1 Scientific Justification

1.1 Mapping Molecular Hydrogen Excitation and Mass in Nearby Galaxies from the SINGS Archive

The fundamental evolutionary process in a galaxy is the conversion of gas into stars. In the Milky Way, all star formation occurs in molecular clouds (Blitz 1995); although, not all molecular clouds are actively forming stars. In galaxies, star formation is triggered whenever the molecular gas surface density is enhanced, for example, by a spiral density wave (Vogel et al. 1988), by increased pressure as in galactic nuclei (Young and Devereux 1991), due to the hydrodynamic shock along the leading edge of bars, and in the transition region at the ends of bars (Sheth et al. 2000, Kenney and Lord 1991). Although the connection between star formation and molecular gas is well-established, the exact mechanisms for initiating, controlling, and inhibiting star formation are not well-known.

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 and rotational-vibrational transitions of H_2 in the near-infrared. CO rotational line emission directly traces the mass of the coldest (T = 5 – 100 K) H_2 while the near-infrared H_2 emission traces the hot (T $\geq$ 1000 K) H_2. This leaves the intermediate, warm (T = 100 – 1000 K) molecular gas unexplored. With Spitzer, the warm (T = 100 - 1000 K) molecular gas can be observed through the pure rotational transitions of H_2 with lower J H_2 lines tracing the 100 - 300 K H_2 and higher J lines tracing the 300 - 1000 K H_2. The H_2(0-0)S(0) (28.2 μm) and H_2(0-0)S(1) (17.0 μm) lines are observed with the Spitzer IRS long-low (LL) modules (14 - 38 μm, with LL2 covering 14 - 21 μm and LL1 covering 21 - 38 μm)(see Figure 1). 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 (at a resolution of ∼ 5 arcsec) across the galaxies (Figure 2). **These strips contain a wealth of data on the spatial distribution of molecular hydrogen yet to be studied.**

We propose to take advantage of the spectacular SINGS IRS LL coverage across both 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 for which we have CO (J = 1 - 0) maps for each galaxy. 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 we will model the warm H_2 mass, excitation-temperature, and

UV radiation field across the galaxies (Kaufman et al. 2006). 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 H_2 excitation mechanisms by comparing the H_2 distribution to UV and optical imagery (U, B, V, R, and H_α) and the mid-infrared spectral diagnostics ([O IV](25.89 μm), a shock diagnostic and the [S III](33.48 μm)/[S III](18.71 μm) ratio, an HII region electron density diagnostic). The latter two are also mapped by the SINGS LL data cubes.

For a pilot study, we used IRS spectral mapping data for M51a (the Whirlpool galaxy, NGC 5194), acquired in Cycle 2 (GO - 20138, PI: Sheth, K.). Building upon CUBISM and PAHFIT (Smith et al. 2007), we have developed a new and unique software code to create extinction-corrected and continuum-subtracted line maps. This capability **is not** available via CUBISM or PAHFIT but is the logical next improvement as it creates a full two-dimensional map of any desired feature. Our software processes IRS low resolution data cubes created in CUBISM, then uses PAHFIT as the engine to simultaneously decompose the spectrum at each point in the map and reconstructs the best fit fluxes for every feature into individual two-dimensional maps. These maps are analogous to a continuum-subtracted H_α map or a CO map which most observers are used to, except that we can produce maps for every mid-infrared diagnostic available to Spitzer. This technique is particularly powerful for blended features such as H_2 S(1) (blended with the PAH feature at 17.0 μm) which cannot be extracted from available software packages.

Maps of H_2 S(0) and H_2 S(1) emission across M51a are shown in Figure 3. These maps were produced with our software. We used these lines to model the excitation-temperature and mass distribution of the warm H_2 across the disk of M51a. In Figure 4, we show the distribution of the warm H_2 mass compared to the excitation-temperature. 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). Comparison of the CO map (the cold H_2) to the warm H_2 shows offsets in the location of the peak emission within the spiral arms. Why is this? Do we see this in other galaxies? Comparisons to UV imagery, optical imagery, and mid-infrared spectral feature maps can help us to answer these questions.

For the 18 galaxies observed by both SINGS and SONG we will address the following:

1. How does the warm (T = 100 - 300 K) H_2 **excitation-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 model the H_2 excitation-temperature and mass distributions across the galaxies (Rigopoulou et al. 2002, Higdon et al. 2006). In addition to modeling the H_2 excitation and mass across the galaxies, we will use H_2 S(0) and H_2 S(1) line ratios to model the radiation field across the galaxies (Kaufman et al. 2006). This will allow us to undertand how the H_2 excitation and mass vary between the nucleus, spiral arms, inter-arm regions, and dust lanes within the galaxies. These observations provide constraints on the energy injection processes (i.e. radiative heating, shocks, turbulence) that heat the molecular phases as a function of position in a galaxy.

2. How do the cold and warm 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? CO (J = 1 - 0) emission traces the cold (T = 5 - 10 K) H_2. The combination of CO data and the H_2 lines for every galaxy will allow us to correlate the different molecular gas phases. Is the warm molecular gas strongly associated with the surface layers of giant molecular clouds as predicted by Kaufman et al. (2006) or an inter-arm component that is bright in H_2 but devoid of CO? 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? Offsets in the location of the cold and warm H_2 are most likely due to the heating sources (such as massive star formation) which we can examine from U, B, V, R, and H_α data. The U, B, V, R and H_α imagery provide a means to identify actively star forming regions within spiral galaxies and determine the age, metallicity, and star formation rate of stellar clusters and associations in actively star forming galaxies (Talbot et al. 1979, Jensen et al. 1981, Calzetti et al. 2005).

3. How do the warm and cold H_2 mass correlate with other mid-infrared spectral diagnostics? The [O IV](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, Smith et al. 2004). With our software, we are able to de-blend the [Fe II](25.98 μm) and [O IV](25.89 μm) lines. This allows us to discern regions where shocks are exciting the ISM. If we observe [O IV](25.89 μm) emission coinciding with H_2, this would imply that the H_2 is excited by shocks. Additionally, the ratio of the [S III](33.48 μm) and [S III](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 relative to the hot ionized gas (and thus the sites of current star formation) in HII regions.

1.2 Utilizing and Extending the SINGS Legacy

The SINGS legacy archive has delivered maps of bright infrared emission features from the LL radial strips as part of their data products. They have created emission line maps using CUBISM but are only able to produce maps of un-blended emission features that are bright across the entire galaxy. They are delivering [Ne III](15.5 μm) and [Si II](34.8 μm) line maps (Kennicutt et al. 2003). **Our software will produce maps of every emission feature in the LL data cubes, even the extremely faint (such as H_2 S(0)) or blended lines (such as [O IV](25.89 μm) and H_2 S(1)) (see Figure 3).** Much of the analysis discussed here constitutes the proposed thesis work of G. Brunner; however, the wealth of data and maps produced will not be fully analyzed in the time frame for his thesis. We believe that these maps will be of use to the larger community and we will release all of the maps and the software to the public following the submission of our analysis for publication.

To date, the SINGS legacy has not studied the spatially resolved spectra across the SL or LL data cubes. Their studies of atomic features (Dale et al. 2006), PAHs (Smith et al. 2007), and H_2 (Roussel et al., in press) use aperture-averaged spectra over the nuclear regions (and extranuclear HII regions in the case of Dale et al. 2006). Our software, maps, and analysis of the spatially resolved H_2 will be an ideal complement to the SINGS legacy.

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 construct CUBISM cube projects (not publicly available) for each of the 18 galaxies that we will be studying. CUBISM is the data reduction software for IRS spectral cubes. 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 software developed by the PI and Co-Is while working on M51a. Our software has the ability to create maps of spectral features that are extremely faint and/or are blended with other spectral features. This allows the recovery of faint H_2 S(0) emission and the H_2 S(1) line (blended with the PAH 17.0 μm complex). Our software takes both SL and LL data cubes in FITS format, processes them, and then 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 our software through a data cube, we save the flux measurement for every line from 14 - 38 μm at every spatial position, and in doing so, we create maps of every feature observed in the LL data cubes. This is a very powerful tool for understanding the spatial variation of mid-infrared spectral features, especially the H_2 lines. Figure 3 displays maps of the H_2 S(0), H_2 S(1), [O IV](25.89 μm), [S III](18.71 μm), and [S III](33.48 μm) emission across a strip of M51a that has been spectrally mapped with the Spitzer IRS LL modules. The H_2 S(1) line and the [O IV](25.89 μm) lines are blended with spectral features (the 17.0 μm PAH complex and [Fe II](25.98 μm), respectively) but our software is able to map the emission across the entire IRS LL strip.

We will use maps of the H_2 S(0) and H_2 S(1) emission to model the warm (T = 100 - 300 K) H_2 excitation-temperature and mass across the SINGS LL strips. The H_2 S(0) and H_2 S(1) lines place constraints on the H_2 excitation and mass within a galaxy. Additionally, ratios of the H_2 S(0) and H_2 S(1) lines probe the radiation field of dense PDRs and molecular clouds in star forming regions. Brunner and Wolfire will lead the H_2 modeling effort.

We will compare the warm H_2 mass distribution to the cold (T = 5 - 10 K) H_2 mass distribution traced by CO emission. 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 will be shared by Brunner, Sheth, and Vogel.

Comparison of the H_2 to the U, B, V, R, and H_α imagery and mid-infrared spectral diagnostics will be shared by Brunner and Dufour. Dufour is an expert on UV, optical, and IR imagery and spectroscopy and will provide insight into the meaning of the comparisons between the H_2 and optical imagery, UV imagery, and IR diagnostic maps.

The data analysis described here is a massive undertaking and coupled with the analysis of H_2 in M51a (from GO - 20057), it will provide the foundation for PI Brunner's Ph.D. thesis on the spatial distribution of H_2 in nearby galaxies.

Galaxy	RC3 Type and Luminosity Class
NGC 0628	SA(s)c I
NGC 2841	SA(r)b I
NGC 2976	SA(pec)c IV
NGC 3184	SAB(rs)cd II-III
NGC 3351	SB(r)b II
NGC 3521	SAB(rs)bc II-III
NGC 3627	SAB(s)b II
NGC 3938	SA(s)c I
NGC 4321	SAB(s)bc I
NGC 4569	SAB(rs)ab I-II
NGC 4579	SAB(rs)b II
NGC 4725	SAB(r)ab I-II
NGC 4736	SA(r)ab II
NGC 4826	SA(rs)ab II-III
NGC 6946	SAB(rs)cd I-II
NGC 7331	SA(s)b I-II
*NGC 0925	SAB(s)d II-III
*NGC 5055	SA(rs)bc II-III

Table 1: Listed are the 18 galaxies that we will study and the corresponding third reference catalogue (RC3) type and luminosity class. 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

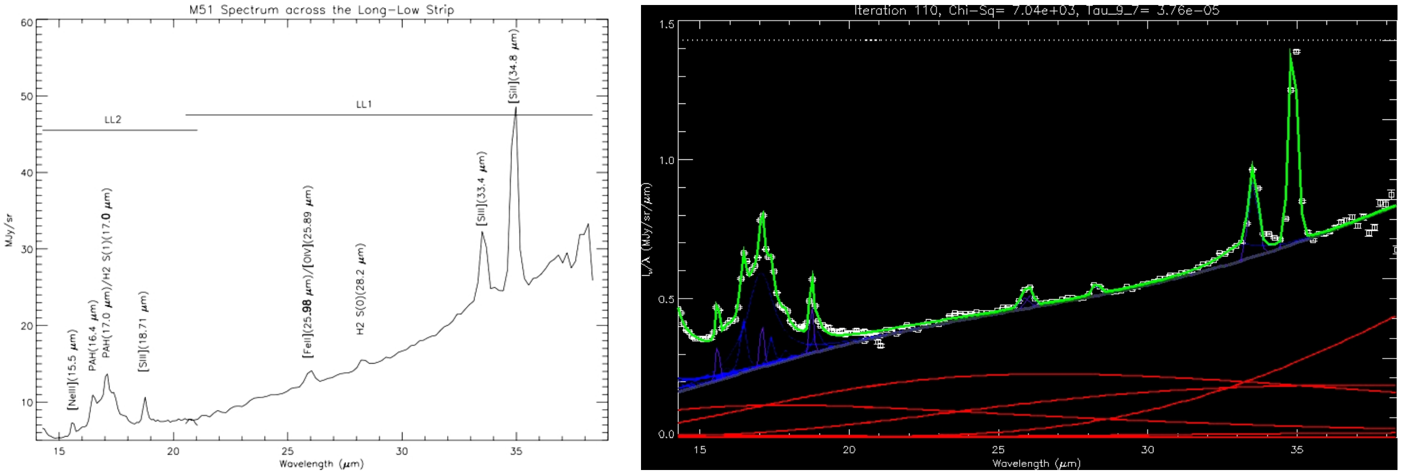

Figure 1: *Left*: A sample LL spectrum taken from the M51a strip (GO - 20138) with spectral features noted. Our study will focus on the H_2 emission across 18 SINGS LL strips. *Right*: We have developed software that processes IRS data cubes and then runs PAHFIT across individual spectra within the data cubes. In doing so, we create maps of all spectral feature between 14 and 38 μm. Here we display a sample PAHFIT spectrum from M51a. The green line is the fit to the entire spectrum, the grey line is the fit to the continuum, the blue gaussian-lorentzians are measurements of PAH features, and the purple lines are the gaussian-lorentzian fits to individual spectral lines.

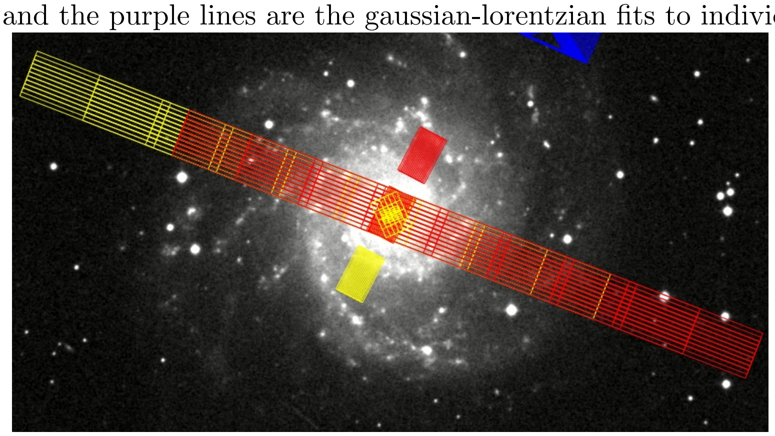

Figure 2: SINGS IRS spectral mapping footprints for NGC 0628. The long red and yellow strips across the galaxy are the LL1 and LL2 coverage respectively. The three smaller parallel rectangles across the central region of the galaxy are the SL1 and SL2 observations. The two smaller sets of footprints over the nucleus are the Spitzer IRS short-high (SH) and long-high (LH) observations. SINGS has acquired similar data sets for 65 galaxies, 18 have been observed by BIMA SONG.

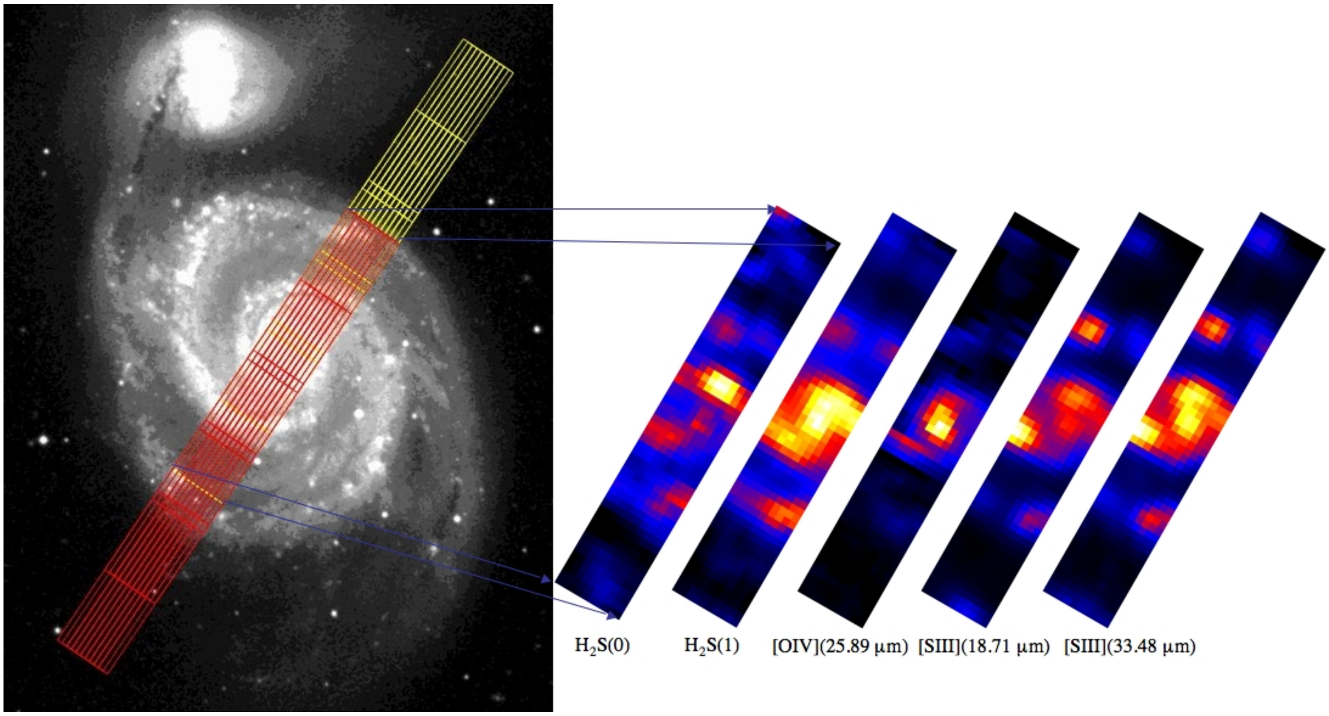

Figure 3: Shown are the IRS LL spectral mapping AORs (*left*) and maps of the H_2 S(0) (28.2 μm), H_2 S(1) (17.0 μm), [O IV](25.89 μm), [S III](18.71 μm), and [S III](33.48 μm) lines (*right*) for M51a (GO - 20138). Maps of the individual lines were created with our software. The resolution of each map is 5.08 arcsec/pixel. For M51a, this corresponds to a beam size of about 0.055 kpc^2.

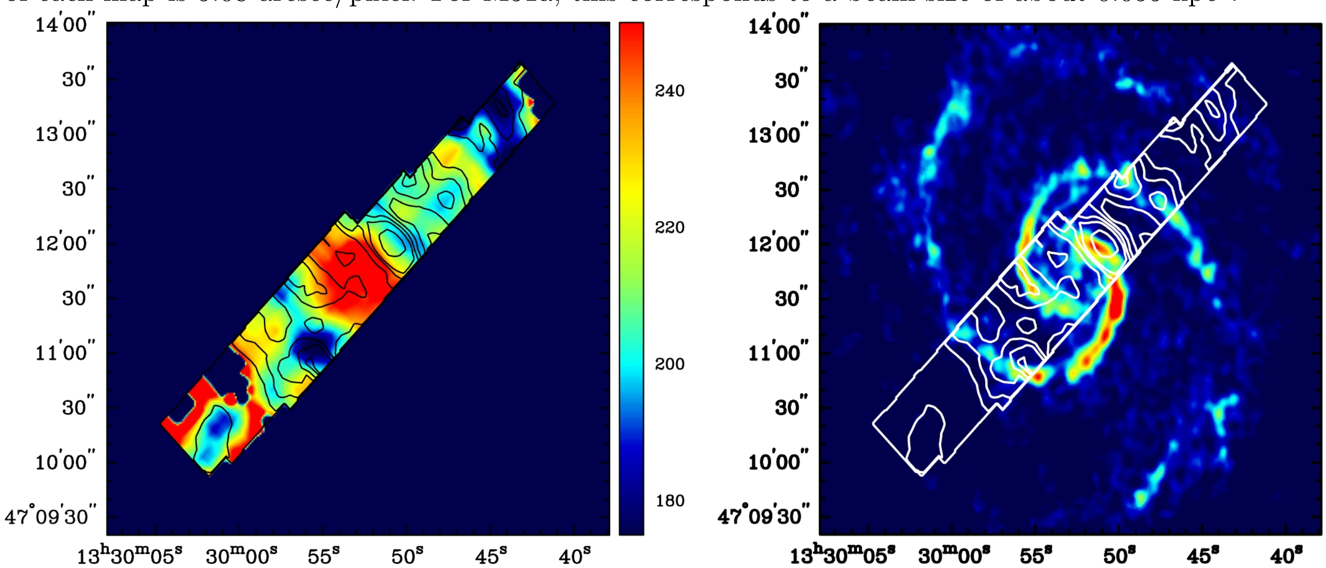

Figure 4: *Left*: Map of the warm (T = 100 - 300) H_2 mass distribution (in contours) plotted over the excitation-temperature distribution (in color). The excitation-temperature is in units of Kelvin; the contours are spaced at 0.5, 0.3, 0.25, 0.20, 0.12, and 0.06 M_{sun}/pc^2. *Right*: Comparison of 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 CO map of M51 was obtained by BIMA SONG. The resolution of the BIMA map is 6 arcsec. Note the offset of the warm H_2 mass contours from the CO emission in the spiral arms.

4 References

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5 Brief Resume/Bibliography

Student 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 software that takes IRS low resolution data cubes and creates line flux maps of every spectral feature in the data cube. He has submitted 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 (Brunner et al. 2007). His thesis will combine the research proposed here with his ongoing research at SSC to study the spatial distribution of H_2 in nearby galaxies.

Administrative PI: Reginald Dufour is a professor in the Department of Physics and Astronomy at Rice University. His interests are observational astrophysics of star forming galaxies, HII regions, and shell nebulae.

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:

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6 Status of Existing Spitzer Programs

Administrative PI R. Dufour is a Co-I on GO - 3412, GO - 20049, and GO - 20057. The GO - 3412 IRS observations of HII regions in M83 have been analyzed and submitted for publication to MNRAS. The GO - 20049 IRS observations of HII regions in M33 have been completed and preliminary results have been presented at IAU symposium number 235 in Prague. The GO - 20057 IRS observations of three halo PNe are pending completion.

Co-I K. Sheth is the PI for GO - 20138. GO - 20138 IRS observations of M51a have been reduced and analyzed and the results for H_2 in M51a have been submitted for publication.

Co-I M. Wolfire is PI on GO - 3679, GO 20012, GO- 20097, and GO - 30295. For GO - 3679, GO - 20012, and GO - 20097 all of the data has been taken and are currently under analysis. Results from of the analysis of PDRs from GO - 3679 are presented in Povich et al., 2007, ApJ. Results for the analysis of data from of GO - 3679 and GO - 20097 on H_2 in PDRs are in preparation.

7 Financial Contact Information

For PIs G. Brunner and R. Dufour
Dr. Heidi L. Thornton
heidi@rice.edu
Assistant Director of Sponsored Research
Office of Sponsored Research MS-16
Rice University
Houston, TX 77005-1892
713-348-6204

For Co-I K. Sheth
Eloise Kennedy
eks@ipac.caltech.edu
Image Processing and Analysis Center
MS-220-6
Pasadena, CA 91125
626-395-1801

8 Cost Plan and Budget Narrative

Below is the narrative for the Rice University Cost Plan (R. J. Dufour, administrative PI) for which the proposal PI, Greg Brunner, is a graduate student. The total costs for the PI and Co-I at Rice for a 1 year period beginning 1 October 2007 is $81,765. Separately Dr. Kartik Sheth of the Spitzer Science Center is requesting $15,000 support during this period though SSC. Co-Is Vogel and Wolfire of the University of Maryland are not requesting separate support. Therefore, the total support requested for this archival project is $96,765.

The primary direct cost items are salaries for G. Brunner and R. Dufour. Since the scientific PI will be a third-year graduate student in October 2007, the stipend will be $24,700 per year (assuming he will qualify for Ph. D. candidacy in September 2007). Brunner just completed six months of residency at SSC as a Graduate Student Fellow working with Sheth et al. on H_2 mapping of M51. Currently this is being submitted for publication and also will be submitted and defended by Brunner for Ph.D. candidacy during the summer of 2007. If this proposal is approved, then the described research will be a major part of Brunner's Ph.D. dissertation. As noted in the proposal, Brunner will be analyzing 2D IRS observations and mapping of molecular hydrogen properties across 18 galaxies previously observed by SINGS, which is a massive amount of data reduction, including comparison with IR-visible imagery of the galaxies. Realistically, such a large project will take longer than a year, but here we are limited to proposing for the first year of research (given some will have already been done by the time the funding is in place). Currently Brunner is being supported by AURA/HST grants involving UV-optical imagery/spectroscopy of emission nebulae and can only work part time on the Spitzer H_2 mapping. However, this should be nearly completed in late 2007 so he will be able to pursue this proposed research full time when funding is in place.

R. Dufour is a Professor of Physics and Astronomy at Rice University and has been at Rice since 1976 studying star-forming galaxies and nebulae. He will be Brunner's primary thesis advisor and administrative PI for this project. He is requesting one month of summer salary support ($10,395). Dufour expects to become involved in the project scientifically as well as administratively at a level of approximately 3 weeks per semester (Rice permits up to 50% of the academic time for research during the 9-month school year) and 1 month during the summer.

Other direct cost items include $4,200 in travel for Brunner to take 5-day trips to SSC to consult with Sheth, to the University of Maryland to consult with Vogel and Wolfire, and one domestic scientific meeting (e.g. AAS) to present the results of this research. Additionally, $4,200 is requested for publication costs (approximately two 15 page ApJ or AJ articles) which is arguably conservative given the large amount of data and galaxies proposed to be studied. Modest amounts is requested for research materials and supplies ($600) and computer services ($1200 – IDL, user fees, and maintenance support). No equipment is requested, all of the hardware (and software) necessary for the project is in place at Rice.

Therefore the direct costs are $35,095 (salaries), $4,200 (travel), and $6,000 (publications, maintenance, and supplies) = $57,332 total. Fringe benefits on the salaries is $12,307 and indirect costs are $24,453. Therefore, the total is $81,785 for the Rice University share of the project cost.

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
	G. Brunner - Student PI	12 months	2058.33/mo	24,700.00
	R. Dufour - Admin. PI	1 month	10,395.00/mo	10,395.00
	Fringe benefits (see attachments)			12,037.00
	Total Direct Labor			47,132.00
	Overhead	Base	Rate	
	See attachments			24,453.00
	Total Overhead			24,453.00
	Material Costs			
	Material Burden			
	Total Material			
	Subcontract Cost			
	Subcontract Burden			
	Total Subcontract			
	Other Direct Cost (ODC)			
	Travel, Publication, Computer Costs			10,200.00
	Total ODC			10,200.00
	Sub-Total Cost			81,785.00
	Total General & Administrative			
	Total Cost			81,785.00