1 Scientific Justification

1.1 Spitzer SINGS a SONG of Galactic Evolution

Galactic evolution is inherently correlated with molecular gas within a galaxy. In the Milky Way Galaxy, we observe molecular gas in dense molecular clouds. The collapse of these molecular clouds triggers a burst of star formation. In other galaxies, we observe molecular gas trigger star formation in spiral arms via the passage of a spiral density wave (Vogel et al. 1983), within nuclear regions of galaxies (Young and Deveraux 1991), and at the ends of bars in barred spiral galaxies (Sheth et al. 2000). Thus, molecular gas serves as the fuel for star formation and is fundamentally connected with galaxy evolution.

Prior to the Infrared Space Observatory (ISO) and the Spitzer Space Telescope (Spitzer), much of our knowledge of the conditions of the molecular gas in galaxies came from studies of CO emission. CO (J = 1 - 0) emission directly traces the mass of the coldest (T = 5 - 10 K) molecular hydrogen (H_2) within galaxies. Spitzer has given us access to the lowest pure rotational levels of H_2. The H_2(0-0)S(0) (28.2 μm) and H_2(0-0)S(1) (17.1 μm) lines can both be observed with the Spitzer IRS long-low (LL) modules (14 - 38 μm, with LL1 covering 14 - 21 μm and LL2 covering 21 - 38 μm). These lines trace the warm (T = 100 - 300 K) molecular gas.

The *Spitzer Infrared Nearby Galaxies Survey* (SINGS) legacy program has surveyed 75 nearby galaxies (Kennicutt et al. 2003). These galaxies range in Hubble type, luminosity, star formation, and nuclear activity. The SINGS legacy has used the Spitzer IRS LL (LL1 and LL2) module in spectral mapping mode to map radial strips across 65 galaxies within their sample. The radial strips cover a range of dynamically distinct regions within galaxies (i.e. nuclei, spiral arms, HII regions, etc.). The strips are roughly 50 x 600 arcsec in area and give us spatially resolved spectra across the galaxies. **These strips contain a wealth of data.** In addition to observing H_2 S(0) and H_2 S(1) in the LL strips, there are a atomic features ([NeIII] (15.55 μm), [SIII](18.71 μm), [FeII](25.83 μm), [OIV](25.89 μm), [SIII](33.48 μm), and [SiII](34.82 μm) and broad PAH complexes at 16.4 μm and 17 μm (Smith et al. 2004).

While the SINGS team is currently studying the H_2 lines (Roussel et al. 2007, in preparation), **they have only done so for the nuclear regions** of the SINGS sample. Their study of the H_2 uses aperture averaged spectra over the nuclei of the 65 galaxies to determine the excitation-temperature, mass, and ortho-to-para ratio (OPR) of H_2 within the galaxies. Their study **does not** explore H_2 outside of the nuclei of the galaxies and they **do not** take advantage of the spatial resolution of the spectra across the galaxy.

We propose to take full advantage of the spectacular SINGS IRS LL coverage across the nuclear regions and disks in order to understand the spatial distribution of the warm (T = 100 - 300 K) H_2 **across a sample of 18 galaxies that have been observed by both SINGS and the Berkeley-Illinois-Maryland-Array Survey of Nearby Galaxies (BIMA SONG) (Regan et al. 2001, Helfer et al. 2003)**. The 18 galaxies (listed in table 1) have been studied as part of BIMA SONG and have CO (J = 1 - 0) maps publicly available on the NASA extragalactic database (NED). CO (J = 1

- 0) emission traces the cold (T = 5 - 10 K) H_2 and the maps allow us to understand the spatial distribution of the cold H_2 mass. We will use the SINGS LL data cubes to map the H_2 S(0) and H_2 S(1) lines across the galaxies. From these lines will will determine the warm H_2 mass and temperature distributions across the galaxies. We will correlate the cold H_2 (traced by CO emission) with the warm H_2 (traced by the H_2 S(0) and H_2 S(1) emission) in order to understand the relationship between the warm and cold H_2. Additionally, we would like to understand the connection between H_2 (both the cold and warm phases) and the mid-infrared spectral diagnostics (17 μm PAH feature, [NeIII] (15.55 μm), [OIV](25.89 μm) as a shock tracer, and electron density determined by [SIII](33.48 μm)/[SIII](18.71 μm)) that we can also map from the SINGS LL data cubes.

We have used IRS spectral mapping data acquired though GO - 20138 (PI: K. Sheth) of M51a (the Whirlpool galaxy, NGC 5194) as a test case for our study (Brunner et al., submitted). In working with M51a, we have created a data analysis pipeline that takes IRS SL and LL data cubes and creates extinction corrected line flux maps. Our pipeline utilizes PAHFIT (Smith et al. 2007) to decompose mid-infrared spectra across the LL data cubes. These maps are powerful tools for understanding the spatial variation of H_2 and other mid-infrared spectral lines.

For M51a, we had both SL and LL coverage of an overlapping strip across M51a. We have used our pipeline to map H_2 S(0), H_2 S(1) (both lines in LL), H_2 S(2), H_2 S(3), H_2 S(4), and H_2 S(5) (all four lines in the SL). Figure 1 shows the maps of the H_2 S(0) and H_2 S(1) emission across M51a. We have used these lines to understand the temperature and mass distribution of the warm H_2 across M51. In figure 2, we show the warm mass distribution compared to the warm H_2 temperature distribution. We find that the H_2 is warmest within the center of the galaxy and is coolest in the spiral arms (which contain the bulk of the H_2 mass). We also compared the cold H_2 to the warm H_2. In the inner spiral arms, we see offsets in the location of the peak emission within the spiral arms. Why is this? Additionally, we are able to map H_2 excitation-temperature and mass in spiral arms out to 7 kpc from the nucleus of the galaxy. The SINGS LL strip cover a much greater distance in the galaxy allowing us to understand how excitation-temperature and H_2 mass vary as a function of galactocentric radius.

We have also studied the ortho-to-para ratio (OPR) across M51a. From our study we found that the lower pure rotational levels (H_2 S(0), H_2 S(1), H_2 S(2), and H_2 S(3)) exhibit an OPR of 3 (or very close to) in the nuclear and spiral arm regions. Under the assumption that the OPR is 3 across the galaxies, we can map the warm H_2 excitation-temperature and H_2 mass across the 18 galaxies that we would like to study.

For galaxies observed by both SINGS and SONG we would like to address the following questions:

1. How does the warm (T = 100 - 300 K) H_2 temperature and mass vary across dynamically distinct regions within galaxies? The majority of the H_2 mass radiates in the lower energy level H_2 lines. In mapping the H_2 S(0) and H_2 S(1) lines across the LL strips we can determine the H_2 excitation-temperature and mass distributions across the galaxies (Rigopoulou et al. 2002, Higdon et al. 2006). This will allow us to undertand how the H_2 temperature and mass varies between the nucleus, spiral arms, and inter-arm regions within the galaxies. We will determine the fraction of warm H_2 that is found in the nucleus of the galaxies and the fraction that is found in the disk and spiral arms. We will also determine how the excitation-temperature and mass changes in spiral arms as a function of galactocentric radius.

2. How do the warm and cold H_2 correlate across dynamically distinct regions in galaxies? Are there offsets in the location of the warm and cold H_2? If so, why? The combination of CO data and the H_2 lines for every galaxy will allow us to correlate the different molecular gas phases. We find that in M51a, the warm and cold H_2 are offset in different regions. Do we observe offsets in the location of warm and cold H_2 in other galaxies? What does this mean?

3. How does the warm and cold H_2 mass correlate with the mid-ifrared spectral diagnostics? The [OIV](25.89 μm) line has been observed to arise from shocks, the stellar winds of Wolf-Rayet stars, high-mass star photoionization, and active galactic nuclei (Schaerer and Stasinska 1999, Lutz et al. 1998, Smtih et al. 2004). With PAHFIT, we are able to de-blend the [FeII](25.99 μm) and [OIV](25.89 μm) lines. This allows us to discern regions where shocks are exciting the ISM. If we observe [OIV](25.89 μm) emission coinciding with H_2, this would imply that the H_2 is excited by shocks. We will use our ability to spatially resolve the mid-infrared emission features to discern the excitation mechanism of warm H_2 in dynamically different regions of the galaxies.

Additionally, the ratio of the [SIII](33.48 μm) and [SIII](18.71 μm) lines provide a determination of the electron density in HII regions. Comparison to the H_2 data will allow us to determing the location of cold and warm H_2 to the hot ionized gas in HII regions. This will allow us to understand the relationship of the hot ionized gas and and the warm and cold molecular gas within the spiral arms of galaxies.

The comparison of H_2 emission to other mid-infrared spectral diagnostics will allow us to understand the conditions of the ISM across galaxies and the processes that excite the ISM. In figure 3, we present maps of H_2 S(0), H_2 S(1), [OIV](25.89 μm), [SIII](33.48 μm), and [SIII](18.71 μm) from M51a.

2 Technical Plan

The SINGS legacy has provided IRS low resolution data cubes for 65 galaxies. As of data release 4 (DR4), there are 16 galaxies observed by SONG that have publicly available SINGS low resolution data cubes. Two more SONG galaxies will have data cubes available via data release 5 (DR5). The 18 galaxies that we will study are listed in table 1.

Data cubes for individual SINGS galaxies are publically available. They can be found at: http://irsa.ipac.caltech.edu/data/SPITZER/SINGS/galaxies/.

We will also acquire the CUBISM cube projects (not publicly available) from the SINGS legacy team for each of the galaxies. CUBISM is the data reduction and analysis software for IRS spectral cubes. Co-I Sheth has access to all of the SINGS data and will help us to acquire the CUBISM cube projects for the 18 galaxies. Both Brunner and Sheth are experts with the CUBISM software.

Data Analysis: H_2 maps, atomic line maps, and PAH feature maps will be created using the pipeline developed by the PI and Co-Is while working on M51a. Our pipeline takes both SL and LL data cubes in FITS format and runs PAHFIT through the cubes (Smith et al. 2007). PAHFIT is a mid-infrared spectral fitting routine that decomposes spectra into individual components and measures the integrated line flux of features. In running PAHFIT through a data cube, we save the flux measurement at every point for every line, and in doing so, we create a map of ever feature observed from 14 - 38 μm.

We will use the MIRIAD package to analyze the CO data and we will use WIP to compare the spatial distribution of H_2, CO, and the mid-infrared spectral diagnostics. Brunner will lead the data analysis though it should be mentioned that Brunner, Sheth, Wolfire, and Vogel all have extensive experience with MIRIAD and WIP. Sheth and Vogel were both integral members of the BIMA collaboration and have tremendous insight into the CO data and results. Interpretation of the H_2 results and the comparisons of the H_2 to CO and H_2 to the mid-infrared spectral diagnostics will be shared by Brunner, Dufour, Sheth, Vogel, and Wolfire.

NGC 0628	NGC 3627	NGC 4736
NGC 2841	NGC 3938	NGC 4826
NGC 2976	NGC 4321	NGC 6946
NGC 3184	NGC 4569	NGC 7331
NGC 3351	NGC 4579	*NGC 0925
NGC 3521	NGC 4725	*NGC 5055

Table 1: Listed are the 18 galaxies that we will study. The (*) denotes a galaxy for which the SINGS LL data cubes will be available in SINGS data release 5 (DR5). SINGS LL data cubes are curently available for the 16 other galaxies.

3 Figures and Tables

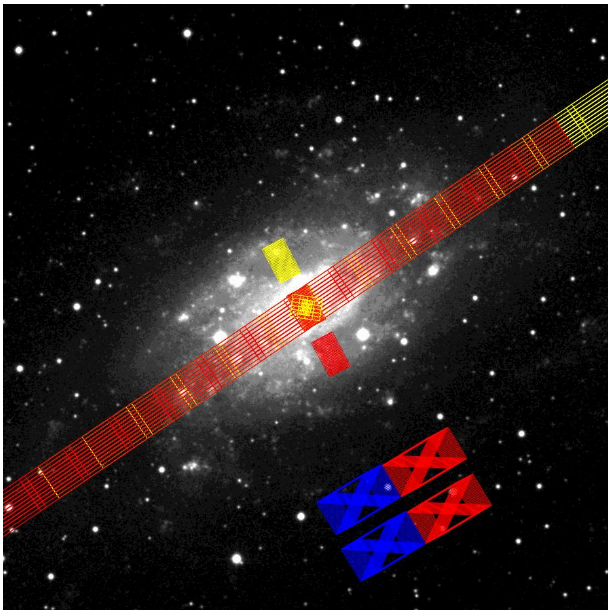

Figure 1: SINGS IRS spectral mapping footprints for NGC 2403. The long strip red and yellow strips across the galaxies are the LL1 and LL2 coverage respectively. The three rectangles across the central region of the galaxy are the SL1 and SL2 observations. The two smaller sets of footprints over the nucleus are the Spitzer IRS short-high (SH) and long-high (LH) observatios. SINGS has acquired similar data sets for 65 galaxies, 18 have been observed by BIMA SONG. SINGS has only studied H_2 for the nuclear regions of each galaxy where the short high (SH), short-low (SL), long-high (LH), and long-low (LL) observations overlap. SINGS has not taken advantage of the spectacular IRS LL coverage across the disks of galaxies. The blue and red boxes in the bottom right of the image are IRS peak up observations.

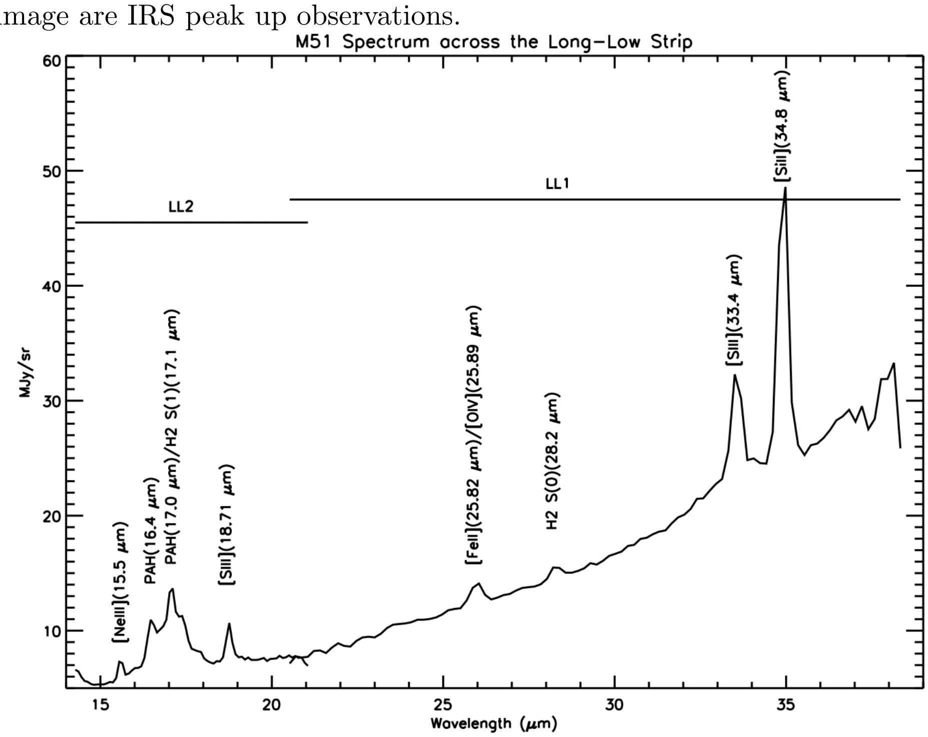

Figure 2: A sample LL spectrum taken from the M51 strip (GO -20138) with spectral features noted. Our study will focus on the H_2 emission across the 18 SINGS LL strips.

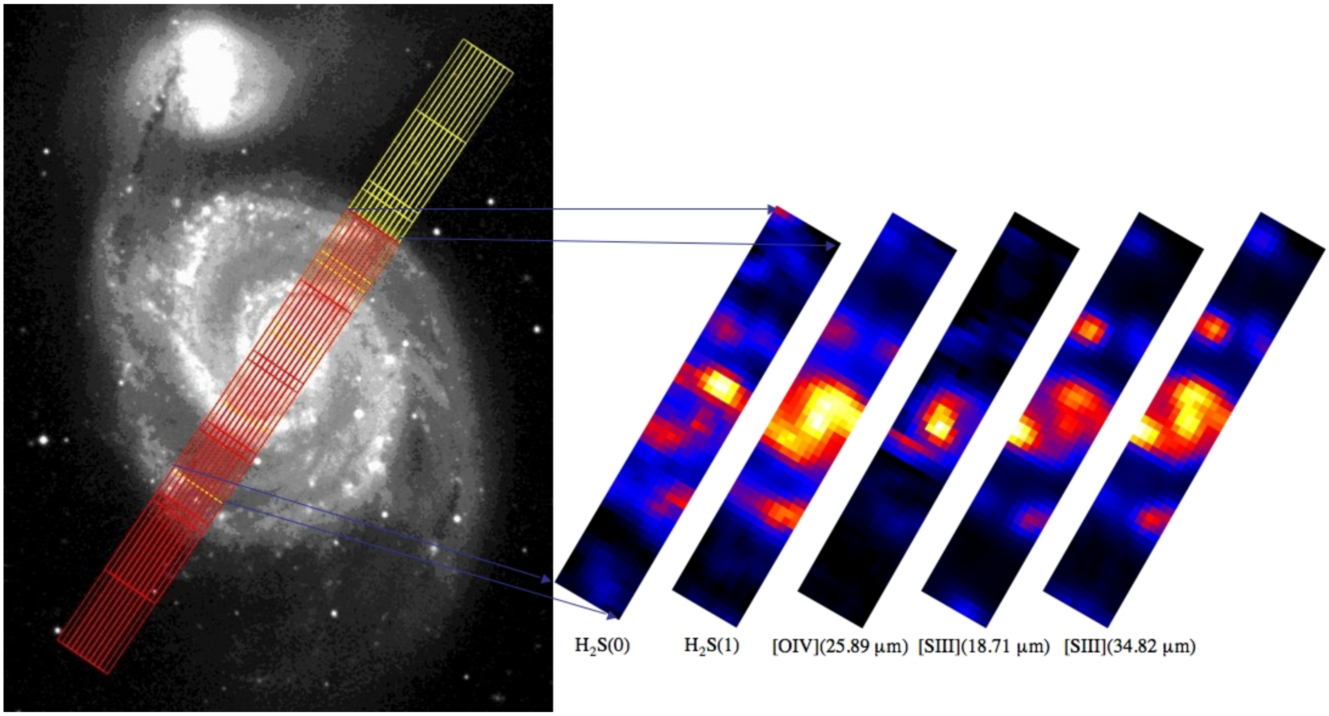

Figure 3: Shown are the IRS LL spectral mapping AORs for M51a (GO - 20138). Maps of the individual lines were created with our PAHFIT pipeline allowing for us to determine the flux of al lines from 14 - 38 μm in the LL data cube. Shown are the maps of the H_2 S(0) (28.2 μm), H_2 S(1) (17.1 μm), [OIV](25.89 μm), [SIII](18.71 μm), and [SIII](33.82 μm) lines.

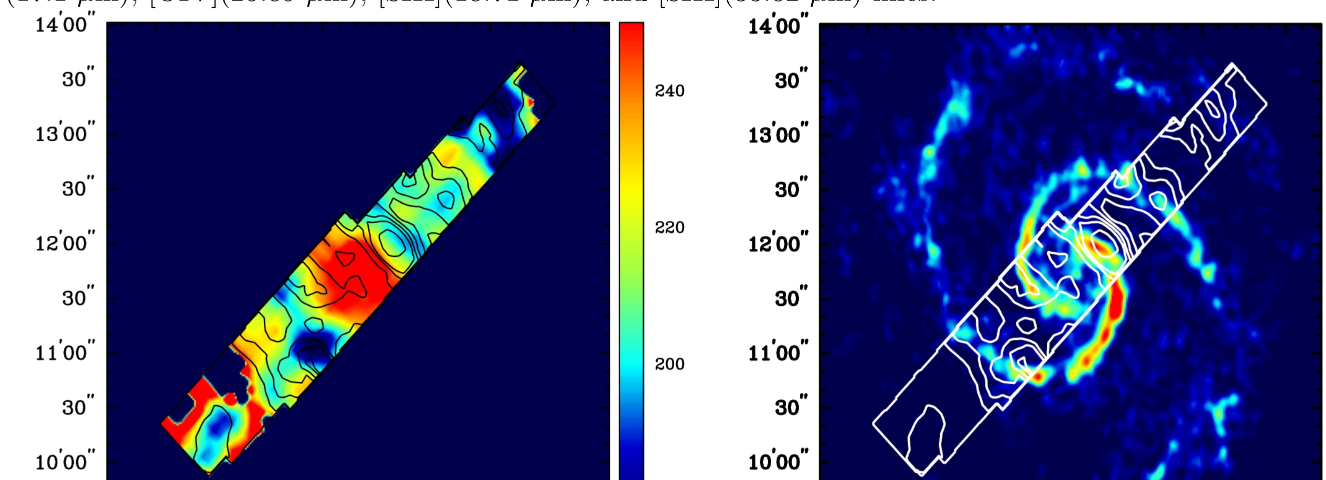

Figure 4: *Left*: Map of the warm (T = 100 - 300) mass distribution (in contours) plotted over the excitation temperature distribution (in color). The temperature distribution is in units of Kelvin; the contours are spaced at .... M_{sun}/pc^2. *Right*: Comparison of the warm H_2 mass to the cold (T = 5 - 10 K) H_2 that is traced by CO (J - 1 - 0) emission. The contours are the same as in the plot on the *left*. The map is in units of ... The CO map of M51 was obtained by the BIMA SONG.

4 References

Brunner et al., 2007, submitted
Helfer et al., 2003, ApJS, 145, 259
Higdon et al., 2006, ApJ, 648, 323
Kennicutt et al., 2003, PASP, 115, 928
Lutz et al., 1998, AA, 333, L75
Regan et al., 2001, ApJ, 561, 218
Rigopoulou et al., 2002, AA, 389, 374
Roussel et al., 2007, TBD
Sheth et al., 2000, ApJ, 532, 221
Smith et al., 2004, ApJS, 154, 199
Smith et al., 2007, ApJ, accepted (currently on astro-ph/0610913)
Schaerer and Stasinska, 1999, AA, 345, L17
Vogel et al., 1988, *Nature*, 334, 402
Young and Deveraux, 1991, ApJ, 373, 414

5 Brief Resume/Bibliography

PI: Gregory Brunner is a graduate student at Rice University and a 2006-2007 Spitzer Visiting Graduate Student Fellow. During the fellowship he worked with Kartik Sheth on IRS spectral mapping data of M51a. He has developed a pipeline that takes IRS low resolution data cubes and creates line flux maps of every spectral feature in the data cube. He is currently working on submitting a draft of the results of a study of the H_2 emission, excitation, and mass across M51a that he completed during the Spitzer Visiting Graduate Student Fellowship.

Co-I: Reginald Dufour is a professor in the Department of Physics and Astronomy at Rice University. His interests are observational astrophysics of planetary nebulae, HII regions, and galaxies.

Co-I: Kartik Sheth is a research scientist at Spitzer Science Center and a member of the Spitzer IRS instrument team.

Co-I: Stuart Vogel is a professor of astronomy and the director of the lab for millimeter-wave astronomy at the University of Maryland. His main research interests are star formation and galaxy evolution.

Co-I: Mark Wolfire is a research scientist at the University of Maryland. He is an expert on modeling photo-dissociation regions.

Selected references relevant to this proposal from the team:

Brunner et al. 2007, submitted
Dufour, R.J. et al.
Dufour, R.J. et al.

Dufour, R.J. et al.
Sheth, K. et al., 2000, ApJ, 532, 221
Sheth, K. et al., 2002, AJ, 124, 2581
Sheth, K. et al., 2004, ApJL, 614, 5
Vogel, S.N. et al., 1993, PASP, 105, 666
Vogel, S.N. et al., 1988, *Nature*, 334, 402
Wolfire, M. et al., 2003, ApJ, 586, 278
Wolfire, M. et al., 1995, ApJ, 443, 152

6 Status of Existing Spitzer Programs

This section should provide the status of any Spitzer programs (observing or AR/TR) on which the PI or ANY of the CoIs are PI or technical contact (TC). This section should NOT have any figures. This section should NOT provide a comprehensive history of every Spitzer program in which you have EVER been involved. If you have more than 5 programs, you may just provide a summary paragraph. If you feel a list of your 10 most recent Spitzer publications really MUST be included, put them here.

Co-I R. Dufour is a Co-I on GO - 3412, GO - 20049, and GO - 20057. What is the status Reggie?

Co-I K. Sheth is the PI for GO - 20138 and Co-I on GO - 20587. The data for program 20138 has been reduced and analyzed and is in preparation for publication. The data for program 20587 has been reduced and is currently under analysis.

Co-I S. Vogel is a Co-I on Go - 20138 and GO - 20587.

Co-I M. Wolfire is ...

7 Financial Contact Information

Provide the contact information for the appropriate person in the institution's Sponsored Research Office (or equivalent) for the PI and Co-I's that require funding support.

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College Park, MD 20742
301.405.6272

8 Cost Plan and Budget Narrative

Put the descriptive budget narrative here. It should describe how the funds will be allocated. There is no page limit to the narrative. Fill in the cost plan table (Spitzer Cycle-4 Budget). Cost plans are limited to one year duration (for Cycle-4: Oct 2007 - Sep 2008) and the funds must be used within 2 years of the award.
Archival and Theoretical Research proposers must send three paper copies of the institutionally endorsed cost plan and narrative to the SSC by Friday, February 24 2007, 5:00 pm (PST).
The Spitzer Science Center's postal mailing address is:
Spitzer Science Center
California Institute of Technology
Mail Code 314-6
1200 East California Boulevard
Pasadena, CA 91125
USA

Table 2: Spitzer Cycle-4 Budget 1 Oct 2007 – 30 Sep 2008

Narrative				
Footnote	Cost Element			
	Direct Labor Hours (by labor category)	Hours	Rate	Amount
	Total Direct Labor			
	Overhead	Base	Rate	
	Total Overhead			
	Material Costs			
	Material Burden			
	Total Material			
	Subcontract Cost			
	Subcontract Burden			
	Total Subcontract			
	Other Direct Cost (ODC)			
	Total ODC			
	Sub-Total Cost			
	Total General & Administrative			
	Total Cost			