~50%.

**Sensitivity, Column Density Limits & Source Count Estimates:** SAGE will have maximum scientific impact and longest duration as a legacy dataset only if the population of red objects is completely sampled down to the confusion limit imposed by Spitzer’s spatial resolution, and the diffuse emission at all spatial scales is mapped at high enough signal-to-noise ratio to determine physical conditions in PDRs, HII regions, and molecular clouds. Figure 2 shows example color-magnitude diagrams for the LMC that illustrate the sensitivity required to study the two populations of greatest interest in the IR, evolved stars and forming stars. IRAC [8.0] sensitivity of $>15^{\text{th}}$ magnitude allows the measurement of YSOs down to a few solar masses depending on their age, as younger YSOs of a given mass are more luminous. This limit also ensures that all evolved stars with mass loss rates $>10^{-8} M_\odot$ yr$^{-1}$ will be detected. The ISO observations by Glass et al. (1999) and Alard et al. (2001) on the Galactic bulge, and by Ramdani & Jorissen (2002) on the low metallicity globular cluster 47 Tuc suggest that mass loss will be unimportant for LMC stars with 8 $\mu$m fluxes below 1 mJy (Fig. 2). Color-magnitude diagrams constructed from other combinations of bands yield similar requirements, of ~45s exposure time with IRAC and 50s with MIPS. With these integration times, diffuse emission in galaxies (e.g. M81; Gordon et al. 2004) is observed to be ~0.5, 1, 1, 5, and 10 MJy/Sr at [5.8], [8.0], [24], [70], and [160] respectively with a resulting signal-to-noise ratio of ~5 per pixel. From these diffuse emission sensitivity limits in the MIPS and IRAC 5.6 and 8 $\mu$m bands, we estimate a minimum detectable column density of $1.2 \times 10^{21} \, \text{H cm}^2$ ($A_V=0.2$ mag) by assuming a solar neighborhood SED for the diffuse dust emission (Desert, Boulanger & Puget 1990) and the LMC gas-to-dust ratio. The IRAC 3.6 and 4.5 $\mu$m bands will also detect this same column density when their angular resolution is degraded to the 160 $\mu$m band. For the study of the diffuse ISM, we will work with residual images, i.e. ones with the point sources subtracted, that we will smooth to improve the signal-to-noise ratio.

The point source extraction of the LMC-survey-test strip with IRAC, which uses the same depth planned for our survey (PI, Hora), demonstrates that we will be near background limited even in the most confused regions of the stellar bar (Fig. 2). We estimate the total number of sources detectable in our survey to be ~6 million by extrapolating the number in this test strip, which were detected in at least 2 IRAC bands, to the 7x7 degree survey area with a correction for the relative stellar density of the bar to the whole LMC (Fig. 1). The ~150,000 evolved stars estimate followed a similar approach but included only sources detected in all 4 IRAC bands having colors $0.2 < [3.6]-[8.0] < 3.5$. The ~50,000 YSOs and HII regions estimate extrapolated the number of sources in the nebulous regions of the test strip, which were detected in all 4 IRAC bands having colors $[3.6]-[8.0] > 3.5$, to the fraction of the surveyed region containing star formation regions, ~0.25 of the whole LMC.

**Mapping Strategy:** The mapping strategy maximizes observing efficiency while minimizing artifacts that compromise data quality that will limit the science. The IRAC and MIPS artifacts fall in two classes: random effects (e.g. cosmic rays, bad pixels) and systematic effects that are tied to pixel location and usually systematically effect rows/columns. IRAC systematic effects include: saturation latents, scattered light, MUX bleed, banding, and column pulldown. MIPS
systematic effects include: streaking due to saturation latents and time dependent responsivity drifts (70 & 160 µm) and insufficient 160 µm coverage in fast scan mode. Clean removal of random effects requires at least 4 overlapping measurements. Systematic effects are optimally removed by combining images taken with a ~90 degree roll angle difference which is achieved with two epochs of observations separated by ~3 months. This strategy is recommended by the SSC and the IRAC and MIPS instrument teams and has been proven in the SINGS data analysis.

To achieve the above goals, four 12s HDR IRAC frames taken in pairs at two different epochs are planned for a total frame time per pixel of 48s. For IRAC, the maximum tile size is 1.1x1.1 degrees (14x28 frames) with half-array steps (similar to the GLIMPSE mapping technique). Steps are done instead of dithers to minimize the time required to cover the desired area. Each IRAC AOR consists of a 14x28 map of 12s HDR frames, with a duration of 10691s. The LMC is mapped with a 7x7 grid of these AORs, taking 145.5 hr per epoch, or a total of 291.0 hours. Each MIPS AOR consists of ten 4 degree fast scan legs with 1/2 array cross scan steps, with a duration of 2.89 hours. The LMC is mapped with a 19x2 grid of these AORs, taking 110 hours per epoch, or a total 220 hours. Tight sequential constraints relative to the roll angle rate of change will be invoked so that neighboring long strips have sufficient overlap. We have carefully designed our MIPS strategy to allow for off-source measurements in every scan leg which will allow for accurate self-calibration of the instrumental effects. The MIPS fast scan mode does not achieve full coverage at 160 µm. We have simulated the combined coverage of the two MIPS 160 µm maps. The simulation shows that the combined map will have a good basket weave pattern with small gaps less than a pixel in size. The well-sampled 160 µm PSF (~3 pixels per FWHM) means that interpolation can be used to fill the gaps. The exposure times per pixel are 60s, 30s, and ~9s at 24, 70, and 160 µm, respectively.

Data Processing and Release Plan to the Community: A uniform legacy data product consisting of a point source catalog and mosaicked images will be provided to the community. We will make immediately available the standard data pipeline products produced by SSC: flux calibrated images and mosaics of the individual AORs. Beginning 12 months after receipt of final observations we will make available source catalogs and mosaic images produced by our enhanced pipelines, with the goal to support Spitzer Cycle 4 proposals. The catalogs and mosaic images will be delivered in six month increments as they are processed. The IRAC and MIPS sources will be merged into one catalog. The IRAC and MIPS mosaic images will have the same size and projection to ensure the images line up.

IRAC pipeline: We will use a modified GLIMPSE pipeline to process the IRAC data. The GLIMPSE pipeline removes or corrects for image artifacts (cosmic rays, column pulldown, banding; see the Spitzer Observer’s Manual); does point source extraction and band merging across multiple observations and wavelengths; and mosaics images. The modifications to the pipeline will include dealing with HDR frames (multiple exposure times), mosaic photometry (instead of single frame), and bandmerging with MIPS data. The IRAC processing effort will be led by GLIMPSE team members Churchwell (lead), Whitney, Meade, Jansen and Babler with guidance provided by Joe Hora (SAO/IRAC instrument scientist), Remy Indebetouw (GLIMPSE team) and Bill Reach (IRAC lead).

MIPS pipeline: The MIPS data will be reduced using the MIPS instrument team pipeline after which we will further process the data using programs designed to remove the transients associated with the MIPS detectors (Gordon et al. 2004, 2005). These programs have been
successfully used on large GTO galaxies (M31, M33, & M101) and all the SINGS galaxies. In particular, we have drawn upon our experience observing other large galaxies in optimizing the LMC observing strategy to best overcome saturation effects in the MIPS bands. The MIPS processing effort will by done by MIPS instrument team members Gordon (lead), Engelbracht, Perez-Gonzalez, Misselt, Kelly, and Latter.

**Source Classification:** We will use the point source catalog of 4 IRAC bands and 3 MIPS bands, derived from this survey in combination with the Las Campanas survey (Zaritsky & Harris 1999), 2MASS and DENIS catalogs to classify the sources in our sample. The ground work for the source classification scheme has already been laid by several members of our team. Cohen (1993) developed a template scheme for the Galaxy. Cohen, Indebetouw, and Churchwell have adapted this scheme to an IRAC and 2MASS color classification scheme for GLIMPSE. Whitney et al. (2004) have developed YSO models for GLIMPSE. Van Dyk adapted Cohen’s classification scheme for the brightest IR sources in the MSX survey of the LMC (Egan et al. 2001). For SAGE, Indebetouw and Cohen will modify the Cohen color classification scheme to reflect the low-metallicity and lower dust content of the LMC sources. IRS spectroscopy will be obtained to support the IR classification, e.g. the IRS spectroscopy of the brighter AGB stars, by Kemper et al. In cycles 3 and 4, Kemper & Tielens will lead follow-up IRS spectroscopic programs of representative samples of LMC sources detected in SAGE.

**Science Teams:** Our proposed work will be tackled by an international team of experts on the LMC, star formation, evolved stars, ISM, dust and source classification. Our large team will be split into smaller science teams to concentrate on the three themes raised in this proposal: ISM, star formation (SF), and evolved stars (ES). Team members’ interests are labeled with the abbreviations in parentheses. Meixner will lead the star formation team, Blum will lead the evolved star team and Reach/ Bernard will co-lead the ISM team.

### 3 References

4 Brief Resume/Bibliography

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2002-pres Associate Astronomer at Space Telescope Science Institute
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Research Experience: 15 years experience in ground-based, airborne and spaceborne IR astronomy; 53 refereed journal publications; JWST/Mid-Infrared Instrument (MIRI) Science Team, PI of numerous projects involving: circumstellar dust, dust radiative transfer, evolved stars, star formation, circumstellar molecular and atomic gas, photodissociation regions; 13 years experience in ground based IR instrumentation, (PI of NIRIM camera), 15 year experience in millimeter interferometry


“UC HII regions & Massive Star Formation” Churchwell, 2002, ARAA, V. 40, 27


“A Quantitative Comparison of SMC, LMC, and Milky Way UV to NIR Extinction Curves,”


5 Observation Summary Table
A draft of the AORs has been submitted. This table summarizes the survey.

<table>
<thead>
<tr>
<th>Target/Field</th>
<th>Position (J2000)</th>
<th>Flux Density/Surface Brightness</th>
<th>AOT/ Bands</th>
<th>Integration Time/Pixel</th>
<th>Estimated AOR Duration</th>
<th># of AORs</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC-IRAC</td>
<td>5:18:48 -68:41:60 (7x7 degree area)</td>
<td>3.6 um: 5 uJy – 1 Jy 4.5 um: 7 uJy – 1 Jy 5.8 um: 41 uJy – 1 Jy 8.0 um: 44 uJy – 1 Jy</td>
<td>IRAC Mapp ing -all</td>
<td>48 s/pixel</td>
<td>10453 s</td>
<td>98</td>
</tr>
<tr>
<td>LMC IPS-Main</td>
<td>5:18:48 -68:41:60 (7x7 degree area)</td>
<td>24um: 0.3 mJy – 1 Jy 70um: .-0.01 - 1 Jy 160um: 0.06 -1 Jy</td>
<td>MIPS Scan -all</td>
<td>50 sec (fast rate)</td>
<td>10417 s</td>
<td>76</td>
</tr>
</tbody>
</table>

6 Status of Existing Observatory Programs

Meixner, the PI, is not a PI nor technical contact on any existing Spitzer programs.

Churchwell, PI GLIMPSE Legacy program:

The GLIMPSE survey has produced over 30 million Catalog sources and 48 million Archive sources which will be delivered to SSC in March 2005. Mosaics from the entire survey should be finished by the end of 2005. Publications from this survey include:


Engelbracht, PID 718: Data obtained, reduced and published (Engelbracht et al. 2004, ApJS, 154, 248)

Gordon, MIPS/GTO: “Dust in Giant Extragalactic H II Regions in M101” The data have been partially obtained (MIPS & IRAC) with IRS data still to come. The MIPS & IRAC data are reduced and a paper is in preparation.

Gorjian/Werner, PID 86: "Imaging and Spectra of X-Ray Selected Seyfert Galaxies," Data is in the process of being obtained.


Hora, PID 125: “Magellanic Clouds Survey” Observations obtained in Nov. 2004, data reduced and source catalogs produced (data shown in Figure 2 of this proposal). Analysis is underway.

Kemper, PID 1094: Spitzer fellowship, data obtained, partially reduced.

Kemper, PID 3591: “The O-rich condensation sequence at low metallicity: Large Magellanic Cloud AGB and post-AGB stars.” Data is not yet obtained.

Misselt, PID 3578: "Infrared Extinction in the Magellanic Clouds" Status - Most data obtained and being analysed. Some data not yet obtained.

Reach, PID 3137: Spitzer-Discovered protostars in the Elephant Trunk Nebula Observations complete. Preliminary analysis complete and sufficient for brightest sources. Detailed analysis of fainter sources and diffuse emission in progress with scientific data analyst being hired.

Reach, PID 3119: Survey of cometary debris trails Observations more than half complete. Pipeline developed and preliminary analysis of all comets observed to date. Results presented at DPS 2004 in Louisville. First paper on Rosetta mission target comet is mostly complete.
Reach, PID 210: Survey of cometary debris trails
Observations complete. MIPS observations included in pipeline developed for PID 3119.
Analysis of IRS data is underway.

Reach, PID 218: Trifid Nebula
Observations half done. Trifid data analyzed, press release at Jan 2005 AAS in San Diego; color image appeared in NY Times; first paper mostly complete. Other targets not yet done.

IRAC, MIPS, and IRS observations completed. A combined Spitzer/Hubble/Chandra/VLA/VLBA/Keck paper on this object currently in preparation.

Van Dyk, PID 226(DDT): “Spitzer Observations of a Nearby Supernova (SONS): SN 2004dj in NGC 2403,” Two of four epochs in IRAC, MIPS, and IRS completed, two still to be scheduled. A paper on the first mid-IR spectra of a supernova, since SN 1987A, is in preparation.

Zaritsky, PID 3393: “Exploring the Nature of Dust in the Outer Disks of Galaxies”
Pipeline processed data for 1 of 2 sources recently obtained by PI.

7 Proprietary Period Modification
To promote follow-up efforts by the community, we waive our proprietary time; i.e. shorten the proprietary period from 12 months to 0 months.

8 Justification of Duplicate Observations
There are several existing programs in the LMC, most notably GTO programs by Werner, Gehrz, and Houck, and GO maps by Chu and Gorgian (each 20-40 arcmin in size). The numerous other programs are largely only a few IRAC frames or MIPS photometry mode pointings in extent, and most are deeper than our survey. In total they cover ~3% of the LMC. We carefully studied several alternative mapping strategies in order to avoid duplication with the ROC targets. Alternative strategies that offer the least time constraints requires 50% additional total observing time making it an undesirable approach.

We suggest that our mapping strategy, including likely embargoes of the tiles and scans which overlap with existing programs, is the most efficient way to produce a high-quality legacy dataset.

9 Justification of Scheduling Constraints
To map the LMC in a time efficient way, our proposed observations will need to be time constrained. We simulated a variety of schemes to map the LMC in IRAC and MIPS with and without timing constraints and with and without duplications. Reducing scheduling constraints while avoiding duplication increases the time request by ~50% making that approach undesirable. Essentially, the mapped regions have to be much bigger to achieve uniform coverage with less time constraints. The size of the LMC maps is such that we can accomplish
the full 7x7 degree area in one IRAC campaign or one MIPS campaign. We have conferred with the SSC about our strategy and found that it could be accomplished with current scheduling practice. We also include a relative time constraint of ~3 months between the two passes of the full 7x7 degree maps so that they will have ~90 degree relative rotation angle which is important for the correction of artifacts. Based on our team members’ experiences with GLIMPSE and SINGS, we would plan to work with the SSC to provide them with optimized AORs for their chosen scheduled date for observations.

10 Data Analysis Funding Distribution

PI M. Meixner: 38%
Co-I E. Churchwell 18%
Co-I K. Gordon 18%
Co-I J. Hora 4%
Co-I R. Indebetouw 4%
Co-I R. Blum 4%
Co-I W. Reach 3%
Co-I M. Cohen 3%
Co-I B. Whitney 3%
Co-I V. Gorjian 2%
Co-I S. Oey 1%
Co-I D. Zaritsky 1%
Co-I J. Gallagher 0.5%
Co-I J. Frogel 0.5%

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