REPORT
OF THE
COMMITTEE ON THE FUTURE OF THE SMA

May 12, 2010

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INTRODUCTION

The Submillimeter Array (SMA) is an interferometer comprised of eight 6-meter antennas designed to operate from about 200 to 900 GHz. It is operated as a collaboration between the Smithsonian Astrophysical Observatory (SAO), part of the Harvard Smithsonian Center for Astrophysics (CfA), and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan. The SMA is located on Mauna Kea, Hawaii, at an altitude of 4,080 meters, adjacent to two other submillimeter telescopes: the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO). The SMA is designed for high spatial and spectral resolution imaging in the submillimeter atmospheric windows, with receivers for 200, 300, 400, and 650 GHz that are now available on all antennas. The current correlator has 4 GHz bandwidth with up to 25 KHz resolution. The SMA antennas can be configured to operate from 24 stations located in four nested rings, corresponding to subcompact, compact, extended and very extended modes, with baseline lengths from 8 to 508 meters. The corresponding angular resolution for each mode at 350 GHz is 2.5, 1.8, 0.8 and 0.3 arcsec, respectively. The SMA, JCMT, and the CSO can also be operated jointly as an interferometer, called the eSMA, with a resolution of ~ 0.2 arcsec at 350 GHz.

The SMA's first scientific results were obtained in 2004 and since that time the SMA scientific productivity has continued to rise rapidly. Currently the observing success rate is ~ 73%. Since 2005 more than 200 papers have been published based on SMA observations. Observing time is in high demand, with an average of ~ 115 proposals received per each 6-month semester, and oversubscription is high where the SMA capabilities are unique, e.g. at 345 GHz the oversubscription is 4.1:1 and at 690 GHz it is 4.8:1.

The SMA performance and operations continue to be improved. Recent instrumentation updates include a phase monitor to assess the atmospheric conditions for interferometry, increased bandwidth (4 GHz) for single receiver use, ongoing improvements to the 400 and 650 GHz receivers, and the development of an active phase correction scheme. All these items have contributed to an increase in observing efficiency and scientific productivity.

SMA IN THE ERA OF ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA), will be a research facility composed of up to 62 high-precision antennas (50 12-meter and 12 7-meter antennas), located on the Chajnantor plain of the Andes in northern Chile, 5000 m above sea level (http://www.alma.nrao.edu). ALMA will operate in 10 bands at wavelengths of 9.6 to 0.3 millimeters (31 – 950 GHz), where the Earths atmosphere above a high, dry site is largely transparent, and will provide unprecedented sensitivity and resolution. The up to 50 antennas of the 12 m Array will have reconfigurable baselines ranging from 150 m to

18 km. Resolutions as fine as 0.005" will be achieved at the highest frequencies, a factor of ten better than the Hubble Space Telescope. ALMA will have 8 GHz bandwidth with dual polarization. At 345 GHz ALMA's sensitivity is 0.2 mJy in 1 minute under medium conditions, which is approximately 100 times the sensitivity of the SMA at the same frequency. Its highest angular resolution at 345 GHz is 0.012 arcsec, which is approximately 30 times smaller than the SMA in the very extended configuration.

The ALMA scientific commissioning will start in early 2010 with 3 antennas and 4 bands. Early science programs will start in the second-half of 2011 with 16 antennas and 3 bands. Inauguration will occur in late 2012 with ~ 50 antennas and 6 bands. ALMA is planned to be complete and start regular operations in 2013 with > 50 antennas fully equipped.

Given the existence of ALMA, with its major increase in sensitivity and angular resolution at submillimeter wavelengths, the question arises as to what can the SMA do in the era of ALMA that is scientifically unique?

FUTURE OF THE SMA COMMITTEE

At the request of Dr. Charles Alcock, Director, Harvard Smithsonian Center for Astrophysics, and with the advice of Dr. Raymond Blundell, Director, Submillimeter Array, the following committee was established to evaluate the future directions for the SMA:

Edwin Bergin (Michigan)
Chris Carilli (NRAO)
Giovanni Fazio (Chair; CfA)
Paul Ho (ASIAA; CfA)
Daniel Marrone (Chicago)
Karl Menten (MPIfR)
Scott Paine (CfA)
Frank Shu (UC/San Diego)
Gordon Stacey (Cornell)

Following preliminary discussions, a telecon was held on 16 September 2008, which, after a welcome and introduction, the following list of options were discussed:

(1) Remain operational at the Mauna Kea site, with one or more of the following options:
    - keep the SMA as it is
    - increase the sensitivity significantly
    - add an array of detectors to each antenna
    - promote eSMA (interferometry with JCMT and CSO)
    - promote VLBI opportunities

(2) Move the SMA to a very high altitude site (Chile at 5.5 km site or Antarctica Dome A) to enable 350 and 200 micron wavelength observations:
   - enables unique wavelength range for observations
   - would support Herschel observations

(3) Add the SMA to the ALMA compact array.

(4) Close the SMA site on Mauna Kea and restore it to its original condition.

As a result of the telecon the Committee decided to pursue only the following two options in more detail:

(1) Remain at the Mauna Kea site and:
   - add an array of detectors (~ 7 in a 2-3-2 configuration) to each antenna.
   - improve the sensitivities of the receivers
   - increase the bandwidth of the system to as much as 32 GHz
   - institute large projects that would support ALMA programs

(2) Move the SMA to a high altitude site:
   - Chile; at a 5500-meter high-altitude site in the Andes mountains
   - Antarctica/Dome A; this option was eliminated because the SMA antennas are not designed to operate at such low temperatures.

The science justification for each option was also discussed in detail, and as a result, two teams were formed to write up the science case for each option and submit the results to the Chair. The teams were: Option (1): Frank Shu (Nearby Galaxies) and Ted Bergin (Galactic science) and Option (2): Chris Carilli, Gordon Stacey, and Karl Menten (fine structure lines, follow up of SOFIA and Herschel observations).

During the telecon Chris Carilli mentioned that the 12-m ALMA test antenna (ATF) may be available. Paul Ho agreed to pursue this further during his visit to the NSF.

Paul Ho later sent the following report: "While at ALMA board meeting last week, I talked to NSF people about the ALMA prototype 12-meter antenna at the New Mexico test facility. It can be transferred to SMA in principle, or to a US facility. The problem with the SMA will be the environmental impact. While we have always said that we might expand to 12 antennas, in reality it may be much more difficult. Even decommissioning one antenna and replacing it with the 12-meter might be difficult. Another option is for SAO to acquire this telescope and place it somewhere as a submillimeter VLBI antenna. That could happen to the European prototype 12-meter antenna which might go to Argentina."

While at a meeting in China, Fazio had the opportunity to discuss the future of the SMA with Reinhard Genzel and Linda Tacconi, Max-Planck-Institute for Extraterrestrial Physics (Germany). Linda stated that the Plateau de Bure Interferometer (PdBI; France) was also examining its future and ruled out putting detector arrays at the focal plane. The argument being the science proposed didn't warrant the cost of the program.

Reinhard Genzel stated that with respect to the future of the SMA it would be better to stay in Hawaii and increase the bandwidth by a factor of 10. Fazio discussed this with Bob Wilson and he thought it was possible.

The Chair proposed that a workshop be established that would not only include the Committee members, but also representative from each of the current mm/submm arrays (and ALMA) to discuss in more detail the future of these instruments.

WORKSHOP ON THE FUTURE OF THE SMA

The Committee sponsored a Workshop on the Future of the SMA at the Harvard Smithsonian Center for Astrophysics on 8 and 9 September 2009. All Committee members were present as well as several invitees: Al Wooten (NRAO; ALMA), Lee Mundy (University of Maryland; CARMA), Pierre Cox (IRAM), and Linda Tacconi (Max-Planck-Institute Extraterrestrial Physics). Also invited were members of the SMA group. The meeting agenda is attached as Appendix A to this report.

Following an Executive Session, a welcome by Charles Alcock, Director of the CfA, and introductory remarks by Giovanni Fazio, the Committee Chair, the morning and the early afternoon of the first day were devoted to presentations of the status and future plans of the current submillimeter arrays. Making presentations were Ray Blundell, Director, SMA, Lee Mundy, Director, CARMA, and Pierre Cox, Director, PdBI. Al Wooten, NRAO/ALMA, also summarized the current status of ALMA and presented its future plans and schedule.

Beginning in the late afternoon of the first day and through the morning of the second day of the meeting presentations were made on the Future of the SMA. Giovanni Fazio (CfA) introduced the two options to be pursued at the meeting: (1) remain at the Mauna Kea site and upgrade the array performance; (2) redeploy the SMA to a high altitude site in Chile that would permit THz observations. Concerning Option (1), Edward Tong (SMA) discussed the improved receiver performance of the SMA that was possible and the development of a wider bandwidth capability. This discussion continued on the morning of the second day of the meeting, with Scott Paine (SMA) presenting the possibility of adding an array of detectors in the focal plane at each SMA antenna. Robert Wilson (SMA) discussed the correlators required to increase the SMA bandwidth significantly and the importance of the Mauna Kea site for very long baseline interferometry. Giovanni Fazio presented a talk on the importance of having the future SMA perform large directed key programs that ALMA may not be able to carry out. Ray Blundell (SMA) closed out the session on Option (1) with a presentation on the cost benefit of the Mauna Kea site.

Presentations on Option (2) began with a discussion by Scott Paine (SMA) of possible site locations in Chile above 5500 meters. Edward Tong (SMA) reviewed the high-frequency receiver requirements and discussed the possibility of their construction. Ray Blundell (SMA) discussed the operations problems of a site in Chile and George Nystrom (SMA) presented the relocation logistics and costs.

The science case for each option was then presented, with Frank Shu and Ted Bergin leading the discussion for the SMA remaining at Mauna Kea and Paul Ho summarizing the science case for moving the SMA to a high-altitude site in Chile for THz (0.2 mm wavelength) operations. Written summaries of these three presentations are given in Appendix B.

Both Frank Shu and Edwin Bergin pointed out that installing focal-plane-arrays in an upgraded SMA at Mauna Kea would permit important observational programs to be carried out that ALMA could not compete with. One such set of programs would be the mapping, in both continuum and CO line emission, of extended objects, such as external galaxies that have interesting structure on a wide range of angular scales, e.g. mapping the molecular interstellar medium of nearby spiral galaxies on scales from 10 pc to 10 Kpc. ALMA is not suited for such large scale mapping because of the large diameter of the individual antennas and associated small field-of-view. Also, installing focal-plane-arrays on all of ALMA’s fifty antennas would be a formidable and expensive task. Another proposed program would the mapping, with arcsec resolution in continuum, line emission and/or polarization, the large- and small-scale structures and kinematics of dense, warm molecular gas in nearby Giant Molecular Clouds (GMC) close to the Sun. Both these programs would be directed key programs and would take multi-years of observing time, however, the results would revolutionize our knowledge of the interstellar medium and its relationship to large-scale star formation and galactic structure, dynamics and evolution.

The primary advantage of a very high altitude site in Chile is that the SMA could operate at THz frequencies, for which ALMA has no current capability. Paul Ho stated that the move to THz frequencies would permit the detection of fainter continuum sources as well as rarer emission lines. At these frequencies, when compared the 345 GHz, the dust continuum emission is 100 times stronger and line intensities are ~ 300 times stronger. An important advantage is the ability to observe the important fine structure lines of N^+ (1.46 GHz) and C^+ (1.9 GHz), as well as ions like H_2D^+ (1.37 GHz), which are very important coolants of the interstellar medium. For example, C^+ line could emit up to 1% of the total luminosity of a galaxy. The higher transitions of CO ($J > 7$; > 860 GHz)) will also be observable, which will be important for probing highly excited gas. There also is the potential for studying the properties of smaller dust grains and comparison of THz and submillimeter polarized emission may reveal the magnetic field structures at different length scales. An important scientific objective would be probing the life cycle of the interstellar medium at higher resolution.

The presentations from each speaker during the Committee meeting are available on the

SMA web site. In addition a presentation on "Conducting Polarimetry Observations with the SMA" by Ramprased Rao (ASIAA) was also added, since this topic was not addressed in detail during the meeting.

EXECUTIVE SESSION OF THE COMMITTEE

On the afternoon of the second day of the meeting the Committee met in executive session to recommend which option for the future of the SMA. Also present at this meeting were Al Wooten, Pierre Cox, Lee Mundy, and Linda Tocconi. Members of the SMA group invited to the executive session for their technical expertise and advice were Ray Blundell, Robert Wilson, Edward Tong, and Scott Paine.

Each option was reviewed and discussed thoroughly.

Having the SMA remain at the Mauna Kea site, accompanied by several important upgrades, offers many scientific advantages. Even during the era of ALMA, the SMA will remain the most sensitive submillimeter array in the northern hemisphere at 345 GHz. With the addition of focal-plane arrays to the SMA, a unique body of science could be carried out that was unlikely to be performed by ALMA, namely, large-area, very high resolution, multi-year mapping programs addressed above. Robert Wilson also pointed out that the Mauna Kea site is very important for submillimeter VLBI. In the long term, the science drivers of increased continuum sensitivity to study weaker sources and larger samples, as well as faint spectral lines from high redshift objects and rare species, will demand significant increases in SMA bandwidth and electronic processing power. The modest number of SMA antennas allows for the adoption of these new technologies. That flexibility, together with unique access to the northern sky, ensures that the SMA can remain at the forefront of submillimeter observational capabilities into the foreseeable future.

Although the move to a high-altitude site in Chile, offers the many unique scientific advantages discussed above, there were numerous problems that were identified:

(1) No high-altitude site with the required infrastructure was identified. The site adjacent to the proposed Cornell Caltech Atacama Telescope (CCAT; 25-meter telescope; 5600 meters altitude) was the most appealing, but the available area would limit SMA operations to the compact mode.
(2) Current single dish THz telescopes, although exploratory in nature, have demonstrated no compelling and unique science at THz frequencies which argues strongly for the need for higher angular resolution.
(3) Even at 5500-meter altitude, THz frequency operations would be limited to about 25% of the time.
(4) Antennas performance, such as pointing and calibration, would have to be improved.
(5) The cost to move the SMA from Hawaii to a site in Chile was estimated to be $30 – 40 million.

The consensus was that the move to THZ frequencies may be premature at this time. A few developments will change this conclusion: Successful technical developments for THz interferometry, the construction of CCAT or a similarly large dedicated aperture for THz astronomy, and substantial reduction of infrastructure costs.

RECOMMENDATIONS FOR THE FUTURE OF THE SMA

After consideration of both the scientific and technical merits of both options, the Committee unanimously recommended that the SMA remain at the Mauna Kea site and that its capabilities be progressively upgraded as soon as possible. If these improvements are carried out, the SMA will remain a very important telescope in submillimeter astronomy even into the ALMA era.

The following upgrades were endorsed:

> **Develop the most sensitive dual polarization receivers in all frequency bands, but concentrate initially on 345 GHz. Increase the bandwidth of these receivers as technology develops. We foresee this as a two-step process.**
>
> **1) The current 4 GHz IF bandwidth, single polarization receivers give a total bandwidth of 8 GHz when the two sidebands are combined. With relatively minor changes, that are available with current technology, the IF bandwidth can be increased to 18 GHz and the receivers upgraded to dual polarization. This would yield a total bandwidth of 72 GHz in two sidebands and two polarizations for an improvement in throughput by a factor of 9.**
>
> **2) The ultimate limit on the bandwidth is about 30 GHz. This is set by the bandwidth of the SIS junctions in the receivers. This would yield a total bandwidth of 120 GHz in two sidebands and two polarizations for an improvement in throughput by a factor of 15. Upgrading the IF and the receivers to handle 30 GHz is possible, but is considerably more complex and would require a longer time frame.**
>
> **Both of these improvements would require more correlator capacity. Currently the SMA throughput is limited by the sampling rate of the present correlator.**
>
> **The increased throughput significantly improves the observing efficiency of wideband observations such as continuum observations and surveys of spectral lines across a spectrum. The sensitivity of continuum**

observations increases by the square root of the throughput. Step (1) above would increase the wideband sensitivity by a factor of 3 and Step (2) by a factor of 3.9. The efficiency of surveys of spectral lines across a wide spectrum would increase proportional to the bandwidth, e.g. a factor of 9 in Step (1) and 15 in Step (2). Narrow-band observations, such as those of a single spectral line, benefit only from the upgrade to dual polarization. Steps (1) and (2) would improve the efficiency of narrow band observations by the square root of 2.

The sensitivity of both the narrow-band and wideband observations can also be improved by increasing the diameter of the current antennas from 6 meters to 7 or 8 meters by adding an outer skirt to each antenna. This would improve the sensitivity by factors of 1.36 and 1.78, respectively.

Additional upgrades recommended include:

a. **Initiate a program to design and install a 3 x 3 focal-plane array at each antenna.**

b. **Add two additional antennas.**

c. **Establish a closer collaboration with CARMA/ALMA/PdBI, particularly in the development of 30 GHz correlators and of 230 GHz wide-band receivers.**

APPENDIX A

AGENDA FOR THE MEETING OF THE COMMITTEE ON THE FUTURE OF THE SMA

WORKSHOP ON THE FUTURE OF THE SMA

2009 September 8 and 9

Harvard Smithsonian Center for Astrophysics

Room 340

160 Concord Ave.

Cambridge, MA 02138

AGENDA

Tuesday, September 8, 2009

09:00 AM *Continental Breakfast*

09:30 AM **Welcome (Charles Alcock, Director CfA)**

09:40 AM **Introduction (G. Fazio)**

10:00 AM **Status of the Current Submm/mm Arrays**

SMA (R. Blundell)

CARMA (L. Mundy)

11:00 AM *Coffee Break*

11:30 AM PdBI (P. Cox)

12:00 PM **Status of ALMA and Future Schedule** (A. Wooten)

12:30 PM *Lunch*

02:30 PM **Future Plans of the Current Submm/mm Arrays**

CARMA (L. Mundy)

PdBI (P. Cox)

03:30 PM **Future of the SMA**

Options Considered by the Committee (Fazio)

04:00 PM **Future of the SMA**

Options to be Pursued (Fazio, Chair)

Upgraded array at Mauna Kea

Improved Performance (E. Tong)

Wide IF Bandwidth Possibilities (E. Tong)

06:00 PM *Dinner*

Wednesday September 9, 2009

08:30 AM *Continental Breakfast*

09:00 AM **Future of the SMA (cont'd)**

Options to be Pursued (cont'd)

Upgraded array at Mauna Kea (cont'd)

- Focal Plane Arrays (S. Paine)
- Correlator and VLBI Issues (R. Wilson)
- Directed Key Programs (G. Fazio)
- Cost Benefits (R. Blundell)

Redeployment to High Altitude Site in Chile

- Site Location at 5500 m (S. Paine)
- High Frequency Instrumentation (E. Tong)
- Operations (R. Blundell)
- Relocation Logistics and Costs (G. Nystrom)

11:00 AM **Science Objectives for Each Option**

Upgraded Array at Mauna Kea (F. Shu, Lead; Ted Bergin)

High Altitude Site in Chile (P. Ho, Lead; C. Carilli, G. Stacey, and K. Menten)

12:00 PM *Lunch*

02:00 PM **Recommendation of Option (Committee Executive Session)**

04:00 PM **Report Schedule and Assignments**

05:00 PM *Adjourn*

APPENDIX B

SCIENCE PAPERS IN SUPPORT OF EACH SMA OPTION

(1) Support of Option 1 (Mauna Kea)

Future of the SMA: Science Case for Molecular ISM of Nearby External Galaxies

Frank Shu

Report from the Future of the SMA Committee: Galactic Science

Edwin Bergin

(2) Support of Option 2 (High Altitude Site)

Moving to 5500-meter Site in Chile for THz Operation

Paul Ho

Future of the SMA
Science Case for Molecular ISM of Nearby External Galaxies

Science Context

We know a lot about the local molecular ISM and its relationship to star formation of the Milky Way Galaxy on the scale of giant molecular clouds (GMCs) and smaller. However, we know relatively little of the relationship of this material to the large-scale structure, dynamics, and evolutionary state of the Galaxy. For example, we have no definitive answers to the following questions: Are the molecular clouds in the spiral arms of the Galaxy (to the extent that we can determine them) different from those between arms? What is the relationship between the inner-edge of the molecular ring and the inner bar structure that has been inferred from infrared images of the Galactic bulge? What is the relationship between CO and H I gas in the Galaxy on scales of 50 pc and larger? Does the metallicity gradient inferred from temperatures variations of H II regions as a function of Galactocentric radius reflect itself in the properties of the GMCs? Have minor mergers inferred from star streams in the Milky Way left any tracers in the distribution, kinematics, or physical and chemical properties of GMCs in their wake?

Similarly, we know a lot about the structure, kinematics, stellar contents, and larger environments in which the cold interstellar medium are embedded in external galaxies. But even in the nearest galaxies, our knowledge of the relationship of these more global properties to the individual properties of GMCs is very limited. Indeed, even the systematic survey in the CO $1 \rightarrow 0$ line by the BIMA SONG project of 44 nearby spiral galaxies has a best angular resolution of only 6 arcsec, which at a mean distance of 11 Mpc implies a linear scale of 660 pc. This is not enough to tell us much about the properties of the individual GMCs, because with a typical linear size of 50 pc, both the dust and molecular emission from a GMC would be severely beam-diluted. Moreover, it is known from studies of the CO $1 \rightarrow 0$ line in GMCs within a few kpc of the Sun that the relationship of this diagnostic line to the local star formation is tenuous. A much better correlation would exist if one studied the CO $3 \rightarrow 2$ transition because it refers to warmer and denser molecular gas that is more indicative of star-forming, dusty, gaseous material. The shorter wavelength of the transition would yield higher angular resolutions for the longest baselines of the array, bridging the gap between the knowledge of the local molecular ISM on scales of GMCs and smaller and that of nearby external galaxies at scales of GMCs and larger. Such a bridge is a necessary first step if astronomers are to progress beyond ad hoc “black-box” rules concerning star formation in numerical simulations of large-scale structure and the formation of galaxies that are used to compare with and to interpret the results of high-redshift surveys.

The Unique Contributions Possible from an SMA Equipped with Array Receivers

Focal-plane array receivers have revolutionized single-aperture mm-wave and submm-wave radio telescopes in an analogous manner as CCDs and infrared cameras did for optical and infrared telescopes. The frontiers are now to adapt this technology to heterodyne detection of molecular lines and for installation on mm and submm telescope arrays.

The scientific viability of university-based mm and submm arrays after 2013 is of course, threatened by the coming of the ALMA telescope. However, installing focal-plane arrays on ALMA telescopes is a very daunting task because of the expense of both the receivers and the added correlation. Moreover, the relatively large diameter of the individual dishes and the associated small field of view implies that ALMA is not suited to the task of mapping extended objects like external galaxies that have interesting structure on scales of a great dynamic range. This then leaves open an important niche, the molecular ISM of nearby spiral galaxies, for a properly equipped SMA.

At the average 11 Mpc distance of the BIMA SONG galaxies, an angular resolution of 1 arcsec would correspond to 55 pc, which would barely resolve individual GMCs if they have similar properties as local examples near the Sun. The field of view of an individual SMA telescope is 40 arcsec, which corresponds to 2.2 kpc for the same object. A mosaic of 100 pointings would cover an area 22 kpc x 22 kpc, which is enough to map the most interesting molecular regions of most spiral galaxies. Moreover, if each telescope had a 7-element receiver-array installed at the focal plane, it would make the telescopes the equivalent of 7 SMAs, with each set of receivers at the same pixel position on the 8 telescopes acting as an independent interferometer. The speed of the resulting facility compared to ALMA, each of whose 50 telescopes has 4 times the collecting area of a SMA dish, would then be as 7 x 8 x 7 is compared to 1 x 50 x 49 x 4, i.e., the ratio is 1:25. The SMAM (submm array mapper) would be 1/25 as powerful as ALMA for observing extended objects (discounting the fact that ALMA is at a better site).

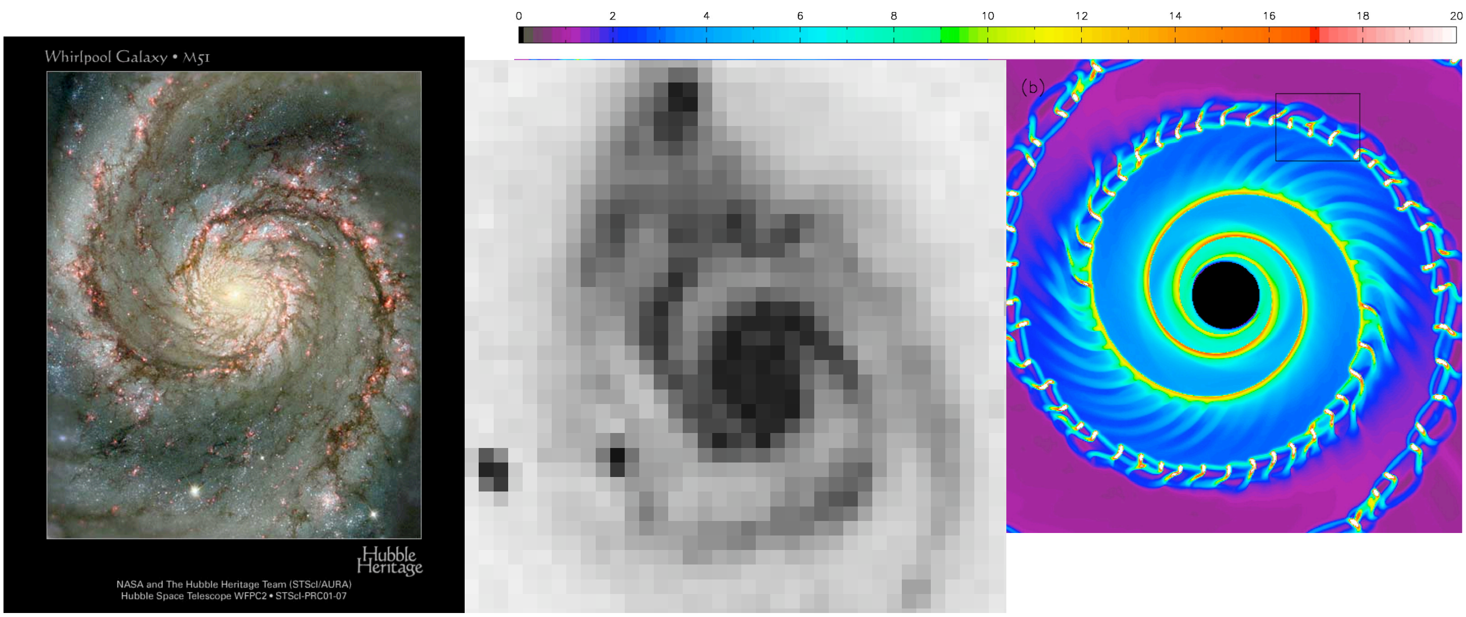
Thus, if each pointing takes half a day, we would need 50 days to map a typical BIMA SONG galaxy, and it would take 2,200 days, or approximately six years, to complete a survey of 44 galaxies. ALMA could do the same job in three months and reach the same sensitivity, but no one would ever get three months of ALMA time for a project like this.

To complete the overall scientific task, one might want to spend a comparable amount of time, six years, to map with exquisite detail the large and small-scale structures and kinematics of dense, warm molecular gas in nearby GMCs close to the Sun. The combined total of twelve years to study the molecular gas and dust that makes stars in the Milky Way and nearby spiral galaxies is sure to rewrite the textbooks on the ISM and its relationship to large-scale star formation and galactic structure, dynamics, and evolution.

A Specific Science Project: Spiral Substructure and Giant Molecular Clouds

One theory for the origin of GMCs is that they are the dense heads of a "feathering instability" in self-gravitating, magnetized, and turbulent molecular gas when it undergoes shock compression in the spiral gravitational potential associated with a galactic spiral density wave (Shetty & Ostriker 2006). Figure 1 compares the optical and nonthermal radio continuum images of M51 with one of the MHD simulations (not tuned to fit this galaxy).

Figure 1. Comparison of optical (left) and radio continuum (middle) images of M51 with a numerical simulation of the development of spiral substructure through the feathering instability of magnetized, turbulent, cold interstellar gas as it passes through the spiral gravitational potential associated with a smooth underlying two-armed density wave associated with the disk stars of this famous spiral galaxy. (Left, optical HST image; Middle, follow up to nonthermal radio emission first mapped by Mathewson, van der Kruit, Brouw 1972; Right, numerical simulation from Shetty & Ostriker 2006.)



If an origin of GMCs in spiral density-wave shocks is correct, then in some sense GMCs are not even material entities, but the highly compressed crests of a nonlinear wave, with material streaming into them from one side of the arm (typically, the inside edge where the optical dust lanes are located) and out of them from the other side, with the molecular mass loss augmented, perhaps, by photoevaporation associated with the formation of OB stars downstream from the dust lanes. Such a description, rather than the usual one of a "cloud" of velocity-coherent material, would indeed rewrite the textbooks. A lot of work needs to be done, observationally and theoretically, before one accepts this attractive and alluring description.

Questions that would be addressed by a SMA survey include:

- Can we detect the motions associated with the feathering instability?
- What are the relationships among the behaviors of the atomic hydrogen gas (as measured by the e-VLA or the Australian SKA Pathfinder), the cold molecular gas (as measured by the CARMA array), the warm molecular gas (as measured by the SMA Mapper), and the H-alpha emission (as measured on ground-based optical telescopes)?

- What is the dependence of the relative spacing of feathers along the spiral arm as a function of the five dimensionless parameters of the problem: fractional gas content, fractional strength of the underlying spiral gravitational field, ratio of angular frequency at which the gas revolves relative to the pattern in units of the local epicyclic frequency, ratios of the turbulent speed of the gas and the Alfven speed to the flow speed perpendicular to the spiral-arm pattern?

The original view of the triggering of OB star formation by two-armed spiral galactic shocks (e.g., Roberts 1969, Roberts & Yuan 1970) has been called into question by a quarter-century long failure to find the associated color gradients (see Fig. 2). However, Gonzalez and Graham (1996) pointed out that the earlier observational efforts to detect such color gradients were badly contaminated by H II regions associated with the formation of giant complexes of O stars in the spiral arms. When they chose a spiral arm region of the galaxy M99 that contained only B stars, which have much less prominent H II regions, they found the predicted color gradients. This observational breakthrough has now been followed up by a more extensive survey involving thirteen ordinary spiral and mildly barred spiral galaxies (Martinez-Garcia, Gonzalez-Lopezlira, Bruzual-A 2009). Ten of the thirteen galaxies exhibit the predicted color gradients, with many showing even the expected reversal in sign as one crosses the corotation circle where the material rotation speed matches the pattern speed (see Fig. 3).

Figure 2. Schematic of the expected color gradients if OB star formation is triggered by the galactic shock associated with a nonlinear two-armed spiral density-wave. (From Martinez-Garcia, Gonzalez-Lopezlira, Bruzual-A 2009).

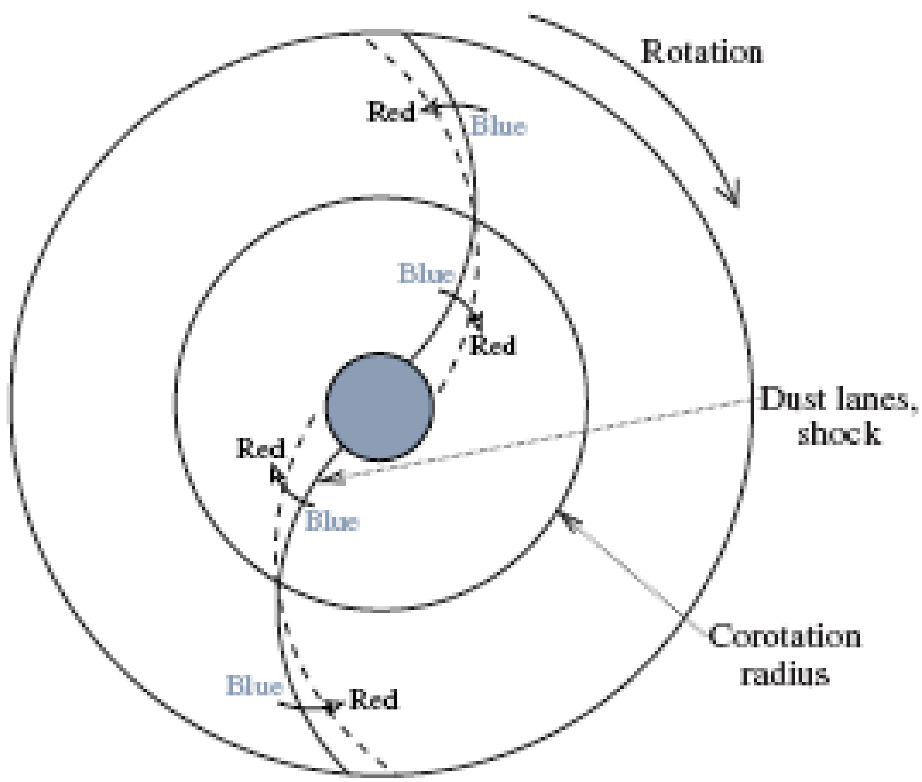
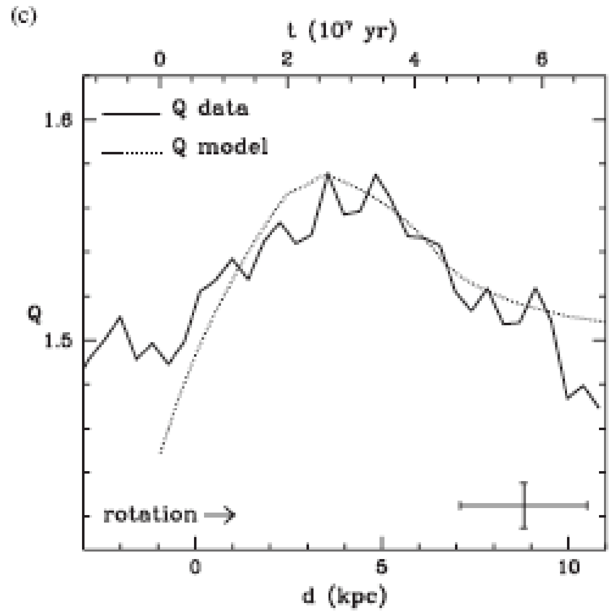


Figure 3. Comparison of a color index Q, constructed to remove the effects of reddening by interstellar dust, from a model prediction and cut through an observed spiral arm. (From Martinez-Garcia, Gonzalez-Lopezlira, Bruzual-A 2009).



Connection with Galactic Star Formation

One interpretation of the feathering instability is that it has an intimate relationship with the role of galactic magnetic fields in enforcing a low overall efficiency of star formation in the current universe of spiral galaxies (Shu et al. 2008). In this picture, continued gravitational collapse can occur only in special regions (typically, molecular cloud cores) where the mass-to-flux ratio has crossed a minimum threshold level (Figs. 4 and 5).

Figure 4. The magnetic field configuration in molecular cloud cores that are undergoing "inside-out collapse" in a region with no rotation (from Galli & Shu 1993).

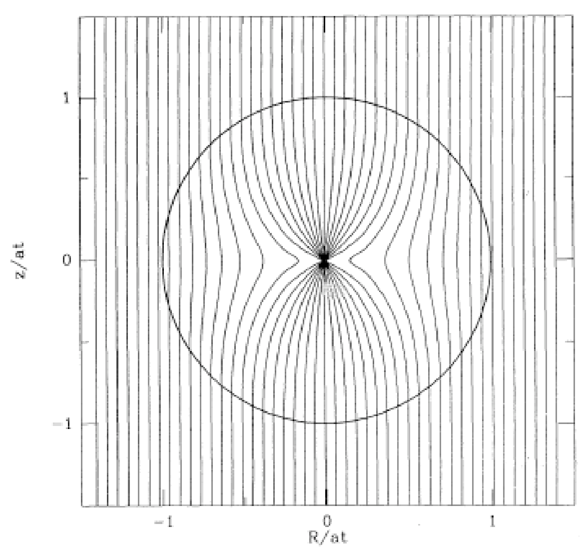
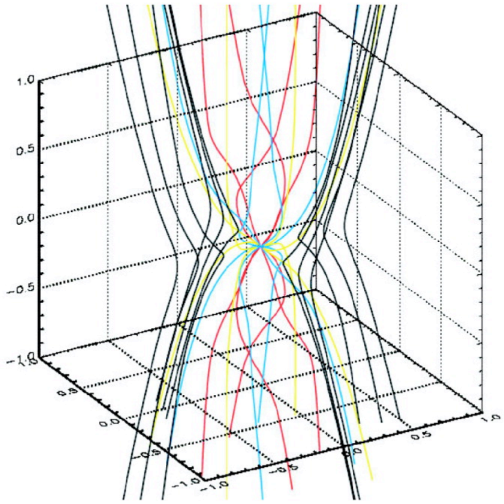


Figure 5. The magnetic field configuration in molecular cloud cores that are undergoing "inside-out collapse" in a region with rotation present parallel to the mean direction of the magnetic field(from Allen, Li, Shu 2003).



Although the theory was developed originally to explain low-mass star formation, recent mapping of the magnetic field in the W51 region of high-mass star-formation region in the polarized radio continuum at 1.3 mm wavelength and 0.87 mm wavelength radiated by aligned dust particles have been made by Lai et al. (2001) and by Tang et al. (2009), respectively, using the BIMA array and the SMA. These results show that the magnetic field on large scales (as outlined by the colder dust emitting at longer mm-wavelengths) does have the uniform and straight morphology predicted by theories in which the field dominates over turbulent motions and self-gravity (Fig. 6). But, in the denser regions (as mapped by the warmer dust emitting at shorter sub-millimeter wavelengths) where the ratio of gas mass to magnetic flux ratio becomes supercritical, gravitational collapse can occur and produce the characteristic pinched "hour-glass shape" predicted by the same theories (Fig. 7).

Figure 6. Map of magnetic field direction inferred by the emission of polarized 1.3 mm radiation from the W51 region of high-mass star formation. (From Lai et al. 2001.)

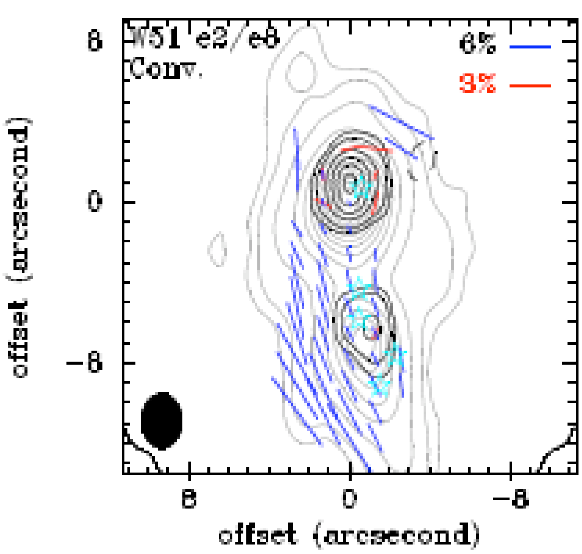
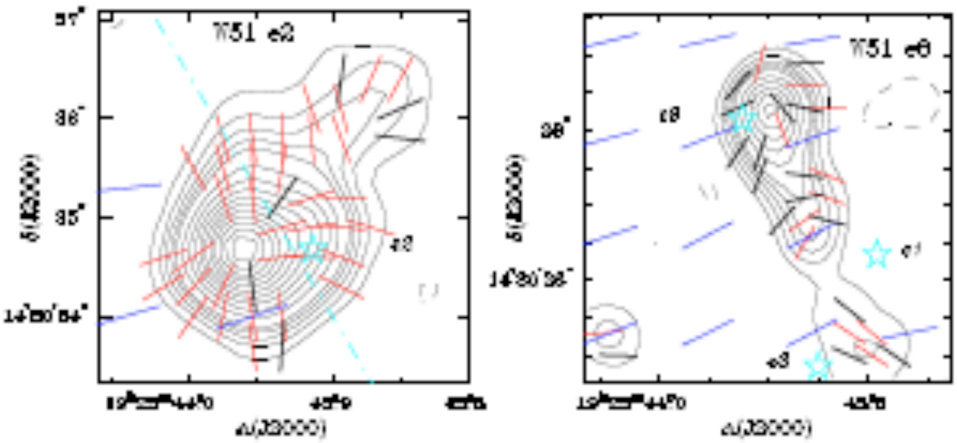


Figure 7. Map of magnetic field direction inferred by the emission of polarized 1.3 mm radiation from the W51 region of high-mass star formation. (From Lai et al. 2001.)



All in all, these observations suggest that, except for the eventual formation of pressurized H II regions, high-mass star-formation in its earlier stages is “just” a scaled-up version of low-mass star formation (see also Keto, Ho, Haschick 1987). Establishing this unifying link, or disproving it, would be one of the major scientific goals of the proposed SMA Mapper. Star formation at high redshifts is also witnessing tremendous growth as a new scientific sub-discipline. To understand the relationship between galactic star formation and star and galaxy formation at cosmological distances in the universe when it was young, we must study the large-scale processes of star formation occurring in nearby galaxies. The proposed SMA Mapper could provide the crucial bridge that spans the gap in our knowledge about the processes that led to the current universe of stars and galaxies.

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Report from the Future of the SMA Committee: Galactic Science

1. Consensus Evaluation

For the past 5 years the SMA has operated as a true ALMA pathfinder doing forefront science expanding from cosmology, galaxies, massive black holes, star formation, planet formation, and atmospheric chemistry on planets and moons. With the inclusion of focal plane arrays the SMA has a unique opportunity to expand their efforts to new frontiers and uniformly probe the actual assemblage of stars in galaxies, exploring the micro-physics on small scales in our galaxy to macrophysics in other nearby galaxies. Such a cohesive program to fully explore the scales of star formation and the evolution of the galactic interstellar medium at high spatial resolution has never before been possible. With new instrumentation the SMA will continue to trailblaze new frontiers even in the age of ALMA. *It is important to state that the best way for this to succeed would be harness observations of projects that take hundreds to perhaps thousands of hours into directed key programs. This will change the scale of the science done by the SMA, but also bring it to a level that is impossible to be done with ALMA or even the multiple-country community based PdBI.*

2. Galactic Science and the SMA Future

After much discussion it was clear to the committee that the incorporation of focal plane arrays on the SMA offers the best opportunity to continue to probe new scientific frontiers. It is notable that the other existing US-based mm-wave interferometer (CARMA) is independently evolving to this same conclusion. Moreover it was suggested that focal plane arrays will eventually be a piece of the long term future of ALMA. We note that important and unique scientific goals must be the driving factors behind any future expansion of the SMA. Below we outline a consensus program, which offers the SMA a path wherein it can continue to be a pathfinder and high impact instrument in the age of ALMA.

A combination of observations and theory over the past several decades have revealed an intimate link between the formation of stars and the natal cloud. Thus the formation of the cloud on the large scale, perhaps by collisions of large scale turbulent flows or shocks in spiral arms, sets the filamentary structure of the over-dense ($n > 1000$ cm^{-3}) regions where stars are born (e.g. Mac Low & Klessen 2004; Myers 2009). Observations from focal plane arrays mounted on the FCRAO 14m (e.g. Goldsmith et al. 2008) have revealed this structure on angular size scales of $\sim 50''$, corresponding to linear scales of 0.04 pc at 140 pc, which is the distance of the nearest star-forming region (Taurus). Interferometers, such as OVRO, BIMA, CARMA, PdBI, and the SMA, probe the inner structure of the condensing cores embedded within the filaments on size scales below hundreds of AU (at the distance ot Taurus).

However, the distribution of molecular gas in the Galaxy is not uniform and does not have a large concentration near the Sun. Rather both molecular gas and corresponding star formation peak in a ring about $\sim 4-6$ kpc from the galactic center, show a minimum between 3-4 kpc and peak again in the galactic center (Sanders et al. 1984; Jackson et al. 2006). However, high (arc-second) and low (arc-minute) resolution star formation studies have primarily focused, but not exclusively, on regions forming low mass stars, within about 500 pc of the Sun. In large part this is due to the reduced spatial resolution of single dish and array telescopes at large distances. Regardless, at present there is no existing high resolution view of star formation in the Milky Way.

This becomes an issue when trying to compare extragalactic studies, which see structure within a galactic disk but have difficulty resolving giant molecular clouds (GMCs), to galactic studies where we resolve within individual GMC complexes. For extra-galactic studies BIMA SONG (Survey Of Nearby Galaxies) provided a moderately high resolution ($6''$) view of 44 nearby galaxies in CO emission. This corresponds to 330 pc at 11 Mpc the average distance of the SONG sample. As an example a typical galactic GMC has a radius of $\sim 20-40$ pc; thus this study did not resolve individual GMCs but rather associations of clouds. Of course SMA, PdBI, and CARMA are now providing observations with arc-second resolution which has an ability to resolve individual GMCs. However, it is difficult to observe a significant sample of individuals galaxies with a range of star formation properties at this resolution.

Looking broadly, for galactic studies we see is a patchwork of studies wherein the large scale is explored with low angular resolution by single dish telescopes, and the smaller scales with high resolution by interferometers. Moreover, at no point, beyond the initial very low (degree-scale) galactic CO surveys (Sanders et al. 1984), has there been a significant effort to link star formation and molecular gas in our own galaxy to the regions we are now seeing in other galaxies. High resolution views of other galaxies exist, but are difficult to extend to numerous systems. Thus, despite all our efforts we currently do not have a theory that links successive evolutionary states from large to small scale, even in our own galaxy. Put in other words: how do molecular clouds form? What are the primary processes that sets the filamentary structure? What role is played by the magnetic field? How do the filaments condense to make stars? What role is played by the external environment? How does star formation in the Milky Way relate to and inform that of other systems?

Focal plane arrays mounted on the SMA would provide a tremendous opportunity to answer some of these questions, which are central to star formation. With a 3 × 3 array it would be more than competitive with ALMA on large scales. For reference the ALMA primary beam at 345 GHz is 18″ as opposed to ∼30″ at the SMA. Thus with a 9 pixel array the SMA would have a factor of 25 greater coverage in area when compared to ALMA. Clearly ALMA has higher sensitivity (factor of ∼ 25 over SMA), but it will be significantly hampered by the reduced field of view and telescope time allocation pressure to perform large mosaics. Large, nearly degree scale, mosaics, such as those possible with an expanded SMA, will be effectively impossible with ALMA.

A science program can comprehensively link star formation at all scales with high resolution. As discussed in the extra-galactic write up to tens of galaxies can be observed in CO emission with arc-second resolution in a reasonable time frame (years). These observations can resolve individual GMCs. On the galactic side the program can focus on complete census within individual GMCs as a function of distance in the galaxy. With increased continuum sensitivity and array receivers the SMA can obtain sub-arcsecond images (∼ 400 AU at 4 kpc in the molecular ring and ∼ 800 AU in the galactic center) of the dust continuum emission. This type of observation (wide field mosaic mapping) was done quite profitably by OVRO/BIMA in dust continuum (Testi & Sargent 1998) and N_2H^+ emission (Walsh et al. 2007). A combination of molecular line observations and dust continuum will be needed to determine distances to the dense condensations seen in dust emission while also providing information on the kinematics (line width and centroid). The aim would be to obtain a full census within individual GMCs. If we take a typical GMC radius of 20 pc this corresponds to an area of $\sim 3 \times 10^6$ square arc-seconds at a distance of 4 kpc (the distance of the peak in molecular gas in the galaxy). But the GMC does not uniformly fill this volume. Assuming a filling factor of 0.1 this gives 3×10^5 square arc-seconds; this is likely a conservative estimate. The SMA primary beam at 345 GHz is ∼ 30″, which is 700 square arc-seconds. With a 3 × 3 array one can cover an area of $\sim 6 \times 10^3$ square arc-seconds. So it would take about 45 pointings to map one full GMC. With 2 pointings per track (night) then that is about 23 nights per GMC. One can explore 5-10 to properly sample the galaxy. Molecular lines can be observed simultaneously with the dust continuum – with wideband backends several lines can be observed simultaneously.

Again the important aspect is to organize under large programs that explore global star formation in the galaxy on the large scale at high resolution. Probing deep into the galactic center would trace how galactic environment might change the characteristics of star formation. This is of great interest as important physical variables such as the gas surface density, average density, velocity dispersion, temperature, and magnetic field strength are all estimated to be much higher near the galactic center than observed in local clouds. One suggestion is that the evolution of gas within the strong gravitational potential may favor the formation of massive concentrations of molecular gas and a mode that favors the formation of massive stars over low mass stars (e.g. Morris 1993; Stark et al. 2004). To date even the famous Orion Molecular Cloud has been done piecemeal, one instrument doing this part, another a different region. No single study has done a cohesive exploration with the same facility and certain not with the capability of resolving within a Jeans length and well above. Finally, the SMA has also been a pioneer of submillimeter polarimetry – a study of galactic and extra-galactic star formation including information on the magnetic field will clearly be unique. A present the SMA has done fantastic work showing the pinching of the field in dense star-forming cores. Polarimetry should clearly be a component of the overall galactic and extra-galactic study.

In all such a study would explore the continuum of star formation in the galaxy in a manner that can directly link to the properties seen in other galaxies. How does the mass function change from object to object? Are there any kinematical features that can be traced back to the origin of the filament? What role does environment play? How does all of this relate to the overall process of star formation in the Milky Way in terms of the far-IR emission - to be mapped with Herschel and SOFIA or the H I? How does the small scale B-field trace that seen on large scales and what does this mean for magnetically mediated star formation theory? These questions, and the others given above, are just a host of broad and frontier science goals to be explored. In sum with array receivers the SMA can continue to be a pioneer – even in the age of ALMA.

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Summary of Option 2: Moving to 5500m site in Chile for THz Operations.

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We considered the scientific potentials of moving the SMA to Chile for THz operations.

Scientific Rationale: The move to Terahertz operations, has the same basic advantages as was the case for moving to submillimeter wavelengths. In terms of continuum sensitivity, we continue to move up the blackbody curve, which for optically thin emission, scales as $S_\nu \sim \nu^4$ for the dust emissivity index $\beta \sim \nu^2$. In terms of line sensitivity, the integrated line intensity continues to increase as $S \sim \nu^5$, principally because of the dependence on the Einstein A coefficient which scales as ν^3. Hence, by moving to Terahertz, we will continue to detect fainter continuum sources as well as rarer emission lines. This is assuming that the receiver noise or system temperature does not increase strongly with ν, and that the atmosphere does not contribute too much noise and attenuation at these higher frequencies.

Science in the Continuum. It is undoubtedly true that at THz, the continuum fluxes will be greater. There is the potential for also studying dust properties of smaller grains. In terms of magnetic field studies, comparison of THz (0.2mm) and submm (0.8mm) polarized emission may reveal the field structures at different length scales.

Science in Spectral Lines. There will be the higher transitions of CO, but also important fine structure lines of N^+ and C^+, as well as ions like H_2D^+. The upper CO lines will be important for probing highly excited material, while the fine structures lines are potentially very important coolants of the ISM. For luminous galaxies, C^+ could carry up to 1% of the total luminosity of the galaxy.

Existing THz operations. The SAO Receiver Lab Telescope (RLT) has been operating on Sairecabur in Chile, with a 0.8m aperture. RLT has detected and mapped the CO (7-6) emission at 805 GHz towards M17 and the CI emission at 809 GHz towards Orion. RLT has also detected the N^+ line at 1.4 THz as has the AST/RO telescope at the South Pole. In addition, the CO (13-12) line at 1.5 THz has been detected with the Condor receiver on the APEX telescope. These successful measurements are still exploratory in nature, in that no new science has been revealed which argues strongly for the need for higher angular resolution.

Potential Site: The leading candidate for SMA in Chile would be the Cerro Chajnantor peak at 5600m. It is apparently above yet another inversion layer which lies above the ALMA site at 5000m, which would yield a more transparent sky. This is borne out by radiosonde measurements. The strongest argument for this site is that the Cornell Caltech Atacama Telescope (CCAT) with a 25m aperture, has been proposed for this site. If SMA were to be co-located with CCAT, it can utilize CCAT for calibration, and provide the long baselines to produce high angular resolution. However, currently CCAT does not have secured funding.

Science Assessment: In terms of compelling unique science which requires subarcsecond resolution in the THz, the case has not yet been made. In contrast to the situation when the SMA was originally proposed in 1984, large single dish telescopes routinely operating at the proposed frequencies are not yet in place. This suggests that the move of SMA to THz operations is ahead of its time.

Operational Assessment: The THz sky is still not perfect in Chile. Likely only part of the time will be usable at THz, perhaps 25%. If we were to operate at lower frequencies during the rest of the time, performance should be better than on Mauna Kea, but would not be competitive with ALMA at 5000m.

Technical Assessment: Instrumentation at THz, and especially interferometry and antenna performance such as pointing and calibration, will need to be developed and improved. Hence, technical readiness will take some more work.

Cost: The greatest concern could be the financial cost of the move to Chile, which has been estimated to be 30-40M USD. This is just the physical moving costs without consideration of instrument development. There is also the operational cost which is the down-time of the instrument during the move, installation, and commissioning.

Conclusion: There is consensus that the move to THz may be premature at this time. A few developments will change this conclusion: successful technical developments for THz interferometry, the construction of CCAT or a similarly large dedicated aperture for THz, and substantial reduction of infrastructure costs.

Attachment: Powerpoint File on Moving to THz.