Submillimeter Array Advisory Committee Report

October 12, 2007

1 Introduction

The Submillimeter Array (SMA) Advisory Committee met at the Harvard-Smithsonian Center for Astrophysics in Cambridge, MA, on September 4 and 5, 2007. Committee members P. Cox, R. Crutcher, E. van Dishoeck, B. Draine, A. Harris (Chair), K. Menten, and T. Phillips were present; R. Genzel was unable to attend. Presentations informed the Committee of progress in scientific, technical, and operational areas in addition to an extensive discussion of the SMA's future plans.

2 Overview

The Committee was very pleased to see that the SMA has hit its scientific stride and is producing a substantial amount of high-quality scientific results. Results at 350 GHz are impressive and unmatched by any other observatory. Star and planet formation is a visible area, with the polarization work in star forming regions and SgrA* unique and especially noteworthy. Observations within the Solar System are impressive. The strength of high-z work in combination with Spitzer is exciting and quite unexpected. The SMA's impact, measured by publications (one per week this year) and presence in the field, is high. As part of its success and increase in visibility, the SMA's user base is expanding modestly, a clear sign of relevance to communities inside and outside of the SMA's parent institutions.

It was clear that there is a strong and mutually beneficial partnership between CfA and ASIAA. The operations model of splitting work between Hawaii, Cambridge, and Taipei is a success. Presentations showed that operations in Hawaii have been maintained despite the loss of key personnel, although the present arrangement is unsustainable in the long run. Instrumental development has slowed as personnel have left or taken other positions. Staffing is the Committee's main concern for the SMA's continued health.

There are a variety of options for the future of the SMA. In a practical sense they will be viable only if funding is available, and to some degree that depends on exciting science results in the near term. It also depends on a positive view by the community, developed both from publication, where large data sets carry high impact, and by observing with the SMA. The scientific productivity of the SMA is good and improving, but would be significantly enhanced by interaction with other members of the SAO and particularly theorists. This may naturally occur as papers are published and talks given.

The SMA can certainly have a place in the ALMA era if it can exploit its flexibility to compensate for its relatively small collecting area. The Committee endorses the plans to form a task force immediately that will investigate science cases for different possible future courses. Whatever the future path, maintaining strong and vigorous scientific and technical staffs will be key to future plans.

A brief summary of the Committee's main recommendations is:

- Continue to focus strongly on
  - Observations in the 350 GHz atmospheric window
  - Polarimetry in the 350 and 650 GHz windows
  - Studying small samples of sources in a coherent program rather than dissecting individual targets one-by-one
  - Phase correction using stratospheric ozone as a beacon for tropospheric water vapor absorption
  - Sensitivity and ease-of-use improvements
- Foster collaborative projects
  - Within the CfA; the connection with Spitzer is an outstanding example, and collaborations with ASIAA theorists would be valuable
  - With Herschel and SOFIA science teams
  - With scientists and engineers at CARMA, IRAM, and other observatories
  - With high-frequency mixer fabricators
- Move quickly on three key staff hires
- Continue eSMA work at moderate priority, and VLBI at low priority.
- Form a task force to thoroughly explore the cases that will carry the SMA into the ALMA era.

3 Science highlights

3.1 Star and Planet Formation

Unraveling the physical and chemical processes during star and planet formation has been one of the main science drivers of the SMA from its conception. The high densities and column densities make star-forming clouds a natural target for submillimeter line and dust continuum observations, providing distinct diagnostics from those available at other millimeter arrays. Indeed, as shown by the strongly increasing publication rate and presentations at conferences world-wide, the SMA is starting to have a significant impact on the field. Highlights in the area of low-mass star formation include the first direct imaging of the hourglass shape magnetic field geometry in protostars (see below); characterizing disks and envelopes in the earliest embedded stages when the star is still being assembled; quantitative studies of protoplanetary disk sizes, temperature, density, and kinematic structures; exciting images of gaps and holes in the newly discovered population of transitional disks; and resolving knotty jets in outflow sources showing increasing evidence for episodic accretion, precession and bending.

In the area of high-mass star formation, impressive subarcsec continuum images reveal Trapezium-like clusters in formation whereas the kinematics of a wide variety of molecular lines stimulate a lively debate in the community whether or not high-mass stars have disks and outflows and whether they form by similar processes as their low-mass counterparts.

In both low- and high-mass star-formation, the most successful projects have involved close interactions with theorists and modelers. The committee strongly encourages SMA observers to strengthen these interactions. Star formation was an area where the power of studying small samples of sources in coherent programs, rather than dissecting individual targets one-by-one, was especially evident.

3.2 Polarimetry

The SMA has made unique and outstanding contributions in polarimetry of star forming regions and of the Galactic center. Especially noteworthy are the clear evidence for an hourglass morphology magnetic field in NGC1333 IRAS4A and an estimate of the field strength. Results for IRAS16293 are equally impressive, while studies of other star forming sources are less advanced, due at least partly to limited sensitivity. These results add significant new evidence in the investigation of the role of magnetic fields in the star formation process. The polarization studies of Sgr A* have yielded unexpected and astonishing results: intraday intrinsic polarization variations that appear to probe the rotation of the black hole photosphere. Moreover, the measured rotation measure provides a limit to the accretion rate onto the black hole. Although SMA polarimetry follows pioneering work carried out at 230 GHz mainly at BIMA, the greater sensitivity of the SMA at 345 GHz and the facts that BIMA is defunct and CARMA and IRAM have not yet started polarimetry make the SMA unique for such studies. Section 7 of this report contains specific technical recommendations for improving the SMA's polarimetric capability.

3.3 Astrochemistry

The reputation of the SMA as a premier instrument for astrochemical studies has been strengthened over the last few years. Broad-bandwidth, high sensitivity observations of star-forming regions show a plethora of lines, including clear evidence for complex organic molecules associated with solar-mass protostars and small scale (few hundred AU) chemical differentiation in both low- and high-mass objects. Understanding the origin of these variations is still elusive, however, and the committee recommends closer ties with astrochemical modelers to assist the interpretation. The first results of legacy line surveys of evolved stars and external galaxies are promising, and the committee applauds the commitment by the teams to make the reduced data and images public. Indeed, both these dedicated line surveys as well as more selected line observations form a rich database for the astrochemical community at large, both for current research and as preparation for Herschel, ALMA and SOFIA.

Other highlights in astrochemistry include exploring the surprising chemistry of SiO in the envelopes of carbon-rich evolved stars (sec. 3.4), the use of SiO to trace weak outflows in confused star-forming regions, and the first spatially resolved tests of protoplanetary disk chemistry models.

3.4 Evolved stars

Much of the most important physics and chemistry in the circumstellar envelopes of evolved stars can be studied in detail with the SMA. A number of interesting results on AGB stars, protoplanetary nebulae, planetary nebulae and a red supergiant were presented. Very strong results were obtained in collaboration with an external scientist who provided detailed modeling of the observations. The first "Legacy Project," a line survey covering the whole 345 GHz band of the carbon star IRC+10216 is well under way. The committee recommended that SMA scientists contact groups running other interferometers (in particular the PdBI) to obtain lower frequency data of molecules that have line imaged in the SMA survey for the purpose of allowing excitation studies. It is important to ensure that enough resources are available to promote timely analysis and publication of the Legacy Projects.

3.5 Solar system astronomy

Many objects in the solar system are well matched to the SMA's primary beam and angular resolution. Indeed a number of highly impressive results have been presented to the committee. Highlights include imaging the Pluto-Charon binary system with the implications on weather on Pluto, the remnants of the 1994 Shoemaker-Levy collision around Jupiter, and the imaging of Uranus' polar regions. The SMA's impact in this area will increase as the results are published in refereed journals.

3.6 External galaxies

The work being done with the SMA on external galaxies is a nice example of coordinated projects and surveys. The studies of the line emission together with the dust continuum at high frequencies (mostly 350 GHz) in nearby galaxies have enabled tracing the dynamics and the physical conditions of the warm and dense gas. These surveys will represent an important part of what will be the scientific legacy of the SMA and constitute a useful preparation of the kind of science, which will be done with ALMA. Detailed studies of particular objects (CenA, NGC1275) have revealed at unprecedented angular resolution the morphology of these galaxies. Finally, the survey of nearby luminous infrared galaxies provides a useful ensemble of data to address issues such as the properties and distribution of the dust *and* dense gas in these objects, follow the changes of properties within one source and compare them with other characteristics, and build a database which can be used as a template to study the gas in high-*z* sub-millimeter galaxies. Work done at higher frequencies would be useful to further constrain the dense gas properties and probe the emission from high-level transitions of molecules other than CO, which would be very useful in comparison work with the transitions of species such as HCN, CN or HNC, which are currently observed with other interferometers in high-*z* galaxies.

3.7 High-redshift observations

The concentrated efforts by the SMA on the study of the dusty, far-infrared luminous galaxies have resulted in a series of successful observations, in particular in the study of the dust emission at 350 GHz. This last program is a follow-up of sources detected in Spitzer and AzTEC/COSMOS surveys. The recent upgrades in sensitivity and performance of the SMA together with its high spatial resolution enable it to pinpoint the position of the sources (which are not detected or barely so in the visible) and help to identify the sources in sometimes crowded regions. Combined with data at other wavelengths, the spectral energy distribution (SED) of the sources can be defined and first estimates of their redshifts made. In a few instances, there are clear indications of sources at redshifts well beyond z=3. In addition, observations done in emission lines have resulted in the detection of the red-shifted 158 microns C^+ line in the z=4.7 quasar BR1202-0725, a remarkable result. However, the small antennas of the SMA preclude the systematic search of the very weak (atomic and/or molecular) emission lines of a large number of high-*z* sources.

The continuum observations are an example of a fruitful collaboration inside of the Smithsonian Center for Astrophysics bringing together two communities and the Committee applauds the work done in this area. The results demonstrate how powerful the combination of the SMA with IRAC/Spitzer is, and, by extension, the unique strength of the SMA when focused and well-designed follow-up programs are done. In view of the importance of the characterization of the SED of high-*z* sources, it would be interesting to also measure the continuum emission at the higher frequencies (e.g., at 650 GHz). This program can also pre-figure the role, which the SMA can and should play in follow-up legacy-type programs based on the findings of future satellites such as Herschel and Planck.

4 Software

SMA software seems to be adequate for its science, but some attention should be paid to this area. The use of IDL provided a quick means of developing SMA-specific software, but also limits what can be done. Increasing data rates from dual receivers, ozone-line phase correction, and faster sampling that may become necessary as 700 GHz receivers and phase correction are deployed are likely to stress the capabilities of IDL, perhaps severely. Establishing an archive with both visibility and image data would enhance the usefulness of the SMA to the broader community. The SMA should consider interacting and collaborating with either the CARMA or ALMA software groups in order to develop pipeline processing capability.

5 Staffing

Although the staffing level is more or less adequate to carry on as is, it clearly is a limiting factor on progress, especially in the area of developing and bringing new receivers on line. The Committee identifies three immediate key hires:

- Hawaii operations manager. While the Hawaii operations are going well at present, having an operations manager based in Cambridge who commutes to Hawaii is not healthy or sustainable in the long run.
- Receiver lab engineer. Staff has moved from this area into management or positions outside the CfA, and lack of high-level engineering has slowed the SMA's progress. Fortunately, this is a good time to advertise for a top-level receiver engineer: Herschel/HIFI is in satellite integration, so experienced engineers will be coming on the job market.
- Instrumentalist/observer. In addition to a receiver specialist, strengthening staff to work at the system level is important for bringing new systems and operating modes on line and testing them.

The idea of bringing in a senior scientist to motivate and lead a larger effort in a given research area is good. As open a search as possible is needed to find someone whose expertise and interests are best matched to the SMA's capabilities and needs.

An important aspect of the SMA, really shared only by CARMA, is the hands-on training of postdocs and students in hardware and software support of millimeter/submillimeter interferometry and science. This should be aggressively pursued. The Committee urges that the SMA continue to encourage postdocs and students to be deeply involved in instrumental and software work. Although we cannot judge how the students and postdocs are integrated in the observatory, we note that they are very important to the observatory and have produced some of the highest-visibility science. Encouraging and assisting them is important and could help the senior staff to complete research projects.

6 eSMA and VLBI

6.1 eSMA

The eSMA is the combination of the 8 antennas of the SMA with the 15 meter JCMT and the 10.4 meter CSO telescopes. eSMA promises to create an array with sensitivity a factor 1.5 greater than the SMA alone, with baselines up to 782 meters for angular resolutions of 0.3” at 345 GHz, compared with the SMA’s 0.45”. Over the last two years, it has been shown that the CSO and the JCMT can be incorporated in the SMA array and be treated nearly as SMA antennas in terms of optical fibers, IF/LO equipment, VME Bus computer, antenna position commands, correlator (for 10 stations), and polarization settings. Very recently, strong fringes have been seen both at 230 and 345 GHz, demonstrating that the eSMA can in principle become usable. The details have still to be fully analyzed and understood, however. In addition, there are specific, separate problems related both to the JCMT and the CSO, which must be smoothed out before operations can start.

As shown by a recent workshop held in at the Leiden Observatory, there is strong community interest in using the eSMA, and many collaborative proposals have already been designed. It is the opinion of the Committee that these science projects should start as soon as possible. However, full science operations can only start once the system is debugged and well understood, and once all telescopes have receivers with approximately equivalent system temperatures, so as to fully take advantage of the potential increase in sensitivity. Some science projects are limited by correlator capabilities.

The Committee felt that the efforts towards a usable eSMA should be continued at the current level, especially in view of the interest of the partners who participate in the eSMA Memorandum of Understanding. A detailed and firm project plan is necessary and a coordination management team should be formed. These efforts should be led by one of the other partners (e.g., JCMT staff) who will make the eSMA a high scientific priority.

6.2 VLBI

There is one VLBI experiment of paramount importance that implicitly requires observations at submillimeter wavelengths: resolving general relativistic effects around the black hole at the center of our Galaxy (Sgr A*). This experiment definitely needs one station to be located on Hawaii for good imaging. It also needs to done at the highest possible frequency, with 345 GHz being the only practical option. Ideally, it would involve ALMA, but early attempts will be possible with stations at Mauna Kea, APEX, and the South Pole. Since this experiment requires as much sensitivity as possible, using the SMA as part of eSMA seems highly desirable. Apart from Sgr A*, observations of selected quasars will be necessary to test and debug the system. The technical problems involved in the eSMA and in phasing up the array for VLBI are similar. Since the Committee sees the Sgr A* experiment to be the *only* science driver for VLBI, however, this activity should not consume large amounts of resources.

7 Near-term recommendations

A primary requirement for the SMA is a strong and innovative technical group. This will be the case whether considering the near term or the long term. The greatest need is in receiver development and correlator development. At the moment the 230 and the 345 GHz bands are available, but the SMA, with its small antennas, is much more likely to do innovative science in the higher frequency bands. Receiver development for frequencies up to about 700 GHz will be of most near-term value for astronomical observations. Above this frequency (the gap frequency for Nb) a very difficult change in materials is necessary and the receivers lose sensitivity rapidly. All of the SMA's receivers need to be state-of-the-art in sensitivity and easy to tune. The Committee recommends concentrating on the 690 GHz band more than the 460 GHz band since the band is wider, the atmospheric transmission about the same, and CO J=6-5 at 690 GHz is more useful than CO J=4-3 at 460 GHz. Dual polarization observations are needed for the best polarimetry capability, as discussed next, and would also double the effective observing time for non-polarimetric observing. Maximizing observing efficiency at 690 GHz is especially important because of the limited periods of good atmospheric transparency.

Polarization is an area where the SMA can excel in the near term and beyond, and concentrating in this area will allow the SMA to continue to obtain transformative polarization science results for several years. The Committee recommends providing dual circular polarization observing capability, first at 350 GHz by completing the 400 GHz receivers, and then with dual polarization capability at 690 GHz. Most observations will be of weak linear polarization, so observations in dual circulation and recovery of the linear polarization components in the correlator will minimize systematic effects. A static waveplate tuned for each band will be needed to convert the receivers' orthogonal linear polarizations to orthogonal circular polarizations. Even without the gains possible by reducing systematic effects, observing simultaneously in orthogonal polarizations and recovering the polarization information with the correlator will increase effective observing time by about a factor of five compared with sequential observations of a single polarization, as the products RR, LL, LR, and RL are produced simultaneously and sequential polarization switching overhead is eliminated.

A real time atmospheric phase correction scheme is needed for the SMA to efficiently operate at high frequencies. The O_3 technique described to the Committee represents a clever and innovative scheme that uses stratospheric O_3 line emission as a source against which to measure the H_2O absorption. The technique is expected to work best in the highest frequency bands and will work throughout the SMA's frequency range with somewhat lower efficiency. If the technique performs well it will be a major benefit (and coup) for the SMA, and this work should continue with high priority.

Many of the exciting recent scientific results were enabled by unglamorous work that made observing more efficient. Examples are work that made the 200 and 300 GHz receivers easy to tune, improvements in software that allows system overviews, and work chipping away at many small improvements in sensitivity that have a large accumulated effect. This work is central to the observatory's success and evolution in operations and in speeding the science for both internal and external users. The Committee recommends that this effort to bring new capabilities on line continues.

8 Mid- and long-term perspectives

The current successes of the SMA, and existing plans to upgrade SMA receivers, ensure that – even without additional major upgrades – the SMA will remain a valuable scientific resource into the ALMA era. When completed, ALMA will greatly exceed the SMA in terms of collecting area, number of elements, and range of baselines, but the SMA will retain the advantage of flexibility: it will be possible to change and upgrade the array hardware to take advantage of evolutions in technology (e.g., lower-noise receivers) and technique (e.g., new methods for phase correction). In addition, the SMA will provide valuable training in submillimeter interferometry for young scientists and instrumentalists.

With ALMA expected to have six or more elements functioning within four years, it is clear that the SMA should be developing a plan for the ALMA era now. This planning will need to be informed not only by ALMA's anticipated performance, but also by what is expected to occur at other sites, such as the Plateau de Bure interferometer (PdBI), CARMA, or the proposed Cornell-Caltech submillimeter telescope (CCAT). For example: PdBI might add antennas for an overwhelming collecting area advantage for northern sources. CCAT, if it becomes reality, would place a 25 meter diameter telescope at a high-transparency site; synergy could be possible were the SMA to relocate near CCAT. In addition, Herschel, Planck, and SOFIA, when they begin scientific operations, may disclose new classes of astrophysical systems that might call for submillimeter interferometric imaging and followup.

The detailed choices for the future are complex, but there appear to be two clear main options:

- To remain on Mauna Kea. If so, hardware upgrades should continue to take place. At a minimum, these upgrades should include improvements in the bandwidth usable for continuum observations, dual polarization capability at high frequencies, and improvement in receiver sensitivity and correlator capability as permitted by technical developments in these areas. Consideration should be given to the possible merits of array receivers.
- To move the 8 SMA telescopes to a site with improved atmospheric transmission, perhaps in Chile. Such a site, allowing interferometric operation at frequencies as high as 1.5 THz (well beyond the highest frequency planned for ALMA), would

create a facility with unique capability. This scenario would involve relocation of the SMA telescopes to a high altitude site, construction of THz frequency receivers, and development of techniques for interferometry and phase correction at these very high frequencies.

The Committee strongly endorses the plan for SAO and ASIAA to create a task force to analyze the scientific case for each of these two options. The core membership of the task force will come from the SMA, SAO, and ASIAA, but it will be valuable to include external members, particularly relatively junior scientists who will make the future SMA a major part of their careers. A compelling scientific case would be needed to justify the expense and disruption of a move to another site. The task force must also develop a detailed understanding of the financial costs associated with a move to a new site, as well as the likely increased cost of operations at the site. Finally, there should be assessment of the intangible but very real costs resulting from the disruption of ongoing research programs, and possible resulting loss of valuable personnel.

In any eventuality, innovation will be central to the SMA's progress into the future. It will be important to reinforce the technical group, especially in the specialized areas of receiver and correlator development to continue the SMA's high standard of technical development and to provide realistic assessments for new instrumentation. Forming connections with high-frequency mixer materials and fabrication laboratories is an essential part of any plan involving THz observations. The SAO, ASIAA, and the SMA have provided an environment that encourages and enables excellent and imaginative science and technology by the SMA's staff; maintaining and developing these strengths will carry the SMA into the future.