Building the Foundation for U.S. Astronomy at m/cm Wavelengths in 2010 and Beyond
A meeting held 3-4 August 2006 Tucson, AZ

Recommendations and Actions[1]
21 August 2006

The meeting succeeded in bringing together an inter-disciplinary cross section of the astronomy community interested in the future development of m/cm astronomy in the U.S. A discussion of science opportunities for which observations at long wavelengths can provide unique scientific insight provided the starting point for the meeting. This discussion was aided by reference to the set of key science areas identified for the Square Kilometre Array. These areas include topics in fundamental physics and cosmology (Epoch of Reionization, dark matter and dark energy, gravity and pulsars, cosmic magnetism), galaxy evolution as probed by HI observations and observations of redshifted CO emission, and the important Cradle of Life topics (protostellar and protoplanetary disks and young stars, molecules and SETI). Additionally, contributed talks on more recent conceptual ideas stimulated even broader discussion.

Within these broad science categories, key science objectives were identified at the meeting by four topical working groups. Through discussion of the working group reports in a meeting of the whole, two specific key projects of extremely broad scientific interest were highlighted as priority opportunities for which m/cm observations are uniquely required:

- Detection and imaging of HI emission and absorption from the EoR;
- A massive sky survey for HI emission from galaxies as a function of redshift. The goal of this "billion-galaxy" survey to redshifts of z=1.5 or higher is to parameterize the properties of dark energy primarily by studying the signature of baryon oscillations. A determination of the cosmic evolution of the gas content in galaxies with unprecedented completeness is also enabled.

Several other exciting opportunities were discussed and noted as important drivers for future telescopes and instrumentation needs, including

- Large sky-area, unbiased searches for radio transient sources on time scales ranging from nanoseconds to years;
- Large sky-area searches dedicated to identifying as much of the pulsar population in the Milky Way as possible, up to ~20,000 pulsars. The primary goals are: (a) to establish a large sample of millisecond pulsars that can be used as a long-term timing array for the detection of the nano-Hertz gravity waves, which result from cosmic strings and from supermassive black-hole mergers; (b) to discover and conduct precise timing observations of those rare, compact, relativistic binary pulsars (with neutron star and black-hole companions), which will allow us to probe gravity over a wide range of environmental conditions, extending to the strong gravity regime of lines-of-sight that graze the event horizon of the black

[1] Included also in this document are two appendices: Appendix A, *Community Workshop Agenda,* and Appendix B, *Goals and Objectives of the Community Workshop.*

hole; (c) to discover and conduct precise timing observations of pulsars orbiting Sgr A* in order to probe space-time close to a rotating, massive, black hole.

- Imaging protostellar and protoplanetary disks at the earliest stages of formation, and edge-on systems at all evolutionary stages, where the disks are opaque at millimeter wavelengths and at all shorter wavelengths owing to dust obscuration.
- Imaging lower-order molecular line transitions from the first galaxies. The lower order CO transitions provide the cleanest measure of the total molecular gas mass—the fuel for galaxy formation, as well as the best method for determining galaxy dynamics, and hence total (gravitating) mass. Further, cm-wave telescopes are the most appropriate for studying emission from high dipole-moment molecules, such as HCN and HCO+, in the first galaxies, due to the large critical densities required for excitation. These molecules are the best tracers of dense gas directly associated with star formation.
- Large area polometric sky surveys to study cosmic magnetism in astrophysical environments at all epochs.

The science areas map into observational opportunities throughout the 250:1 range of frequencies (0.1 to 25 GHz) that comprise the m/cm wavelength spectral band. Several Workshop speakers highlighted the fact that covering this enormous frequency range necessarily demands that we think in terms of multiple technical solutions. As a specific example, an array of inexpensive dipole antennas was agreed to be an optimal technical solution for constructing the very large collecting area needed at frequencies below ~300 MHz for imaging EoR/HI in emission and absorption. At higher frequencies, from ~300 MHz to 25 GHz, an array (or arrays) of parabolic antennas appears to be the optimal way to cover the nearly 100:1 broad spectral bandwidth.

The discussion on how to realize the key science opportunities for the U.S. community was framed around three spectral regions.

<u>Low-frequency band, 100 – 300 MHz:</u>
The enthusiastic support for the EoR/HI project as a "must do" project was considered in two phases. The first phase is dedicated to detection of the phenomenon and characterization of its signature. This phase, it was agreed, is best done by means of the many experiments currently underway (LOFAR, MWA, PAPER, 21CMA). The second phase, after detection, would be dedicated to imaging EoR/HI emission and absorption over a very large sky area. This would require an array of much larger collecting area, and one with higher resolution, than those planned for the pathfinder experiments. The array must be one that is optimized for surface brightness sensitivity. It must be located on a site with the lowest possible RFI contamination. Currently, an EoR array is still considered to be part of the SKA project because EoR imaging science is expected to require the square kilometer of collecting area and because it is directly germane to the cosmological history of atomic hydrogen, another major emphasis of the SKA. However, technology for EoR science can be developed much more quickly than for the rest of the SKA frequency range. For this reason, the workshop participants considered it appropriate that EoR arrays be constructed independently. Given strong interest and activity in the U.S., a roadmap for EoR science should be developed for presentation to

the next decadal survey that outlines a decision tree for deciding whether a larger array needs to be built in the 2010-2020 decade, and if so, what are the steps to its realization. The road map should be developed in cooperation with our international colleagues who are working on EoR experimental arrays such as LOFAR and MWA.

Mid-frequency band, 300 MHz – 3 GHz:

An array that covers the mid-frequency band is of great interest particularly for the large-area survey of HI emission from galaxies at redshifts to 1.5, or higher. In addition, this band appears to be extremely promising as a large radio synoptic survey telescope (LRSST) that would provide a powerful probe of the transient radio universe. LRSST would deliver large samples from radio-only populations as well as synergistic capabilities to the optical LSST and to gravitational wave observatories. Finally, two of the key science areas for the SKA, gravity studies with pulsars and cosmic magnetism, are also enabled with the extension of this band beyond the 1.4 GHz rest frequency of HI to about 3 GHz. The international SKA project has also focused major emphasis on the HI redshift survey, and here again it is in the U.S. interest to work with the SKA project to construct a roadmap, including definition of the U.S. implementation role, leading to this capability. The work plan for the US Technology Development Project (TDP) for the SKA will include projects that are relevant to this frequency range.

High-frequency band, 3 GHz to 25 GHz:

Frequencies above 3 GHz are of great interest for using pulsars to probe the metric around Sgr A*, for mapping Galactic foregrounds relevant to detection of CMB polarization, for redshifted line emission from CO, HCN and HCO^+, for astrometric observations of redshifted H2O masers, and for "Cradle of Life" enterprises. There is clear interest in reaching 25 GHz (or even higher, if affordable) for the purpose of understanding protoplanetary and debris disks that are too dense to probe with ALMA. Long-baseline capability (1000s of km) is essential for imaging the details of disks (and for making movies of disks undergoing planet formation over a period of many years), and of the stellar black holes and neutron stars that reveal the same energy collimation and jet flows that are so ubiquitous in quasars. The radio astrometric precision of 10 microarcsec will rival the accuracy of future space-based optical telescopes and allow us to obtain fundamental parameters of stellar masses and distances. In addition, relative astrometric measurements of extragalactic water megamasers may lead to values of the Hubble constant more accurate than 3%, providing a critical constraint on the equation of state of dark energy.

The SKA technical plans for research capability at frequencies > 3 GHz are still being developed. However, high frequency technical development is a particular strength of the U.S. community owing to work being done for ALMA, EVLA, ATA and the DSN array. There are many examples in the U.S of innovation and development underway or planned with a solid focus on reducing the cost of receiving, detecting and processing cosmic signals at frequencies > 3 GHz. For this reason, it was agreed that this band was the best of the three important wavebands for the U.S. to take a leading role. TDP work for this frequency band would build upon the existing U.S. technical and scientific foundation and focus on maximizing A/T as a function of frequency for a fixed cost budget. The implementation roadmap for these capabilities will be developed based on the achievements of the TDP, again in close consultation with the international SKA project. An important question for the U.S. community is whether the key science at frequencies > 3 GHz requires a new ~$1B telescope or whether existing U. S. facilities, augmented with additional collection area, is a suitable alternative.

Recommendations:

1. Encourage strong NSF support for EoR/HI pathfinder experiments such as that currently being provided to MWA and other initiatives. The science is extremely compelling, and vital, to studies of the physics of the early universe.
2. Encourage the U.S. representatives to the International SKA Steering Committee (ISSC) to promote development of a roadmap for EoR/HI science. The plan should include a meaningful participatory and contributory role for U.S. researchers and a realistic assessment of the U.S. timescale for major financial commitment.
3. Encourage the U.S. representatives to the ISSC to promote the development of a roadmap leading to an array optimized for a very large-scale survey of HI in galaxies to z=1.5 (or higher redshift) and for surveys for transients, pulsars, and Faraday rotation. The plan should include a meaningful participatory and contributory role for U.S. researchers and a realistic assessment of the U.S. timescale for major financial commitment.
4. Develop the scope of work for the TDP within the U.S. community such that the TDP supports the role agreed for U.S. involvement in item 3 without duplication of efforts underway by other SKA international groups.
5. Develop a roadmap for activities within the TDP that builds on existing capabilities in the U.S. at frequencies > 3 GHz, including capabilities at Arecibo, ATA, EVLA, VLBA, and GBT, that can be used to inform planning by the international SKA project. The roadmap planning should be done in cooperation with the international SKA project.

Action Items:

1. Identify a work plan for the NSF-funded TDP that takes into account activities taking place within the national centers (NAIC and NRAO), and at U.S. universities and institutes, following the recommendations noted above.
2. Set up US Working Groups on:
   - EoR (to establish an EoR/HI roadmap for defining the context and plan for a large telescope to image the EoR/HI.)
   - Precision astrometry that exploits the capability of m/cm astronomy to achieve exceptionally high angular resolution on long baselines.
   - Dark Energy and the Radio LSST. The task is to outline in detail the scientific and technical requirements for the HI sky survey extending to high redshifts, along with an all sky Faraday rotation survey, a Galactic census of pulsars, and a synoptic survey of the transient radio sky.

- Optimization of pulsar timing for probing Sgr A* and for use of millisecond pulsars as gravitational wave detectors.
- Definition of the requirements for imaging nearby protoplanetary disks and for detecting redshifted molecular lines in the early universe.

3. Plan the next two "Chicago" meetings (date and venue)
   - Chicago 3: 2007 Q1 (post Senior Review, pre Argentina/ISSC meeting in March 2007. The focus of the Argentina/ISSC meeting will likely include a discussion of descoping options for the SKA; the U.S. position on this issue should be planned in advance of the SKA meeting.)
   - Chicago 4: TBD. One proposal is to schedule the meeting as part of the NRAO 50th anniversary celebration in June 2007.

Meeting SOC/LOC

Robert L. Brown (NAIC)
Chris Carilli (NAIC)
Jim Cordes (US SKA Consortium)
Dale Frail (NRAO)
K. Y. Lo (NRAO)
Emmanuel Momjian (NAIC)
Yervant Terzian (US SKA Consortium)

Appendix A

Building the Foundation for U.S. Astronomy at m/cm Wavelengths in 2010 and Beyond

Community Workshop
Loews Ventana Canyon Resort, Tucson, AZ
August 3,4 2006

AGENDA

Plenary Session in Salon B

Thursday August 3

(Continental breakfast, in meeting room, available 7:30 am)

Session 1: Meeting Objectives **Chair K. Y. Lo**

08:00 Meeting Overview, Organization, Purposes and Goals **R. Brown**
08:20 Discussion/Refinement of Meeting Objectives **All**

Session 2: Key Science **Chair Y. Terzian**

Description of Key Science Opportunities at m/cm Wavelengths in the next ~10-20 years

08:30 Opportunities Identified in Current Planning-I **C. Carilli**
09:00 Opportunities Identified in Current Planning-II **M. Reid**

New Opportunities & Ideas…Contributed papers

09:30 Radio Transients **J. Cordes**
09:45 The Future of Supernova Observations **C. Stockdale**

10:00 **Coffee**

10:25 The High Energy/Radio Connection **F. Harrison**
10:40 Deep Wide-Field Optical Surveys **A. Dey**
11:00 The Nature of CO Emission in z>6 Quasars **D. Narayanan**
11:15 Next Gen Radio Arrays, CMB, & Early Universe Astrophy **S. Myers**
11:30 Mind the Gaps: High Res Imaging of Protoplanetary Disks **J. Lazio**
11:45 Solar Radio Physics of the Future **T. Bastian**
12:00 U.S. Astronomy Facilities in the 21st Century **R. Dickman**

12:15 **Buffet Lunch at Hotel, Salon C**

Session 3: Key Science in Context **Chair D. Frail**

Discussion of the Relation of m/cm Science Opportunities to Science at Other Wavelengths and with Science that Confronts Astrophysical Theory

13:15 Survey Science at Optical/IR Wavelengths **M. Strauss**
13:45 Star/planet formation **L. Hillenbrand**
14:15 Cosmology **S. Furlanetto**
14:45 Extreme physics (GRBs, Black holes, GR tests) **S. Kulkarni**

15:15 **Coffee**

15:45 **Breakout Working Groups**

Salon D (a) Fundamental Physics (Lead: **D. Backer/J. Lazio**)
Salon E (b) Cosmology (Lead: **C. Hogan**)
Salon F (c) Galaxies, Galaxy Formation and Evolution (Lead: **R. Windhorst**)
Salon J (d) Stars and Planets; ISM; Astrobiology (Lead: **A. Sargent**)

18:00 **Dinner on Hotel Breakout Patio** (No-host bar)

20:00 **Session 4: Free Format Brainstorming** **Chair: J. Cordes**

<u>Friday August 4</u>

(Continental breakfast available 7:30 am)

08:00 **<u>Breakout Working Groups (Continue/Conclude)</u>**

<u>Plenary Session in Salon B</u>

09:00 **Session 5: Working Group Reports** **Chair: M. Lewis**

Concise Reports from the Working Group Leaders; discussion

10:30 **Coffee**

Session 6: Instruments and Options **Chair: C. Carilli**

Instrument Requirements and Options for Meeting the Science Opportunities

11:00 Frequencies $\leq$ 300 MHz **C. Lonsdale**
11:30 Frequencies ~300 MHz to 3 GHz **P. Dewdney**
12:00 Frequencies 3 GHz to ~25 GHz (higher?) **S. Weinreb, J. Welch/G. Bower**

12:30 **Buffet Lunch at Hotel Salon C**

13:30 Open Discussion of Instruments and Options **All**

Session 7: Science in Frequency Space **Chair: R. Brown**

Discussion: Associating Science Opportunities with Frequency Bands

14:15 Opportunities at Frequencies $\leq$ 300 MHz (Raconteur: TBA)
14:45 Opportunities at Frequencies ~300 MHz to 3 GHz (Raconteur: TBA)
15:15 Opportunities at Frequencies 3 GHz to ~25 GHz (higher?) (Raconteur: TBA)
Discussion

Coffee

Session 8: Meeting Conclusions **Chair: Meeting SOC**

16:20 *Discussion: Actions and Recommendations*

Appendix B

Goals and Objectives of the Community Workshop

Robert L. Brown

1. Statement of our vision for the key scientific objectives of US astronomy at m/cm wavelengths in the next decade and beyond.

2. Statement expressing our understanding of the multi-disciplinary context in which the *key scientific objectives of US astronomy at m/cm wavelengths* are established and a statement of the unique insight that observations at m/cm wavelengths bring in that context.

3. Concise assessment of the primary instrument requirements—parameters of the facilities required—that are necessary to address the *key scientific objectives of US astronomy at m/cm wavelengths* and the primary technological challenges they present.

4. Statement of the parameters for which the widely-recognized, international, SKA project meets the primary instrument requirements. Assessment of whether alternative approaches to a monolithic SKA exist for meeting the primary instrument requirements and, if so, note the arguments for pursuing them. (That is, discuss—from a US perspective—whether the SKA is better structured as a telescope or as a program of internationally-accessible, next-generation, facilities). In all cases, discuss the technology development to be done in the US and the role of the TDP in organizing the development.

5. Assessment of the efficacy of the partnership between national centers and academic researchers in the future development of US astronomy at m/cm wavelengths.

6. Recommendation as to the best way to partner with the international SKA project (if that's what we seek to do).

7. Draft ideas regarding proposals we wish to make to the next decadal survey of astronomy and astrophysics.