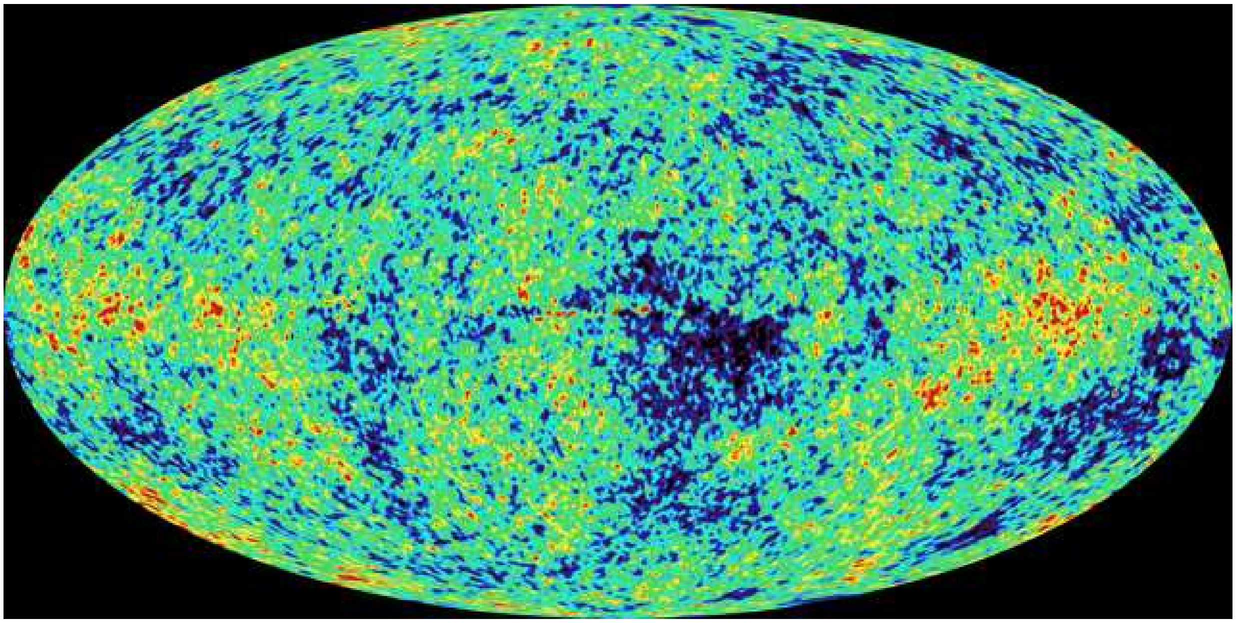

Report of the
Radio, Millimeter and Submillimeter Planning Group
for the
National Science Foundation Division of Astronomy
2005 Senior Review

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October 2005

1 Executive Summary

Nearly all of the most intriguing unsolved questions in astronomy require clues gleaned from observations contributed by multiple facilities within the NSF-AST portfolio, as well as ones funded privately or by other federal and state agencies. The challenge to all of astronomy is to devise a strategic and coordinated program which maximizes scientific productivity, technology development, education and outreach on the short term, and, at the same time, lays the groundwork for an equally bright future.

Radio, millimeter and submillimeter wavelength (RMS) astronomy encompasses five orders of magnitude in wavelength and explores angular scales down to 100 micro-arcseconds. By exploiting a combination of very different technologies, designs and observing modes with little overlapping capability, the U.S. RMS facility "system" today provides unique and vital clues to astronomy's unsolved riddles either alone or in close synergy with observing programs at other wavelengths and with theory and simulation. As part of the continuing exercise of strategic planning for the future, the Radio, Millimeter and Submillimeter Planning Group (RMSPG) was charged to review progress toward implementation of the recommendations of the several recent National Research Council (NRC) science discipline reviews of relevance to RMS astronomy, most notably, *"Astronomy and Astrophysics in the New Millennium"* (AANM), the report of the 2000 Astronomy and Astrophysics Survey Committee (AASC). Long-term investment by the National Science Foundation (NSF) in highly innovative RMS astronomy programs both in the universities and at the national centers, the National Astronomy and Ionosphere Center (NAIC) and the National Radio Astronomy Observatory (NRAO), has made the U.S. RMS program the strongest in the world. This document updates the long range outlook for RMS science and the facility requirements needed both to achieve its discovery potential and to maintain U.S. leadership in the field.

After summarizing the context for this report in Section 2, we review and update, in Section 3, the main science drivers outlined in the AANM report which continue to dictate the RMS long range strategy. The resultant requirements which should define the suite of RMS facilities are presented in Section 4, and a facility development strategy which will lead to their delivery is outlined in Section 5. Section 6 reiterates our conclusions in the context of the priority recommendations that were made in the 2000 AASC report. We also provide in separate appendices a summary of current facilities comprising the Radio–Millimeter–Submillimeter Facility "System" (Appendix A), the principal technology drivers and opportunities (Appendix B) and a summary of the synergy between RMS goals and facilities and those at other wavebands (Appendix C). A glossary which attempts to define the myriad of acronyms used in this report is included in Appendix D.

The principal components of the RMS strategy outlined in this document can be summarized as follows:

- The detailed characteristics of the Cosmic Background radiation remain fundamental to our understanding of the origin of the universe and its evolution from the earliest moments to the present time. Continued investment in CMB science, as discussed by the report of the joint DOE/NASA/NSF Task Force on Cosmic Microwave Background Research (TFCR), promises further insight into the early universe astrophysics. For a full understanding of CMB observations, detailed mapping of the galactic and extragalactic foregrounds will require the resources of key centimeter to submillimeter telescopes.

- The Atacama Large Millimeter Array (ALMA) will soon be the first "world-funded" telescope, and U.S. astronomers must be prepared to achieve maximum science return on the NSF investment in ALMA. In the time leading up to full ALMA operations, the U.S. astronomical community must be enabled to pursue ALMA pathfinder science, through the interferometric capabilities of the Combined Array for Submillimeter Astronomy (CARMA) (and the non-NSF funded Submillimeter Array, SMA) and through deep, wide-field surveys for target detection and spectroscopy using single dishes. The long range strategy must include a fully functional ALMA, with funding for its complete receiver complement, operations, upgrades and user support.

- The University Radio Observatories (UROs) are the training grounds for future generations of researchers who will both develop new technology and discover new science. The U.S. needs well trained RMS astronomers with strong instrumental capabilities to keep the field at the forefront of international research efforts. While the investment in major global facilities insures continued current preeminence of the U.S. program worldwide, it would be "penny wise and pound foolish" not to invest modest funds in training the next generation of scientifically and technically skilled astronomers.

- The long range strategic goal for centimeter to meter wavelength astronomy is the construction of the next generation facility, the Square Kilometer Array (SKA). The SKA will be an international collaborative project and will require innovative technology. Within the international SKA effort, there is a critical need for a concerted and aggressive U.S.technology development program, as recommended in the AANM report, with a short term goal to develop the U.S. SKA concept for presentation to the 2010 NRC astronomy and astrophysics decadal survey.
- As world-class telescopes, the core centimeter wavelength national instruments probe the most fundamental astrophysical questions. Continued enhancement of the existing premier national instruments should emphasize the *unique* capabilities of Arecibo (high sensitivity surveys for gas-rich galaxies and Faraday tomography of the Galactic magnetic field, pulsar surveys and timing for tests of GR, radar studies of the orbits and characteristics of near-Earth asteroids), the Expanded Very Large Array (EVLA) (separation of AGN's and starbursts in obscured galaxies, images of massive star formation sites, particle acceleration in micro-quasars, X-ray binaries and radio galaxies), the Green Bank Telescope (GBT) (Galactic disk-halo interface, high redshift CO, CMB foregrounds), and the Very Long Baseline Array (VLBA) (Local Group proper motions, maser motions around supermassive black holes, evolution of GRB's, supernovae and novae). The current core national facilities will both deliver SKA precursor science and serve as testbeds of SKA technologies and techniques.
- Within the framework of the U.S. SKA program, the development of the design concept for the SKA as well as the required technology innovations should be undertaken as a close partnership between the universities and both national observatories. Notably, the Allen Telescope Array (ATA) will demonstrate the U.S. SKA approach of achieving significant collecting area by combining a large number of small dishes, the "Large N/Small D" concept.
- The second phase of the EVLA project (EVLA-II) would provide the highest resolution in any waveband of the earliest galaxies, resolve the central regions and probe the environment of relativistic jets at all cosmic epochs, resolve dusty cores of galaxies to distinguish star formation from AGN, and provide AU-scale images of the accretion process (e.g., disks) for massive stars. The science objectives of the EVLA-II project remain critical to the science vision articulated in the AANM report and a path to their attainment must be found.
- Modest NSF investment in a meter wavelength facility over the next 3-5 years should emphasize the development of a U.S. capability to detect and image the neutral intergalactic medium at $z > 6$ as a truly unique probe of the process of reionization.
- The observations provided by RMS facilities are critical to the science goals of other federally-supported astronomical facilities on the ground and in space. For example, ALMA and JWST will make a powerful combination for the exploration of early galaxies. Herschel/SOFIA require the wide-field survey capability contributed by the URO millimeter and submillimeter facilities. The VLBA will image the violent phenomena detected by GLAST which occur in the strong gravity regime within tens of Schwarzschild radii of black holes. The long range planning for RMS astronomy should reflect such synergies with other major federal investments.

2 Context for the RMS Planning Group Review

The Radio, Millimeter and Submillimeter Planning Group (RMSPG) is a community effort to review the current status of progress towards implementation of the recommendations of the recent NRC discipline survey reports relevant to the fields of radio, millimeter and submillimeter astronomy. Those reports include *"Astronomy and Astrophysics in the New Millenium"* (AANM), *"From the Sun to the Earth – And Beyond"* , *"Connecting Quarks with the Cosmos"* (Q2C) and *"New Frontiers in the Solar System"*. The Letter Report of the National Research Council (NRC) Board on Physics and Astronomy, Committee on Astronomy and Astrophysics, *"Review of Progress in Astronomy and Astrophysics Towards the Decadal Survey"*, has recently reaffirmed the process of decadal priority setting as resulted in the AANM report.

The overall program for astronomy for the 2000-2010 decade put forward in the 2000 AASC report is exciting, ambitious and expensive. Since the time of the issuance of the AANM report, Congress passed legislation that called for a doubling of the NSF budget over five years, and the NSF Division of Astronomical Sciences (AST) budget itself increased some 30%. However, budget prospects for the remainder of the decade today appear less optimistic. In addition, the major projects endorsed by the astronomy decadal surveys take longer to complete than their original schedules, largely because of fiscal constraints. The most ambitious involve capital costs many times larger than previous facilities, will require continuous commitment of significant sums for operations and renewal, and involve international partnerships. For example, ALMA, proposed as the US-only Millimeter Array (MMA) in the 1990 report, is now a truly global effort that will not be completed until 2012. The complex nature, technical challenges and costs associated with construction and operation of the proposed facilities and the fiscal realities imposed on the NSF as the funding agency raise substantial hurdles to the implementation of the long-range strategy for the ground-based astronomy put forward in the AANM report. As with its decadal priority setting exercise, the NSF and the astronomical community as a whole must face the challenges of programmatic balance together. The NSF-AST Division has called for the need to consider the redirection of some portion of its budget from current activities towards ones that explicitly lay the groundwork for future advances. To perform this examination of the current AST allocation and in line with the recommendation contained in the AANM report that the NSF should conduct regular reviews of its facility portfolio (AANM p. 185), NSF-AST initiated plans in Spring 2004 to conduct such a "Senior Review" in 2005. We fully endorse the need to examine the AST portfolio to insure the continued preeminence of the U.S. ground-based astronomical endeavor for the foreseeable future.

In order to organize community input into this review, the RMSPG was convened in fall 2004 under the auspices of Associated Universities, Inc.(AUI) at the request of the NSF-AST. It has since functioned quite independently of AUI and both of the U.S. national radio observatories. To insure continuity with the AANM report, the RMSPG is constituted identically of the members of the 2000 Astronomy and Astrophysics Survey Committee (AASC) subpanel on radio and submillimeter astronomy. It should be noted that the current effort is in no way sponsored or endorsed by the National Research Council.

As a largely informal, community effort, the RMSPG has attempted to apprise the interested astronomical community of its committee activities through a public website *http://www.astro.cornell.edu/∼haynes/rmspg.* This posting includes a detailed compilation of facility capabilities generated with the cooperation and assistance of their directors which was most helpful to the Planning Group in understanding the current U.S. RMS program. The RMSPG has not, however, had access to nor considered actual proposals submitted to NSF. This report focuses on the facility capabilities required to achieve specific science objectives, as outlined in Section 3, without regard to proposal details or presentation, management or reporting issues.

The RMSPG fully endorses and reemphasizes the recommendations made in the AANM report and its own 2000 Radio and Submillimeter Astronomy panel report. The current activity is intended to provide an update of the field in light of new discoveries and technological developments as community input to the Senior Review process.

3 Scientific Themes and Questions

Our vision for the future of the radio, millimeter, and submillimeter-wave astronomy portfolio stems directly from the science questions which we, as astronomers, wish to explore. In this section, we recall and update the scientific themes of the AANM main report and the Radio and Submillimeter Panel Report for the AANM. In the years since the release of these documents in 2000, there have been other strategic planning reports, in particular the 2002 NRC report "Connecting Quarks with the Cosmos" (CQC). Significant progress towards the goals outlined in these documents has been made in the past five years, which we will highlight below.

We present the science in five themes, based on the AANM main report and our Panel Report: the origin and evolution of the Universe (Section 3.1), galaxies (Section 3.2), stars (Section 3.3), planetary systems (§3.4), and life (Section 3.5). These themes are of universal interest across the disciplines and wavelengths of astrophysics, and we show how the RMS programs (current and proposed) fit into the larger picture. We arrange the science case around key outstanding astrophysical questions within these themes, which are used as discussion points for the goals of the RMS instrument portfolio and the launch of the future RMS development program — the questions and issues at mid-decade will be connected to the instruments, existing or planned, that are needed to address them. The questions that radio to submillmeter astronomy addresses are the universal questions of astronomy at all wavebands, and there is significant overlap with the goals of the physics community. For example, the CQC report focuses on the broad theme of *fundamental physics* — RMS astrophysics addresses key areas within this topic also. Note that in addition to fundamental cosmological and physics questions, astronomy must also deal with the amazing complexity present in the Universe, from the myriad molecules in interstellar space, to the Galaxy of stars, to the black hole cosmic accelerators, to the mystery of presence of life itself in the Universe. RMS astronomy explores all of this, the microscopic, the macroscopic and the cosmic.

3.1 The Origin and Evolution of the Universe

The fundamental goals in this thematic area address the question posed in the AANM Report *"How did the universe begin, how did it evolve from the soup of elementary particles into the structures seen today, and what is its destiny?"* The linchpin in this program is the study of the CMB, the observations of which are wholly contained within the wavelength range covered by the RMS portfolio. The quantification of the "Dark Sector," which dominates the mass-energy of the Universe, and illumination of the "Dark Ages" will be active areas of observational and theoretical studies through the next decade. There is a rich interface between particle physics and the astrophysics of the Universe, as described in CQC, which mapped out a joint DOE/NASA/NSF program. A large number of the experiments and facilities in the RMS astronomy portfolio address key CQC questions — in particular Dark Energy (the CMB, the Sunyaev-Zel'dovich, or SZ, effect, and gravitational lensing), and Birth of the Universe (CMB polarization).

1. How was the Universe born, how did it evolve, and what is its future?

Measurements of anisotropies in the temperature and polarization of the CMB have sharpened our understanding of the geometry and mass-energy budget of our Universe, leading to the dawn of "precision cosmology." This remarkable convergence of theory and observation was made possible by an ambitious suite of complementary NSF and NASA funded experiments, with results from the ground-based ACBAR, CBI, and DASI telescopes, the balloon-borne BOOMERANG and MAXIMA missions, and the WMAP satellite (see Figure 1) contributing this past half-decade. The new "Standard Model" resulting from these observations, against which future cosmological tests will be pitted, has as dominant components "dark energy" and "dark matter." These results, led by the data from WMAP, SDSS, and the supernova projects, were recognized by Science magazine as the "Breakthrough of the Year" for 2003.

Observations of the polarization of the CMB are opening up a new vantage point from which to explore early universe astrophysics. The next generation of experiments aim at detecting the extremely faint polarization signatures of gravitational lensing by large-scale structures and eventually the detection of the imprint of gravity waves generated at the end of inflation. Key enabling technologies include large-format focal plane arrays and

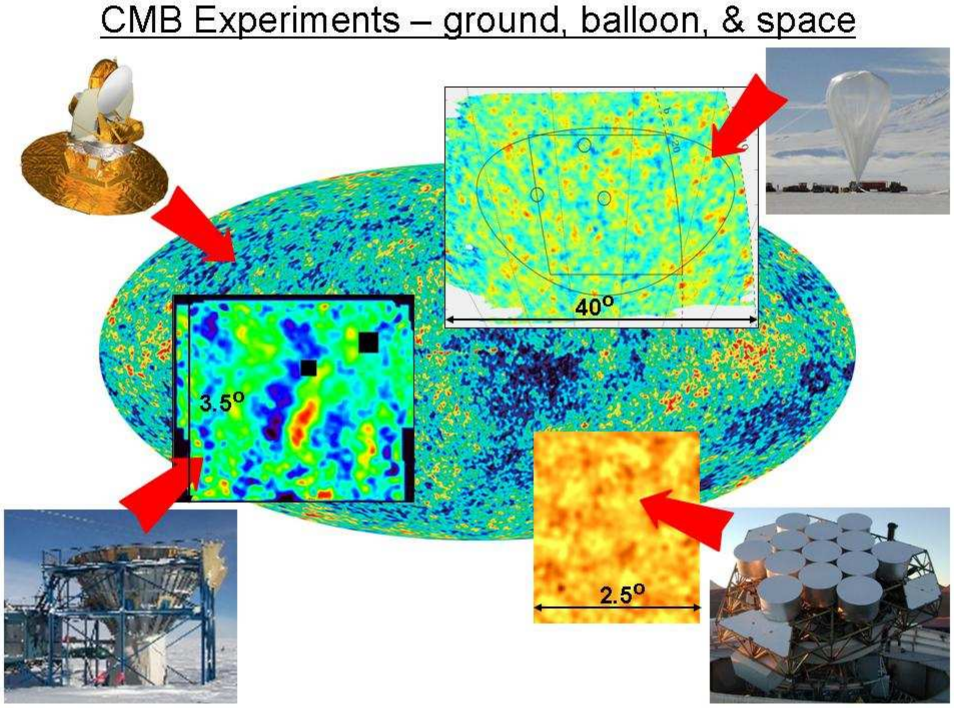

Figure 1: Observations of the Cosmic Microwave Background (CMB) are carried out by a complementary program of ground, balloon, and space-based instruments. NASA funded satellite and balloon missions (top left: WMAP, top right: BOOMERANG) map large areas of the sky, while NSF-funded ground based telescopes (bottom left: ACBAR, bottom right CBI) focus on providing higher sensitivity and higher resolution views over a smaller area. This comprehensive view of the CMB has led to a "new standard cosmological model" and the dawn of precision cosmology. Courtesy of the WMAP, BOOMERANG, ACBAR and CBI groups.

interferometric "mega-correlators" to allow the development of the thousand-plus element cameras and arrays needed to reach sub-microKelvin sensitivity levels. In addition, it will be necessary to understand and map the galactic and extragalactic CMB foregrounds to much higher levels of accuracy than we can currently achieve, which will require the resources of the key centimeter to submillimeter telescopes as well as specialized foreground explorer experiments.

A more detailed discussion of CMB science goals and the required instrument development is given in the report of the DOE-NASA-NSF *Task Force on Cosmic Microwave Background Research* (TFCR) which has recently been submitted to the interagency Astronomy and Astrophysics Advisory Committee (AAAC) and the High Energy Physics Advisory Panel (HEPAP).

The relative redshifts of spectral lines formed by different physical processes can be used to set limits on the variation of the physical constants over cosmological time. The 18 cm OH lines, as observed in highly redshifted galaxies, can provide an opportunity to test for any changes in the values of the fundamental physical constants, without being affected by systematic uncertainties arising from relative motions where the distinct lines may arise in different clouds. Very sensitive observations made with large aperture centimeter wavelength telescopes will allow tests of the constancy of the physical constants over cosmological times.

2. What is the dark sector — "dark energy" and "dark matter" — made of?

One of the most surprising discoveries of modern cosmology is that the Hubble expansion of the Universe is accelerating, with the bulk of the mass-energy in a form akin to a Cosmological Constant (i.e., with negative

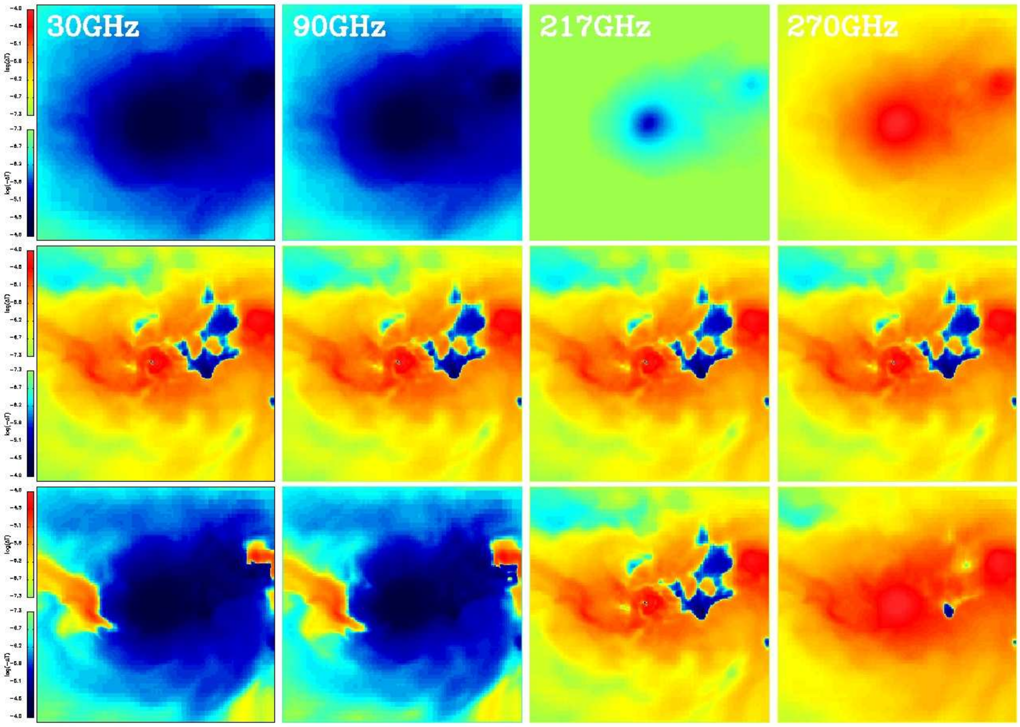

Figure 2: Maps of the thermal (top), kinetic (middle) and combined thermal plus kinetic SZ effects (bottom) arising from a simulated $z = 1$ cluster at 30, 90, 217, 270 GHz. The maps are color-coded on a log10 scale in units of Kelvin. The size of the region shown is $2\mathrm{h}^{-1}$ Mpc, which corresponds to $14.4'$ at z=0.2 in the Λ CDM cosmology. Courtesy of Daisuke Nagai (University of Chicago).

pressure). This so-called "dark energy" comprises 73% of the energy density of the Universe, based on CMB observations and OIR observations of Type-I supernovae. Furthermore, the matter sector, which makes up the remaining 27% of the Universe, is in turn dominated by "dark matter," likely in the form of non-baryonic elementary particles. Characterization of the properties of the dark energy and dark matter are prime goals of astrophysics in the new millennium, as proposed in the programs of CQC. Besides the increasing precision of CMB-based determinations of the the dark energy and dark matter densities (see above), future RMS studies will explore the nature of the dark sector using other probes.

Centimeter and millimeter-wave observations of the SZ effect provide a key technique for constraining the equation of state of dark energy through the measurement of the growth of structure in the Universe over cosmic time. The Compton scattering shadows of massive clusters of galaxies seen against the backdrop of the CMB provides a redshift-independent signpost for identification of a large cluster sample out to high redshift (see Figure 2). Compact interferometers and large-format bolometer arrays on moderate diameter submillimeter telescopes will conduct large SZ surveys which require the scanning of large areas of sky with high surface brightness sensitivity on scales from $10''$ to $5'$. These clusters will then be followed up by the larger centimeter and millimeter facility instruments as well as telescopes in other wavebands (e.g. for redshift identification).

Constraining the nature of dark matter requires study of the properties of dark matter dominated systems such as the cores of galaxies and the centers of galaxy clusters. The phenomenon of gravitational lensing provides a direct probe of the gravitational potential which is complementary to dynamical studies of stars or galaxies. Radio wavelength observations of lens systems are important both to see the lensed images through the obscuring center of the lensing galaxy and to achieve unmatched high angular resolution through interferometry, particularly with very long baseline interferometry (VLBI). The new centimeter-wave facilities (EVLA and ATA)

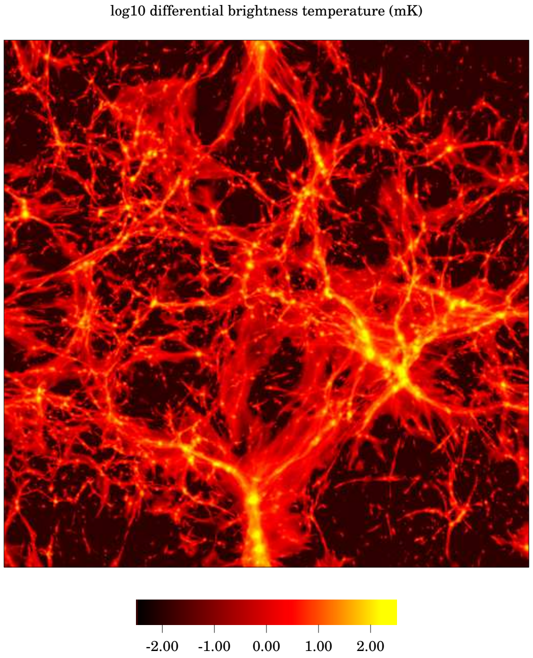

Figure 3: The differential brightness temperature in mK relative to the CMB at $z = 10$ from a simulation by Shapiro *et al.* (2005) of the universe prior to reionization or Lyα pumping. The simulation is for a ΛCDM gas/N-body simulation with 1024^3 cells and 512^3 particles in a box 700 kpc on a side (comoving units). Courtesy of Paul Shapiro and Kyungjin Ahn (U. Texas).

will greatly increase the sample of lenses available for study and will probe the cores of galaxies to unprecedented levels of precision, while in the next decade the SKA will measure the growth of large scale structure by observations of the 21-cm HI line and by the weak lensing of background radio sources by large-scale structure. This is a science driver for the SKA at frequencies below 1 GHz, which would be able to see significant numbers of galaxies out to redshifts $z = 1.3$, at an epoch when dark energy is beginning to be relevant to cosmological evolution.

3. What happened during the cosmic “Dark Ages”?

As the universe cooled from its hot and dense beginning, most protons and electrons combined to form atomic hydrogen, releasing the CMB at $z \approx 1089$. Subsequently, the universe entered the “Dark Ages,” which were ended by the epoch of reionization (EOR) when luminous stars and quasars reheated and ionized the Universe. The first structures emerge during the Dark Ages, forming mini-halos, leading to the first stars. Our knowledge of this important period is extremely limited, and the redshifted 21cm HI line provides the most direct observational probe. Calculations indicate that the densities in mini-halos can decouple the HI spin temperature from the CMB, producing signals that will be detected by EOR demonstrator experiments and, in the future, imaged at meter wavelengths by the SKA (Figure 3). In the EOR epoch, which may have had several stages between an early onset at $z \approx 17$ (as indicated by WMAP) and full reionization at $z \approx 6$ (as seen by the Gunn-Peterson effect in quasars), the first luminous objects, stars or quasars, reheated and reionized the Universe. Once ionizing sources are present, the HI levels can be pumped by Lyα (coupling the HI spin temperature to the gas kinetic temperature via the Wouthuysen-Field effect), and cavities will be carved out by HII regions. These fluctuations in the HI line can be observed with low-frequency (meter wavelengths) radio telescopes, in particular the EOR demonstrator projects and eventually the SKA. Observations of these features are essential complements to attempts to see the first stars with JWST.

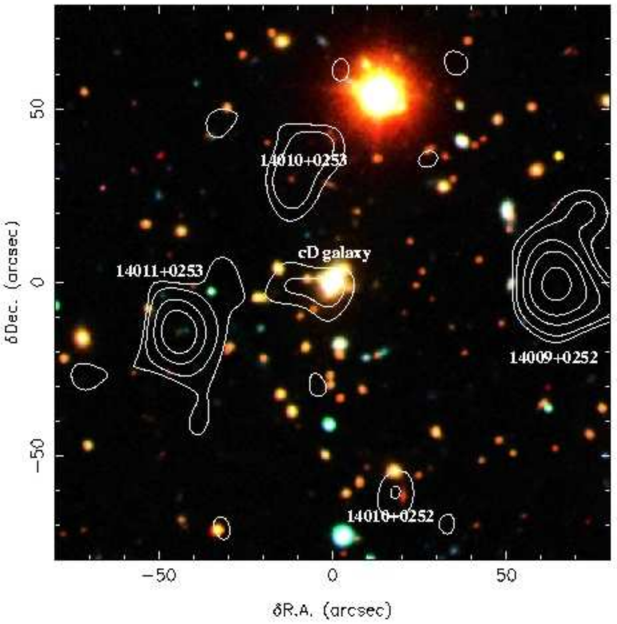

Figure 4: Contours of the 850 μ emission made with the SCUBA instrument on the JCMT superposed on a combined UBI image made with the Hale 5 m telescope of the massive cluster lens Abell 1835 at a redshift $z = 0.25$. Note that there are possible optical counterparts to most of the submillimeter sources, but not the brightest one. From Ivison *et al.* (2000, Mon.Not.Roy.Astr.Soc., 315, 209).

3.2 Origin and Evolution of Galaxies

In the standard ΛCDM cosmological model, galaxies are supposed to grow in a "bottom-up" way, accumulating mass through mergers and accretion. This picture also includes the process of galaxies and proto-galaxies aggregating in larger scale structures such as filaments, clusters, and groups — the "cosmic web". Furthermore, recent evidence links supermassive black holes and the phenomenon of active galactic nuclei with the galaxy formation process as well as with the evolution of clusters of galaxies. Testing this picture requires observations from X-ray through radio wavelengths. Fundamental physical issues are addressed by this line of research, including the CQC questions "What is Dark Matter" which dominates the dynamics of galaxies and galaxy clusters as well as "Did Einstein Have the Last Word on Gravity" and "How Do Cosmic Accelerators Work and What Are They Accelerating" which are linked though the existence of supermassive black holes and the phenomenon of Active Galactic Nuclei.

4. How and when did galaxies form?

Galaxy formation and evolution includes the growth of the galactic gravitational potential wells and the Universal history of star formation, which are tied together by the evolution of large-scale structure and merging of galaxy halos which assembles proto-galactic subunits and triggers conversion of gas to stars in mature galaxies. Since the AANM, it has become more clear that much of the truly intense cosmic star formation, and hence galaxy formation, is hidden from view at optical and near-infrared wavelengths, and only next generation mid-to-far infrared telescopes in concert with the radio to submillimeter instruments will be able to observe this critical phase in the development of galaxies. We have recently learned how quickly galaxy formation proceeded through the detection of dust and molecules in a QSO at $z = 6.4$, with apparently solar abundances. Catching galaxies and proto-galactic objects in the act of forming starts and assembling is the next step in the process of understanding this fundamental process.

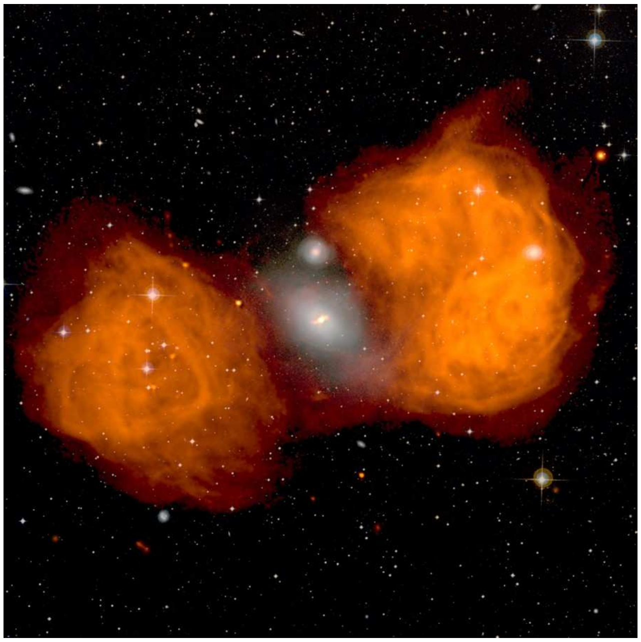

Figure 5: The 20 cm continuum emission from the radio source, Fornax A, shown in orange superposed on an optical image, from the Palomar Observatory Sky Survey II, centered on the giant elliptical galaxy, NGC 1316. Derived from VLA mosaic observations with $20''$ resolution, the radio lobes extends over $50'$ east/west. This central galaxy cannibalizes the smaller galaxy to the north and strips away material that spirals toward a black hole at the center of the giant galaxy, where there is a faint radio core and jet within an x-ray emitting plasma in the central region. High-energy particles are "beamed" away in opposite directions from the radio core and eventually smash into the tenuous material 500,000 light years from the galaxy to produce the large radio lobes. Slow changes in the direction of the beam as well as the dynamical influence from cosmic magnetic fields produce the intricate filamentary pattern seen in the lobes. Courtesy of NRAO/AUI/NSF.

Surveys for dust-enshrouded forming galaxies via observations of the continuum dust emission will be carried out in the coming decade with bolometer cameras on moderate-to-large aperture submillimeter telescopes, providing hundreds of targets for study. Subsequent high-resolution imaging with interferometer arrays and spectroscopic studies of the molecular content with large telescopes will be combined with observations of the stellar components and interstellar medium at optical and infrared wavelengths to constrain galaxy evolution models. It is unclear at this time to what extent the bulk of star formation occurs in the sub-structure merging process or whether the merging is "dry", with star formation already having occurred in smaller proto-galactic units. The galaxy assembly process can be probed by observing the gas kinematics, using HI and CO lines, and high sensitivity and high resolution are critical for such detailed studies.

The origin and evolution of clusters of galaxies is another crucial aspect of galaxy formation, in particular for the massive elliptical galaxies that preferentially inhabit these environments. Cluster studies have been reinvigorated by high quality X-ray images and spectra from Chandra and XMM-Newton, combined with radio observations of relic radio halos and radio lobes from cluster AGN. The Chandra and XMM-Newton images show "bubbles" or holes in the X-ray emission that correspond to the location of the radio lobes seen in VLA radio images, indicating that the energy output of AGN going into relativistic jets is significantly impacting the intra-cluster gas (see Figure 5. For example, this could be a heating mechanism for the prevention of cooling flows in cluster cores. In the future, the next generation large arrays will probe the cluster radio environments out to the highest redshifts. At more moderate redshifts, the gas content in and around cluster galaxies can be measured in the HI line. In addition, radio and millimeter observations will measure the electron pressure in the cluster medium through the Sunyaev-Zel'dovich effect which will probe shock physics and weigh the baryon

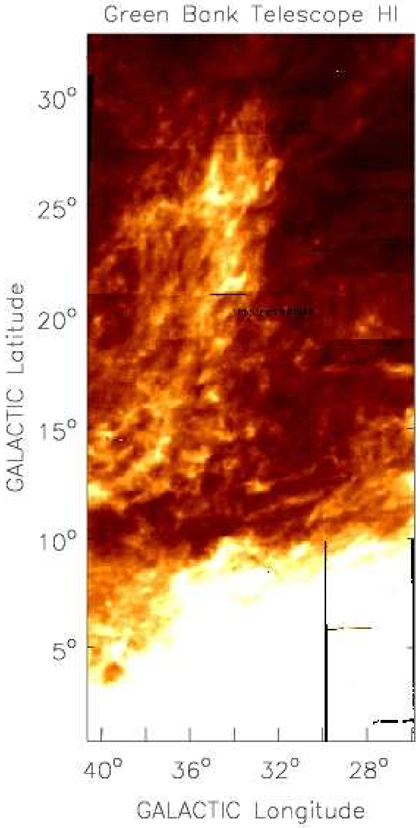

Figure 6: A large HI plume rising 30 degrees out of the Galactic plane in preliminary GBT data from Y. Pidopryhora (Ohio Univ.) and F.J. Lockman (NRAO) illustrates the disk–halo connection. Circulation of interstellar matter between the disk and halo distributes metal-enriched matter throughout the Galaxy and can control the tempo of star formation. Courtesy of NRAO/AUI/NSF.

content in the plasma phase.

5. How were supermassive black holes formed and how do they evolve with time?

The supermassive black holes that lie at the heart of a quasar or radio galaxy, each containing a billion solar masses (the size of a satellite galaxy like the Large Magellanic Cloud) and capable of emitting in excess of a trillion solar luminosities in accretion energy, are perhaps the most extreme objects in the Universe. Much of this energy emerges in ultra-relativistic particles (as evidenced by synchrotron radiation in radio jets) demonstrating the existence of an efficient acceleration mechanism. One of the recent discoveries is that there appears to be a significant correlation between the mass of a central black hole and the mass of the galactic bulge in which it resides. This implies not only that central massive and supermassive black holes are ubiquitous, but that there is a mechanism for feedback between the formation of the black hole and that of its parent galaxy.

Observations with the current suite of radio telescopes complement observations by X-ray satellites, probing the relationship of the earliest supermassive black holes to the earliest galaxies. Most notably, relativistic jets from active galactic nuclei are most prominent at radio frequencies, and current radio arrays are able to resolve the structure on the critical kiloparsec and parsec scales. The next generation meter and centimeter wave arrays will have the resolution and sensitivity to observe these same phenomena at high redshift, even well into the EOR. As has been demonstrated in the precision tracking of maser spots in NGC 4258, future arrays will be able to identify and exploit maser emission from circumnuclear accretion disks in order to measure black hole masses for less remote AGN to a few percent accuracy. With the increased sensitivity of the next generation

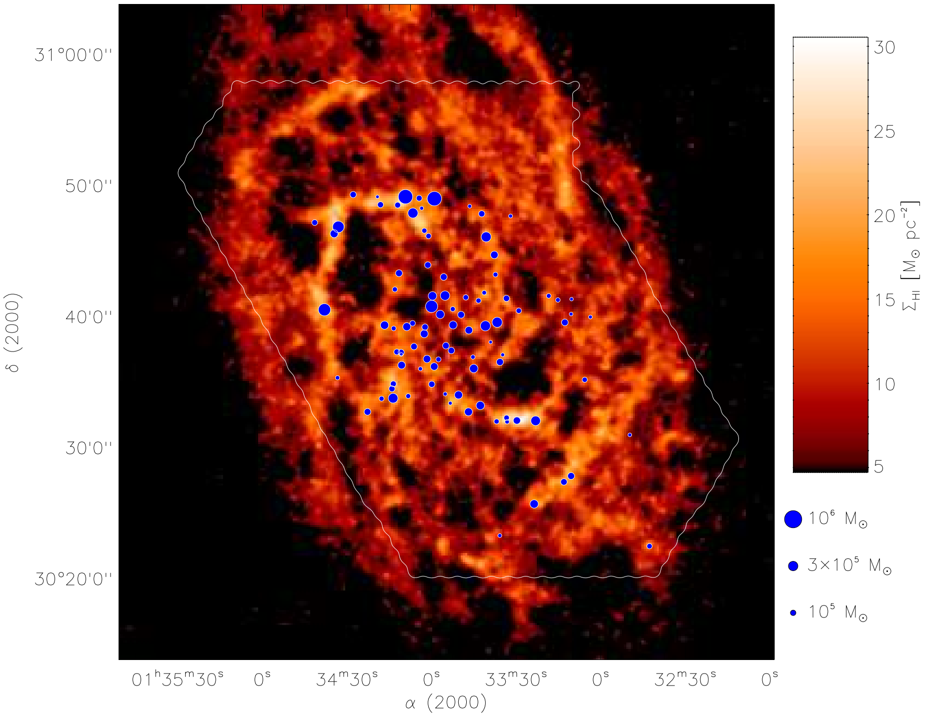

Figure 7: Complete Berkeley-Illinois-Maryland array (BIMA) CO survey of giant molecular clouds (GMCs) to a limiting mass of $10^5 M_\odot$ in the Local Group galaxy M33 superimposed on an HI map of the galaxy made at Westerbork. Each blue dot is proportional to the mass of an individual GMC, which is enlarged for clarity. The map shows two astonishing things not seen before: that the GMCs lie only on the filaments of HI, and that they occur only in the inner region of the galaxy, despite the near constancy of the HI surface density to the edge of the map. This image shows that the filaments are a necessary pre-condition for GMC and thus star formation, that the CO forms from the HI rather than vice-versa, and from a quantitative analysis, that the GMCs are formed in regions of high hydrostatic pressure. Courtesy of BIMA.

telescopes, the accretion disks in a wider variety of systems will be studied.

6. How do galaxies such as our Milky Way evolve?

A wide variety observable phenomena within our Milky Way galaxy and in other galaxies signify key stages in the life cycle of the component stars, gas and dust, cosmic ray particles, magnetic fields, and stellar remnants. Observations in different bands of the electromagnetic spectrum give us different pieces of the larger puzzle — it is through the grand synthesis of what we see from gamma rays through to ultra-low frequency radio waves that understanding of the bigger picture will emerge. Radio to submillimeter observations allow us to probe cool molecular and atomic gas not accessible by any other means, to peer into deeply obscured regions of star formation, to chart the galaxy from the outermost reaches to the very center, and to feel out the tenuous threads of magnetic fields and particles that permeate the disk. The current and next generation of X-ray to infrared satellites, ground-based optical and infrared observatories, and submillimeter to radio wave telescopes and arrays will revolutionize our understanding of the dymamics of the ever-changing Galaxy.

Understanding galaxy evolution is intimately linked to the determination of the mechanisms through which stars are formed out of giant molecular clouds, the processes triggering cloud collapse and the interplay of all stellar and gaseous components. Made feasible with the single dish telescopes equipped with cameras incorporating detector arrays, surveys of the entire Galactic Plane in dust continuum, atomic, and molecular tracers, will

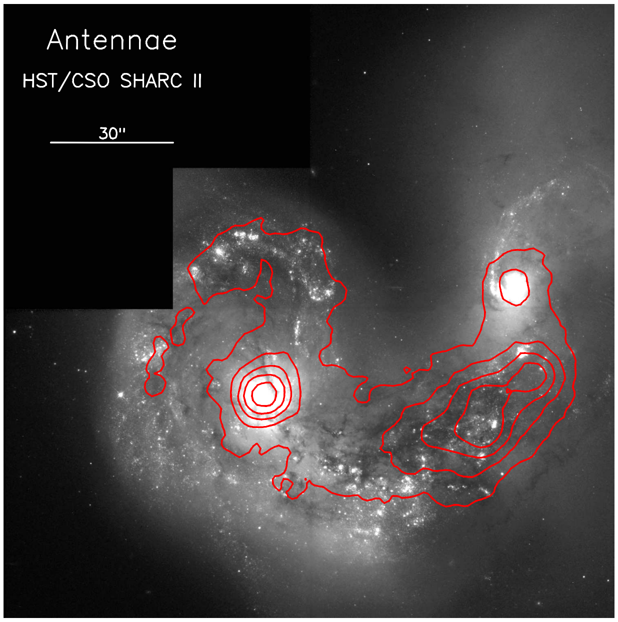

Figure 8: Distribution of the submillimeter dust continuum emission from the Antennae, a pair of interacting spiral galaxies at a distance of 19 Mpc, observed with CSO/SHARC II (red contours; 350 microns) overlaid on the HST I-band image of the region. Strong submillimeter emission is seen in a deeply dust-enshrouded overlap region of the ISM of the colliding galaxies from which most of the luminosity of the system emerges. The densest and most intense regions of star formation are completely obscured at optical wavelengths. Contour levels are 15, 30, 45, 60, and 80% of the peak (1.1 Jy/beam). Courtesy of CSO/Caltech.

complement other ground and space-based OIR surveys to reveal the details of Galactic structure and its formation and evolutionary history. While wide area optical surveys such as 2MASS, the SDSS and future LSST ones will track the complex history of the stellar components, while wide area HI and continuum studies will trace similar large–scale streams, loops and plumes that betray past accretion events and clearly illustrate the disk-halo connection (see Figure 6). Sensitive millimeter and submillimeter arrays will allow molecular cloud surveys to be carried out for a wide range of galaxy types, providing the detailed clues needed to constrain global star formation models beyond the Milky Way. Detailed studies of multiple species such as illustrated in Figure 7 will reveal the picture of star formation in benign local environments as well as allow the exploration of nearby analogues of the chaotic conditions associated with merger events illustrated by the Antennae in Figure 8.

Recent precision astrometric techniques now yield VLBA distance measurements to 2% accuracy at 2 kpc and proper motions with an accuracy of better than 1 km s^{-1}. The next generation arrays will be able to map spiral structure throughout the Milky Way, establishing a firm distance ladder as well. VLBA observations of multiple sites of H_2O masers in the spiral arms of M33 have yielded a direct measurement of galactic rotation (for the first time in the history of astronomy), and with a few more years of observation a distance accuracy of 3% may be achieved. The next generation high resolution centimeter wavelength arrays extend these measurements throughout the Local Group and beyond.

3.3 The Origin and Evolution of Stars

The origin of stars provides a fundamental question for astronomy; understanding their origin is essential for understanding the origins of galaxies (Section 3.2) and planets (Section 3.4). The rich chemistry observed in

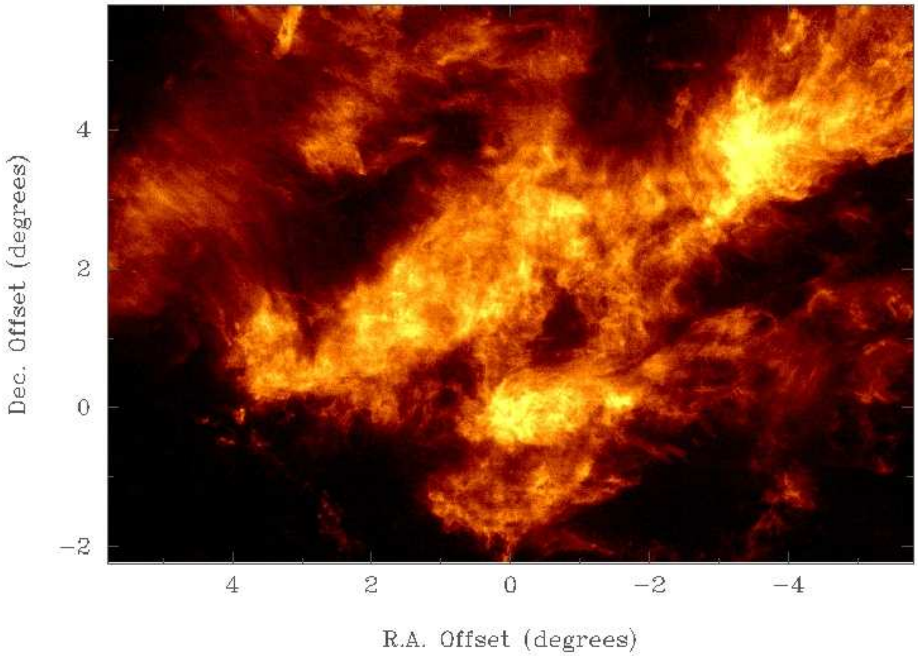

Figure 9: ^{12}CO $J = 1 - 0$ imaging of the Taurus molecular cloud complex obtained with the 32-element, heterodyne, focal plane array on the FCRAO 14m telescope. The image reveals regions of bright emission associated with star formation and a diffuse component with structural patterns that can be linked to the magnetic field. Such high spatial dynamic range images enable researchers to investigate the dynamics of molecular clouds and the processes that regulate star formation. Courtesy of FCRAO/UMass.

star forming regions of molecular clouds may provide the first steps toward the building blocks of life (Section 3.5). Molecules in circumstellar regions can produce masers, providing unique opportunities for observations with extreme resolution. As stars evolve off the main sequence, they enrich the interstellar medium with heavy elements. Supernovae and gamma-ray bursts provide extreme events that probe cosmic expansion and the cosmic dark ages. The end states of stellar evolution (white dwarfs, neutron stars, and black holes) are exotic objects that provide laboratories for fundamental physics. The Sun is not only an archetypal star but the key for life on Earth.

6. How do stars and sub-stellar objects form?

Since the AANM report, our insight into star formation has been dramatically altered by observations across the radio to submillimeter bands, complementing infrared and optical observations, particularly with the Spitzer Space Telescope. Yet for every answered question there are many unsolved puzzles. We now see that low-mass stars can form in small condensations whose kinematics can be probed only by the few molecules that are not frozen onto dust grain surfaces. We now know that substellar objects are as common as stars, but we do not understand how they form. We have just begun to see objects forming with very low luminosities, which may be forming sub-stellar objects. We do not yet understand what determines the multiplicity and masses of stellar systems. Despite theoretical and observational progress on the origin of massive stars, we lack understanding of massive star formation and what determines the mass function of stars, resulting in one of the key uncertainties in simulations of galaxy formation and evolution.

To address these questions, we look forward to the operation of the new millimeter and submillimeter interferometers and the development of large aperture telescopes at excellent sites. Together, these will form a potent alliance with infrared observations by Spitzer, Herschel, SOFIA, and future instruments in space. These

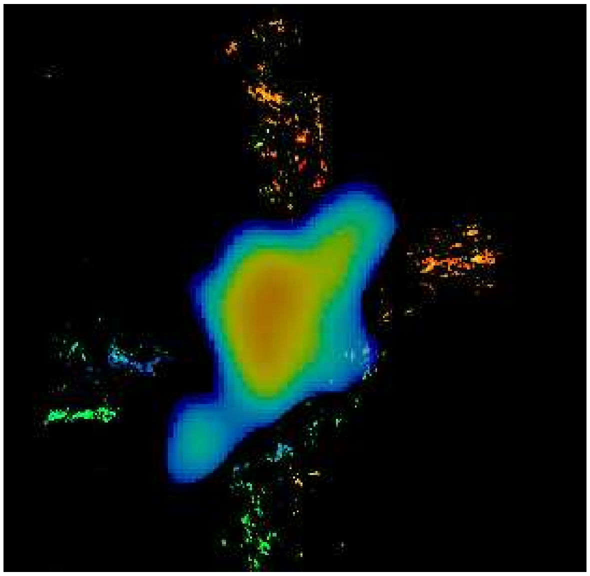

Figure 10: Radio source “I” (also called IRc2) in the Orion-KL massive star forming region. The radio continuum emission imaged with the VLA at 0.04 arcsec (20 AU) resolution appears as an elongated structure at the center of image and may be an edge-on accretion disk of a forming high-mass star. The numerous bright “spots” are SiO masers mapped with the VLBA, color coded by their line-of-sight velocity. The masers are red-shifted toward the NW and blue-shifted toward the SE, consistent with rotation about an axis perpendicular to the disk elongation. Future EVLA observations could provide 10 times better angular resolution with far greater sensitivity and, when combined with VLBA movies of the maser proper motions, will provide a unique image of a high-mass star’s accretion disk in action. Courtesy of NRAO/AUI/NSF.

instruments will also allow us to trace chemical changes from the collapsing cores of molecular clouds into disks that form around young stars and lead to planet formation (Section 3.4). The ability to penetrate into the most obscured regions of the galaxy makes radio to submillimeter observations particularly effective in probing the most critical phases of the stellar birth process.

Surveys of nearby clouds with focal plane bolometer and receiver arrays are revealing the intricate structure and clarifying the locations of dense star forming regions within the larger molecular clouds (Figure 9). Submillimeter interferometers will allow detailed analysis of the dynamical evolution of collapsing dense cores, providing discrimination between competing theories. Sensitive Zeeman observations of the interstellar magnetic field, both in HI and in high density tracers like CCS, are enabled by large apertures and interferometers. Proper motions and trigonometric parallaxes to young objects can be measured with VLBI; such studies of T Tauri established the distance to the Taurus molecular cloud within 2%, an accuracy that dramatically improves our knowledge of the properties of young stars and constrains the uncertain evolutionary tracks.

Studies of clustered star formation with high spatial resolution can determine the mass distribution of clumps and test theoretical models of star formation, which can then be used to explore how the stellar mass function depends on conditions, including metallicity. Large numerical simulations are being employed to investigate the interplay of turbulence and magnetic fields in shaping cloud structure and evolution. These simulations can be tested with large-scale maps of dust, tracing extinction, and molecular and atomic lines, tracing gas. Magnetic fields, which may regulate protostellar collapse, accretion, and outflows, can be mapped in exquisite detail by VLBI observations of masers in massive star forming regions.

The formation of the most massive stars is not understood theoretically, but observations indicate that they form only in massive clusters. Large-aperture submillimeter telescopes and interferometers will build on recent work

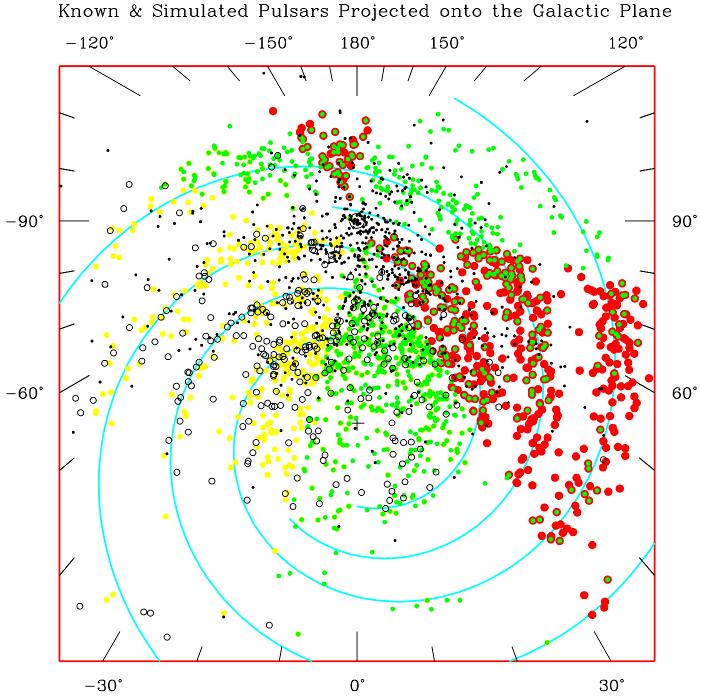

Figure 11: Projection onto the Galactic plane of survey pulsars assuming a birth rate of 1 per 167 years. Symbols denote several subsets of real and simulated pulsar subsets: Known pulsars in the Parkes multibeam survey public catalog (open circles); known pulsars from the Princeton Catalog (black dots); simulated detections for the on-going Arecibo survey (red dots); simulated detections for an all-sky GBT survey (green dots); simulated detections for final all-sky Parkes multibeam survey (yellow dots). Courtesy of the NAIC/Arecibo PALFA consortium.

identifying the massive, dense cores that are the likely precursors of massive star clusters. VLBI observations of masers can probe the distribution and kinematics of molecular material in star forming regions with resolutions of order 0.1 to 1 AU (Figure 10). Together with studies of hyper-compact HII regions at centimeter wavelengths, these observations will provide an evolutionary picture of massive star formation that can guide theoretical work.

8. How does space-time and matter behave at extreme density and pressure?

Stellar remnants offer opportunities to probe general relativity in the strong field limit. The radio to submillimeter spectrum in turn provides a unique window into these mysterious objects. Radio observations of pulsars can test nuclear physics at densities greater than those in the nuclei of atoms. Surveys with large aperture telescopes (see Figure 11) will provide many targets for precise measurements, including some in globular clusters. This will place strong constraints on the equation of state of neutron stars. Highly sensitive telescopes can yield a complete census of pulsars in the Galaxy, including those in the disk, globular cluster pulsars, runaway pulsars that will escape the Milky Way, and very notably, pulsars in the Galactic center orbiting the central black hole, Sgr A*, which will provide rich opportunities for studying strong-field gravity. Initially, existing single dish telescopes (Arecibo and the GBT) will discover many key objects. But large array telescopes operating at ~ 20 cm for the Galactic disk and at ~ 3 cm for a Galactic center survey are needed to deliver a complete census. The detected pulsar population will include members of every possible outcome of massive-star evolution, including pulsar-black hole and pulsar-pulsar binaries and, if they exist, sub-millisecond pulsars. Compact binaries will allow unique tests of relativistic gravity in the strong field limit and the equation of state at extreme densities. Precision pulsar timing can be used to test fundamental aspects of gravitation, for example, the Cosmic Censorship Conjecture and the No-Hair theorem. The current large antennas and future high-sensitivity arrays will locate a network of highly-stable millisecond pulsars whose motions can reveal the presence of low-frequency

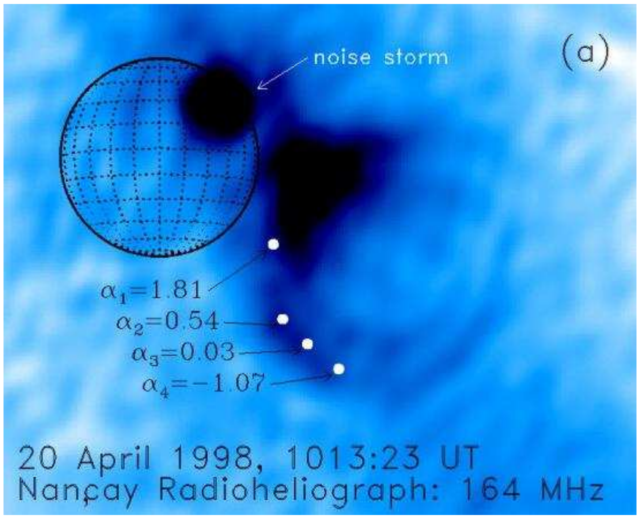

Figure 12: A 164 MHz snapshot image of a coronal mass ejection at the time of maximum flux. Background emission from the Sun has been subtracted, and time variable radio emission from a noise storm is present to the northwest. FASR will provided a dedicated facility for synoptic studies of the coronal magnetic field. Radio observations at low frequencies can capture and track events extending away from the solar surface, while future meter wavelength radar capabilities such as proposed for Arecibo and the SKA precursors may study Earth-bound CMEs. Courtesy of NRAO/AUI/NSF.

gravitational waves propagating through the Galaxy. These can potentially be traced to their origins in massive black-hole binaries, topological defects in space-time, and other sources.

Supernovae and, potentially, gamma-ray bursts are valuable probes of the very early universe, but they are not fully understood. Young supernova remnants can be imaged and their evolution directly measured with VLBI. Coupled with Hα measurements, which give the expansion speed, the observed angular expansion of a supernova gives a direct, geometric distance measurement. The conclusion that at least some gamma ray bursts represent the most visible ramification of the final collapse of the core of a massive star to form a black hole resulted from radio interferometric and scintillation measurements of the "afterglow." VLBA observations support models in which an ultra-relativistic jet forms and beams its emission in our direction. Similar radio observations, combined with better multiwaveband time coverage, will continue to explore the aftermath of the explosion and the process of black-hole formation.

9. How does the Sun affect the Earth?

The Sun, especially the variability in its behavior on short and long timescales, has a profound effect on life on Earth. In addition, as the nearest star, the Sun provides the same model for understanding other stars as the Milky Way provides for galaxies. In particular, it provides insight into the behavior of stars on the main sequence. A detailed, quantitative understanding of the Sun's magnetic field will help us understand magnetic fields on other stars and their roles in stellar/sub-stellar atmospheres, energetic activity, and the evolution of mass loss. The Sun and heliosphere provide unique opportunities to observe astrophysical processes in exquisite detail. Studies of the magnetic field require the combined power of the Frequency Agile Solar Radiotelescope (FASR) and the Advanced Technology Solar Telescope (ATST) on the ground, and the Solar Dynamics Observatory (SDO) in space. FASR, operating from centimeter to meter wavelengths, will be uniquely able to make direct quantitative measurements of the coronal magnetic field and its evolution. Of particular interest is the prospect of measuring the magnetic fields of coronal mass ejections (CMEs) (see Figure 12 and thereby predicting the impact of solar storms on Earth. Arecibo plays a critical role in the chain of incoherent

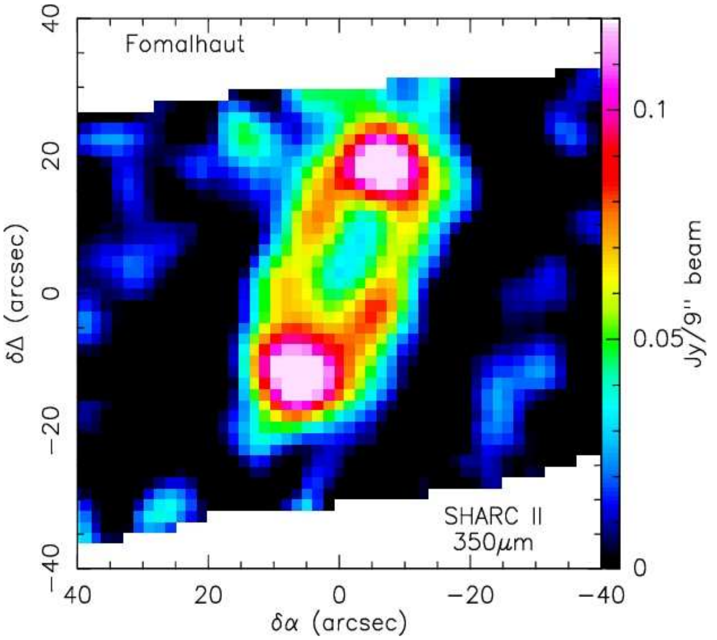

Figure 13: Fomalhaut at 350 μ, imaged with CSO/SHARC II. The results confirm the ringlike morphology but also show that the geometric center is displaced from the star by about 8 AU and that the ring has an apocentric enhancement of approximately 14% in integrated column density. The displacement can be interpreted in terms of elliptical orbital motion due to gravitational perturbation by an unseen planet. The contours are at 0.2, 0.4, 0.8, and 1.6 mJy arcsec^{-2}, and the rms noise is 0.15 mJy arcsec^{-2}. Courtesy of CSO/Caltech.

scatter radars used to study the global effects of the Solar cycle. The addition of a new ionospheric modification capability, currently underway, offers the potential to turn the Arecibo antenna into a "solar radar", providing ground based measurements of CME density and velocity. Powerful new capabilities for remote radio sensing will be developed for the future meter wavelength radio arrays.

3.4 The Origin and Evolution of Planetary Systems

The origin of planetary systems connects studies of star formation (Section 3.3) to studies of our own solar system and the origin of life (Section 3.5). Triggered by the discoveries of disks around forming stars and of extrasolar planets, the activity in this area is intense. RMS instruments play a central role in this field, complementing OIR studies.

10. How do planetary systems form and what determines their properties?

Since planetary systems form from disks, our understanding of the diversity of planetary systems requires complementary understanding of disks and their evolution. Direct images of protoplanetary disks by millimeter interferometers preceded the discovery of "proplyds" as visible nebulae around young stars in the Orion nebula. Existing interferometer arrays, with resolutions $\leq 1''$, have resolved a few disks in both spectral lines and the dust continuum. Continuum images provide disk density distributions, sizes and masses; line images constrain the velocity fields and radial temperature profile. Molecular lines can trace the gas mass if the chemistry is sufficiently well understood. Current arrays can detect species as complex as formaldehyde or methanol, but only in the outer reaches of the largest, brightest disks. We therefore look forward to more detailed studies of disks around young stars by centimeter to submillimeter interferometer arrays in the coming years. Infrared

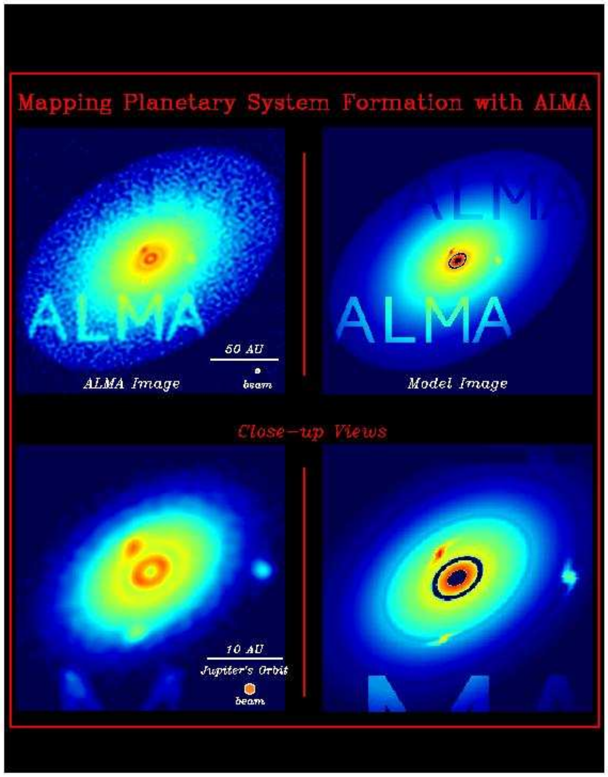

Figure 14: Simulations of potential ALMA images of disks around embedded young stars, showing the formation of giant planets. The model disk has a central hole 3 AU in radius and protoplanet-driven overdensities at 9, 22, and 37 AU. The word ALMA in the model images has a line stroke 4 AU wide and 35 AU high and is used as a gauge of image fidelity. Courtesy of NRAO/AUI/NSF.

observations with Spitzer and JWST can detect very young disks around forming stars, but cannot resolve them to learn about the formation of the disk. With vastly improved image fidelity compared to existing arrays, the new suite of interferometers will be able to investigate both the inner envelope and disks in deeply embedded protostars, while the excellent spatial resolution and high excitation tracers available at submillimeter wavelengths will enable selective studies of young disks; in the next decade the vastly improved sensitivity and resolution will be the key to fully understanding protoplanetary disks. Current theories tie grain coagulation to planetary formation processes; the tiny grains found in the interstellar medium must coalesce to form the planets. Infrared spectroscopy of silicate features with Spitzer is tracing the disappearance of small grains but cannot probe the largest grains, which should be settling to the mid-plane — these can only be probed at longer wavelengths. Preliminary hints of grain growth have been seen by existing arrays, but the next generation centimeter and millimeter wave arrays are required to understand this crucial process.

For example, imaging of nearby debris disks with the JCMT and CSO show inner holes and evidence for planets on elliptical orbits (Figure 13). Whether such planets form by core-accretion or disk instabilities, there should be an earlier phase in which a gap at the protoplanetary radius is formed but which is surrounded by substantial reservoirs of disk material. In this phase, substantial protoplanetary migration is expected to occur, and it holds the key to understanding the distribution of planetary system properties. Detailed simulations have shown that $\sim$1 AU gaps at distances of 1-10 AU cannot be detected with even the largest of the current infrared interferometers (Keck Interferometer and VLTI). ALMA alone will be able to image such disk substructures at nearly AU resolution, in both dust continuum and spectral line emission from a variety of molecular and atomic tracers, and will provide the most capable 'protoplanet-hunting' capabilities of any instrument envisioned over the next decade (Fig. 14). Longer wavelengths are needed to trace the evolution of dust in the planet-forming

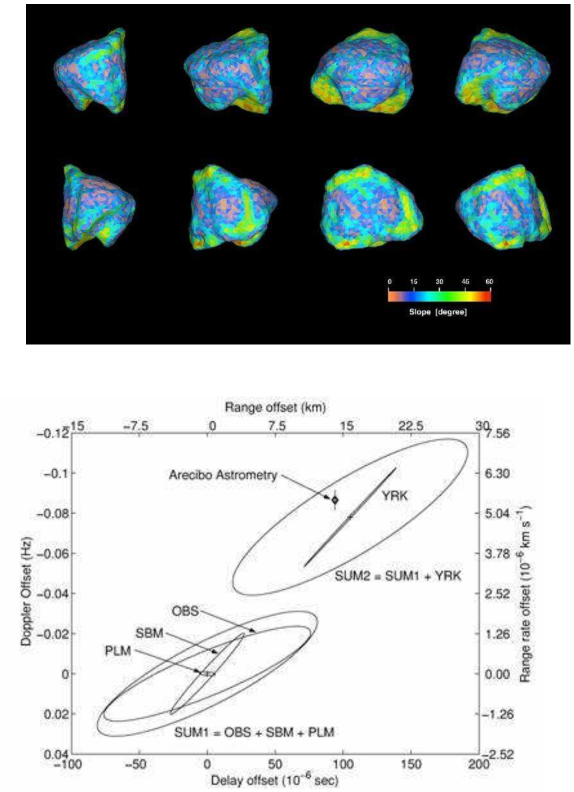

Figure 15: Upper: A shape model viewed at different aspect angles for the small (0.5 km) near Earth asteroid 6489 Golevka. The model was derived from ground based radar delay-Doppler images (Hudson *et al.*, 2000, Icarus 148, 37). Color coding represents the local gravitational slopes. Lower: The predicted locations of Golevka derived from high precision range/Doppler astrometry for Golevka with the Arecibo and Goldstone radars, with and without the Yarkovsky effect, the small non-gravitational force on solar system bodies due to the delayed thermal emission of absorbed sunlight which can modify the orbits of small solar system bodies (Chesley *et al.*, 2003, Science, 302, 1739). The Yarkovsky effect is important as it can nudge small main belt asteroids into resonance states with, primarily, Jupiter. The resultant orbital perturbations can propel them into the inner solar system. In some instances, the Yarkovsky effect will be the limitation in the determination as to whether a potentially hazardous object will pose a threat to the Earth.

zone. The dust optical depths in the inner regions of young disks, where terrestrial planets are expected to form, are quite large even in the millimeter regime. Thus, a high-resolution ultra-high sensitivity centimeter array such as the SKA is needed to probe terrestrial planet formation in the habitable zones of disks. The next-generation centimeter and millimeter arrays will permit the first direct imaging of the Kuiper Belt region in disks, and will be able to probe rotational transitions well into the planet-forming regions. If core accretion scenarios of Jovian planet formation are correct, there should be a gas-rich evolutionary phase in which dust signatures are weak. Due to the small size of the inner disk, such a phase will only be within the reach of ALMA and the SKA.

11. What are the properties of Solar system bodies?

Study of the evolution of planetary systems beyond the debris disk phase is best done by decoding the evolution of our Solar system. Solar system objects can be studied in detail that is impossible for other planetary systems. For the foreseeable future our own Solar system will remain the chief laboratory for the study of the individual bodies that make up a planetary system. Many of the small bodies in our Solar system, such as meteorites, comets, asteroids and Kuiper Belt objects (KBOs), retain information about the chemistry of the primitive Solar system and, hence, are one of the keys to understanding its formation. Studies of planetary and satellite atmospheres, such as those of Mars and Titan, will be dramatically enhanced by observations using sensitive large single dishes and by high-resolution interferometer arrays. Comets in particular are difficult objects to image with current telescopes and arrays since a tremendous range of length and time scales are important, and thus the next generation instruments will be needed to cover the range of scales and to follow these objects as they evolve with sufficient sensitivity and resolution.

Several hundred KBOs have been discovered over the past decade. They are thought to have formed very early in the outer reaches of the protoplanetary disk around the Sun, and to have undergone very little evolution since then. Size estimates depend on assumptions about their visible wavelength albedos; without good size information it is not possible to characterize the physical properties of their surfaces. KBO sizes can be estimated by combining visible and thermal IR measurements, e.g. using Spitzer. The emission from cold KBOs at large distances (> 40 AU) can be very effectively measured with submillimeter telescopes. The LSST will find large numbers of KBOs, and large millimeter arrays and telescopes will be able to measure their thermal emission to obtain the size distribution and to characterize their physical properties.

Near Earth Objects (NEOs) are of considerable interest as primitive bodies, possible repositories of useful resources, and potential hazards to the Earth. Current searches aim at finding all NEOs with sizes greater than about a kilometer that pose a potential hazard to Earth. The LSST will find large numbers of NEOs with smaller sizes. While OIR observations can provide estimates of sizes, composition, and orbital properties, measurements by interplanetary radars are needed to fully characterize their physical properties such as size, shape and internal structure as well as densities for the approximately 16% of NEOs that are in binary systems. Radar also allows the precise distance and velocity measurements needed to derive the orbital parameters of NEOs with sufficient precision to determine whether any of them pose a future threat to the Earth. Upgrades to centimeter-wave facilities and development of new arrays will greatly improve the sensitivity of this work.

3.5 The Origin and Evolution of Life

Is life a cosmic imperative or is it an accident that happened only on the Earth? This is one of the most fundamental questions, which has astronomical, chemical, and biological aspects. The discoveries by radio astronomers of the rich organic chemistry of the interstellar medium, shows that the chemistry of life can flourish even in otherwise inhospitable Galactic dust clouds. The detections of more than 100 planets orbiting nearby stars have strengthened the view that at least primitive life forms could be found elsewhere in the universe. The discovery of life on the Earth in very extreme circumstances (on the bottoms of Antarctic lakes, in sulfurous vents at the bottom of the ocean, and even in granite rock) encourages the view that life may be widespread.

12. How did life arise in the Universe?

Upcoming space missions like Kepler, TPF, and Darwin should give us a census of Earth-like planets. Another goal for TPF/Darwin is to search for bio-markers, such as ozone and methane, in the spectra of reflected starlight from terrestrial planets. To avoid false alarms, we must study the chemical evolution of planetary systems in formation, to learn about abiotic processes that might confuse the bio-markers. It is now widely believed that molecules important to the development of biological systems were delivered to the early Earth by planetesimals and their associated interplanetary dust particles. Such studies have direct relevance to the origin of life and its occurrence in the universe. More complex organics, such as those seen in meteorites and comets, can be studied with centimeter to submillimeter wave telescopes and arrays (see Figure 16), which are now achieving the sensitivities and wavelength coverage necessary to efficiently probe pre-biotic molecules in the interstellar medium.

Clues to the origin, and possible persistence, of life within our solar system are also within the grasp of RMS instruments. Titan, while too cold to support life as we know it, provides a unique opportunity to examine

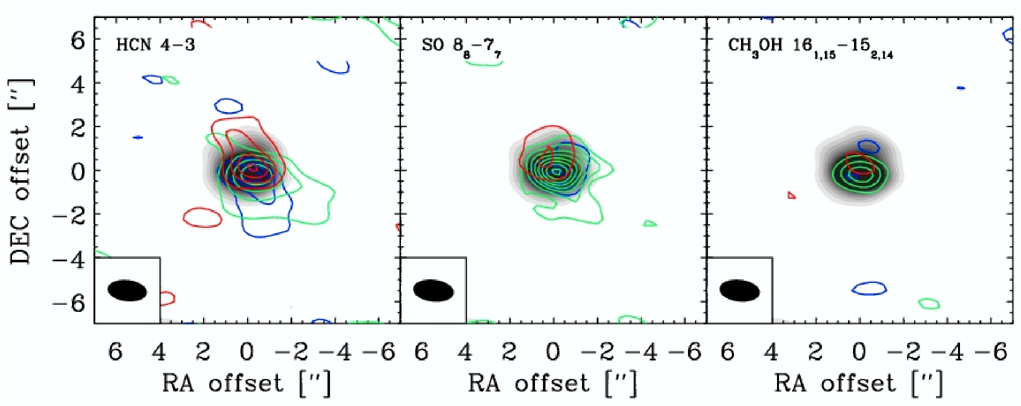

Figure 16: The images of several organic molecules in the accretion envelope of the prototypical Class 0 young stellar object NGC1333 IRAS2A made with the SMA at 350 GHz (850 microns). With a resolution of less than 2 arc seconds, these images, and those of more than a dozen other species with lines in the 350 GHz band, allow the chemistry of the envelop to be probed at a size scale of less than 200 AU. Courtesy of J.K. Jorgensen, Harvard-Smithsonian Center for Astrophysics (Jorgensen *et al.*, 2005 ApJ in press).

prebiotic chemistry such as that which may have operated on the early earth. Because Titan subtends only $0.''9$ at opposition, imaging studies of molecules in Titan's atmosphere are difficult, but essential, if we are to understand this unique moon. Existing and soon to be operational millimeter and submillimeter arrays will provide important next steps, such as the detection of important tracers and their isotopologues, but the full sensitivity of ALMA will be needed for high dynamic range studies of the more complex hydrocarbons that constitute the earliest steps toward life.

Stars in the late stages of evolution return matter to the interstellar medium through prodigious stellar winds and supernova explosions. This matter is enriched in heavy elements, which make life possible. However, the secrets of red giant mass loss remain hidden in the complex region between the stellar photosphere and the dust formation zone. This region can be probed in detail by connected-element and very long baseline interferometers, which can image the stellar photosphere and measure the proper motions of SiO and H2O masers, which straddle the dust formation zone.

Recent hints from spacecraft orbiting Mars hint that either volcanism or life remains active on this planet. Deciding between the two requires additional trace compounds such as formaldehyde, ammonia, hydrogen sulfide, etc., to be detected and *imaged*. Spacecraft provide one route to this continued exploration, but RMS facilities provide another. The GBT and other RMS telescopes can provide long term monitoring of the climate of this fascinating world.

13. Is there intelligent life elsewhere in the Universe?

While detection of microbial life on another planet would immediately imply that the origin of life is not an extremely rare event, we will still not know how commonly life evolves to human-level intelligence. Because life on Earth took nearly 4 billion years to evolve to this point, a significant fraction of the age of the Galaxy, it is possible that we are unique. The possible existence of extraterrestrial intelligence (ETI) is the astronomical question with the broadest implications beyond astronomy. The most direct approach to finding ETI is to search for the electromagnetic emissions from alien technologies. Radio searches have been carried out sporadically over the past 40 years. They seek signals that differ from naturally produced radiation by being either very narrow band or in the form of regular pulses. Both optical signals, presumably from giant pulsed lasers, and radio signals expected from intentional beacons have been sought. The distances between the stars are so large that leakage radiation, such as might be transmitted from the equivalent of our television or FM stations, is

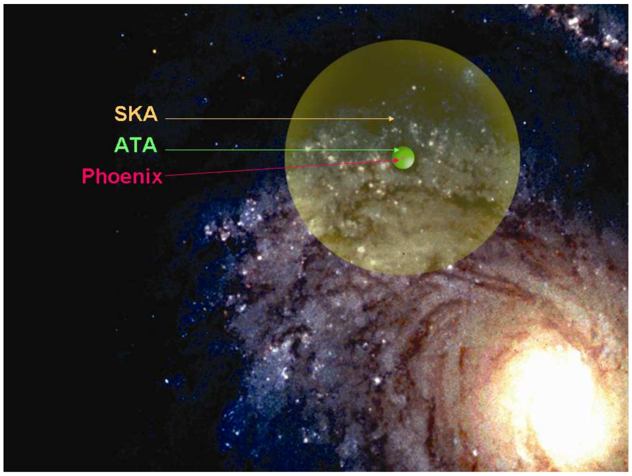

Figure 17: The figure illustrates the volume of the galaxy that might be searched by past and planned targetted searches. The pink dot is the (completed) project Phoenix search. The green sphere is 300 pc in radius within which lie the million stars that will be accessible to the ATA. The large sphere shows the volume that could be explored for signals of comparable strength by the SKA. Of course, the luminosity function of ETI sources is not yet known so that the absolute search volume for any survey cannot be determined. Courtesy of the SETI Institute.

too weak to be detected by any of our current radio telescopes. Thus the searches have been for intentional beacons.

The SETI@home project used distributed computing on over five million personal computers to search for signals in the data recorded in a spatially unbiased survey in the neighborhood of the 21-cm HI line that piggy-backed on the Arecibo telescope during regular observing programs. Searches to date have been sensitive enough to have detected a transmitter with 10^{11} Watts EIRP (approximately the power associated with many airport terminal acquisition radars) out to the most distant target at 155 light years. Although only a limited volume of parameter space has been searched to date, the lack of confirmed signals, other than local radio interference,suggests that contact will not be easy. The Allen Telescope Array is designed to look for SETI signals in two of its four frequency bands at the same time that it is carrying out other astronomical surveys with the other two bands, yielding an overall improvement will be a factor ≥ 100 in speed compared to the best previous searches. In another decade between 100,000 and 1 million stars can be studied over 1 to 10 GHz to about the same signal strength. Again if found, the emitter must be a beacon, but the increase in the number of stars that can be studied should raise the odds of a detection. In the long run greater sensitivity will be required for this search, and the SKA, with its 100 times greater collecting area, will expand the volume of the Galaxy that is studied. For the nearest stars out to 300 pc, leakage radiation, rather than special purpose beacons, will be detectable. The advances in search volume represented by these new instruments are illustrated in Figure 17.

4 The RMS Facility Requirements

The broad range of astrophysical themes and questions identified in Section 3 requires observations of the entire electromagnetic spectrum. The observational workhorses of radio-to-submillimeter wavelength studies are rotational molecular lines, the 21-cm atomic HI transition and recombination lines, thermal bremsstrahlung and dust emission, and nonthermal synchrotron emission. In addition, the thermal blackbody emission of the Cosmic Microwave Background constitutes a class by itself as a cosmological probe. Continued contribution of the RMS view of critical phenomena throughout the Universe relies upon observing these spectral line and continuum features to unprecedented levels of sensitivity and angular resolution. To complement high resolution capabilities, wide area high sensitivity surveys are needed to identify targets, explore the time domain, yield statistics and establish foregrounds. Those surveys, in turn, require instruments specifically designed for that purpose, i.e., the RMS equivalent of the Schmidt telescope.

Because the RMS spectrum spans nearly 5 decades in wavelength, coverage of the required observational parameter space requires a variety of telescopes and instrumentation. Figure 18 presents a map of science goals and observational parameter space for the principal topical areas discussed in Section 3. Table 1 highlights a few of the most prominent examples of how key RMS tracers and probes will provide insight into the critical questions discussed in Section 3; there are, of course, many others. In Table 1, we also indicate which of the existing or proposed RMS facilities will provide critical observations required to address these same science questions. Details of the facilities themselves are found in Appendix A.

The objective of our long-range strategy is to provide coverage of the wavelength-resolution plane, as shown in Figure 18, with little or no redundancy. We emphasize again that fundamentally different technological approaches are required to achieve the science goals in different wavelength ranges. The elements of the roadmap for RMS astronomy reflect the need for facilities which fall into the three basic categories as follows:

1. World-class high resolution capability at R and MS wavelengths

Once discovered, an astrophysical phenomenon is generally best studied at an angular scale given by a characteristic source size and a typical distance. From near the event horizon of a supermassive black hole to large-scale fluctuations in the cosmic microwave background, important angular scales span well over 8 orders of magnitude. The highest resolution attainable from the ground is a hard limit, given by the wavelength divided by the Earth's diameter; the lowest resolution is not limited by telescope dimensions, but by the speed at which major portions of the sky can be surveyed. The resolution-wavelength coverage of the major RMS facilities is shown in Figure 19. The limits of the telescopes are indicated where they are most effectively used. The existing facilities in this category (see Appendix A for their details) are ALMA, at MS wavelengths and the EVLA and VLBA at meter to centimeter wavelengths. Future strategy must encompass the following elements:

- ALMA, and its use by the U.S. community, must be fully supported. NSF should support CARMA as an interferometric ALMA science pathfinder in advance of full ALMA construction. CARMA's heterogeneous nature also provides an instantaneous spatial dynamic range and imaging fidelity that will be unique even in the ALMA era.
- The EVLA will continue to be a heavily used, flexible and extremely productive astronomical facility. Completion of the first phase (EVLA-I) program and support for its operations and use by the astronomical community is a fundamental requirement. The capabilities of the yet-unfunded second phase (EVLA-II) remain critical to the achievement of the AANM science goals.
- The VLBA is the only dedicated facility for highest resolution science. Its incorporation with the other large centimeter facilities into the HSA is enabling exploration at the microjansky level and into the time domain with entirely new levels of precision. Continued support of the VLBA is imperative.
- The future of meter-to-centimeter wave astronomy will be the development of a next generation facility (or facilities) which delivers unprecedented collecting area to this wavelength regime: the SKA. Currently in the concept design phase, the SKA may someday supercede the EVLA/VLBA, but that timescale for,

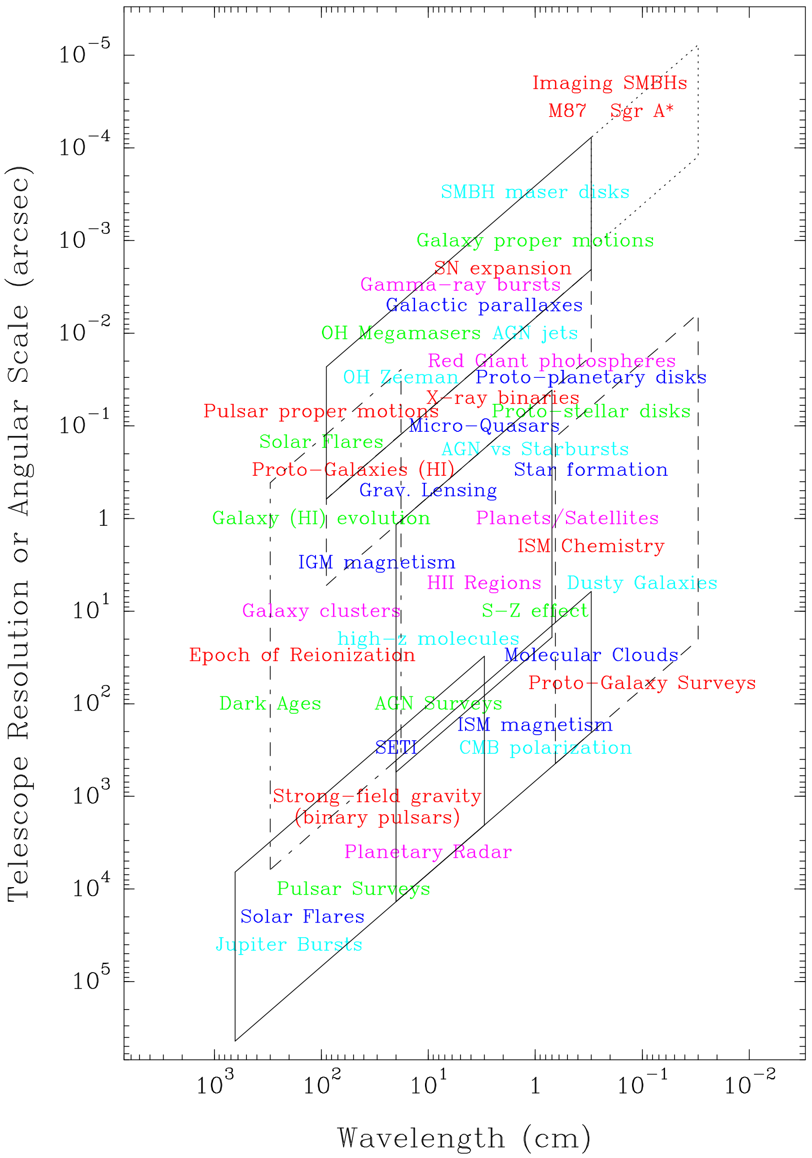

Figure 18: Science targets superposed on the observational parameter space of existing and proposed major radio telescope facilities (shown in Figure 19). The general wavelength and telescope resolution (or angular scale) that best matches the science target is indicated by the text. This demonstrates the extremely broad science program for radio astronomy.

and certainty of, that eventuality will not be clear until the wavelength coverage, design specifications and location of the SKA are determined. In any event, it is imperative for the future of meter to centimeter wave astronomy that the U.S. play a leadership role in the design and development of the SKA. To accomplish this, NSF must provide adequate support for the U.S. SKA technology development and demonstrator instrument programs.

2. World-class “fast” survey capability at R and MS wavelengths

Fast survey capabilities are required for statistical studies of galaxy, star and planet formation to supply the targets for the high resolution studies. This need is highlighted by CMB studies, by searches for high-z sub-

Question	Tracer/probe	Associated RMS Facility
1. Origin of the Universe	CMB polarization	CMB experiments
	RMS foregrounds	MS single dishes
	Variation of physical constants	Arecibo, GBT
2. The "Dark Sector"	SZ effect	CARMA, SPT, MS single dishes
	Gravitational lensing	EVLA, VLBA, SKA
	Local Group motions	VLBA
	Dark matter in galaxies	EVLA, Arecibo, SKA
3. The "Dark Ages"	EOR HI line	meter wavelength precursors/SKA
4. Origin of Galaxies	Continuum dust emission	ALMA, CARMA, SMA, MS single dishes
	High redshift CO/HI,CII	EVLA, ALMA, GBT, MS single dishes, centimeter wavelength precursors/SKA
5. Black Hole-Galaxy Connection	First AGN's	EVLA, VLBA, SKA
	Circumnuclear kinematics	VLBA, SKA
	Jet evolution	EVLA, VLBA, SKA
6. Evolution of Galaxies	Galactic plane surveys	Arecibo, GBT, MS single dishes
	Rotational kinematics	VLBA, EVLA
	Evolution of HI with z	Arecibo, GBT, EVLA, SKA
	Evolution of molecular clouds	EVLA, ALMA, CARMA, SMA, MS single dishes, SKA
7. Origin of stars	Chemistry and dynamics	ALMA, CARMA, SMA, GBT, MS single dishes
	Continuum dust emission	ALMA, CARMA, SMA, MS single dishes
	Massive stars/IMF	MS single dishes, ALMA, EVLA, VLBA
	Magnetic fields	ALMA, EVLA, Arecibo, GBT, SKA
8. Extreme physics	Pulsar detection/surveys	Arecibo, GBT, precursors/SKA
	Precision pulsar timing	Arecibo, GBT, EVLA, SKA
	Pulsar astrometry/motions	VLBA
	SNe/GRB evolution	EVLA, VLBA, SKA
9. Sun-Earth Connection	Coronal magnetic field	FASR
	Coronal mass ejections	meter wavelength precursors/SKA
10. Origin of Planets	Molecular/dust imaging of disks	CARMA, SMA, ALMA, MS single dishes
	Disk gaps	ALMA
	Inner disk emission	ALMA, SKA
11. Solar System Bodies	Solar system radar	Arecibo (+ GBT as receiver)
	Chemistry of small bodies	ALMA
	Cold KBO's	ALMA, MS single dishes
	Thermal emission from KBOs	ALMA, CARMA, SMA, MS single dishes
12. Origin of Life	Pre-biotic molecules	EVLA, ALMA, MS single dishes
	Mass loss chemistry, motions	EVLA, VLBA
	Monitoring of atmospheres	GBT, MS single dishes
13. Are We Alone?	SETI	precursors/SKA

Table 1: Summary of the principal science issues and questions outlined in Section 3, the RMS tracers or probes required to address them, and the RMS facilities which will make major contributions to their understanding. The observational capabilities of the facilities are summarized in Appendix A. "MS" refers to "millimeter and submillimeter".

millimeter galaxies, and by surveys for star-forming cores in our Galaxy. Here mapping speed is the figure of merit: how much sky area can be covered per unit time to a given sensitivity limit. In this domain, filled aperture telescopes with large arrays of bolometers are preeminent at MS wavelengths. A schematic diagram that illustrates the complementarity of detector arrays on MS single dish telescopes with interferometers is shown in Figure 20. At meter to centimeter wavelengths, this function will be fulfilled by multifeed arrays on the giant single antennas, such as the recently installed Arecibo L-band (21 cm) Feed Array, and/or multibeaming arrays. Today, the operational facilities in this category (see Appendix A for their details) are the Arizona

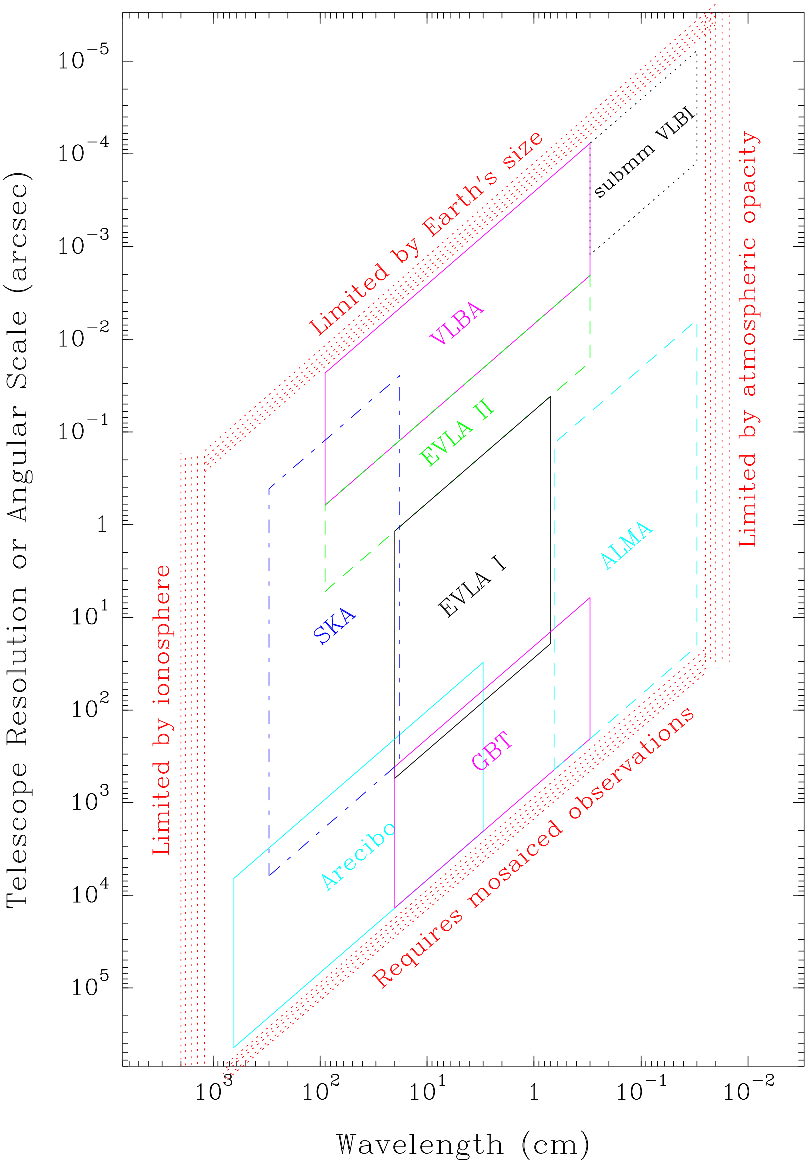

Figure 19: Capabilities of the major RMS telescope facilities. Solid lines delineate the wavelength–resolution space for the existing major national facilities where they are most effective. Dashed lines indicate proposed facilities; the dash-dotted line is for a future project, the SKA; and the dotted line for a future capability in submillimeter VLBI, using ALMA and other telescopes that requires no new antenna construction. The wavelength range covers the entire RMS window in the electromagnetic spectrum, which is limited by ionospheric reflection at long wavelengths and molecular absorption at short wavelengths. The finest angular resolution is limited by the Earth's diameter; at low angular resolution the entire available sky can be mapped by mosaicking techniques. There is minimal overlap in telescope capabilities. With the construction of the EVLA-II, ALMA, and the SKA over the next two decades, most of the available observational parameter space will be efficiently covered by this suite of telescopes.

Radio Observatory (ARO; not currently funded by NSF), the Caltech Submillimeter Observatory (CSO), and the Five College Radio Astronomy Observatory (FCRAO) at MS wavelengths and Arecibo and the GBT at meter to centimeter wavelengths. Future strategy must encompass the following elements:

- Although absolutely essential to optimal use of ALMA and other facilities including JWST and GSMT,

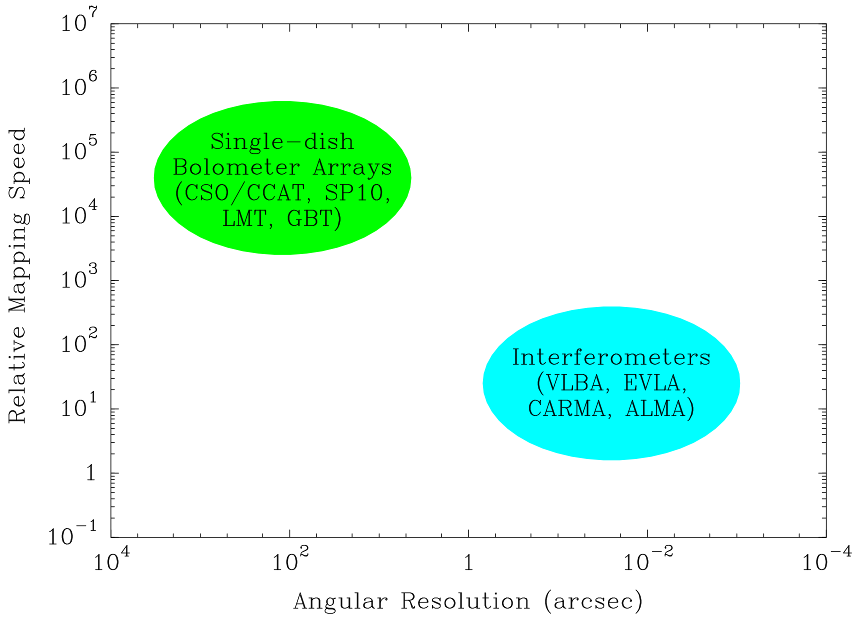

Figure 20: Relative mapping speed as a function of angular resolution. Complementary capabilities are essential for statistical studies of galaxy and star formation. The broad bandwidths of incoherent detectors and the ability to fabricate large arrays of these detectors give a huge advantage in mapping speed to suitably instrumented single dish telescopes for surveys. Such surveys are particularly essential to optimal use of ALMA and also provide extremely useful complements to surveys at other wavelengths, such as OIR. Wide area continuum and spectroscopic surveys are equally critical at the longer wavelengths where entirely different technology is required to achieve fast mapping.

it is unclear at this time what will comprise the wide-field capability for millimeter to submillimeter astronomy. The South Pole Telescope (SPT; funded by the NSF Office of Polar Programs) will contribute after its primary role in CMB/SZ effect work has been completed. The GBT may contribute at the longest wavelengths (3 mm) and for the northern extreme of the ALMA sky. We expect major contributions from the soon-to-be completed Large Millimeter Telescope (LMT; under construction in Mexico without NSF funds) and the Cornell-Caltech Atacama Telescope (CCAT; a 25 m telescope which would be built without NSF AST funds). LMT is the evolutionary successor to the FCRAO 14 m telescope and CCAT will be the successor to the CSO. The LMT will be optimal for wavelengths longer than 1 mm and sources not too far south, while CCAT will be optimum for shorter wavelengths and southerly sources. The much smaller beam of CCAT versus SPT will allow much lower confusion limits, and, because of its more accessible location, CCAT will be more operationally flexible. In this sense, SPT is the pathfinder and CCAT will follow up. Since LMT and CCAT have not requested NSF funds for construction, the NSF role is to be open to requests for instruments and perhaps operations, in return for national access.

- With its huge collecting area, Arecibo remains supreme for sheer sensitivity at wavelengths longward of 3 cm. Installation of the Gregorian optical system at Arecibo in the 1990's finally offered the big dish access to a true focal plane. The addition of the 7 beam array for 21 cm line and continuum studies in 2004 has revolutionized programs for mapping the sky with Arecibo which now involve more than 100 astronomers organized in teams to undertake legacy surveys. Arecibo is crucial for SKA precursor science and as an SKA technology testbed. NSF must support Arecibo to preserve its high sensitivity (and radar) capabilities until they are replaced by some future facility.
- Completed only 5 years ago, the GBT stands alone for its tremendous frequency flexibility, clean beam, full steerability, and location in the National Radio Quiet Zone, itself a unique resource to passive radio science. Continued NSF support for the GBT should allow development of an instrument complement that achieves full potential and focuses on those science contributions that are unique to the telescope.

- The Allen Telescope Array (ATA; construction funded through private and state resources) has the potential to provide wide field survey capability for centimeter wavelength astronomy, and, as noted below, serves as an SKA science and technology precursor. As with the other URO facilities, the NSF should consider competitive proposals for ATA instruments and perhaps operations in return for national access to the facility.

3. "Unique design" capabilities at R and MS wavelengths

Not all science objectives are fulfilled by either of the above facility categories. Additional requirements can be likewise categorized by special but critical purpose. Among the most critical are the following:

- Precision pulsar timing requires the highest sensitivity capability at meter-to-centimeter wavelengths, currently provided by Arecibo and the GBT, to be eventually superceded by the SKA.
- Centimeter wavelength radar of Solar System objects is unique to Arecibo, but requires also the bi-static complement of the GBT for study of NEOs (for which the return time is too short to allow switching from transmit to receive mode) and the planets Jupiter and Saturn and their satellites and rings (for which the return time can exceed the length of time the object is visible from Arecibo). The only alternative to Arecibo for Solar System radar is the smaller NASA Deep Space Network Goldstone antenna, which has as its primary role, spacecraft tracking and navigation. Continued support of the Arecibo radar system is critical not only for Earth-bound science studies, but also in support of NASA mission probes, as discussed in Appendix C.
- Solar and space weather studies require specially instrumented facilities. FASR is planned to be a dedicated solar facility, providing data products to the solar physics community. Arecibo's incoherent radar system plays a critical role in studies of the ionosphere today and may develop a future capability as a "solar radar'. The development of meter wavelength large array facilities such as the proposed Long Wavelength Array (LWA) and Mileura Widefield Array (MWA) also promise potential for a new generation of solar studies.
- Modest facilities are specially designed to conduct specific "experiments" such as the measurement of the CMB polarization, wide area SZ effect surveys or the detection and imaging of EOR HI signatures. The CMB/SZ effect studies remain critical and should be supported as outlined in the TFCR report. The cosmological potential for exploration of the "Dark Ages" at meter wavelengths is tremendous. The NSF must insure that US astronomers are able to develop the technologies and techniques to undertake these difficult experiments so that they are positioned to exploit this wholly new window into the earliest times.
- Pathfinder facilities undertake precursor science and/or are used as instrument demonstrators in advance of the deployment of full world-class facilities. University-based pathfinder facilities offer the "value-added" opportunity to provide hands-on training and education to the next generation of technically skilled scientists. They include the ATA as a demonstration of the US SKA "large-N/small-D" concept and CARMA as a science pathfinder and testbed for next generation instrumentation for ALMA.

The balanced and strategic combination of facilities in these three categories will insure continued U.S. scientific productivity and technical leadership for many years to come.

5 A Strategy for the RMS Facility "System":

Long-term investment by the National Science Foundation (NSF) in highly innovative radio astronomy programs both in the universities and at the national centers, the National Astronomy and Ionosphere Center (NAIC) and the National Radio Astronomy Observatory (NRAO), has made the U.S. RMS program the strongest in the world. The U.S. national radio facilities are unique in the world; there are no alternatives to their capabilities in any other sector. Continued investment in cutting edge technologies, innovative instruments and novel techniques, incorporating the principle elements discussed in Section 4, will provide the strongest assurance of continued scientific discovery and retention of U.S. leadership in RMS astronomical research. In this Section, we present a scheduled facility strategy, as illustrated in Figure 21, which continues US leadership in RMS astronomy, incorporates the buildup of the MS program in the ALMA era and lays out the groundwork for construction of the SKA in the next decade. Key points reflected in the RMS facility long range plan are:

- Ground based CMB experiments are critical to the investigation of the cosmic background and its polarization. We emphasize the importance of supporting future innovative CMB experiments and defer to the Task Force on Cosmic Background Research (TFCR) and its report on future directions in this field.
- ALMA is an international, breakthrough instrument of immense capability, poised for completion in 2012. ALMA will serve a much larger community than identified with traditional "radio astronomy" and demonstrates a potential institutional framework for future global research facilities. Its success is paramount to all of us. In order to compete in this truly global partnership, the U.S. astronomical community must be armed with the tools needed to optimize the return on the U.S. investment in ALMA, including adequate support for ALMA operations, data analysis and the associated theory as well as access to critical complementary facilities that ensure optimum scientific exploitation of ALMA, most of which are provided by the university facilities. We note particularly that CARMA was highly ranked by the AANM report and will begin science operations this winter.
- The University Radio Observatories program was formalized as a special unit of AST in the 1980's to coordinate the development and operation of the U.S. RMS telescope "system". These facilities have served as innovative pathfinders for advancements in U.S. RMS astronomy and provide critical science capability to the U.S. community at large. As new facilities have come on line over the years, many others have been retired or privatized. The universities provide the best environment for the training and education of the next generation of astronomers with both scientific and technical expertise.
- The long range strategic goal for center to meter wavelength astronomy is the construction of the next generation facility, the Square Kilometer Array. The SKA will be an international collaborative project. On the short term, the SKA concept, particularly its US program, must be developed for presentation to the 2010 NRC astronomy and astrophysics decadal survey, particularly through funding for technology development, as recommended by the 2000 AASC report.
- As world-class telescopes, the core centimeter wavelength national instruments – Arecibo, the GBT, the EVLA and the VLBA –must be supported both for operations and instrument development at adequate levels to ensure their continued premier performance for centimeter wave science until the SKA supercedes them. The design, scope and schedule of the SKA is currently too uncertain to predict its bearing on the current core facilities; we suggest that a ∼2015 timeframe may be appropriate for a review of the U.S. centimeter and meter wavelength program.
- Within the US, the development of the SKA must be undertaken as a tight partnership between the university community and the national centers. The university community should contribute significantly to demonstrator instruments, precursor science, instrument design, and the development of enabling technologies under a fully coordinated national approach. Modest investment in the lowest frequency (meter wavelengths) component of the SKA is likely to achieve significant science return on a 3-5 year timescale, in particular, to explore the epoch of reionization.

- The EVLA-II project would provide the highest resolution in any waveband of the earliest galaxies, resolve the central regions and probe the environment of relativistic jets at all cosmic epochs, resolve dusty cores of galaxies to distinguish star formation from AGN, and provide AU scale images of regions of massive star formation. The science objectives of the EVLA-II project remain critical to the science vision articulated in the AANM report and a path to their attainment must be developed by the next decadal survey.
- The clues provided by RMS facilities are critical to the science goals of other federally-supported astronomical facilities on the ground and in space. As examples: ALMA and JWST will make a powerful combination for the exploration of early galaxies; Herschel/SOFIA require the wide field survey capability contributed by the URO millimeter and submillimeter facilities; and, the VLBA will image within tens of Schwarzschild radii of the sources detected by GLAST. Thus, the timescales for the RMS strategy, as illustrated in Figure 21, reflect the synergy with these other major federal investments.

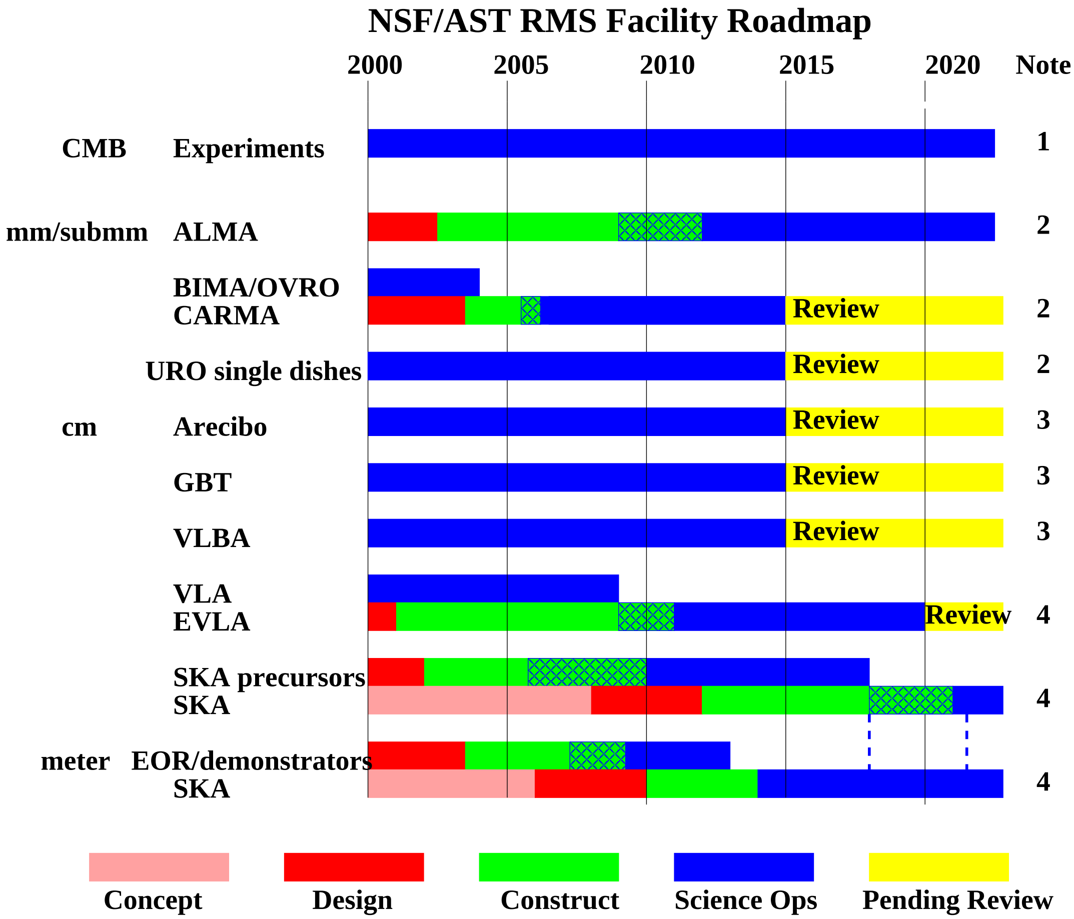

Figure 21: The RMS facility 15-year vision.

1. The TFCR includes planning for CMB experiments; we concur with the emphasis detailed in that report.
2. CARMA begins science operations in early 2006, while ALMA will begin partial array operations in 2009. University-run single dishes operating at millimeter and submillimeter wavelengths enable the array science by providing source surveys for target detection and spectroscopy. The U.S. millimeter-submillimeter system should be reexamined midway through the next decade, ∼2015, to insure that U.S. astronomers are optimally equipped to exploit ALMA science.
3. As progress towards the development of the SKA proceeds, a review of the U.S. centimeter and meter wavelength program should occur midway through the next decade, ∼2015, to consider the mature core facilities in the context of the SKA at that time.
4. The SKA is the next generation meter-to-centimeter wave telescope. At this time, its design, operating wavelengths and location are very uncertain. Options under study by the international SKA project include both a single facility design and ones covering meter and centimeter wavelengths separately and exploiting different technologies. The representation of the SKA in two places in the figure above is meant to reflect these on-going discussions. The relationship of the EVLA to the SKA should be reviewed about the time that the SKA becomes fully operational.
5. FASR does not easily fall into the general rubric of the facilities included in this roadmap because of its distinct science direction, community and operational mode. We emphasize that FASR was recommended for construction in both the AANM report and the Solar and Space Physics Decadal Survey “The Sun to the Earth – and Beyond,” and will be able to make quantitative measurements of the Sun’s coronal magnetic field and how it changes over time.

6 Conclusion

RMS science addresses a broad range of key astrophysical questions, either uniquely (e.g. CMB, sub-milliarcsecond imaging, nanosecond pulsar timing, solar system radar) or in complement with datasets obtained at other wavelengths. The RMS facility portfolio (National and University facilities) provides observing capability over 5 orders of magnitude in wavelength (10 MHz to 1+ THz) and angular scales down to 100 microarcseconds. In this document, we have tried to lay out a path to insure the continued success of the U.S. RMS program. In full concordance with the recent CAA report *"Review of Progress in Astronomy and Astrophysics Towards the Decadal Survey"*, we reaffirm our endorsement of the priorities and programs presented in the AANM report and our own panel report specifically as follows:

1. We reendorse the integrated "one-system" approach to facilities proposed by the 2000 Astronomy and Astrophysics Survey Committee (AASC) report *"Astronomy and Astrophysics in the New Millenium"*. As noted specifically in the AANM report, the private RMS telescope facilities have traditionally granted large fractions (more than 30%; AANM pp. 206-7) of telescope time without regard to institutional affiliation: The URO program has long been the RMS paradigm for the current Optical/Infrared (OIR) astronomy Telescope System Instrumentation Program (TSIP). In addition to providing national access to unique science capabilities, the URO environment fosters the education and training of the next generation of technically skilled scientists.

2. We reemphasize, in accord with the AANM report for all of astronomy, the need for NSF planning of support for a comprehensive program of both direct (user grants for data analysis) and indirect (associated theory, source surveys, complementary follow-up observations) efforts in order to insure the full return on U.S. investment in major astronomical facilities.

3. We reaffirm commitment to the completion of ALMA on schedule and delivery of its full science capability. ALMA will deliver transformative capability for high sensitivity, high resolution studies of early galaxies, protostars and protoplanetary disks and giant planets in formation. ALMA represents a major new investment by the NSF in AST Division science within the context of an international partnership.

    - The schedule for ALMA construction must be maintained and its prime science capabilities delivered. Furthermore, it is essential that ALMA be properly supported during operations in order to achieve its scientific promise. As technology develops, ALMA instrumentation must be upgraded to keep the facility at the cutting edge of science.
    - U.S. astronomers must have access to facilities and support to conduct wide area surveys to identify targets for ALMA studies, to conduct follow-on redshift surveys and to map structures on larger scales, in order that they be well positioned to exploit ALMA's superb capabilities to the fullest. Filled aperture telescopes equipped with large arrays of bolometers and flexible spectrometers (z-machines) will provide the surveys that are essential to optimal use of ALMA and also provide necessary complements to surveys at other wavelengths to explore the gamut of issues associated with the origin and evolution of galaxies, stars and planets.
    - ALMA needs to meet its design requirement to be an instrument for all astronomers. Science quality images will be a basic data product which will be archived and delivered to astronomers along with the raw data and calibration information. This new level of capability for ground-based instruments is an integral part of making ALMA easily accessible to the whole astronomical community and is central to maximizing the United States' scientific return on its investment in ALMA.

4. We reendorse the continued enhancement of the existing premier national instruments, emphasizing the *unique* capabilities of Arecibo (high sensitivity surveys for gas-rich galaxies and Faraday tomography of the Galactic magnetic field, pulsar surveys and timing for tests of GR, radar studies of orbits and characteristics of NEOs), the EVLA (separation of AGN's and starbursts in obscured galaxies, AU scale images of massive star formation sites, particle acceleration in micro-quasars, X-ray binaries and radio galaxies), the GBT, (Galactic disk-halo interface, high redshift CO, CMB foregrounds), and the VLBA, (Local Group proper motions, maser motions around supermassive black holes, evolution of GRB's, supernovae and novae).

  - Continued access to the unique core capabilities is a requirement to allow pursuit of astronomy's science objectives.
  - We reassert the need to fill in the sampling of spatial frequencies represented by the additional antennas proposed under the EVLA-II program in order to achieve the highest image resolution and fidelity especially for evolving sources.

5. We reemphasize the critical need for a concerted and aggressive U.S. technology development program leading towards the eventual construction of a flexible and broad capability world-class SKA, but also emphasizing intermediate-term (3-5 years) science and technical objectives as well.
   - Near-term investment in SKA technology development must emphasize concept design of the U.S. program for presentation to the 2010 decadal survey.
   - Modest investment in focused, multiple approaches to low frequency array design should be pursued over the next 3-5 years. First priority should emphasize the capability to detect and image the neutral intergalactic medium at $z > 6$, as a unique probe of the process of reionization (AANM p 45).
   - The path toward the SKA, especially at wavelengths shorter than 10 cm, includes many technical challenges whose solution is not currently available and may not be for some time. The existing facilities serve as testbeds for many SKA technologies and techniques and are critical to SKA precursor science, especially at shorter wavelengths. We note particularly that many of the techniques and instrumentation being developed for the EVLA are important for the design and development of the SKA. Concurrent exploratory deployment of the Large N/Small D concept as represented by the ATA is also necessary.

6. Echoing the emphasis given by the AASC especially in light of WMAP and other recent results, we restress the importance of studying the cosmic microwave background via ground-based experiments (AANM p. 24).

7. In conjunction with the similar recommendation in the NRC Solar and Space Physics report *"From the Sun to the Earth – and Beyond"*, we reendorse the construction of a dedicated ultrawide band solar radioheliograph, the Frequency Agile Solar Radiotelescope (FASR), with capabilities commensurate to studies of solar phenomena, particularly those related to magnetic energy storage and release in the solar corona.

8. Even within constrained budgets, we encourage increased priority towards making RMS facilities easier to use by the broad astronomical community, providing data reduction pipelines for standard observing modes, and producing immediate-use public data products.

9. We reiterate the statement in our AASC panel report that *"the open skies policy, allocating telescope time based purely on scientific merit, enables the best science to be undertaken." (p. 213)*

10. We reaffirm the importance of exploiting public curiosity about such issues as the origin of the universe, galaxies, stars, planets and life itself to increase public awareness and knowledge of science and the commitment of the astronomical community to the training and education of students at all levels.

11. We commend the efforts of NSF and its staff in activities associated with spectrum management issues on both a national and international level. Continuing vigilance to preserve the spectrum for astronomical research use is imperative. The current legislated quiet zones surrounding Green Bank and Arecibo (National Radio Quiet Zone in the vicinity of Green Bank and Coordination Zone near Arecibo) are extremely important resources for radio science.

Historically, the NSF has held prime responsibility for the U.S. investment in RMS astronomy; this investment has established the U.S. program as the world leader in the field. As we move forward amid the magnitude and complexity of the global facility paradigm, technological hurdles and funding constraints, issues of programmatic balance and strategy will increasingly challenge the NSF and the astronomical community. A continuing dialogue will be necessary among all parties to assure that investment continues to lead, in a concerted and coherent manner, toward long term science achievement and technological innovation.

A The Radio–Millimeter–Submillimeter Facility "System"

One of the items specifically requested of the RMSPG is a full summary of the range of the facilities available to the community. Closely following the definition of telescope "system" outlined in the AANM report (AANM pp. 26-27) The RMS "system" encompasses a range of observational facilities: major national facilities; smaller scale university facilities, some supported by the NSF; and experiments/demonstrators of limited duration, for example, directed at studies of the CMB and the epoch of reionization. These three categories have very different funding needs, histories, and characteristics. Taken together, they provide a lean and balanced portfolio with all parts needed to address the scientific issues identified in the previous section. In this Appendix, we review the current RMS facilities and their individual roles in the RMS telescope *system*.

With the assistance of individuals associated with each of the facilities, we have compiled summaries of the capabilities, designs, operational histories and scientific goals and achievements, of the various facilities; these more detailed summaries are available at *http://www.astro.cornell.edu/~haynes/rmspg/projs_a.htm.* Because of the fundamental differences in technology and tradition between facilities that operate principally in the long (centimeter to meter) and short (FIR to submillimeter to millimeter wavelengths) wavelength regimes, we discuss the two categories of facilities separately in the next subsections.

A.1 Meter to Centimeter Wavelengths: Towards the Next Generation Radio Telescope

A.1.1 The U.S. National Radio Facilities

It is important to note that the U.S. national facilities are the world's best centimeter wave radio telescopes, which is why our foreign colleagues are so eager to use them. There are no comparable "private" facilities, and continued access to the the unique capabilities of Arecibo, the GBT, the EVLA and the VLBA are critical to U.S. astronomers. As noted in the AANM report, the U.S. national centers, NRAO and NAIC, provide both leadership and telescope access. We restate, from the AASC Radio and Submillimeter Panel report, *The radio astronomy community is justifiably proud of both its national centers, NRAO and NAIC, ...* (AANM p. 200).

Current U.S. National Centimeter Wavelength Facilities

Facility	Wavelength range	Angular resolution	Distinctive characteristic
Arecibo	3 to 80 cm	$3.5'$ at 21 cm	Collecting area; radar
GBT	3 mm to 3 m	$1'$ at 2 cm	Unblocked aperture; wide frequency coverage
EVLA	7 mm to 4 m	$0.4''$at 6 cm	Imaging array
VLBA	3 mm to 1 m	$0.001''$ at 0.7 mm	Imaging array

Each of these four major national radio telescopes offers unique capabilities: Arecibo and the GBT provide high sensitivity to low surface brightness and extended sources such as atomic and molecular clouds and to faint phenomena such as pulsars; the EVLA (EVLA-I), provides high resolution imaging of the full gamut of centimeter-wave phenomena from radio stars to radio galaxies; and, the VLBA provides the highest possible angular resolution for bright objects. The scientific topics addressed by them are likewise broad, and as illustrated by a representative sample in Figure 18, include most of the topics of greatest interest in contemporary astronomy: e.g., the CMB, epoch of re-ionization, accretion disks around super-massive black holes, AGN jets, gamma-ray bursts, gravitational lensing, galaxy formation & evolution, star formation and proto-stellar disks, interstellar chemistry, pulsar timing and tests of relativity, and solar system studies including imaging planetary radar. Particular highlights associated with each of these facilities are as follows:

Arecibo 305m Telescope: As the world's largest radio-radar telescope, Arecibo offers unique high sensitivity and radar capability. Now with the advent of the Arecibo L-band Feed Array in 2004, wide area mapping surveys conducted by large community consortia are being undertaken. Among the most promising studies are:

- The wide area continuum and spectroscopic surveys will explore whether gas-rich but optically "dark" galaxies exist and will use Faraday tomography to determine the distribution and spatial structure of the magnetic field of the Milky Way.
- Pulsar surveys and timing including tests of GR, exotic equations of state and constraints on the stochastic background of cosmological waves
- Radar imaging of Solar System bodies and their motions, including the orbits of near-Earth asteroids

Future developments for Arecibo should exploit its large collecting area, its radar capability, and the use of the big dish as a testbed for SKA technologies such as a many-pixel 4-10 GHz focal plane array. Partnerships with the university user community should be exploited in areas such as spectrometer and software development, the undertaking of large scale legacy-class surveys and the development of data archives. Arecibo also plays a critical role in incoherent scatter studies under a separate statement of work through the NSF Division of Atmospheric Sciences (ATM) in the Geosciences Directorate.

Green Bank Telescope: Completed in 2000, its unblocked aperture, active surface, frequency flexibility, full steerability and location in the National Radio Quiet Zone, render the Green Bank Telescope uniquely suited for wide area mapping of extended structures such as galactic HI, surveys of highly redshifted molecular line and multi-species studies over a broad range of redshifts, details studies of the chemical pathways that produce complex bio-marker molecules in the ISM and the role of magnetic fields in the regulation of star formation and the structure of the ISM. Among the most exciting possibilities are:

- The nature of the Galactic disk-halo interface and of the high velocity clouds, making critical use of the GBT's clean beam.
- Detection of highly redshifted CO and other species over a wide wavelength range will determine the conditions in galaxies during their peak era of star formation.
- High sensitivity and precision surveys of point sources at 26-40 GHz will determine the extent of contamination of the CMB measurements by foreground sources probably the dominant limitation on future CMB experiments.

The Expanded Very Large Array: The EVLA project promises a 10-fold improvement in the capabilities of the current VLA, itself the world's most productive ground based telescope. Currently underway, the first phase of the EVLA (EVLA-I) will improve the continuum sensitivity by up to a factor of 40 and will provide complete frequency coverage from 1 to 50 GHz, giving noise limited imaging in all bands. The new correlator, contributed by Canadian partners, will offer a huge increase in spectral capabilities. A suite of new telescopes, spread throughout the state of New Mexico (EVLA-II) will increase the spatial resolution of the EVLA by a factor of ten and will fill in the gap in spatial frequencies between the VLBA and the existing VLA. The complete sampling of spatial frequencies, possible once the EVLA-II is completed, will allow high fidelity imaging of structures on all angular scales, and is particularly critical for the study of AGNs/starbursts in high-z galaxies and evolving sources such as the expanding shells of novae and supernovae. In parallel with ALMA, the EVLA will emphasize (near) real-time imaging and the development of pipeline process for standard observing modes. Future science targets are numerous and we highlight only the following:

- Image the earliest galaxies and separate starbursts from AGNs
- Provide AU-scale images of massive star formation
- Study relativistic jets and particle acceleration in micro-quasars, X-ray binaries and radio galaxies

Very Long Baseline Array: As the world's only dedicated VLBI array, the VLBA provides a full complement of instrumentation for its receiver bands to allow time critical images of motions and source evolution and for unparalleled astrometry to microarcsecond accuracy. In combination with the large single dishes Arecibo and the GBT, and the phased VLA, the VLBA is being used as a High Sensitivity Array (HSA) to probe faint sources at sub mJy levels at submilliarcsecond resolution. It should be noted that the HSA is not a new facility, just an optimal use of the existing ones to explore new science parameter space. The successful demonstrations of "eVLBI" (electronic transmission of data via wide-band fiber optic networks) offers a (near) real-time imaging capability, with greatly increased bandwidth and hence sensitivity, has the potential to revolutionize VLBI observing modes and strategies for the study of evolving sources such as γ-ray bursts, supernovae and novae, masers in motion around supermassive black holes and pulsar parallaxes. The VLBA will be a major contributor to the science of GLAST both for laying the ground-work for this mission and for conducting critical follow-up observations.

Dramatic results can be expected in the following projects:

- Determine the dark matter density in the core of lensing galaxies
- Measure pulsar and maser parallaxes to map the structure of the Milky Way
- Observe maser motions around supermassive black holes to measure BH mass and geometric distances.

A.1.2 Development of the Next Generation Radiotelescope: the SKA

The overall long term goal for meter to centimeter wave radio astronomy is the development of the vastly improved capabilities discussed in the AANM report under the SKA project. A program of technology development for the SKA was the top ranked moderate scale project in RMS astronomy endorsed by the AASC (AANM p. 37). Although progress in the U.S. towards SKA design has been limited by the availability of funds for the technology development, we reiterate that the SKA will revolutionize the study of objects and phenomena that are currently undetectable at centimeter wavelengths. (AANM p. 41).

Facility	Wavelength range	Angular resolution	Distinctive characteristic
SKA	1 cm to 3 m	wide range	Collecting area; wide fields; time domain

The SKA Concept: The goal of the SKA is to combine a two order of magnitude increase in sensitivity over existing array telescopes with widefield survey capability for continuum sources, spectral sources, and time variable sources. The specifications include high polarization purity, agility in sampling the time and frequency domains, and a total frequency range of 0.1 to 25 GHz. It will be a premier discovery instrument at flux density levels below one microJy and it is being designed to answer key questions in physics, astrophysics and astrobiology. Among them are:

- Massive surveys (10^8 to 10^9 sources) in HI up to $z \sim 2$ and in continuum for weak and strong-lensing studies. These will yield constraints on the dark energy equation of state parameters, w_0 and w_1, complementary to those of Type 1 SN measurements.
- Test of gravity in the strong field limit using pulsars with black hole companions and using pulsars as detectors of long wavelength gravitational waves.
- Detection and characterization of redshifted 21 cm HI line emission from the neutral intergalactic medium during the time of reionization.

The broad milestones for the SKA project include site selection and concept identification later this decade; prototype and demonstrator arrays late this decade and early next decade; full construction proposals submitted to multiple national agencies early next decade; construction of the full array commencing in the middle of next decade. Of prime importance to the U.S. community is adequate funding for preparation of the SKA concept design in time for presentation to the next NRC Astronomy decadal survey committee.

SKA Demonstrators: While construction of the full SKA is not expected to begin until some time in the next decade, it is both possible and desirable to reap scientific benefits from SKA technologies long before the full SKA is built. A number of modest scale facilities are currently under development both to achieve specific near-term science goals and to demonstrate technologies of direct relevance to the SKA. For example, the ATA, with its collection of several hundred small dishes, serves as the demonstrator of the US-led ‘Large-N/Small D” concept for the SKA. The tabulation below considers only projects now underway that have been identified to us; this list is expected to evolve as SKA development proceeds.

Demonstrator instruments linked to SKA science including U.S. involvement

Facility	Wavelength range	Ang. res.	Distinctive characteristic/science
ATA	3 to 60 cm	$1'$ at 21 cm	"Large-N/Small D" demonstrator; wide area surveys, SETI
LWA	3 to 30 m	$2''$ at 4 m	High resolution concept demonstrator; nonthermal phenomena
MWA	1 to 3.7 m	$3.4'$ at 1.5 m	Wide field concept demonstrator; image EOR, transients
PaST	1.5 to 6 m	$5'$ at 6 m	Wide field concept demonstrator; detect EOR

We emphasize that detection and exploration of the EOR at meter wavelengths offers enormous science potential. Facilities are currently under design and construction in several other countries (Australia, China, The Netherlands). U.S. involvement in these projects is necessary so that U.S. astronomers can partake from the start in EOR observational science.

A.1.3 FASR: A Next Generation Radioheliograph

The Frequency Agile Solar Radiotelescope (FASR) was recommended for construction in the AANM report (where the Radio and Submillimeter Panel considered its technical feasibility, while its science was rated by the Solar Panel), and more recently, it was rated number one among small projects by the Solar and Space Physics Decadal Survey "The Sun to the Earth – and Beyond". FASR will be a solar dedicated radio telescope designed to perform dynamic, wideband, imaging spectroscopy with angular, spectral, and temporal resolution commensurate with the physical phenomena that occur on the Sun. FASR will provide unique measurements and diagnostics designed to address key science issues such as:

- The nature and evolution of coronal magnetic fields and their relationship to the heliosphere
- The physics of solar flares and the drivers of space weather
- The physics of the quiet solar atmosphere

As a dedicated well-calibrated instrument that is operational for at least a solar cycle (2 × 11 yrs), FASR will make major contributions to synoptic studies. It is also expected to play a significant programmatic role in forecasting and real-time monitoring of solar and space weather activity.

FASR will provide an inherently three-dimensional view of the solar chromosphere and corona. For example, in the case of a flare and associated CME, FASR will simultaneously image the energy release volume through associated broadband coherent radio bursts, electron acceleration and transport processes through the centimeter wavelength incoherent gyrosynchrotron radiation, the genesis of the CME and prominence eruption in the low corona, and the associated "EIT wave" in thermal chromospheric emission, providing an unprecedented view of the spatial and temporal couplings between each of these phenomena.

Facility	Wavelength range	Angular resolution	Distinctive characteristic
FASR	1 cm to 10 m	20/freq(GHz) $''$	Ultra-wideband radioheliograph

In order to provide frequency coverage from 30 MHz to 30 GHz, FASR will consist of three separate antenna systems combining different size dishes (2 and 6 m) at higher frequencies and log-periodic or active dipoles at the lowest frequencies. It thus serves as a wideband testbed instrument of the large-N/small-D SKA concept.

A.2 Millimeter to Submillimeter Wavelengths: Maximizing the ALMA Investment

When completed in 2012, ALMA will be the flagship instrument for millimeter to submillimeter astronomy and the first truly global astronomical facility operated through a partnership among North America, Europe and Japan. ALMA is a technical and engineering challenge because of its location at a high altitude (5000 m) site in the high Atacama altiplano region of northern Chile, the highest permanent, astronomical observing site in the world. Both due to its location at this superb site and to technological advances in antenna and receiver design, ALMA will, in fact, be a much more capable instrument than envisaged at the time of its endorsement by the 1990 AASC.

Facility	Wavelength range	Angular resolution	Distinctive characteristic
ALMA	0.3 to 3 mm	$0.02''$ at 1 mm	Imaging array; superb site

ALMA will image the redshifted dust emission from evolving galaxies at epochs of formation as early as $z \sim 10$, to image and reveal the kinematics of heavily obscured regions throughout the universe, and to produce unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects in the Solar System. ALMA combines the clarity of detail in images provided by a heavily-populated interferometric array together with the brightness sensitivity of a fully filled aperture. It is specifically designed:

- To allow the detection of CO or CI emission from Milky Way-like galaxies at $z \sim 3$,
- To map the gas kinematics in protostars and protoplanetary disks around young Sun-like stars to distances of 150 pc
- To detect gaps created by planets forming in disks

First science will be undertaken with the partial ALMA array in 2008, ushering in a new era in astronomical research in the millimeter to submillimeter range. Following the AANM report (p. 24), we reaffirm the commitment to the urgency of the completion of the ALMA and delivery of its full science capability.

A.2.1 Rounding out the MS "System"

While ALMA will provide exquisite detail over relatively small fields, other capabilities such as wide field mapping, survey speed and spectroscopic flexibility will be required to provide the targets for ALMA studies, to place them in the context of their larger scale environments and to explore their physical conditions in greater detail. A small but vital suite of complementary facilities must also be part of the RMS roadmap in order to insure maximum return on the ALMA investment.

With ALMA the first world-class MS facility, the university facilities at MS wavelengths have filled the short-wavelength gap in the coverage of the national facilities and opened these wavelength regions to study in the pre-ALMA era. Smaller university consortium based facilities will continue to play vital roles in the ALMA era, not only providing hands-on experience in equipment development for undergraduate students (fostering interest in the sciences) and graduate students (training the next generation of RMS astronomers) but also providing unique science capabilities that ALMA cannot. We point out again that the RMS portfolio has long acted as *"one system"* (AANM p. 189), with traditionally significant fractions ($> 30\%$) of the telescope time at the university facilities being awarded to the community at large.

The MS "system" therefore includes both ALMA, the SMA (federally funded through the Smithsonian Institution) and a number of moderate-scale facilities, tabulated below. Currently the university facilities supported by NSF AST include CARMA, the CSO (replaced early in the next decade by the CCAT), and the FCRAO 14 m (soon to be replaced by the LMT). The SPT, funded by the NSF Office of Polar Programs (OPP) will contribute after its primary role in CMB/SZ effect work has been completed. With two small telescopes, the Arizona Radio Observatory (ARO) is funded by state and private sources. Until ALMA comes on line, these observatories will provide the only window to these short wavelengths routinely available to US astronomers.

Facility	Wavelength range	Angular resolution	Distinctive characteristic
CARMA	0.8 to 2.6 mm	$0.10''$ at 1 mm	Hybrid array for large area mapping, SZ studies
SMA	0.35 to 1.6 mm	$0.15''$ at 0.45 mm	High resolution submillimeter array
LMT	0.8 to 4 mm	$6''$ at 3 mm	Collecting area, spectroscopic flexibility
CSO/(CCAT)	0.3 to 2.1 mm	$30''$ at 1 mm	Source surveys, spectroscopy, (superb site)
SPT	0.8 to 3 mm	$1'$ at 2 mm	Source surveys, SZ studies, superb site
ARO	0.6 mm to 4.6 mm	$21''$ at 1 mm	Molecular searches

In complement to the high resolution capabilities of the SMA and ALMA, the more modest university-based facilities are optimized to map the extended molecular clouds surrounding hot cores, and to provide the wide-area surveys and detailed spectroscopy, especially redshifts that place the detailed ALMA images in context. With its hybrid configuration, CARMA provides unique imaging characteristics in addition to a northern-hemisphere location. Large single dish telescopes located at transparent sites (CSO/CCAT, SPT, LMT) and equipped with many-pixel bolometer arrays are vital to ALMA for source surveys and follow-up spectroscopy as well as to allow full exploration of the development of clusters of galaxies and their peculiar velocities through studies of the SZ effect, to study the thermal emission from minor solar system bodies such as comets and asteroids, and to enter the chemical laboratories of interstellar molecules. Among the most promising scientific priorities are:

- To provide constraints on the nature of dark energy through its effect on the growth of massive clusters of galaxies by large area surveys and detailed imaging of the redshift independent Sunyaev-Zel'dovich effect (SPT, CARMA, LMT).
- To identify hundreds of thousands of obscured high redshift galaxies, to determine the redshifts photometrically and to use them to study the evolution of large scale structure from the earliest epochs (CSO/CCAT, SPT, LMT, CARMA)
- To probe the detailed structure and kinematics of circumstellar and protostellar disks, identifying the physical processes which dominate the star and planet formation processes (CARMA, SMA, CSO/CCAT, LMT, ARO)

The LMT will be optimal for wavelengths longer than 1 mm and sources not too far south, while the CSO successor CCAT will be optimum for shorter wavelengths and southerly sources. The much smaller beam of CCAT versus SPT will allow much lower confusion limits, and operationally, CCAT will be more flexible. In this sense, SPT is the pathfinder and CCAT will follow up. Since LMT and CCAT have not requested NSF funds for construction, the NSF role is to be open to requests for instruments and perhaps operations. Together, the suite of capabilities offered by the modest scale facilities will allow U.S. astronomers to fully exploit the potential of ALMA.

A.3 Cosmic Background Experiments

Direct observations of the CMB are uniquely within the purview of RMS astronomy and huge advances have occurred in the last decade, thanks to a coordinated strategy of both space- and ground-based programs. A Task Force on the overall U.S. CMB research program (TFCR) will soon report to the Astronomy and Astrophysics Advisory Committee and HEPAP. We fully endorse continued support for a concerted strategy that enables the next generation of CMB experiments but to avoid duplicating their efforts, we do not discuss them further here.

B Technology Drivers and Opportunities

From the time of Galileo's first telescope, new discoveries in astronomy have depended on the introduction of powerful new observational tools exploiting the latest technological developments. This is especially true in radio astronomy, where the emerging electronics and communications industries fueled by unprecedented new technologies developed during World War II, have led to a series of remarkable discoveries which have largely defined the agenda of current astronomical research. The discovery of nonthermal cosmic radiation, radio noise storms on the Sun and Jupiter, radio galaxies, quasars, pulsars, gravitational lensing, cosmic evolution, extrasolar planetary systems, cosmic masers, giant molecular clouds, and the cosmic microwave background, most of which were unpredicted and probably unpredictable, were the result of exploiting new technologies as indicated below.

- Highly directional antennas: nonthermal Galactic radiation, Jupiter noise bursts, pulsars
- Microwave and millimeter technology: solar noise storms, radio galaxies, molecular cloud, protostars
- Low noise antennas: Cosmic microwave background
- Radio interferometry and Fourier synthesis: radio galaxies, quasars, gravitational lensing
- Computing technology: gravitational radiation, extrasolar planets
- High speed tape recording and stable atomic frequency standards: cosmic masers, relativistic jets
- Bolometer Arrays: submillimeter galaxies

Even the classical complex challenge of setting the hierarchical distance scale of the universe is being addressed in new and more direct ways with radio observations of gravitational lenses, the S-Z effect in distant clusters, expanding supernovae remnants, and extragalactic cosmic masers.

The next generation of new radio telescopes will address many of the problems raised by these discoveries. But, these are today's problems. Will they be the problems that will challenge astronomers in future decades? If history is any example, the excitement of new radio telescopes will be not in the old questions which are answered, but in the new questions that will be raised by the new telescopes with their better sensitivity, better angular, spectral, and time resolution, higher dynamic range, bigger fields-of-view, faster mapping speed, and perhaps other parameters that we haven't yet thought of.

Over the next decade more new discoveries will come from advances in

- High speed massive computing and signal processing: potential pulsar-black hole binary.
- New algorithms for data handling and wide-field high dynamic range imaging: solar weather, pulsar surveys.
- Low cost miniaturization of low noise wide bandwidth rf and signal processing devices: For implementation of large interferometric arrays (EoR, SKA) and large single dish focal arrays (CMB-Polarization and foregrounds, galaxy and SZE surveys).
- Broad band long distance data transmission: interferometric imaging of the heart of AGN.
- Antenna metrology and use of CFRP: precision submillimeter telescopes for surveying the dusty universe and understanding the chemistry of star and planet formation.
- Implementation of large Focal Plane Arrays on existing antennas and arrays: wide area time domain surveys for pulsars and transients; wide area surveys of complete populations.
- Fabrication of large bolometer arrays: for surveys for an inventory of galactic star formation to the history of star formation measure through dusty high z galaxies to the growth of clusters and the nature of the dark energy through SZE measurements of clusters to testing inflation through polarization measurements of the CMB.
- Low noise detectors for millimeter and submillimeter wavelengths: early galaxies; faintest sources.
- Compact low cost cryogenic systems:

C Synergy with Other Wavebands and Facilities

While this report is specific to scientific approaches and facilities rooted in the radio, millimeter and submillimeter regime from the ground, RMS astronomy is tightly coupled with other efforts in the field. In this section, we explore such synergies, centered first around the scientific topics discussed previously and then around the various major facilities planned to become operational in the next 10–20 years.

C.1 Synergy with the Science

Nearly all cosmic objects radiate across multiple wavebands; others are observable primarily in a one principal band. To complete the "cosmic palette", we must sample different portions of the electromagnetic spectrum to gain a complete understanding of planets, stars, clouds, galaxies, and the universe as a whole. The RMS end of the spectrum provides a probe of both violent and quiescent processes with resolution as fine as tens of microarcseconds or fields of view extending degrees across, penetrating deep into objects that are often obscured at optical wavelengths. Similarly, IR, optical, uv, X-ray, and gamma-ray telescopes view celestial phenomena in different but complementary manners.

A description of all examples of synergy between the RMS and shorter-wavelength bands could occupy an entire, long book. More comprehensive examples are included at the individual summaries linked to the RMSPG Facilities Compilation web page: *http://www.astro.cornell.edu/∼haynes/rmspg/projs_a.htm.*

Here we list only a small fraction of such examples, covering a diverse range of physical phenomena.

Tests of Gravity: High precision timing analyses of pulsars provide stringent tests on theories of gravity and the Equivalence Principle, the precision mass determinations of pulsars and their companions and the orbital evolution resulting from gravitational wave emission in accord with General Relativity. The application of pulsars are detectors of long-wavelength gravitational waves such as those produced by inspiraling supermassive black holes that result from galaxy mergers will rely on monitoring pulsars with Arecibo, the GBT and the SKA. Future pulsar timing programs at Arecibo will undoubtedly include timing of the numerous but relatively weak pulsars found in on-going surveys (see Figure 11). In addition to tests of relativity, the discovery and precision timing of fast and possibly sub-millisecond pulsars will test and exclude model equations of state and could possibly signify the importance of quark matter in the cores of neutron stars.

Origin and Evolution of the Universe: The Sunyaev-Zeldovich effect offers a method to characterize secondary CMB anisotropies. The main measurements are carried out in the RMS portion of the spectrum (e.g., SZA, ACT, SPT), supplemented by X-ray observations (Chandra, XMM-Newton, ASTRO-E, Constellation X) that determine the density of the scattering plasma. Both optical and radio observations of gravitational lenses can find multiple images of gravitationally lensed quasars. Optical observations with the next generation telescopes including LSST and GSMT are needed to confirm the presence of a lens by measuring its redshift, while radio interferometry with the EVLA and VLBA resolves the image, thereby revealing the distortion imposed by the foreground matter. The combination provides the information needed to determine the mass distribution of the lens, which leads to inferences regarding the distribution of dark matter as well as the values of key cosmological parameters.

Origin of Galaxies: Many of the highest redshift galaxies currently detected are extremely luminous at IR (Spitzer, JWST) and submillimeter wavelengths. Indeed, half of the star formation in early galaxies is invisible at optical wavelengths, as evident in Figure 4. ALMA, SPT, and CCAT will probe deeply to sample forming and newly formed galaxies over a much wider range in luminosity than currently possible. VLBA and EVLA observations determine definitively whether the extraordinary IR/submillimeter power derives from a massive starburst or a "monster" - a supermassive black hole accreting gas from its surroundings. Only a combination of the clues gleaned from multiwavelengths observations will lead us to a complete picture of the rates and modes of star formation in the early universe and the interaction between the formation and growth of galaxies, stars and supermassive black holes.

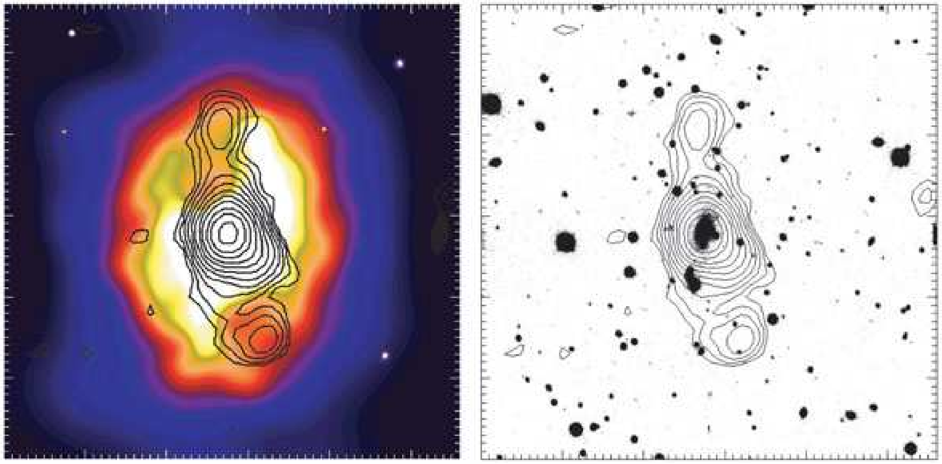

Figure 22: Cluster of galaxies MS0735.6+7421, whose hot medium is dynamically interacting with the jets of one of its galaxies. The X-ray image (Chandra, left) and optical image (right) are superposed with the 1.4-GHz radio contours (VLA). The X-ray cavities, about 200 kpc across, are filled with radio emission. From McNamara *et al.*, 2005, Nature, 433, 45.

Evolution of Galaxies in Clusters: Much of the mass in clusters of galaxies lies in the hot gas seen by X-ray telescopes such as Chandra, XMM-Newton, and the planned Constellation X. RMS observations (EVLA, CARMA, ACBR, CBI, SZA, SPT, ACT) are just as critical to understanding the intracluster and intergalactic medium, through their ability both to trace the relativistic electrons and magnetic fields and, to detect the Sunyaez-Zel'dovich effect, thereby specifying the density of the gas (Figure 22). Recent combined Chandra and VLA observations have demonstrated that the jets of radio galaxies in some clusters carve out cavities in the gas and provide the energy source that maintains the high temperature. Such jet interactions are thought to play an important role in regulating the growth of supermassive black holes and their host galaxies by inhibiting the infall of gas onto galaxies during their active jet phases.

Active Galactic Nuclei (AGN): X-ray emission from jets is quite common, as found by Chandra. These are the same jets that have been imaged with the VLA over the past two decades. Combined VLBA, EVLA, Chandra, HST, and soon LSST images tell the complete story of how the jets start out at ultrarelativistic flow speeds, then eventually decelerate while producing TeV electrons with astonishing efficiency. On parsec scales, combined VLBA, RXTE, CGRO, and soon GLAST monitoring will establish the relation between the superluminal knots and the variable high energy emission.

Intensive monitoring of the X-ray (RXTE) and IR flux and VLA or VLBA images of both X-ray binary systems and radio galaxies has demonstrated that relativistic jets are intimately connected with accreting black holes. Events near the event horizon - sudden ordering of the magnetic field or a clump of gas plunging toward the black hole - shoot bursts of energetic plasma down the jets, forming radio knots that escape down the jet at superluminal apparent speeds. Future combined EVLA/VLBA and Constellation X monitoring will explore the relationship between changes in the the X-ray continuum and line emitting plasma close to the black hole and injection of energy into the jet.

The History of Stripping, Tidal and Merger Events: The current paradigm of galaxy formation incorporates a picture of buildup through tides, mergers and accretion at earlier epochs. The kinematical clues gleaned from spectral imaging of the atomic hydrogen and CO distribution far from the parent bodies in distorted systems allow the development of detailed models of the interaction history. In clusters, the effect of the intracluster medium as traced by X–ray emission, combined with HI maps, can be reproduced in numerical simulations which combine ram pressure stripping and galaxy harassment. In nearby systems, the widespread HI distribution such as seen in the M81 group (Figure 23) combined with deep optical imaging shows the formation

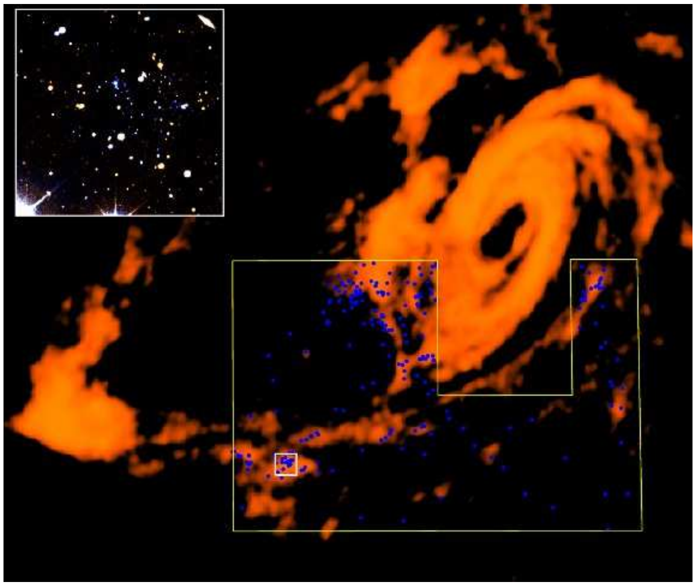

Figure 23: Contours of the HI distribution spread throughout the M81 group by Min Yun (Univ. of Massachusetts) reveal the extent of the tidal damage in the system. Blue dots indicate the locations of hot blue stars formed since the tidal event, discovered by Patrick Durrell and Megan DeCesar (Penn State). Courtesy of the Pennsylvania State University.

of dwarf galaxies in pockets of denser tidal debris.

Star Formation: Exploration of the process of stellar birth requires observations across the electromagnetic spectrum, with particular emphasis on infrared, submillimeter, and millimeter wavelengths. The shape of the spectral energy distribution is the primary tool for studying the dust, the luminosity, and the evolutionary state, with near-infrared probing the star, mid-infrared the disk, and far-infrared to submillimeter the envelope. High spectral-resolution observations at MS wavelengths are needed to study the gas. CSO/CCAT, CARMA, SMA, ALMA, LMT, and GBT will complement shorter wavelength data from Spitzer, SOFIA, Herschel, JWST, and SAFIR.

Stellar Evolution: Sudden, short bursts of gamma rays were a complete mystery until the combination of gamma-ray, X-ray, and optical/IR observations demonstrated that they lie in remote galaxies. Our current paradigm pictures a gamma ray burst as a manifestation of an ultra-relativistic jet produced during a "hypernova," the cataclysmic implosion of the core of a very massive star to form a black hole. Solving the mysteries of how nature creates such an extreme, highly focused flow, and how that flow evolves with time will require the combined effort of Swift, fast-response optical telescopes, the VLBA, and radio scintillation measurements. In fact, we don't know what sources inhabit the truly dynamic radio sky, but the detection and statistical characterization of continuum transients, with a sensitivity 6 orders of magnitude better than previous studies, through surveys in complementary frequency ranges at Arecibo, LWA, MWA and ATA, will complement studies of similar energy bursts detected at other wavelengths by burst detectors such as Swift, HETE-2, GLAST and LSST, and by LIGO.

Origin of Planetary Systems: We learn about the formation of planets in circumstellar disks from imaging and spectroscopy at near-infrared to radio wavelengths, with each probing different parts and aspects of the disk. The continuum is sensitive to dust, low-resolution spectroscopy probes the ices, and high-resolution spectroscopy studies the gas. Such observations across wavelength ranges from 2 to 3000 microns probe the composition and evolution of the disks. Exploration of planet formation requires high spatial resolution, hence ALMA, EVLA, and SKA will complement TPF and Extreme Adaptive Optics on GSMT.

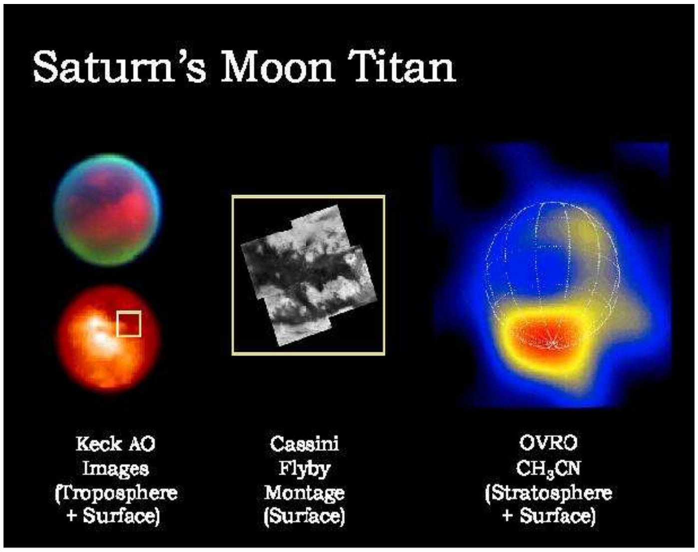

Figure 24: Left: Ground-based K-band Adaptive Optics (AO) images of the leading and trailing hemispheres of Saturn's moon Titan. The color stretch at top highlights troposphere haze (blue) and polar clouds (green). Middle: Cassini high resolution montage of the Fensal-Aztlan region of Titan from the Sept. 7, 2005 flyby. Right: Owens Valley 0.9" image of the acetonitrile emission from the southern polar stratosphere and upper troposphere. Only long term monitoring with ground-based RMS and OIR facilities can provide the very long baselines needed to study the seasonal cycles of this world. Courtesy of Antonin Bouchez (Keck image), Cassini Mission/NASA, Mark Gurwell (OVRO image).

Magnetically Active Regions on the Sun: Our understanding of solar flares and other high-energy events on the Sun have benefited greatly from joint radio (VLA, Arecibo), optical (ATST), uv (SDO), X-ray, and gamma-ray observations. The radio band samples gyrosynchrotron radiation from energetic electrons. The EVLA will directly image the many electron beams created by sudden energy release during flares, while ALMA will image regions with the highest energy electrons. FASR will provide the solar, heliospheric, and space physics communities with highly complementary data that will add significantly to their science missions and will uniquely provide direct measurements of coronal magnetic fields.

C.2 Synergy with Other Major Facilities

Another way to approach synergy is to examine how the RMSPG facilities directly relate to the future NASA missions and major NSF initiatives. Here, we give brief examples.

Planetary Probes: Many of the spacecraft that explore the solar system require the assistance of the most sensitive, highest-resolution radio telescopes and interferometers to communicate with the control centers on the Earth. Most recently, the Cassini mission utilized the VLBA to track the spacecraft motion during descent and the GBT to acquire the signal from the Huygens probe that landed on Titan. Both instruments measured wind speeds in the Titan atmosphere. As illustrated in Figure 24, ground based observations provide the long term monitoring necessary to understand the seasonal cycles on Titan. Other planetary probes rely on surface topology constructed from ground-based radar imaging exploiting the Arecibo radar. For example, Arecibo observations provided the shape model and other information for the current Japanese Hayabusa sample return mission to the small NEO 25143 Itokawa. No other current technique - 15 m resolution at a distance of 0.038 AU corresponding to an angular resolution of 0.5 milliarcsec - can substitute for this radar capability.

JWST: One of the primary objectives is to study the evolution of galaxies from their formation to the present epoch. JWST will, however, be sensitive mainly to the stellar component. The longer wavelengths and higher resolution of ALMA, CARMA, and the SMA are needed to map the dense gas, determine the rotation curves and therefore mass distribution, and separate close pairs of merging galaxies as well as subgalaxy components of galaxies undergoing assembly. The EVLA and will be sensitive to the jets of energetic particles that can have a major influence on the galactic environment, while the VLBA and mm-VLBI will identify the black holes that form at the cores of the galaxies.

Planck: The fluctuations in the CMB will be measured by Planck. Because of their finer resolution, ALMA and CARMA will follow the evolution of structure through the Sunyaev-Zel'dovich effect. Arecibo, the GBT, EVLA, ATA, MWA and SKA all will contribute to detailing the cosmic process that transforms primordial hydrogen clouds into bona fide galaxies.

GLAST: Study of blazars, pulsars, and thus-far unidentified gamma-ray sources is the main goal of GLAST. Light curves with daily fluxes will require monitoring with the VLBA and mm VLBI in order to relate the gamma-ray variations to the structure in the jets. Pulsar studies need to be complemented by measurements at lower radio frequencies with Arecibo, the GBT, SKA, and LOFAR in order to obtain a complete picture of the still poorly understood emission processes. The EVLA will be instrumental in identifying the unidentified GLAST sources, while the VLBA will be used to characterize their nature.

LIGO/LISA: The main sources of gravitational waves are expected to be neutron stars, black holes, and gamma-ray bursts. Radio telescopes and arrays have already proven to be crucial for locating and determining the physical properties of these exotic objects, and will be ready to follow the evolution of sources after gravitational waves are detected. On-going programs using precision timing of an array of millisecond pulsars using Arecibo and the GBT will provide verification of the presence of major gravitational disturbances and constrain the stochastic background of cosmological gravity waves.

SAFIR: The follow on to Spitzer and Herschel, SAFIR is planned to be a 10-m class cooled FIR/submillimeter telescope with a launch perhaps in the 2020 time frame. The ground based FIR/submillimeter programs planned for CSO/CCAT will serve as a key scientific and technological precursor/complement for SAFIR, exploring the nature of dusty galaxies and star forming regions and also serving as a testbed for SAFIR technologies.

Orbiting-VLBI: By extending the resolution of ground-based interferometers, orbiting VLBI, using antennas in space in conjunction with those on the ground, can provide the highest possible angular resolutions. U.S. facilities played a critical role in the success of the Japanese-led project VSOP in the late 1990's which demonstrated that many extragalactic objects have submilliarcsec structure that only space-VLBI resolutions can probe. Although this was principally a demonstration experiement that space VLBI was feasible, exciting results were detected such as intraday variability and brightness temperatures greater than 10^{13} K. Future missions currently under discussion such ARISE, VSOP-2 and RadioAstron promise resolutions sufficient to resolve and image the accretion disk of M87, the nearby supermassive black hole candidate. Only with this instrument can the formation of radio beams and the interaction of the accretion disk and the black holes be directly studied.

Solar missions: FASR especially will provide complementary views of the active and dynamic Sun during the course of various space missions focused on Solar studies including STEREO, Solar B, SDO and SIRA. For example, FAST will provide unique observations of the nascent stages of the coronal mass ejects which STEREO will observe at greater distances from the Sun.

ATST: Endorsed by both the AANM report and its counterpart in the Solar and Space Physics community, the Advanced Technology Solar Telescope (ATST) is a joint NSF AST-ATM major initiative to construct a ground based 4m telescope optimized to observe the Sun at optical and IR wavelengths. Among its science goals is the study of the nature and evolution of magnetic field in the solar atmosphere. FASR's three-dimensional view of coronal magnetography and seismology as well as its studies of magnetic energy storage and release in the solar corona will greatly supplement ATST measurements to understand the phenomenology of "solar weather".

GSMT: The AANM report strongly endorsed plans to construct a large (30 m class) optical telescope or Giant Segmented Mirror Telescope as a “powerful complement to [JWST]” (AANM, p. 11.). The forefront RMSPG facilities will similarly complement both the GSMT and JWST. ALMA will explore the cold, molecular universe on angular scales of ~ 10 mas, a good match to the planned GSMT adaptive optics resolution of ~ 10 mas. The sampling density of submillimeter galaxies, for which ALMA can measure redshifts using the [C II] and [N II] lines, is expected to be similar to that seen optically by the future GSMT. A comparison of the two populations will be critical to understanding the high redshift universe. High signal-to-noise optical spectra will be to estimate the metallicity of the gas and stars in galaxies at $z > 3$; for the brightest of these, ALMA will provide some isotope information, yielding a clue to the nucleosynthetic history of the earliest stellar populations. The EVLA, VLBA and SKA will image central starbursts to separate their energy components and the image the flares in nearby giant and supergiant stars and also map the 3-dimensional distribution of temperature and density in nova shells. GSMT programs exploring the formation of planets will likewise parallel ones with CARMA, ALMA and the SMA.

LSST: The Large Synoptic Survey Telescope is targeted to the study of astronomical phenomena in the time domain. Evolution of the radio counterparts of novae, supernovae, and microquasars will be imaged unobscured by the EVLA and VLBA. A principal objective of the LSST is the discovery of large numbers of asteroids throughout the Solar System. Solar system radar studies with Arecibo, using the GBT or Goldstone in bistatic mode, will characterize the orbits of NEO’s while the CCAT will detect thermal emission from KBO’s.

D Acronyms used in this Document

Summaries of the RMS facilities, as compiled by the RMSPG for the purpose of writing this report, can be found at: *http://www.astro.cornell.edu/∼haynes/rmspg/projs_a.htm.*

AANM: *"Astronomy and Astrophysics in the New Millenium"*, the report of the 2000 Astronomy and Astrophysics Survey Committee (AASC).

AASC: The Astronomy and Astrophysics Survey Committee (AASC) appointed by the National Research Council to undertake the decadal survey.

ACBAR: Arcminute Cosmology Bolometer Array Receiver, a CMB experiment.

ACT: Atacama Cosmology Telescope, a CMB experiment.

ALMA: Atacama Large Millimeter/Submillimeter Array.

Arecibo: 305 m telescope of the NAIC.

ARISE: Advanced Radio Interferometry between Space and Earth, a proposed NASA mission for space VLBI.

ARO: Arizona Radio Observatory.

ATA: Allen Telescope Array.

ATST: Advanced Technology Solar Telescope.

AUI: Associated Universities, Inc.

BIMA: Berkeley–Illinois–Maryland Array; now part of CARMA.

BOOMERANG: Balloon Observations of Millimetric Extragalactic Radiation and Geophysics, a CMB experiment.

CARMA: Combined Array for Millimeter Astronomy.

Cassini: Cassini spacecraft.

CCAT: Cornell-Caltech Atacama Telescope.

CME: Coronal mass ejection.

CQC: 2002 NRC report "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century".

CSO: Caltech Submillimeter Observatory.

DASI: Degree Angular Scale Interferometer.

DOE: Department of Energy.

DSNA: Deep Space Network Array.

EVLA: Expanded Very Large Array.

EVLA I: First phase of EVLA project, designed to increase the sensitivity and, especially, the spectral capability of the existing facility by the addition of new receivers, construction of a new digital correlator and significant software improvement; Currently funded, beginning 2001 with expected completion in 2012.

EVLA II: 2nd phase of EVLA project, designed to increase the angular resolution of the VLA by a factor of 10 through the construction of additional antennas spread throughout New Mexico (the New Mexico Array). The EVLA II proposal was submitted in 2004 and is currently under review.

eVLBI: (Near) real-time VLBI imaging by transmission of data over internet to central correlator (vs physical shipment of disks),

e2e: End-to-end development of software tools for users to aid from proposal submission to observations to data reduction,

FASR: Frequency Agile Solar Radiotelescope.

FCRAO 14 m: The 14 m telescope of the Five College Radio Astronomy Observatory. It is due to be replaced by the LMT in 2006.

GBT: Green Bank Telescope.

GLAST: Gamma-ray Large Area Space Telescope.

GRB: Gamma-ray bursting source.

GSMT: Giant Segmented Mirror Telescope, the large aperture (30 n class) ground based OIR telescope endorsed by the AANM report.

Herschel: A 3.5m aperture, space-borne observatory with capabilities in the wavelength range from 60 to 670 μ. It is part of the ESA Cornerstone mission program, scheduled for launch in 2007.

HSA: High Sensitivity Array, the use of multiple core facilities (VLBA, EVLA, GBT and Arecibo) for the highest sensitivity VLBI.

HST: Hubble Space Telescope.

JWST: James Webb Space Telescope.

Large N/Small D: Large number of small diameter dishes: the U.S. approach to the SKA design which achieves the required large collecting area through the combination of large numbers of small antennas.

LMT: Large Millimeter Telescope.

LWA: Long Wavelength Array.

LSST: Large Synoptic Survey Telescope.

MAXIMA: Millimeter Anisotropy Experiment.

MWA: Mileura Widefield Array.

NAIC: National Astronomy and Ionosphere Center.

NASA: National Aeronautics and Space Administration.

NEO: Near-Earth object.

NMA: New Mexico Array.

NRAO: National Radio Astronomy Observatory.

NRC: National Research Council.

NSF: National Science Foundation.

OIR: Optical and Infrared Astronomy.

OPP: Office of Polar Programs.

OVRO: Owens Valley Radio Observatory; its millimeter array is now part of CARMA.

PaST: Primeval Structure Telescope.

RadioAstron: Russian mission for space VLBI.

RMS: Radio, Millimeter and Submillimeter.

RMSPG: Radio, Millimeter and Submillimeter Planning Group; the authors of this report.

SDSS: Sloan Digital Sky Survey.

SKA: Square Kilometer Array.

SMA: Submillimeter Array.

SDO: Solar Dynamics Observatory

SOFIA: Stratospheric Observatory for Infrared Astronomy.

Spitzer: Spitzer Space Telescope

SPT: South Pole Telescope.

SZ effect: Sunyaev-Zel'dovich effect.

TFCR: Task Force on Cosmic Background Research, an NRC panel working concurrently with the RMSPG.

VLBA: Very Long Baseline Array.

VLBI: Very long baseline interferometry.

VSOP-2: Japanese mission for space VLBI

WMAP: Wilkinson Microwave Anisotropy Probe.