Section D: Science Investigation

D-1 Overview

D-1.1 Executive Summary

The fundamental process in the evolution of galaxies is the transformation of the interstellar medium (ISM) into stars and the subsequent return of material back to the ISM. Yet many phases of this lifecycle, such as the formation and destruction of molecular clouds, are poorly observed. STIM, the Space Terahertz Interstellar Mapper, will for the first time provide maps with sufficient angular and velocity resolution, coupled with expansive spatial coverage, to reveal these processes on a galactic scale. STIM, a free-flying observatory with an eight- beam heterodyne receiver system, will produce maps in the 1.9 THz line of ionized carbon, the dominant emission line of interstellar medium, and the 1.46 THz line of ionized nitrogen, the third brightest far-infrared line and a key diagnostic of the ionization state of the ISM. STIM has a highly experienced Principal Investigator, Project Manager, and investigation team, and it uses Herschel-demonstrated receiver technology, an existing, flight qualified helium cryostat, and a well-proven spacecraft design. STIM directly addresses the NASA research objectives 3D.2 (the evolution of galaxies) and 3D.3 (star formation).

STIM will survey more than 280 square degrees of the Galactic plane in ionized carbon ([C II]) line emission at 1.9 THz (158 μm), the brightest spectral line in the Galaxy; and ionized nitrogen ([N II]) line emission at 1.46 THz (205 μm), a tracer of the star formation rate. At $\sim$1.5′ angular resolution and <1 km/s velocity resolution, **STIM will detect every interstellar cloud with $A_V \geq 0.4$ in the surveyed region**, and, through excitation and kinematic diagnostics provided by [C II] and [N II] line emission, **will illustrate how atomic and molecular clouds are formed and dispersed in the Galaxy**. STIM will make 3-dimensional maps of the structure, dynamics, turbulence, energy balance, and pressure of the Milky Way's Interstellar Medium (ISM), as well as the star formation rate.

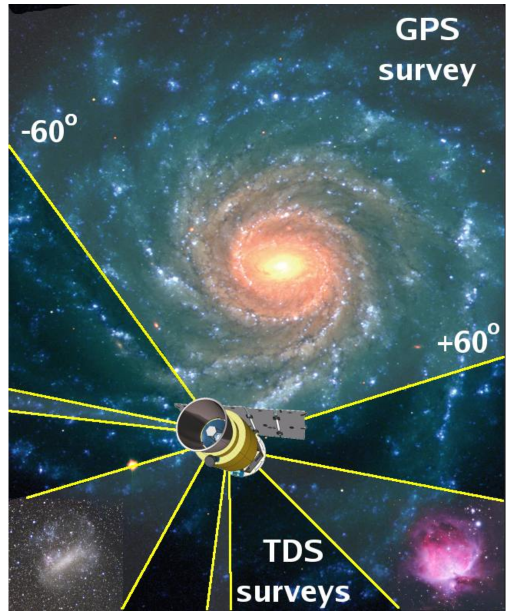

Figure D-1: *The proposed regions to be surveyed by STIM in its Galactic Plane Survey (GPS) and Targeted Deep Survey (TDS) modes. The GPS 120° longitudinal swath of the Galactic Plane reveals major components of the Milky Way ISM, such as the Galactic Center, molecular ring, spiral arms, and interarm regions. The targeted surveys cover Outer Galaxy targets like the Orion GMC and nearby external galaxies like the LMC.*

D-1.1.1 Summary of Science Objectives

STIM will provide a comprehensive understanding of the inner workings of our Galaxy by exploring the connection between star formation and the life cycle of interstellar clouds. We will study the formation of molecular clouds from diffuse atomic gas, the feedback of high mass star formation on the lives of atomic and molecular clouds, and the effect of these processes upon the global structure and evolution of the Galaxy. The detailed understanding of star formation and evolution of stars and gas in the Galaxy is directly relevant to star formation in other galaxies. The nature of the feedback mechanism of massive star formation with its interstellar environment is pivotal to the evolution of galaxies. **Within NASA's research objectives on galaxy evolution and star formation, STIM addresses the following high priority goals**:

1. Determine the anatomy and topology of interstellar gas
2. Study the creation and disruption of star-forming clouds in the Galaxy.
3. Determine the parameters that affect the star formation rate in a galaxy.
4. Measure the energy balance and mass flow within the Galactic Center
5. Provide templates for star formation and (inter)stellar feedback in other galaxies.

D-1.1.2 Summary of Mission Approach

STIM will utilize two heterodyne receiver arrays to produce a total of eight $1.5'$ pixels in the focal plane, each with 1024 spectral channels. These array components will be directly leveraged from the Herschel HIFI instrument design, to maximize flight heritage and minimize cost and risk. STIM will map more than 280 square degrees of the inner Galaxy including the Galactic Center, Galactic molecular ring (Figure D-1) as well as several arm and interarm regions. STIM will detect and resolve both spectrally and spatially all Giant Molecular Clouds (GMCs), all significant H II regions, and all cold neutral medium (CNM) atomic clouds with $A_V \geq 0.4$ mag in the surveyed region.

The STIM heterodyne receivers provide sub-km/s velocity discrimination and sufficient bandwidth to detect and resolve line emission from every Galactic cloud in the surveyed region. The data products will include:

1. A high fidelity database of spatially and velocity resolved far-infrared [C II] 1.9 THz (158 μm) and [N II] 1.46 THz (205 μm) fine-structure line emission in the Galaxy.
2. A combination of STIM's data products with existing line and continuum surveys to characterize the structure and dynamics of interstellar clouds and their relation to star formation.

The data are produced in large scale (Galactic Plane Survey) and selective (Targeted Deep Survey) modes:

- **GPS: Galactic Plane Survey** spanning the scale height of neutral interstellar gas in the Plane, and providing an expanded panoramic survey of the central $\sim$1 kpc of the Milky Way: $-60° > l > 60°$; $-1° < b < 1°$, extended to $-2.2° < b < 2.2°$ for the Galactic Center region, $|l| < 10°$.
- **TDS: Targeted Deep Surveys** of selected regions in the Outer Galaxy, including a survey of the entire **Orion GMC** and a **Magellanic Cloud Survey** of selected regions in the LMC and SMC, and a square-degree survey of the nearby spiral galaxy M33.

STIM's launch date, mission lifetime, and capabilities make it ideal for placing the Milky Way in the context of external galaxies that will be observed in the same spectral lines with Herschel.

D-1.2 Science Background

Via spatially and spectroscopically resolved [C II] and [N II] line emission, STIM probes uniquely the pivotal formative and disruptive stages in the life cycles of interstellar clouds. It provides new insight into the relationship between interstellar clouds and the stars that form from them, a central component of galactic evolution.

Neutral interstellar gas is the dominant mass component of the ISM, and tends to exist as two phases in rough thermal pressure equilibrium: a diffuse warm neutral medium (WNM) with hydrogen densities at the solar circle of $n{\sim}0.3$ cm^{-3} and $T{\sim}8000$ K, and a denser, cold neutral medium (CNM) with $n{\sim}40$ cm^{-3} and T$\sim$70 K (Kulkarni & Heiles, 1987; Wolfire et al., 2003). Turbulence provides a broader spectrum of conditions (Mac Low et al., 2005; Gazol et al., 2005), but thermal balance drives neutral gas toward these phases. With sufficient shielding column, $N > 10^{20} - 10^{21}$ cm^{-2} of hydrogen nuclei, the CNM clouds begin to harbor molecular interiors. Above $N \sim 10^{22}$ cm^{-2} they become fully-molecular, gravitationally bound and stars may form in their interiors (McKee, 1989). The largest condensations take the form of GMCs with large masses $10^5 - 10^6$ $M_\odot$ and are responsible for most of the star formation in the Galaxy. These ISM components are shown schematically in Figure D-2.

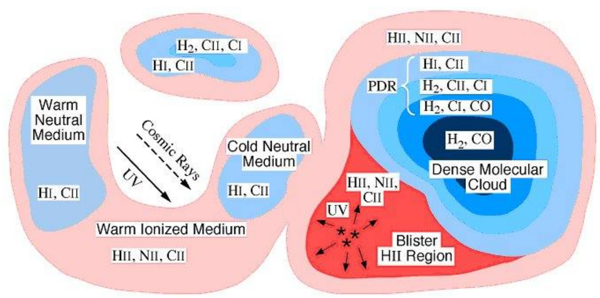

Figure D-2: *Schematic representation of ISM components. STIM detects and maps in the Galaxy the higher column density CNM component, the H_2/C^+ component, the photodissociation region (PDR) surfaces of molecular clouds, the H II component and (with H I) the WNM/CNM ratio.*

Ultraviolet radiation from massive stars not only heats the CNM and WNM and determines the relative portions of these phases, but it also ionizes gas and heats it to 10^4 K, producing H II regions. The destructive impact of UV radiation on the surfaces of neighboring clouds is a key part of the stellar/interstellar feedback that governs galactic evolution. This stellar feedback likely determines the fraction of cloud gas which is converted to stars. CNM clouds are destroyed by the interstellar UV field produced by the global (many hundreds of pc) OB stellar population. If global star formation rates are high, the interstellar field is high, thereby lowering the CNM population by converting them to ionized or WNM gas. This conversion then throttles the rate of GMC formation, and thus the global star formation rate. These stellar feedback effects are likely to regulate star formation rates in galaxies.

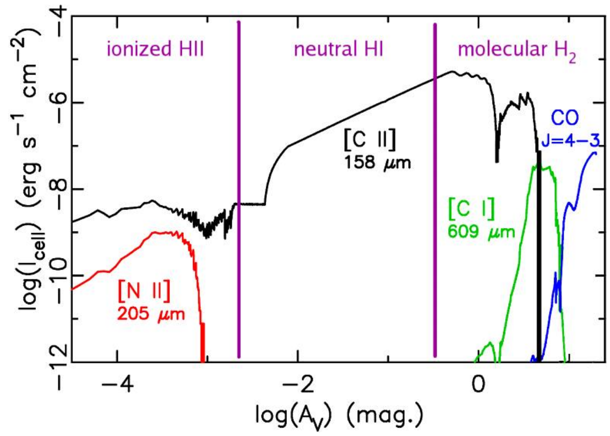

Figure D-3: **The uniqueness of STIM's [C II] and [N II] surveys.** *A model depiction of the intensity of diagnostic lines of carbon and nitrogen species as viewed through a UV-illuminated cloud from depths of A_V=0 to 20 mag. Vertical purple lines overlay the HII-to-HI-to-H_2 boundaries found at the edges of dense interstellar clouds. This figure demonstrates that [C II] will probe H_2 clouds with little CO, and depicts the need to use [N II] to disentangle the portion of [C II] emission stemming from ionized gas.*

D-1.3 Unique Roles of the Far Infrared Carbon and Nitrogen Lines

The far infrared fine structure lines of ionized carbon and nitrogen represent the crucial "missing links" in understanding the global evolution of interstellar gas in the Galaxy.

Vast surveys in the neutral hydrogen 21 cm line and the 2.6 mm CO J=1-0 line have been performed and constitute our best understanding of the Galactic atomic and molecular gas, respectively. However the interstellar components associated with the crucial assembly and destruction of clouds are poorly probed by such surveys! The "missing links" in the analysis of the Galactic ISM are the fine structure lines of ionic carbon and nitrogen; not only are they among the most powerful coolants of the ISM (together they account for almost 1% of the bolometric luminosity of the Galaxy), but they probe crucial aspects of interstellar clouds that are missed by existing surveys (Figure D-3). **[C II] emission barometrically selects clouds of atomic hydrogen that are often difficult to distinguish from WNM in maps of 21 cm H I emission, and identifies molecular clouds that are devoid of CO emission. [N II] line emission probes diffuse ionized gas invisible to optical and radio recombination line surveys. All of these points are crucial to identifying the yet unobserved links between the evolutionary stages of interstellar clouds.**

Since [C II] line emission efficiently probes both neutral and ionized gas (Figure D-3), it is necessary to disentangle the two components in order to cleanly interpret the line emission. The 1.46 THz [N II] line stems from the same low-density ionized gas as [C II]; therefore it provides a way to separate the multiple excitation components that comprise the [C II] emission. In its own right, the [N II] line provides a sensitive extinction-free probe of ionizing photons in the Galaxy, a measure of the star formation rate necessary to build a Schmidt Law for the Milky Way, a goal of this mission.

D-1.4 Overview of STIM Capability

STIM is a uniquely capable mission that brings many orders of magnitude more angular and spectral resolution to the study of [C II] and [N II] in the Galaxy than the full Galactic Plane survey performed by the FIRAS instrument on COBE. It will be the first mission to spatially *and* spectrally resolve individual clouds and their constituent interstellar components on a galactic scale.

STIM achieves 3σ intensity limits of 3.5×10^{-5} (t/1 sec)$^{-1/2}$ and 1.5×10^{-5} (t/1 sec)$^{-1/2}$ erg s^{-1} cm^{-2} sr^{-1} in the [C II] and [N II] lines, respectively. With this sensitivity, STIM can detect the GMCs, CNM clouds, and H II regions discussed above. The CNM clouds typically have sizes r$\sim$3 pc and subtend $> 1'$ of angle at a distance of 8.5 kpc, filling the STIM beam. These CNM clouds will therefore be both spatially and spectrally resolved. STIM will resolve in [C II] the surfaces of all GMCs illuminated by the local (or brighter) interstellar radiation field and the [C II] and [N II] emission from H II regions with Emission Measure (EM) > 50 cm^{-6} pc. [C II] originates in both neutral and ionized gas, whereas [N II] arises solely from ionized gas. STIM [N II] observations will provide the most sensitive and detailed maps of star formation rates in the Galaxy, and are crucial for separating the ionized and neutral components of [C II] emission.

The main features of the STIM survey are:

- High spatial resolution, $\sim$1.5 arcmin (3 pc at $d = 8$ kpc).
- Very high spectral resolution, <1 km/s.
- High dynamic range: 10^5 spatially and 10^3 spectrally
- More than 10^6 spatial pixels
- High sensitivity: STIM will catalogue all neutral clouds with columns $N > 5 \times 10^{20}$ cm^{-2} and all ionized clouds with EM > 50 cm^{-6} pc. Convolved to the 7° angular resolution and 3000 km s^{-1} spectral resolution of FIRAS/COBE, the STIM baseline surveys are 10^5 times more sensitive!

These capabilities will be put in broader context in Section D-3.

D-2 Science Goals & Objectives

D-2.1 Revealing the Anatomy of Interstellar Gas

STIM will provide an unprecedented 3-dimensional global map of the distribution of clouds of ionized gas, atomic gas, and molecular clouds (via their dense atomic surfaces) as a function of radius (R) and height (z) in the Galaxy. It will allow measurement of the gas heating rate and interstellar pressure to be made throughout the Galaxy. It will reveal poorly understood interstellar components; cold atomic (CNM) clouds that are not always discernable from H I emission and molecular clouds that are devoid of CO emission.

STIM's unique blend of sensitivity, angular resolution and spectral resolving power allows it to map and diagnose *all components of the warm and cold interstellar medium*. STIM will survey the Galactic Center, spiral arms, interarm regions, and the molecular ring, where much of the star formation occurs in the Galaxy. Galactic rotation allows velocity separation of the clouds along the line of sight. We can compute the density of clouds (i.e., the number of clouds per kpc^3) and their size distribution as functions of R and z, and see how clouds are clumped together in spiral arms or supershells. In regions of cloud clustering, the superb velocity resolution of STIM will measure the random motions of clouds, and diagnose *large scale turbulence*.

COBE FIRAS observations show that the ionized component of the ISM radiates strongly in both [C II] 158 μm and [N II] 205 μm (Wright et al., 1991). To distinguish the origin(s) of [C II] emission, velocity-resolved measurements of the small scale distribution of the ionized gas must be made in [N II] and compared to the [C II] distribution. **STIM will conclusively determine the origin of the [C II] emission from various regions in the Galaxy**, and will enable the portion of the [C II] emission coming from the CNM neutral gas to be unambiguously determined.

If the CNM clouds are seen in H I, which determines their column and mass, the ratio of CNM [C II] to H I intensity provides a measure of the [C II] emissivity per H atom which rises monotonically with gas density and thermal gas pressure. **STIM will survey over a large portion of the Galactic Plane, thereby enabling the construction of the first barometric maps of the Galactic disk**. These maps will be used to determine the ambient thermal pressure in different environments (e.g., the spiral arms versus interarm regions, turbulent versus quiescent regions). The pressure maps and the maps of cloud distributions and properties can be correlated with star formation rates to understand stellar/interstellar feedback mechanisms.

Where extended emission is seen in H I with no [C II] counterpart, we can attribute the H I emission to extended low density gas – either WNM or thermally unstable gas with densities below that of CNM (Figure D-9). To achieve the required sensitivity for this extended gas, we will smooth the data to larger ($\sim$10 km/s) velocity and spatial ($\sim 10'$) bins. In this way, STIM can map the CNM/WNM mass fraction in the Galaxy, and determine how much of the neutral gas is in clouds rather than in warm or unstable components.

In addition, the [C II] line dominates the cooling of CNM clouds. Therefore, we directly obtain the gas heating rate of clouds as a function of radius throughout the Galaxy. Besides the fundamental interest in tracing the energy flow in the Galaxy, the observations also can test our theoretical hypothesis that the heating is provided by the grain photoelectric heating mechanism in diffuse clouds. This hypothesis has been tested (positively) in denser clouds illuminated by stronger fields, but it is not yet certain whether in weak UV fields other mechanisms (i.e. ambipolar diffusion of the magnetic field) may be important. The test involves comparing the heating with the observed incident radiation field and the gas density in a sample of clouds.

D-2.2 Witnessing the Formation & Destruction of Clouds

The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been directly observed! STIM is designed with the unique combination of sensitivity and resolution in the [C II] line needed to observe cold atomic clouds assembling into giant molecular clouds (GMCs).

The overall topology of the cold, neutral medium is currently unknown. H I 21 cm line emission does not distinguish contributions from warm and cold atomic material. Yet, the configuration and velocities of the cold, neutral clouds are central to all theories that describe the formation of giant molecular clouds. Currently, our principal diagnostic of these clouds is absorption of the H I 21cm line and opti-

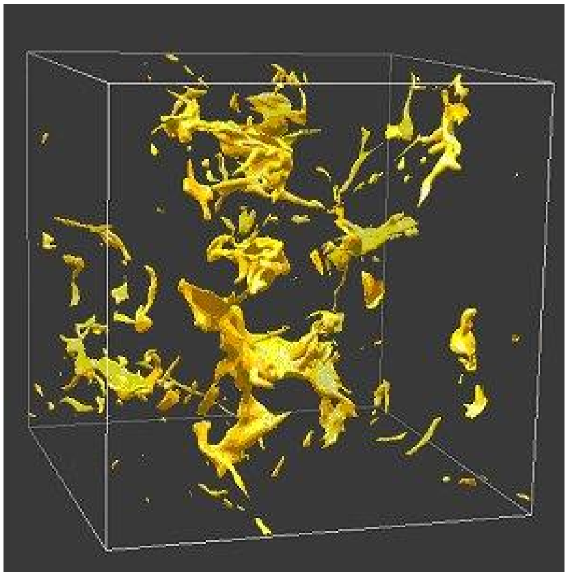

Figure D-4: *The ISM is a complex environment with structures on all scales and velocity dispersions. The surfaces of clouds corresponding to* $n = 30\ cm^{-3}$ *are shown within a 6 pc region from a 3-D magnetohydrodynamical simulation of cloud formation (Juvela et al., 2003). Neither COBE nor BICE had the spatial and spectral resolution to unravel the structure of the interstellar clouds or their formation process.*

cal lines (Ca) toward continuum sources. Such pencil-beam measurements do not reveal the gas distribution and kinematics of these critical regions. With its ability to spectroscopically image the extended [C II] emission, STIM will define the topology and dynamics of cold, neutral clouds to provide definitive constraints to all models of star forming clouds.

Turbulence may play an important role in the formation and evolution of interstellar clouds. In a standard scenario where CNM clouds are formed from WNM gas by thermal instability, we can picture the role of turbulence in two ways: large scale instabilities, density waves and supernovae drive compressional motions that can trigger the thermal instability (de Avillez & Breitschwerdt, 2005). Alternatively, regions undergoing thermal instability experience a dynamic radiative transition from the WNM to the CNM, due to the large density contrast between these two phases. This transition is known to generate turbulence and to set up the CNM into a complex network of pancakes and filaments (Kritsuk & Norman, 2002, also Figure D-4). Because of this dynamic nature of both the triggering and evolution of the thermal instability, departures from thermal pressure equilibrium may be widespread in the ISM (Heiles & Troland, 2003), and the notion of a dynamic multiphase ISM has been proposed, where turbulent diffusion regulates phase exchange processes. Only a careful study of both the spatial structure and kinematics of gas in transition between phases can tell us the role of turbulence and dynamic pressure in the lifecycle of the ISM.

The spectroscopic images of [C II] emission can be used to derive properties of turbulent flows within the cold, neutral clouds, and within molecular clouds that can be directly compared to those of the underlying CO emitting material (Heyer & Brunt, 2004). The cooling in shear layers is expected to be dominated by [C II] cooling at temperatures lower than ~200 K and is > 10 times brighter than the CO emission (Falgarone et al., 2007). Thus, [C II] is a better tracer of turbulent shears than is CO and will yield the rate of turbulent dissipation in shear layers.

Theories of molecular cloud formation are guided and constrained by observations of the atomic and molecular gas components. Four mechanisms have been proposed to consolidate gas into GMC complexes (Figure D-5): (1) self-gravitating instabilities (Kim & Ostriker 2002,2007) within the diffuse gas component (often in a spiral arm where density is highest and the Jeans time is shortest), (2) collisional agglomeration of small, long-lived molecular clouds, (3) accumulation of material within high pressure environments such as shells and rings generated by OB associations, and (4) compression in the randomly converging parts of a turbulent medium. STIM can distinguish these processes from each other and consider new cloud formation schemes by:

- Accounting for **all** of the molecular hydrogen mass (the H_2/C^+ clouds as well as the H_2/CO clouds) when computing global measures of the interstellar medium.

- Making a more complete, better characterized catalogue of interstellar clouds than CO or H I surveys.
- Constructing spatial and kinematic comparisons with sufficient resolution, spatial coverage and dynamic range to probe a wide range of interstellar phases and environments.

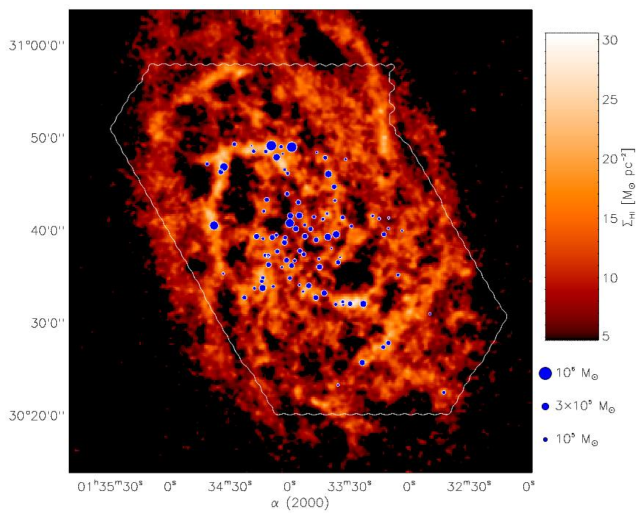

Figure D-5: *The location of GMCs in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the H I 21 cm line (Engargiola et al., 2003). These observations show that GMCs are formed from large structures of atomic gas, and foreshadow the detailed study of GMC formation that STIM will provide.*

Currently, associating diffuse gas (H I) with molecular gas (CO) is difficult owing to the large differences of emitting volumes of the H I line and the CO line (see Figure D-6). Unlike [C II], a significant fraction of the H I emission can come from low density WNM gas. [C II] emission barometrically picks out clouds of atomic CNM gas and H_2 clouds with little CO. Regions of GMC formation may therefore be tracked by higher than average cloud densities (number of clouds per kpc^3), or regions with individual clouds with higher than average columns or pressures. With STIM's velocity resolution, these regions can be linked to superrings or spiral arms or convergent parts of a turbulent medium. STIM will identify the sequence of phase transitions as the gas transits through the spiral potential, and **will witness the process of cloud formation** directly from the atomic substrate or from small H_2 clouds. For example, dust lanes along the inner edges of spiral arms often show neither H I nor CO emission (Wiklind et al., 1990; Tilanus & Allen, 1991), and are therefore likely to be in an intermediate phase; sufficiently dense and self-shielded to harbor H_2 but not CO (Grenier et al. 2005, see also Figure D-2). These clouds will be seen in [C II] by STIM.

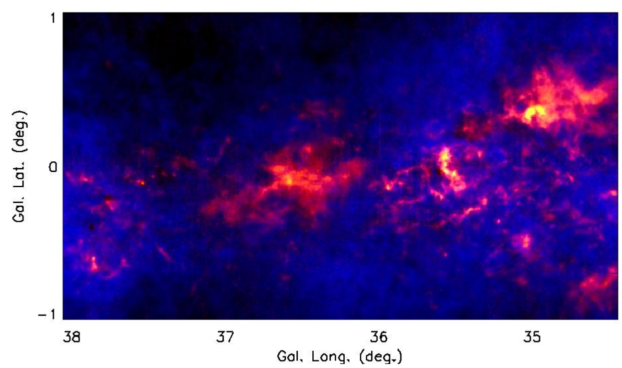

Figure D-6: *This 3-color image is constructed from the VLA Galactic Plane Survey and the BU-FCRAO Galactic Ring Survey. Blue corresponds to the HI 21cm line integrated between V_{LSR} of 50-55 km/s. The red and green images correspond to ^{13}CO J=1-0 emission over the same velocity interval but with integrated intensities of 0-5 K km s^{-1} (red) and 4-10 K km s^{-1} (green). Even within these narrow velocity intervals, it is difficult to associate atomic gas with star-forming molecular material owing to the long path lengths contributing to the HI 21cm line emission relative to the CO emitting columns. The [C II] line provides a more direct connection of the cold, neutral atomic gas to star forming molecular clouds.*

The high spectral resolution of STIM enables crucial kinematic studies of the Galaxy to be made. STIM will determine the kinematics and thermal pressures of most supershells, fossil superrings, and molecular clouds just condensing via gravitational instability of old superrings. STIM will detect many of the CNM clouds formed out of WNM in the shells, and the larger column density clouds, which may harbor H_2. With these detections STIM will determine the role of OB association-driven supershells and superrings in the production of molecular clouds and the cycling of gas between the various phases of the ISM (Elmegreen, 1989; McCray & Kafatos, 1987).

STIM witnesses the disruption of clouds: [C II] and [N II] measure the photoevaporating atomic or ionized gas driven from clouds with UV-illuminated surfaces, thereby converting the clouds to WNM or to diffuse H II regions. Thus, STIM can directly determine the rate of mass loss from all catalogued clouds, and their destruction timescales.

D-2.3 Measuring the Star Formation Rate in the Galaxy

STIM, using the [C II] and [N II] maps, will provide an extinction-free measure of the star formation rate and its relationship to the gas density.

Star formation within galaxies is commonly described by two empirical relationships: the variation of the star formation rate per unit area with the gas surface density (atomic + molecular), $\Sigma_{\rm SFR} \sim \Sigma_{\rm gas}^n$ (Schmidt, 1959) and a surface density threshold below which star formation is suppressed (Kennicutt, 1989; Martin & Kennicutt, 2001). The Schmidt Law has been evaluated from the radial profiles of Hα, H I, and CO emissions for tens of galaxies. The mean value of the Schmidt index, n, is 1.3 ± 0.3 (Kennicutt, 1989), valid for kpc scales. This empirical relationship is used in most models of galaxy evolution with surprising success given its simplicity. Oddly, there has been little effort to evaluate the Schmidt Law in the Milky Way owing to the difficulty in deriving the star formation rate as a function of radius within the plane. Previous studies have been typically limited to tangent point locations where IRAS point sources can be linked to molecular line emission from high density tracers (Luna et al., 2006).

The STIM survey of [C II] and [N II] emission provides the optimum set of data to calculate the Schmidt Law in the Milky Way. The [N II] line is an excellent tracer of the star formation rate as it directly measures ionizing luminosity with unmatched sensitivity, angular and spectral resolution, and is unaffected by extinction. The [C II] line, in conjunction with H I 21-cm and CO line emissions, provide the first coherent map of the neutral interstellar gas surface density and its variation with radius.

STIM may help us understand the origin of the Schmidt-Kennicutt Law. For example, it will correlate the thermal pressures on the surfaces of GMCs (which may relate to the star formation rate inside) with surface densities of H I and CO. It may uncover regions around OB associations devoid of GMC-forming CNM clouds. The current high rate of star formation in associations may impoverish large regions of the clouds needed to start the star formation cycle in the future. Such measurements are pivotal to models of star formation feedback & global galactic evolution.

D-2.4 Determining the Energy Balance & Mass Flow within the Inner Galaxy

The compressed and turbulent interstellar medium of galactic nuclei provides a completely different environment for star formation than the relatively quiescent disk. STIM will explore the Galactic Center with sufficient spatial ($\sim$3 pc) and spectral resolution to separate large clouds and trace material as it falls into and through the Center region. STIM will study the origin of the mysteriously low [C II]/FIR flux ratio (Nakagawa et al., 1998), all of the center's massive cloud complexes, and the bar. High-velocity resolution observations will provide a new kinematic map of the gas, ultraviolet fields, and star formation in the nucleus.

The central region of the Galaxy has two major features that will be the primary objects of study with the [C II] and [N II] data from STIM:

(1) the tilted nuclear disk, mostly atomic and well studied in H I, but with some molecular component as well (Burton & Liszt, 1978; Liszt & Burton, 1978; Burton & Liszt, 1992), and (2) the central molecular zone, containing $\sim$4 x 10^7 $M_\odot$ of molecular gas, representing the strongest concentration of gas in the Galaxy. ISO observations of the Galactic Center region (Goicoechea et al., 2004) demonstrated the utility of far-infrared line diagnostics, but those observations had neither the velocity resolution nor the areal coverage to reveal the full dynamical situation.

Current models and observations of Galactic gas dynamics show (Binney et al., 1991; Morris & Serabyn, 1996) that gas migrates inward through the Galaxy as a result of angular momentum loss, perhaps largely caused by the bar, and therefore it passes through the nuclear disk following X1 orbits, which are elongated along the bar. As it approaches a radius of $\sim$ 200 pc, the orbits become self-intersecting, so the gas shocks and is compressed, thereby becoming predominantly molecular. The shocks lead to angular momentum loss, which causes the molecular gas to enter X2 orbits, elongated perpendicular to the bar. Most of the mass of the central molecular zone is on X2 orbits. The clouds in that zone migrate inward as a result of dynamical friction and magnetic drag on time scales of $\sim$ 3 x 10^8 years, forming stars as they go (Stark et al., 1991; Figer et al., 2004) and ultimately feeding the activity in the central parsec.

With the proposed STIM surveys, we can study this full range of scales, and investigate the atomic-to-molecular transition that occurs at 200 pc. A measurement of the dynamics made possible by the high velocity resolution of STIM will be important for distinguishing the gas on X1 and X2 orbits.

Since [C II] emission will arise from both the atomic clouds and the surfaces of the molecular clouds, a comparison between it and CO emission will reveal both the locus of the shocks, as well as the preshock and postshock dynamics. Shocks effectively transfer some fraction of the clouds' orbital kinetic energy into heat, which then escapes primarily through line emission. By measuring this emission, we can estimate the amount of orbital energy that has been dissipated and estimate the rate of mass inflow from the decaying orbits. This quantity is a crucial datum for understanding both the mass budget of the Galactic Center, including the time- averaged rate of star formation in the Central Molecular Zone, and the evolution of the Galactic Center magnetic field.

One of the puzzles of the central molecular zone is why the molecular gas there is so much warmer than elsewhere in the Galaxy. The temperature of clouds in the central molecular zone is typically about 40-80 K, and it ranges up to even a few hundred K (Morris et al., 1983; Belmont & Tagger, 2006). This is the temperature range in which [C II] is most efficient at radiative cooling. There is currently no universal consensus on what the heating source is, although various possibilities have been considered, including dissipation of MHD turbulence, viscous heating associated with cloud shear in the strong tidal field of the Galactic Center, and heating by copious X-rays. When combined with the cooling that can be inferred from existing molecular line surveys, the proposed observations of [C II] allow for a thorough characterization of the cooling rate in the Galactic Center. The cooling rate provides the heating rate, assuming that most clouds are in thermal equilibrium. Then, for the first time, the various hypotheses for how Galactic Center clouds are heated can be confronted with the actual heating rates required, as well as with a measurement of how the heating rate varies with depth into the cloud.

Finally, the data from STIM will be of considerable value for extending our current characterization of the tilted nuclear disk. While it has been studied in both CO and H I (Burton & Liszt, 1978; Liszt & Burton, 1978; Burton & Liszt, 1992), its content of warm, diffuse clouds remains poorly known. Furthermore, the dynamics of gas in this region provides one of the best ways of modelling the bar potential of this crucial, central part of the Galaxy.

D-2.5 Constructing a Milky Way Template

STIM maps of the Milky Way Galaxy will provide physical insight to the ISM processes needed for the interpretation of spatially unresolved observations of distant galaxies.

[C II] 158 μm, the strongest Galactic cooling line, will be the premier diagnostic tool for studying external galaxies with future far-infrared (FIR) observatories (SOFIA, Herschel) and in the submillimeter for galaxies with large redshifts (Atacama Large Millimeter Array). In such spatially unresolved galaxies, however, only global properties can be measured. To interpret the measurement of extragalactic [C II] one must turn to the Milky Way for the spatial resolution needed to disentangle the various contributors to the total [C II] emission. At present, there is debate on the dominant origin of the [C II] emission in the Galaxy: diffuse H II regions, CNM clouds, or the surfaces of GMCs. STIM will solve this mystery. The [C II] and [N II] intensities depend on the strength of the UV heating and on the amount of gas in the appropriate ISM phase. The STIM mission covers a broad range of density and UV intensity, thus establishing the relationship between physical properties, [C II], [N II], CO, H I, FIR emission, and star formation. This study will provide the "Rosetta Stone" for translating the global properties of distant galaxies into reliable estimators of star formation rate and state of the ISM.

D-3 Science Requirements

STIM's Science Traceability Matrix is displayed in tabular form in Science Foldout 1. The following sections describe the most important points of the matrix in additional detail.

D-3.1 High Resolution Spectroscopy

STIM will have adequate velocity resolution to isolate separate components in a cloud complex.

The superposition of many clouds along the line of sight can be disentangled with spectral line techniques. Fitting to a model of Galactic rotation is often the only way to determine each cloud's distance and location within the Galaxy. It is the spectral resolution that gives us a 3D rather than a projected 2D map of the Galaxy. Moreover, internal dynamics are revealed from the variance of measured velocities and profile line widths within interstellar clouds. With resolution finer than 1 km s^{-1}, a line profile can disentangle processes such as turbulence, rotation, and local effects such as protostellar outflows. These kinematic components play a vital role in the sculpting of interstellar clouds, and a survey that has the goal of understanding their evolution **must** be able to separate the velocity components.

D-3.2 Large Scale Mapping

STIM will map a large enough area to sample the full range of Galactic environments.

Interstellar pressure, elemental abundances, and radiation field vary as a function of Galactic radius, so it is necessary to probe from the inner Galaxy out to at least the Solar circle to obtain a statistically meaningful survey that encompasses the broad dynamic range of conditions in the Galaxy. Large cloud ensembles, as gathered by surveys, are required to average properties extracted from clouds at varying stages of evolution. Large scale mapping places detected interstellar structures in an environmental context. Finally, neutral interstellar gas is affected by many physical processes that operate over a broad range of spatial scales. High spatial dynamic range observations are required to follow the gas distribution and kinematics through each spatial scale. To meet these objectives we will carry out an unbiased Galactic plane survey (GPS), and targeted deep surveys (TDS) of selected areas in the Galactic plane.

Galactic Plane Survey (GPS)

This moderate sensitivity survey will sample the Galactic plane at longitudes $-60^\circ > l > 60^\circ$ and $-1^\circ < b < 1^\circ$ in 24 seconds of cumulative integration time per $1.5'$ resolution element. This survey region includes the Galactic Center, the molecular ring ($l \sim -23°$), spiral arm regions ($l \sim -50°$), and interarm regions ($l \sim -40°$). In addition, numerous shells, bubbles, and star formation regions appear throughout our survey area as seen, for example, on MSX 8μm emission maps. Thus, our survey probes the Galactic regions where the full cycle of cloud formation and destruction occurs. **STIM's angular and velocity resolution will be ~ 280 and $\sim 10^3$ times that of the COBE survey, allowing the [C II] and [N II] emission regions to be disentangled along a given line of sight.** The STIM data will be invaluable in interpreting the recent Spitzer GLIMPSE and MIPSGAL surveys of the Galactic Plane (Benjamin et al., 2003; Carey et al., 2006).

Targeted Deep Surveys (TDS)

The deep sensitivity surveys will consist of observations of 100-600 seconds of integration per $1.5'$ beam towards selected regions of the GPS survey, the Outer Galaxy, and a sampling of the most nearby galaxies, notably the Large and Small Magellanic Clouds. The GPS survey only allows detection of clouds with columns of $A_V \geq 0.4$, and so only uncovers the more massive CNM diffuse clouds. Our deep surveys allow a much broader range of diffuse clouds to be studied, down to a column $A_V \sim 0.1$. In addition, for fixed A_V, CNM clouds in lower pressure regions, or in regions with lower heating rates are more difficult to detect. Deep surveys therefore also extend our ability to detect clouds along the line of sight in such regions.

STIM's targeted surveys will overlap with important regions of special interest to Galactic astronomy. The Outer Galaxy survey will include the Perseus OB star formation region and molecular cloud complex that is a part of the Cores to Disks Spitzer Legacy program and a large map of the Orion Molecular Cloud, which features a full complement of ancillary data which STIM will be able to draw from and contribute to. A small survey of high-latitude clouds will include the Polaris Loop, featuring dense CO cores, newly formed molecular clouds, and dynamical structures in H I emission. The Magellanic Cloud surveys will allow exploration of the differences in cloud properties coming from very different dynamical and metallicity environments.

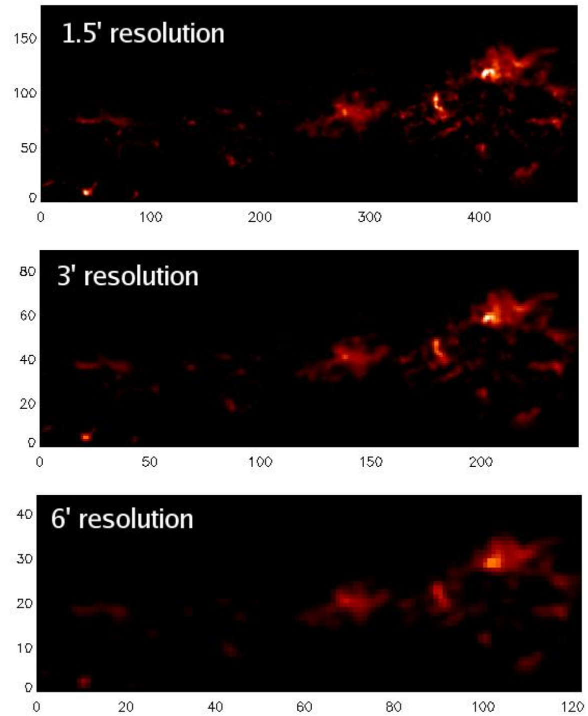

Figure D-7: *Integrated intensity of ^{13}CO J=1-0 emission over V_{LSR} of 50-55 km/s from the BU-FCRAO Galactic Ring Survey at different multiples (2,4,8) of the observed resolution of $45''$. The corresponding grid size of each image reflects Nyquist sampling at each resolution. The threshold of the halftone corresponds to 4σ of the full resolution image. Owing to beam dilution, one marginally detect the small, isolated clouds on the left 1/3 side of the image at a resolution of $6'$.*

D-3.3 Angular Resolution and Fully Sampled Maps

STIM will angularly resolve individual CNM clouds at the distance of the Galactic Center.

Previous surveys of [N II] and [C II] were limited to very small regions (KAO, ISO) or had low angular resolution (COBE, BICE) (Bennett et al., 1994; Nakagawa et al., 1998). STIM will fully sample both species over large regions of sky to their diffraction limited resolution of 1.7′ and 1.3′, respectively. Arcminute resolution with proper sampling is crucial to disentangling different clouds and cloud components over large distances in the Galaxy. At a distance of 10 kpc, GMCs subtend 10′, CNM clouds or small molecular clouds subtend 1-2′, diffuse H II regions about 20′. Such diffuse H II regions tend to dominate [N II] and [C II] emission from ionized gas (McKee & Williams, 1997) and are a substantial component of the ionized gas in the Galaxy. For these large-scale ISM components, it is possible to trade some angular resolution for sensitivity. Figure D-7 demonstrates that we can spatially smooth up to 6′ resolution when it is necessary to attain the highest possible sensitivity to faint diffuse gas.

D-3.4 High Sensitivity

STIM will have sufficient sensitivity in [C II] to detect diffuse atomic clouds at the distance of the Galactic Center and sufficient sensitivity in [N II] to detect diffuse H II regions in the molecular ring.

Figure D-8 shows the required STIM sensitivity for detecting [C II] and [N II] from photodissociated cloud surfaces and for distant (∼10 kpc) clouds in the inner Galaxy. Our most demanding requirements lie in the search for the formation of molecular clouds and the measurement of the warm ionized medium in the Galaxy. In low density gas, the brightness temperature of [N II] emission is expected to be about half that of the corresponding [C II] emission. A flux limit of 10^{-6} erg s^{-1} cm^{-2} sr^{-1} will detect [N II] in diffuse H II regions as far away as the Molecular Ring, achievable in 20 seconds of integration with velocity smoothing to 5 km s^{-1}, appropriate for ionized gas. Spatial smoothing will also be employed for probing large-scale ISM components as described in Section D-3.3. Tracing the formation of GMCs requires the detection of cold neutral clouds of relatively low column densities of $\sim 5 \times 10^{20}$ cm^{-2}. The expected [C II] emission at high interstellar pressures would be

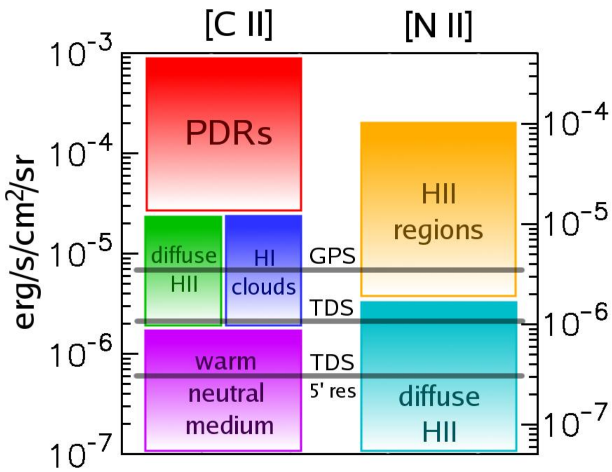

Figure D-8: *Comparison of STIM's sensitivity with [C II] and [N II] integrated intensities for diffuse interstellar components (A_v=0.1 to 1 magnitudes) which constitute the building blocks for molecular clouds, and UV-irradiated molecular cloud surfaces and HII regions (with 10 to 10^5 times the local interstellar radiation field). The corresponding sensitivities (3σ rms noise) of STIM's two survey modes (see section D-1.1.2 for definitions) are indicated by the top two horizontal gray lines. The bottom gray line shows the improved sensitivity of smoothing to 5′ angular resolution.*

10^{-5} erg s^{-1} cm^{-2} sr^{-1}, detectable in 12 seconds with STIM. The STIM Deep Survey allows the study of smaller columns of gas, and/or regions of lower interstellar pressure, such as in the Solar vicinity.

Figure D-9 shows a simulation of [C II], CO and H I spectra along a line of sight through the Galaxy. Observed CO and H I spectra (top) and simulated [C II] spectrum are provided for 15 seconds (middle) and 300 seconds of total integration (bottom). The simulations indicate that three distant CNM clouds of columns (left to right) of 3, 5, and 7 $\times 10^{20}$ cm^{-2} are detectable. The H I has a considerable WNM component. The blue peaks shown in the figure are surfaces of molecular clouds.

CO J=1-0

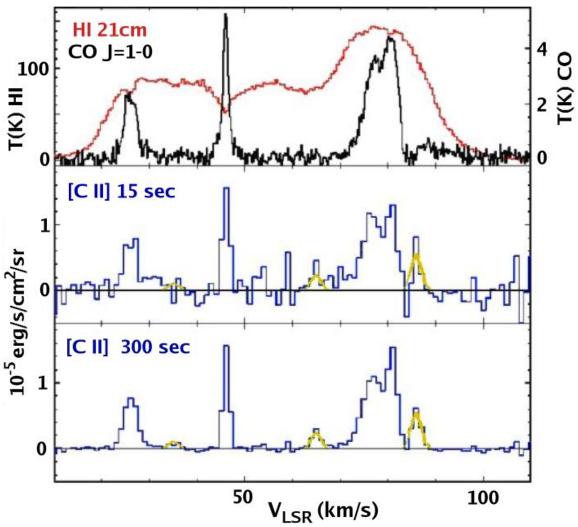

Figure D-9: *Observed CO and H I spectra (top) and simulated [C II] spectra for 15 seconds (middle) and 300 seconds (bottom) integration. The yellow curves indicate three distant CNM clouds with A_v ranging from 0.1 to 0.5 magnitudes.*

D-3.5 A Terahertz Carbon and Nitrogen Survey: Complementarity with other Missions & Surveys

STIM is timely. STIM will provide the best corresponding interstellar cloud survey to the GLIMPSE and MIPSGAL Spitzer Legacy programs and contemporary H I and CO line surveys. It naturally complements heterodyne instruments on Herschel and SOFIA, and provides capabilities far beyond the reach of balloon-borne experiments.

D-3.5.1 Relationship to Existing Data Sets

The fine structure lines of ionized carbon and nitrogen are essential to accomplishing the science defined in this mission, as described in Section D-1.3; they are among the dominant coolants of the ISM, and are the "missing links" in diagnosing the global state of the ISM and the formative and destructive evolution of interstellar clouds and star forming regions. However, observations performed by STIM are also highly complementary to the existing large scale surveys performed in other atomic and molecular species.

CO: For tenuous clouds of column less than about $N < 2 \times 10^{21}$ cm^{-2}, CO is photodissociated and the CO emission either disappears entirely, or if present, is a very unreliable measure of the molecular mass. The more opaque clouds in the 5×10^{20} to 3×10^{21} cm^{-2} range may be primarily H_2, which is extremely difficult to detect directly. These clouds have most of the carbon in C^+, which makes [C II] the only reliable probe. [C II] not only detects the CO clouds (via the emission from their C^+ surfaces), but also the H_2 clouds at intermediate column, and the mainly atomic clouds with $N < 5 \times 10^{20}$ cm^{-2}. Recent J-K extinction maps (Figure D-10) confirm these components are present. Thus, the [C II] detects a broader range of clouds than the CO, and allows us to see the possible assemblage of clouds of ever greater column, from atomic clouds, to H_2 clouds, to CO clouds.

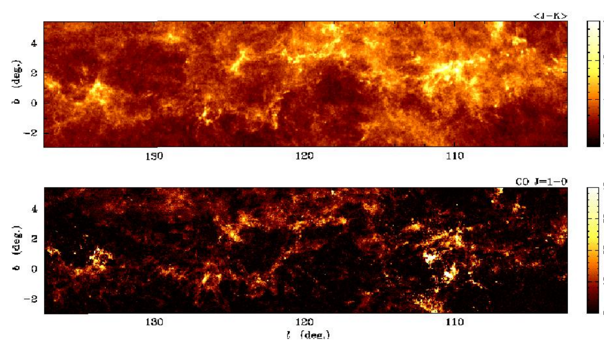

Figure D-10: *Near infrared $J - K$ extinction maps (top) depict significant interstellar gas not probed by CO (bottom). [C II] line emission will barometrically select young molecular clouds that have formed H_2 but not CO.*

The CO surveys will complement the STIM survey by helping to identify molecular clouds whose surfaces STIM detects and whose ionized gas seen in [N II] may be expanding into the ISM (Dame et al., 2001; Onishi et al., 2005; Jackson et al., 2006).

H I: The STIM surveys enhance substantially the interpretation of existing H I surveys. The most comparable datasets for STIM are the Southern Galactic Plane Survey with 1′ resolution (McClure-Griffiths, 2005) and the VLA Galactic Plane Survey (Stil et al., 2006). These

H I emission maps are sensitive only to column, whereas [C II] is sensitive to density times column. The [C II] therefore picks out the cloud regions with density > 30 cm^{-3}, whereas the H I is often dominated by the WNM emission (see Figure D-9). In fact, H I clouds can appear in absorption, in emission or undetected against the confused background and foreground WNM. When H I and [C II] are both seen in emission, the ratio provides the gas density and pressure in the cloud. When extended and broad H I emission is seen without a [C II] counterpart, WNM or thermally unstable gas is identified.

[C I]: Moving from the CNM through the surfaces of molecular clouds to their cores, the predominant form of carbon transitions from C^+ to CO, with high abundances of C in the transition region. Unbiased surveys of the [C I] fine structure lines, with parameters similar to the STIM survey, have recently become feasible (Martin et al., 2004; Zhang et al., 2001). Maps from STIM coupled with CO and [C I] data, will follow carbon in all its forms in position, velocity, cooling rate, temperature and pressure as the interstellar gas evolves.

Infrared Continuum Surveys: MSX, Infrared Astronomical Satellite (IRAS), Infrared Space Observatory (ISO) and Spitzer GLIMPSE and MIPSGAL Galactic plane surveys permit locating dark clouds, supershells, and star forming regions using the IR continuum. STIM provides the best corresponding interstellar cloud survey that will place these 2D imaged structures in a broader context by identifying their gaseous structural and kinematic counterparts.

D-3.5.2 Complementarity to Other Missions

STIM builds upon the heritage of three pioneering surveys which provided coarse pictures of [C II] and [N II] emission in the Galaxy. COBE (spatial resolution 7°, velocity resolution >1000 km/s), BICE (spatial resolution 15′, velocity resolution 175 km/s), and the Infrared Telescope in Space (IRTS, spatial resolution 10′, velocity resolution 750 km/s). None of these missions had sufficient spectral or spatial resolution to locate clouds, or separate one cloud from another along a given line of sight, and thus could not draw specific conclusions about cloud properties or distributions, or even the origin of the [C II] or [N II] emission (Hollenbach & Tielens, 1999). *STIM has about the same sensitivity to surface brightness as these missions, but adds orders of magnitude in spatial and spectral resolution.*

Besides COBE, BICE and IRTS, other platforms include the now defunct Kuiper Astronomical Observatory and Infrared Space Observatory, which did not survey the Galaxy in [C II] and [N II], but made pointed observations. The Spitzer Space Telescope has no spectroscopic capability at these wavelengths. Herschel's HIFI instrument (2009-2013) and (SOFIA, 2009+) will have the capability to observe both [C II] and [N II] at high spectral resolution. The Herschel Guaranteed Time program will devote significant time observing [C II] and [N II] but only in limited selected targets. The advantage of STIM, however, is its ability to provide large scale coverage. Herschel/HIFI will have a 10″ field of view at the [C II] line, and the lower resolution PACS instrument will provide a 50″ field of view – in comparison to STIM's two $1.5' \times 6'$ receiver arrays which will observe simultaneously. Furthermore, Herschel & SOFIA are general purpose observatories with a variety of instruments and many competing science goals; they will simply not obtain the large-scale maps that a dedicated, wide-field mission like STIM can provide.

A scientific and technical precursor to STIM is the Stratospheric Terahertz Observatory (STO), led by STIM Project Scientist Chris Walker. STO, a funded NASA suborbital program, is an 80 cm, balloon-borne observatory designed to map Galactic Plane emission in a number of far-infrared lines. STO is scheduled to fly in December 2010. The first STO flight instrument is designed to be nearly identical to that of STIM's. Indeed, the STO focal plane unit (FPU) will serve as an effective demonstrator for the STIM FPU. Being a Long Duration Balloon mission, STO's observing time is limited to 14 days. During this time it will survey a 30 square degree longitudinal swath of the Galactic Plane in [C II] and [N II]. An LDB instrument typically flies at most once every two years. If STO were to observe only [C II] and [N II], it would take nearly 20 years for STO to survey a similar size region of sky as STIM will. Even then, the map would be limited to that part of the Galactic Plane observable from Antarctica. The STO map will serve as a precursor for STIM and help the Science Team (many of whom are involved in STO) optimize STIM's observing program.

D-4 Data Products and Requirements

The STIM surveys will observe [C II] and [N II] spectra over large contiguous areas on the sky; including the Galactic Plane, the Orion Region, and the Magellanic Clouds. The total baseline mission data volume is 90 GB, which is easily accomodated by current magnetic disk storage. The final products of this imaging campaign are three dimensional data structures that describe line intensity as a function of position on the sky (e.g. l, b coordinates) and spectroscopic (velocity) axis. The data cubes will be written in FITS (Flexible Image Transport System) formatted files. This format is the basis for all widely used image analysis programs. The data produced by STIM is virtually identical to that produced by the Submillimeter Wave Astronomy Satellite (SWAS); indeed Gary Melnick (SWAS PI) will lead the ground data system effort at SAO as was done for SWAS. A description of the basic processing and archiving of the data may be found in Section D-6.3.

D-5 Minimum Science Mission

The STIM mission is highly robust to achieving the Minimum Science Mission.

The Minimum Science Mission is defined as the minimum acceptable scientific return for the mission, below which the mission would not be worth pursuing. The power of STIM is its unprecedented combination of wide area coverage, angular resolution, sensitivity, and velocity resolution. This combination of capabilities enables for the first time the investigation of the interstellar gas life cycle on a galactic scale. The science objectives are defined by the requirement to observe the full range of environments in the Galaxy, including the Galactic Center, molecular ring, arm, and inter-arm regions. The baseline 6-month science mission accomplishes this by mapping 120° of galactic longitude to a nominal sensitivity sufficient to detect all atomic clouds with A_V less than 0.4. The principal science goals can still be accomplished by mapping a smaller region, or the same region with lower angular resolution, with lower velocity resolution, or with lower sensitivity. These descopes address the key technical uncertainties in the mission, and can be applied during development to constrain cost growth.

The minimum Galactic plane survey would comprise the central $\pm 10°$ in Galactic longitude with a latitude coverage of $\pm 2.2°$ and one half of the remaining Galactic plane out to 60° longitude with $\pm 1°$ of latitude coverage. This minimum science mission would survey 160 square degrees of the Galaxy as opposed to the baseline 288 square degrees.

D-5.1 Mission Lifetime

The most significant driver on mission lifetime is the hold time of the superfluid helium cryostat. STIM uses an existing flight qualified cryostat with demonstrated performance. Nevertheless, unanticipated poorer performance in the cryogenic system, particularly the radiative cooling system, could result in reduced lifetime. The minimum survey, however, can be observed in 4 months.

As will be discussed in Section D-6.1, the cryostat has 50% lifetime margin over the baseline mission and more than 100% margin over the minimum mission. The principal value of the lifetime descope is to minimize the risk of schedule and cost growth during development.

D-5.2 Sensitivity

The STIM focal plane array must have adequate sensitivity in [C II] to detect diffuse atomic clouds at the distance of the Galactic Center and sufficient sensitivity in [N II] to detect diffuse H II regions in the molecular ring. Since it is possible to trade off observing time for sensitivity, a less sensitive focal plane array will result in a smaller mapped region over the life of the mission. Using the same minimum galactic plane area as in Section D-5.1, minimum mission receiver noise temperature is a factor $(288/160)^{1/2}$ higher than nominal. The sensitivity calculations for STIM assume a receiver noise temperature of 2000 K, so the highest acceptable noise temperature would be ~ 2700 K.

As will described in Section D-6.1, recent measurements of the flight HIFI mixers at this frequency have demonstrated significantly better system noise temperatures. The main benefit of accepting this descope would be in preserving schedule at SRON.

D-5.3 Pixel Count

Adequate Local Oscillator (LO) power is required for each of the pixels in the focal plane array. If the JPL LO sources are unable to produce adequate power, the pixel count would need to be reduced. A similar mapped area argument can be applied to the acceptable pixel count. Since mapping speed is roughly proportional to the number of pixels in the focal plane, the minimum mission science goal of mapping 160 square degrees could be accomplished by using three-pixel arrays.

Tests of the identical HIFI LO chains have shown power outputs of greater than 10 μW, or 2.5 μW per pixel for the baseline arrays, well in excess of the 1 μW required per pixel.

D-5.4 Angular Resolution

The need to descope the angular resolution specification could arise from a number of causes. For STIM, the most likely cause of degraded angular resolution would be inadequate pointing knowledge smearing the reconstructed image beyond the baseline 1.5′. Another possible cause would be a need to restrict data rate to the extent that smearing during On-the-Fly mapping is significant. Degrading the resolution by coadding pixels could also compensate for sensitivity shortfalls in the instrument. Finally, an unlikely but conceivable descope would be to reduce the antenna size below 0.5 m because of difficulties in fabrication or the need for additional black radiator area. In these four scenarios, degrading the angular resolution would significantly relax requirements on other system resources.

The atomic interstellar medium is best characterized as turbulent and inhomogeneous (Dickey et al. 2004) with no preferred size scale for structures, so there is a graceful degradation with angular resolution. The STIM baseline performance has been set at 1.5′ to match a 3 pc cloud at the 8 kpc distance of the Galactic Center. Significant structures can still be expected at 3′ angular resolution (Figure D-7). The savings due to the exercise of this descope would be in the control of cost growth in the spacecraft. Current MATLAB models of pointing performance show margin over the STIM requirement.

D-5.5 Minimum Mission Summary

The Minimum Science for STIM will be a 180 square degree map of the Galactic plane in the [C II] and [N II] lines at a sensitivity adequate to detect diffuse H II and H I clouds at the distance of the Galactic Center. The base performance allows degradation singly of the following parameters:

- Mission lifetime: 4 months
- Receiver sensitivity: T_{rec} (DSB) = 2700 K
- Pixel count: 3 pixels per band
- Angular resolution: 3′

D-6 Science Implementation

D-6.1 Instrumentation Summary

STIM will benefit tremendously from flight qualified mixer, low-noise amplifier, and local oscillator technology that was developed for the Herschel mission. It will also utilize a flight qualified, superfluid helium cryostat developed by Ball Aerospace. The digital autocorrelation spectrometers used on STIM have heritage from ESA (ODIN) and NASA (MLS) missions.

The observational goal of STIM is to make high spectral (<1 km/s) and angular resolution ($\sim 1.5'$) maps of the Galactic plane in two astrophysically important atomic transitions: [C II] line emission at 1.9 THz (158 μm), and [N II] line emission at 1.46 THz (205 μm). To achieve the angular resolution requirement we have designed STIM to have an aperture of 50 cm. To achieve the target spectral resolution, STIM will utilize a heterodyne receiver system. To provide sufficient mass margin for a superfluid helium cryostat with a sufficiently long mission lifetime, STIM will be a free-flying observatory launched into a 28.5°, 500 km high orbit from Kennedy Space Center by a Pegasus-class vehicle. The instrument portion of STIM consists of (1) the telescope, (2) eight heterodyne receivers (4 at the 1.9 THz [C II] line and 4 at the 1.46 THz [N II] line), (3) an eight channel autocorrelator system, (4) the instrument control electronics, (5) the star tracker, and (6) the cryostat (see Foldout Figures, 2.1, 2.2, 2.3, and 2.4). The spacecraft portion of STIM is derived from the BATC STP-SIV bus and contains (1) the solar arrays and power regulation system, (2) the attitude control system (ACS), (3) the spacecraft computer, (4) the solid-state memory for data storage, and (5) the spacecraft transponder.

A block diagram of the STIM instrument is shown in the Instrument Foldout: Figure 2.1. Key instrument parameters are listed in Instrument Foldout: Table 2.0. The STIM optical system consists of a 50 cm diameter reflector, a secondary reflector, a calibration load flip mirror, and 10% reflective dielectric beam splitters for local oscillator (LO) injection. The telescope provides an f/10 beam that is split into horizontal and vertical components by a polarizing grid. Simple reimaging optics convey the combined sky and LO beams through two cryostat windows to the [C II] and [N II] arrays located on the $\sim$2K cold plate. The diffraction limited, full-width-half-maximum (FWHM) beamsize on the sky will be $\sim$1.3 and 1.7$'$ on the [C II] and [N II] lines, respectively. Our observing strategy for the main survey is to make adjacent On-the-Fly (OTF) strip maps of the Galactic plane. An ambient load/cold-sky calibration (CAL) will be performed at the beginning and end of each strip map. During each strip map (lasting as long as 20 minutes) the calibration load will be regularly observed. With this mode of operation, secondary chopping is not required. The calibration load flip mirror actuator will use flex-pivot technology utilized on ISO and Spitzer. As with SWAS, the primary and secondary mirrors will be diamond turned aluminum, with a surface finish of $\leq$ 5 μm RMS. The telescope support structure will be made of composite materials.

D-6.1.1 System Description

A cut-away view of STIM showing the placement of the receiver system is shown in Instrument Foldout: Figures 2.2 and 2.3. The receiver will consist of two, orthogonally polarized arrays of phonon-cooled, HEB mixers operating at $\leq$4 K. One 4 pixel array is optimized for the [C II] (1.90 THz) line, the other for the [N II] (1.46 THz) line. The mixers will be pumped by two, fixed tuned solid-state LOs. The [C II] and [N II] LOs chains will produce single Gaussian beams. A chain of four, 10% reflective dielectric beam splitters will be used to divide and inject each LO into the appropriate mixer array. The LOs and beam splitters are mounted on an optical bench located between the telescope and cryostat. The cryostat outer housing, optical bench, and telescope are passively cooled to 130K by a large Winston cone pointed at cold space. Smaller Winston cones served a similar function on SWAS, where they cooled selected receiver components. Since STIM is a high resolution, heterodyne mission, the telescope need not be cooled and can also serve as the primary heat radiator at the base of the Winston cone (See Instrument Foldout: Figure 2.2). By passively cooling the cryostat outer housing, the boil-off of helium is decreased and the mission lifetime extended by more than a factor of 3. Cooling the LO will increase its output power by about 50%.

The first stage, low-noise IF amplifiers (LNAs) will follow the design used in HIFI (see Instrument Fold-Out Figure 2.7) and operate at a physical temperature of 20 K. In

Phase A LNAs capable of yielding comparable noise performance at a higher physical temperature (∼40 K) will be evaluated for flight use. The IF center frequency will be 3.4 GHz, with an instantaneous bandwidth of 2 GHz. As demonstrated on HIFI, this IF frequency and bandwidth can be supported by NbN, phonon-cooled mixers. At our highest observing frequency (1.9 THz, the [C II] line) a 2 GHz IF bandwidth will provide 316 km/s of velocity coverage. A velocity coverage of this order is needed to accommodate the wide velocity dispersion expected in the data toward the inner parts of the Galaxy. The eight IF signals from the mixers pass through an ambient temperature IF processor where they are further amplified and downconverted to baseband (0-2 GHz). STIM will use eight, 2 GHz wide, 1024 lag, autocorrelators as the back-end spectrometers for the mixer arrays. We have baselined autocorrelators over acousto-optical spectrometers because of their significantly lower mass, volume, and cost. A single-chip, 2 GHz wide correlator has been demonstrated by two companies; Spaceborne Inc. and Omnisys Instruments. An ambient temperature flight instrument electronics box will house (1) the IF and correlator boards, (2) the LO/HEB/LNA bias board, (3) instrument computer,(4) a power conditioning board, and (5) the sythesizer/power amplifier board for the LOs. Each board will reside in its own shielded compartment.

D-6.1.2 Expected Sensitivity

Recent lab measurements on waveguide and quasi-optical HEBs in the 1 to 2 THz range have yielded double side band (DSB) receiver noise temperatures in the 1000-2000K range. For our sensitivity calculations we have conservatively assumed a receiver noise temperature of 2000K and single-sideband (SSB) system noise temperature, T_{sys}=4000K. With the 24 second integration time per Nyquist-sampled resolution element characteristic of the unbiased, Galactic Plane survey (GPS) mode, we will be able to achieve an rms noise level of $\leq$ 1 K at a $\leq$1 km s^{-1} velocity resolution. The STIM instrument characteristics are summarized in Instrument Fold-Out 2: Table 2.0.

D-6.1.3 Component Selection

Technical Approach to Mixers

STIM will utilize the same HEB mixer technology developed at SRON University of Technology Delft, and JPL in support of the HIFI instrument on Herschel.

HEB mixers, both in space qualification tests for HIFI and at high altitude ground-based observatories, have been shown to have the sensitivity needed for the proposed STIM science investigations. A plot of the noise temperature of HEB receivers as a function of frequency is provided in Figure 2.6 of the Instrument Fold-out. Transitioning these superconductive HEB mixers to the 1×4 arrays baselined for STIM is a straightforward repackaging of flight qualified components. The 1.46 THz array will be provided by JPL and the 1.9 THz array by SRON.

Technical Approach for Local Oscillator hardware

JPL has developed and delivered flight-qualified solid state local oscillator (LO) chains for HIFI Band 6L and Band 6H that meet STIM requirements.

HIFI Band 6L covers the 1400-1600 GHz region while Band 6H covers the 1600-1900 GHz range. These LO chains meet the requirements placed on them by the STIM mission, and consist of GaAs Monolithic Microwave Integrated Circuit (MMIC) power amplifier modules and JPL-designed and fabricated waveguide GaAs planar multiplier Schottky diode circuits. The power handling capacity of first stage GHz Schottky diode multipliers has been quadrupled due to the development of novel multiple-device planar circuit topologies, new GaAs device fabrication techniques, and extremely high cutoff frequency planar diodes.

The performance of the LO chain that covers the high end of Band 6H for HIFI is shown in Figure 2.5 of the Instrument Fold-Out. At 130 K ambient temperature the chain produces more than 10 μW at the frequency of importance for STIM. The 6H Flight Spare (1.9 THz) chain is currently at JPL in a controlled environment. HIFI is now undergoing final spacecraft I&T and is scheduled to launch in August 2008. The HIFI project management has agreed to release this chain to STIM once HIFI is launched. This chain will be used to pump the [C II] mixer array on STIM.

Local oscillator sources to cover the 1400-1600 GHz range (Band 6L) were also developed and delivered for the HIFI instrument by JPL. An LO chain following the HIFI Band 6L design will be used to pump the [N II] mixer chain on STIM.

Spectrometers

STIM will utilize eight high-efficiency, low-power digital correlation spectrometers. The baseline spectrometer (shown in Figure 2.8 of the Instrument Foldout) can process two, 2 GHz wide receiver IF's, each with 1024 channels. We will explore an upgrade to 3 GHz bandwidth during Phase A. Four of these units would more than meet the spectrometer requirements of STIM. The 8×12 mm Multi-Chip Module shown in the figure will be upgraded in 2008 to a new single chip spectrometer ASIC, 5×6 mm in size with lower power consumption and higher bandwidth. With this upgrade, only two of the units shown in Figure 2.8 will be required to process the output of all 8 STIM receivers. The spectrometers have been tested up to 25 kRAD total dose with no degradation in performance and less than 1% increase in power consumption. They have also been tested in vacuum and are designed to be operated in space.

D-6.1.4 Cryostat

The STIM mixer arrays and low noise amplifiers will be kept at cryogenic temperatures in a modified version of the space-qualified Ball Lightweight Low Cost (LLC) Cryostat.

This Helium II cryostat, which has been designed, built and tested by Ball for SMEX missions. It will be rebuilt using some of the existing hardware with design modifications to accommodate the requirements of the STIM instrument. This is a low cost, low risk approach that is well suited to the STIM mission and will leverage off the considerable Helium II cryostat heritage at Ball.

Figure D-11: *LLC cryostat during cold vibration tests.*

Figure D-11 shows the current LLC Cryostat. Figure 2.4 in the Instrument Fold-Out 2, shows a cutaway view of the LLC with the major parts and their planned reuse.

The cryostat tank internal plumbing and liquid level sensing will be rebuilt to allow it to be filled in either vertical or horizontal position. The tank design will be modified to increase the helium volume and lifetime by 15%, while decreasing the overall system mass. This will be done by replacing the toroidal tank with a roughly spherical one. The mass savings that results from eliminating the cavity tube and thinning the reinforced areas of the tank near the tube more than compensates for the additional helium mass.

The STIM mixer arrays and associated optics are small enough to be mounted on top of the tank where they will operate at approximately 2 K. The low noise amplifiers will be mounted on the inner vapor cooled shield where they will operate at approximately 20 K. Additional modifications will be considered to reduce the vacuum shell and girth ring mass. Quartz windows will be added to the vacuum shell and vapor cooled shields to pass the desired sig-

Item	Demonstrated LLC cryostat performance	Modified LLC cryostat estimated performance	STIM requirement
Loaded Mass	107 kg	97 kg	$\leq$ 100 kg
Helium volume	95 liters	109 liters	109 liters
Helium life @ shell T	2.0 months @ 300K 19 months @ 60 K	8.8 months @ 130 K	$\geq$6.0 months @ 130 K
Detector Temp. (K)	1.5 K	2.0 K	$\leq$ 4.0 K
Launch Hold	60 hours (modeled)	60 hours	$\geq$ 12 hours (TBD)
Resonant Frequencies	72 Hz axial, 65 Hz lateral	72 Hz axial, 65 Hz lateral	$\geq$ 20 Hz (Pegasus)

Table D-1: *Modified LCC Cryostat will meet STIM Requirements*

nals from the telescope. The external plumbing will be modified to meet the requirements of the launch faring envelope. The LLC cryostat design information and the parts to be reused will be donated by Ball to STIM.

The modified LLC cryostat meets the requirements of the STIM mission. Table D-1 shows the demonstrated performance of the current LLC cryostat, the modeled performance of the modified and rebuilt cryostat and the STIM requirements. Figure D-12 shows the helium life for the current and modified cryostat as a function of vacuum shell temperature. The fill level of the liquid helium II will be monitored on the ground with a standard superconducting wire probe in the tank. On orbit, the helium II mass and boil off rate will be determined using thermal capacitance gauging, which has been used successfully on the Spitzer cryostat. Three gauging events are planned, with a total heat input of 37 joules, which will reduce the mission helium life by less than an hour.

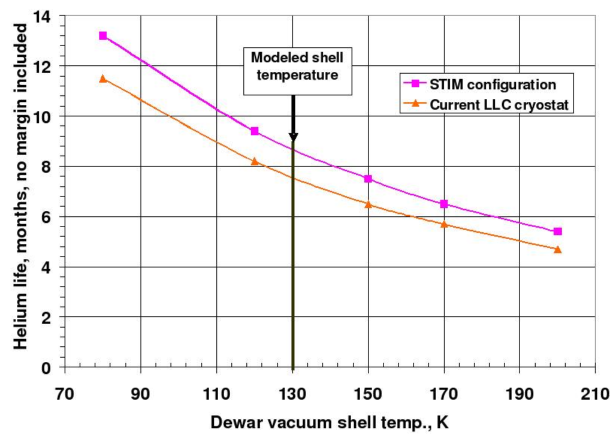

Figure D-12: *Helium life as a function of vacuum shell temperature for STIM instrument loads.*

D-6.1.5 Cryo-Radiator/Winston Cone

The cryostat helium lifetime is a function of the cryostat vacuum shell temperature. To minimize this temperature, we will use an innovative approach to radiatively cool the cryostat shell using the primary antenna reflector as a thermal radiator.

The primary reflector surface will be designed to radiate well at the 25 μm thermal wavelength and reflect well at the 150-200 μm science wavelengths. There are a number of good candidates for surface coatings, including aluminum coated FEP (Teflon), which has heritage in spaceflight applications. We have measured the THz reflectance of this material in our laboratories and found it acceptable. These coatings will be further evaluated in Phase A.

A Winston cone will shield the radiator from the Sun and Earth. The cone will have a base diameter of 54 cm, a height of 70 cm and will reject almost all the radiation that enters at more than 55° from the cone axis. The cone's internal surface will have a highly polished, reflecting surface. Since the science observing schedule will avoid pointing the Winston cone (and primary reflector) any closer than 55° to the Sun or Earth limb, the radiator will see only deep space. Winston cone radiators were successfully used on SWAS as part of the thermal control system. APART and ZEMAX modeling of the Winston cone/primary antenna combination indicate no stray light issues.

The antenna primary reflector/cryo-radiator will be thermally linked to the optical bench and cryostat vacuum shell with flexible thermal links. The optical bench and cryostat vacuum shell will be thermally isolated from the Winston cone, star-tracker and spacecraft by low conductivity support struts and 25 layers of high performance MLI. The outer MLI surface will be covered in silver coated FEP, to provide low solar absorption and high infrared emittance. The instrument thermal model shows that this configuration will be effective in cooling the cryostat shell temperature to a temperature of 130 K as shown in the thermal schematic (Figure D-13). The cryostat model is based on the LCC cryostat test data and indicates that for a shell temperature of 130 K and the STIM instrument heat loads, the helium life will be 8.8 months (Figure D-12).

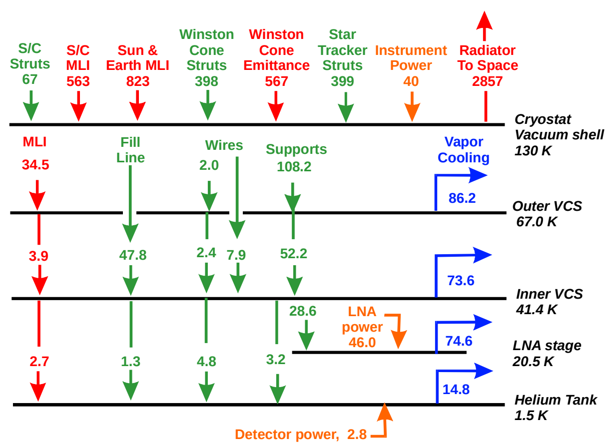

Figure D-13: *STIM instrument on-orbit thermal schematic. Powers are in mW.*

D-6.2 Mission Concept

The objective of the STIM mission is to map the inner 120° of longitude of the Galactic Plane in the emission lines of [C II] and [N II], to map targeted outer Galaxy regions like the Orion Giant Molecular cloud, and to produce sensitive maps of specially chosen extragalactic targets such as the Magellanic Clouds and face-on spiral galaxies like M33. To provide a high level of mass margin for the instrument cryostat (and hence a good mission lifetime), STIM will be launched in a 28.5° inclination low-Earth orbit.

The rate of nodal precession is 6.4° per day, allowing a complete orbital visibility cycle to be completed in nearly two months. Orbital visibilities are limited by a 55° avoidance angle for the Sun and Earth limb, and by a 40° maximum incidence angle for the spacecraft solar panels during the illuminated part of each 90 minute orbit.

The most efficient observing strategy for all STIM surveys is On-the-Fly mapping (OTF). The satellite is slewed to the Galactic latitude limit for a particular scan (e.g., at $b = -1°$). The satellite is then slewed to partially compensate for the orbital motion so that it accomplishes the scan through the target in the available half orbit. STIM will reach the end of the mapping leg (e.g. at $b = +1°$) just as the Earth limb constraint is reached. At that point, STIM will slew to the next target in the observing sequence for the other half-orbit. The optimal observing sequence will be generated by the same NASA Spike toolkit that has been successfully used by HST, Spitzer, and FUSE. Given the angular constraints and the available slew rate for the Ball spacecraft, STIM will be >80% efficient in performing mapping operations. Readouts of the spectrometer will occur every 1-2 seconds, which is consistent with scan speed and the Allan variance time of the detectors.

Assuming a launch in mid March 2012 and after a 15-day In Orbit Checkout (IOC) period, science observations commence on April 2012. The launch cannot precede 15 February as it would place the critical Galactic Center region inside the 55° Solar avoidance zone. Visibility of the main Galactic Plane Survey (GPS) region rises to 70% shortly after the beginning of science observations. On the "other" half orbit, high Galactic longitude and latitude targets like Perseus OB and the Polaris Flare are available. By May, the Magellanic Cloud mapping will begin on the "non-GPS" portion of each orbit. Similarly, by August, the Orion molecular cloud mapping projects will begin.

Table D-2 summarizes the various mapped regions and the total amount of time that will be ascribed to each map and the sensitivity limits per diffraction-limited beam in the first 180 days after science operations. To minimize risk, STIM will quickly map much of the GPS region with 12 seconds of integration time per independent beam within the first 3 months of operation, and then repeat the mapping coverage to achieve the targeted GPS sensitivity.

Survey	Area deg^2	#days	3σ rms/beam 10^{-6}erg/s/cm^2/sr
GPS	280	90	7.1
LMC & SMC	10	20	2.8
OG/Orion	13	40	2.3
high-b clouds	6	18	2.3
M33	1	12	1.1

Table D-2: *Summary of Observing Plan for the first 180 days of science time.*

D-6.3 Data Analysis and Archiving

Raw STIM data will be downloaded three times daily to the Goddard Space Flight Center (GSFC) and transferred daily to the SAO data center where backups and preliminary data quality checks are performed. In the first stage of processing, telemetry frames are decompressed, reformatted, stored to disk, and transferred to SAO where the data reduction pipeline occurs under the supervision of the Ground Data System Lead.

The primary data pipeline task is to regrid the irregularly sampled On-the-Fly (OTF) data onto a regular grid. The science team has extensive experience with the processing and analysis of data from heterodyne focal plane instruments and arrays (7 element submillimeter array on the SMT and a 32 element 3mm array on the Five College Radio Astronomy Observatory 14-meter telescope). The basic unit of OTF data is a file comprised of all readouts of the backend spectrometers for all measurements taken between and including the required reference and off-source measurements which intertwine and book-end the scanned data, respectively. An image field is comprised of many such units. The headers for all units are stored in a relational data base server, which allows for efficient data retrieval. Raw but calibrated spectra are formed from the on/off source measurements and system temperatures computed from on-board temperature loads. The spectra are Doppler-corrected, coadded and convolved onto a final output grid. A baseline is subtracted from each spectrum and stored for later consideration of the continuum level. The full data cube is then written to a FITS formatted file to be distributed to the science team and national data repositories. The final archive of regridded, calibrated, floating-point spectra over $\sim$300 square degrees of sky at 1.5′ resolution is 2 GB in size, representing a very manageable dataset and a factor of 45 reduction from the raw data volume. A web-based interface to the database will be developed to enable efficient extraction of sub-fields of the data cube centered on interesting objects.

D-6.4 Science Team

The STIM mission is supported by an outstanding team of scientists with extensive experience in observations, modeling, theory and interpretation of astrophysical aspects of the interstellar medium, star formation, and Galactic structure.

The STIM science team provides world-class capabilities and relevant experience in all key areas of the mission. Unless otherwise noted, NASA support for science team efforts are included in the STIM budget.

The Principal Investigator Erick Young (UA) is responsible for the overall conduct and success of the STIM project. Young brings 29 years of experience with various NASA and ESA space projects, including nearly 20 years as Deputy PI of the MIPS instrument on Spitzer. He led the development of the focal plane arrays for the Spacelab II Infrared Telescope, MIPS, and NIRCam. He also has been on the science teams of virtually all of the other space infrared astronomy missions, notably IRAS, NICMOS, ISO, and WFC3.

The Project Scientist and Deputy PI is Christopher Walker (UA). He is responsible for overall scientific leadership of the project and is an integral member of the project management team. Walker is a world leader in submillimeter instrumentation, and is founder of the Steward Observatory Radio Astronomy Laboratory (SORAL). He is Principal Investigator for the Stratospheric Terahertz Observatory, the SuperCam 64-element array receiver, and numerous other instruments.

Craig Kulesa (UA) is the Instrument Scientist. He will be responsible for the overall design of the STIM instrument and ensuring that it meets the performance requirements. He has extensive experience in the construction of submillimeter and infrared instruments.

Paul Goldsmith (JPL) brings his experience as both Project Scientist on Herschel and as the leading authority in quasi-optical techniques. He will participate in the instrument development as well as lead studies of the interstellar lifecycle.

Chris Groppi (UA) will serve as Deputy Instrument Scientist. He has extensive experience in the testing of heterodyne systems. He will assist Kulesa in managing the instrument development effort.

Mark Heyer (UMass) will lead the science efforts pertaining to the global ISM structure of the Milky Way. He has extensive experience in conducting large scale surveys from his leadership roles in CO surveys conducted from FCRAO.

Jonathan Kawamura (JPL) will lead the [N II] mixer effort at JPL. He has directly applicable experience as Herschel Band 6 lead as well as experience in THz observations.

Christopher Martin (Oberlin) will act as mission planning lead for STIM. As the AST/RO winter-over scientist for two years at the South Pole, Martin became an expert in operating and scheduling a complex radio telescope.

Gary Melnick (SAO) will be Ground Data System Lead for STIM. As PI for SWAS, Melnick has detailed experience in all aspects of the implementation and operation of a space science mission. In particular, he will apply his experience from SWAS in converting satellite data into useful scientific products. As described in SAO proposal P6863-12-07, Melnick is a federal employee, and his salary is not being charged to NASA.

Mark Morris (UCLA) is an authority on the Galactic Center, and he will lead the STIM science program in that area.

David Neufeld (JHU) will contribute to the detailed modeling of ISM microphysics and dynamics. His experience includes being Co-I on SWAS.

Paolo Padoan (UCSD) is a noted theoretician working in the area of star formation, with a particular interest in the role of turbulence. He will lead STIM investigations in that area.

Edward Prather (UA) will lead the STIM EPO effort. He has extensive experience in this area as Program Director for the NASA Center for Astronomy Education and as Deputy EPO Officer at the Astrobiology Institute (LAPLACE).

Antony Stark (SAO) will be the GDS Deputy. He will be responsible for the overall architecture of the GDS. He brings his experience in conducting surveys as PI of the AST/RO and co-PI of the South Pole Telescope.

Mark Wolfire is an authority on the theory of the ISM, particularly the energy balance in clouds and Photo Dissociation Regions. He will lead the STIM theory effort.

Harold Yorke has worked extensively in both the ISM and star formation theory. He also brings valuable space experience as Herschel Project Scientist. He will lead STIM studies of interstellar dynamics.

D-7 Science Enhancement Options

Given the short mission lifetime and the rapid availability of data to the scientific community, we are not proposing any Science Enhancement Options.

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