Associated Universities, Inc.

October 2008

FUTURE PROSPECTS FOR US RADIO, MILLIMETER, AND SUBMILLIMETER ASTRONOMY

Report of the Committee on the Future of US Radio Astronomy

[Revised February 2009]

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Sponsored by

Associated Universities, Incorporated

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Executive Summary

Associated Universities Incorporated convened the Committee on the Future of US Radio Astronomy to investigate the role of observations at radio, millimeter, and sub-millimeter (RMS) wavelengths in answering fundamental questions in astronomy, and to publish a "white paper" that will be relevant for the broad astronomy community and timely for the planning of the next Decadal Survey. The Committee solicited and received extensive advice from the community and prepared the present document.

In Chapter 2 of this document, we discuss the scientific agenda in the framework of five overarching questions:

- ***How does the cosmic expansion evolve, and what physical phenomena control this expansion?***
- ***How do galaxies assemble and evolve?***
- ***How do stars and planetary systems form?***
- ***How do space-time, matter, and radiation behave in extreme environments?***
- ***How are high energy particles accelerated by compact objects?***

We describe selected examples illustrating how RMS observations can address these questions, in the context of a broad "multi-messenger" scientific strategy involving observations at all bands of the electromagnetic spectrum as well as high energy particles and gravitational waves.

In Chapter 3, we describe the technical agenda. First we describe the growing importance of multi-wavelength and synoptic surveys as a discovery strategy for astronomy and how this strategy is enabled by advances in information technology. Then we list the capabilities of current and planned major RMS facilities, both US and international, and we describe how these capabilities will advance by orders of magnitude as a result of technical developments currently underway.

In Chapter 4 we summarize the report and put forth some key goals and recommendations for the upcoming decadal survey, as follows:

Goal 1: Maintain a balanced and vigorous program in RMS science and technology development.

To achieve this goal, we must develop technology for acquiring, processing, and retrieval of large-scale data sets. We must support and engage the larger astronomical community in developing and analyzing data from multi-wavelength surveys. We must provide balanced support to the national observatories, university radio observatories, and individual investigators. We must retrofit selected existing facilities with advanced focal plane instrumentation to carry out forefront science.

Goal 2: Ensure that the US reaps the scientific benefit of its investment in ALMA.

The Atacama Large Millimeter Array (ALMA) is likely to be the premier discovery facility in ground-based astronomy during the coming decade. To achieve this goal, we must support the development of pathfinder telescopes for ALMA science, especially those outfitted with large format focal plane arrays, and we must provide grant support for ALMA users.

Goal 3: Develop technologies for the era of Square Kilometer Array science.

Compelling scientific cases exist to build telescope facilities having a collecting area on the order of one square kilometer, more than an order of magnitude greater than any current RMS facility. At least two, and possibly three, different types of SKA facilities will be required to span the three decades of the electromagnetic spectrum from meter to centimeter wavelengths. A number of precursor telescopes are under development in the US and abroad to demonstrate the technology and probe the science. Although construction of a full-scale SKA project is unlikely to begin for several years, we strongly recommend that the US continue to aggressively support the development of enabling technologies that will be needed for SKA-class facilities and implementation of these technologies in SKA pathfinder facilities.

Goal 4: Nurture partnerships leading to SKA-class facilities.

Like ALMA, an SKA-class facility will probably require an international effort for it to be realized. Indeed, several countries are taking the lead in developing major precursors to the SKA. In order that the US is prepared to become a full partner when the time is ripe to undertake the construction of an international SKA-class facility, it is imperative that US astronomers, both those at the national observatories and at the university observatories, have the support necessary to participate fully in the international effort to develop technologies, precursors and plans for SKA-class facilities. To ensure international cooperation, the US should continue to nurture an international "open skies" policy for access to major RMS telescope facilities worldwide.

1. Introduction and Overview

In early 2007, Ethan Schreier, the President of Associated Universities (AUI), with enthusiastic concurrence from the AUI Board of Trustees, convened a committee called the *Committee on the Future of US Radio Astronomy.* The charge to the committee was:

> "To determine radio astronomy's role in answering fundamental questions in astronomy as an integral part of a broad scientific agenda, the committee will focus on the science questions expected to be most important over the next one to two decades, and to investigate how radio, millimeter and sub-millimeter (RMS) observations can best contribute. RMS observations will be considered within the context of all multi-wavelength astronomy investigations by existing and planned major facilities.
>
> "The committee will solicit input from the community at large. Its goal is to publish a 'white paper', which will be relevant for the broad astronomy community and timely for the planning of the next Decadal Survey."

The committee members were selected by Dr. Schreier after extensive consultation with members of the community and the committee chair. The membership (Table 1) is intended to represent a diverse range of institutions and to include members of the astronomy community having both broad scientific perspective and expertise in a wide range of RMS techniques.

To carry out its task, the committee convened for three meetings: on April 5-6, 2007, in Boulder, CO; June 16-17, 2007, in Charlottesville, VA (to coincide with the 50th anniversary celebration of NRAO); and November 16-17, 2007, in Boulder, CO. Between each meeting, the committee held several teleconferences.

Committee meetings were open and announced in advance. In addition, we invited various guests to our meetings in April and June to provide us with expert advice on particular scientific and technical topics. We held two open "town hall" meetings, at the NRAO 50th Anniversary Science Symposium in Charlottesville and at the AAS meeting in Austin, TX in January, 2008. We also maintained a public website (see http://www.aui.edu/future_committee/) where any interested person could view our progress and provide commentary. Finally, we distributed a preliminary draft of this report to more than 30 astronomers whose collective expertise spanned a broad range of astronomy, RMS and otherwise. Almost all of these astronomers responded with detailed advice, and the present document has been revised extensively in response to this advice. Nonetheless, our report should be viewed only as the consensus of the committee itself and not necessarily representative of the larger astronomical community.

The upcoming decadal survey will set priorities on facilities, and our committee felt that it would be counterproductive to focus on the relative merits of existing and proposed RMS facilities. Therefore, we decided at the outset that we should focus our attention on science opportunities and emerging technologies, not facilities. Moreover, a number of fundamental and transformative discoveries have resulted from observations at RMS wavelengths, while at the same time a complete understanding of the cosmos and physical phenomena requires at least a multi-wavelength, and potentially a multi-messenger (electromagnetic, particle, gravitational) approach. Accordingly, our committee sought to identify important scientific opportunities that can be studied uniquely in the RMS windows or where RMS observations are an important component of the multi-wavelength synergism.

The RMS facilities will continue to contribute substantially to the study of the Sun and solar system objects, but the committee lacked the expertise to address these areas adequately, and so decided to limit its considerations to astronomical phenomena beyond the solar system.

We hope that this report will provide some useful guidance to the astronomical community and to the upcoming decadal survey committee. Of course, the survey committee will have several reports at hand when it begins its work, addressing not only astronomy enabled by RMS facilities but astronomy enabled by the full range of electromagnetic, gravitational, and astro-particle facilities. Indeed, this report is not the only one addressing RMS facilities. For example, a comprehensive report on RMS astronomy was prepared by Martha Haynes and colleagues for the 2007 NSF Senior Review of astronomical facilities (http://www.astro.cornell.edu/~haynes/rmspg/). Other reports, some of which are referenced here, provide further details of the scientific capabilities of particular existing and proposed RMS facilities.

Here we do not attempt to prioritize RMS facilities, nor do we attempt to describe the full range of scientific opportunities that may be addressed by observations with existing or planned facilities. Rather, we describe a few exemplary opportunities, selected according to our sense of their fundamental importance and the prospects of making significant advances in the next two decades. By way of preparation, subgroups of our committee prepared a series of "white papers" on various topics of astronomy, which can be found at http://www.aui.edu/future_committee/. The entire committee reviewed these papers. In Chapter 2 of this report we provide our consensus view of some of the most promising scientific opportunities described in the white papers. Of course we are aware that some of the most important scientific advances with RMS facilities will be in areas which we have not chosen to highlight. But even so, we think that the examples we present in Chapter 2 make a very strong case for continued support of development of RMS facilities.

"RMS" astronomy encompasses a very broad range (factor $\sim 10^5$) of wavelength bands (equivalent to the range from optical to gamma rays), employs diverse technologies, and addresses a broad and diverse range of astronomical themes. As is the case for all bands of the electromagnetic spectrum, the facilities and technologies for RMS astronomy have made great advances in the past decade. Moreover, we have identified a number of emerging technologies that will greatly advance the power of both existing and planned facilities, as we shall describe in Chapter 3.

Finally, in Chapter 4, we discuss some of the strategic issues that will need to be addressed by the decadal committee and provide a few recommendations regarding those issues.

Table 1. Members of the Committee

Dick McCray, University of Colorado, Chair
Don Backer, University of California Berkeley
Chris Carilli, National Radio Astronomy Observatory
Bryan Gaensler, University of Sydney
Reinhard Genzel, Max Planck Institute
Nick Gnedin, Fermilab
Martha Haynes, Cornell University
Sebastian Heinz, University of Wisconsin
Joseph Lazio, Naval Research Laboratory
Tony Readhead, Caltech
Anneila Sargent, Caltech
Eric Wilcots, University of Wisconsin
Tony Wong, University of Illinois
Fred Lo, National Radio Astronomy Observatory, consultant
Bob Brown, National Astronomy and Ionosphere Center, consultant*
Jack Burns, University of Colorado, Executive Secretary

** replaced by Don Campbell near the end of the process*

2. The Scientific Agenda

Much of research in astronomy today is driven by a few overarching questions:

- ***How does the cosmic expansion evolve, and what physical phenomena control this expansion?***
- ***How do galaxies assemble and evolve?***
- ***How do stars and planetary systems form?***
- ***How do space-time, matter, and radiation behave in extreme environments?***
- ***How are high energy particles accelerated by compact objects?***

These questions are not new; one can find them phrased in various ways in many strategic planning documents (e.g., NRC 2000; NRC 2003; RMSPG 2005; ASV 2007). Indeed, they have motivated astronomers for decades and even centuries. Nor are they the only important questions. The dramatic changes that we have seen during the past decade or two are not in the questions themselves, but in the strategies that astronomers have developed to address them. Those strategies have evolved rapidly as a result of enormous advances in our knowledge of the phenomena and in the technologies available to investigate them.

Here, we do not aim to recapitulate the progress in addressing these questions, which are discussed extensively in the aforementioned documents. Instead, for each question we describe a few highlights to illustrate how the nature of astronomical research is evolving, paying particular attention to the role of RMS facilities.

2.1 How does the cosmic expansion evolve, and what physical phenomena control this expansion?

Twenty years ago, most astronomers thought that the cosmic expansion could be described by Friedmann solutions with no cosmological constant. The values of the Hubble constant (H_0) and the age of the universe had uncertainties of roughly a factor of two. Today, we know that the cosmic expansion is either accelerating or that our theory of gravity on large scales needs to be modified (DETF 2006). Either way, this is an exciting time for cosmology for which truly multi-wavelength campaigns are needed to achieve a deeper understanding. We can measure the cosmological parameters (energy densities of various components, the value of H_0, and the age of the universe, etc.) to a precision of roughly 10%. This description of the cosmic expansion has been the result of a remarkable concordance between observations of angular structure in the cosmic microwave background radiation (by several experiments on the ground, on balloons, and in space), optical observations of supernovae, large scale redshift surveys of the distribution of galaxies, and X-ray observations of galaxy clusters.

Yet, we completely lack the understanding of how the Standard Model of physics and cosmology needs to be extended to accommodate these new phenomena. More accurate measurements of H_0 and of the evolution of cosmic structure will enable us to determine whether the observed cosmic acceleration is due to a new physical field or an apparent manifestation of a new gravity law. Two critical questions are:

1. What is the value of the parameter $w = P/\rho$ that characterizes the equation of state of dark energy?
2. Is dark energy properly characterized by a cosmological constant ($w = -1$), or does it have some other time dependence – i.e., how does w depend on cosmic time?

Figure 2.1.1 illustrates the current state of precision on our determination of the value of w. It shows that the value of w is constrained by a combination of measurements of the CMB fluctuations (from WMAP), large-scale structure in the distribution of galaxies, and measurements of H_0 from Type Ia supernovae. More precise measurements of the CMB fluctuations by the Planck satellite and further mapping of the large-scale distribution of galaxies will tighten the acceptable range of parameter space illustrated by Figure 2.1.1, so that the uncertainty in the value of w will be dominated by the uncertainty in the measurement of H_0.

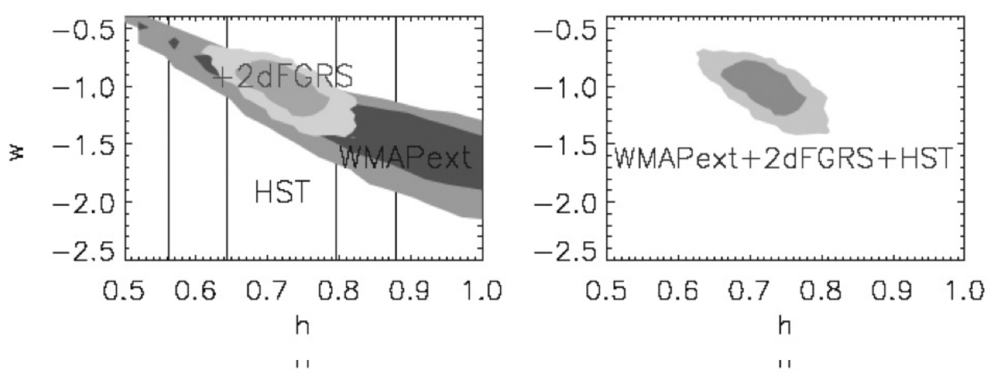

Figure 2.1.1: This figure shows the covariance of cosmological parameters and the importance of an independent measurement of H_0. The left frame shows the covariance of w and H_0 based on CMB and large scale structure measurements. The right frame shows how the HST SN H_0 measurement isolates parameter space. Improved measurements of the CMB with PLANCK will require improved measurements of H_0 to ensure full realization of precision cosmology (Greenhill et al. 2002).

The roles of RMS observations:

2.1.1 Measuring H_0 directly from observations of H_2O masers orbiting active galactic nuclei

The Seyfert 2 galaxy NGC 4258 has a sub-pc scale accretion disk in its nucleus that can be traced by VLBI imaging of its H_2O maser emission. Hernstein et al *(1999, Nature, 400, 539)* determined a highly accurate geometric distance of 7.2 Mpc for this galaxy. Since the recessional velocity of NGC 4258 is only 470 km/s, the possibility of non-Hubble flow motions of several hundred km/s precludes a direct estimate of H_0. However, NGC 4258 has been used to re-calibrate the Cepheid-based extragalactic distance scale.

If galaxies like NGC 4258, but more distant and within the ``Hubble flow," can be discovered and imaged with VLBI observations, then direct determinations of H_0 are possible. The "Water Maser Cosmology Project" (WMCP) team of scientists from NRAO, CfA, and MPIfR is systematically pursuing this goal. The team uses the VLBA, along with large aperture telescopes such as the GBT and the Effelsberg 100-m telescope, to find, monitor and map the H_2O maser emission from distant NGC 4258-like accretion disks in AGN.

One of the most promising candidates for distance measurement is UGC 3789, which, with a recessional velocity of 3300 km/s, is well into the Hubble flow. This source was discovered with the GBT, and its H_2O masers have been imaged with the VLBA/GBT/Effelsberg. The GBT spectrum displays the characteristics of a sub-pc scale accretion disk surrounding a SMBH: systemic velocity components flanked by high-velocity components separated by up to +/- 750 km/s.

A map of the H_2O masers in UGC 3789 with positional accuracies approaching 5 μas is shown in figure 2.1.2. As for NGC 4258, the maser spots fall in a linear pattern with the blue- and red-shifted high-velocity components straddling the systemic velocity components, which is indicative of an edge-on disk. The angular extent of the detected spots is 1.5 mas, about a factor of 10 smaller than for NGC 4258 and consistent with UGC 3789's much greater distance.

Figure 2.1.2 shows a position-velocity plot constructed along the position angle of the linear pattern of spots. One can clearly see a Keplerian rotation curve for the high velocity components, indicating a rotation speed of 600 km/s at an angular radius of 0.5 mas. This implies a central SMBH of 10^7 (D/50 Mpc) Msun, where D is the distance.

The distance to such a source with an edge-on rotating disk is given by $D = V^2/A\theta$, where V and A are the rotational velocity and centripetal acceleration at an angular radius θ. Centripetal accelerations can be measured from the drift over time of Doppler shifts of maser features. Preliminary measurement of A, based on one year's monitoring with the GBT, gives distances consistent with H_0 near 70 km/s/Mpc and an anticipated uncertainty of about 10%.

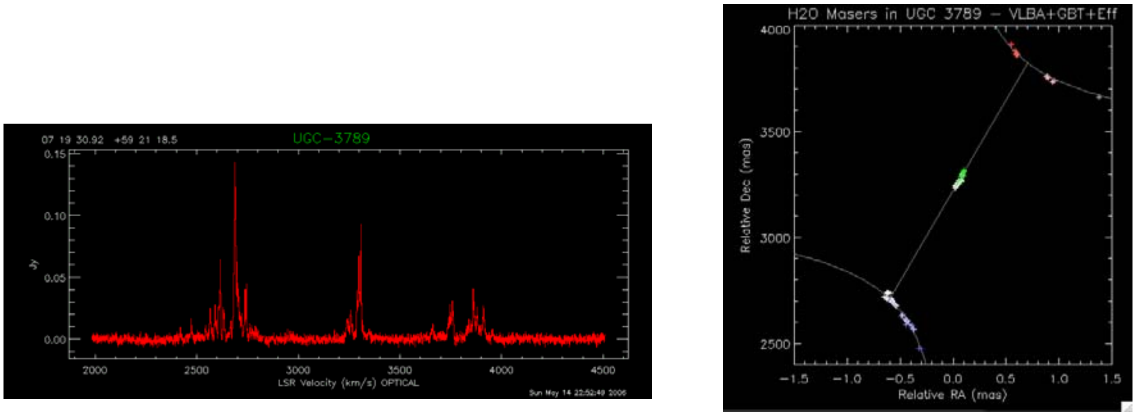

Figure 2.1.2: The water maser disk in UGC 3789 (Braatz et al. 2007, IAUS 242, 399). The right frame shows the GBT spectrum, and the left shows the Keplerian rotating disk as imaged with the HSA.

These observations of UGC 3789 verify the WMCP technique and imply that, using only one source, the WMCP can already measure H_0 with precision comparable to the Hubble Key Project.

Ongoing work using the GBT and VLBA indicates that perhaps a dozen to a few tens of maser sources are detectable, with distances at least as great as a few hundred Mpc; one recently discovered maser source has a redshift of 2.6. With a combined analysis of all suitable sources, it should be feasible to measure H_0 to a precision of 3%.

2.1.2 Measuring the evolution of cosmic expansion

A key to understanding the nature of dark energy is to measure the evolution of the cosmic expansion with time. The first direct evidence for dark energy came from the Hubble diagram determined through observations of type Ia supernovae. One may also measure the evolution of cosmic expansion with comparable and possibly better precision by observing the large-scale structure in the distribution of galaxies and clusters. This can be done with redshift surveys of galaxies and also by large scale surveys of the distribution of clusters of galaxies. Clusters can be detected efficiently through their X-ray emission and at mm and sub-mm wavelengths through their distortion of the microwave background radiation spectrum, the "Sunyaev-Zeldovich effect". In the near future, sub-mm telescopes such as the SPT will detect more than 10^4 clusters through the S-Z effect, while the German/Russian e-ROSITA X-ray mission under development is expected to detect more than 10^5 clusters. Since these two techniques measure different moments of the distribution of hot intragalactic gas in clusters, the data are complementary and can be cross-calibrated to check their reliability as measures of large-scale structure evolution.

As discussed in the report of the Dark Energy Task Force (DETF 2006), centimeter wave radio astronomy offers a powerful spectroscopic tool for the study of the evolution of large scale structure in the HI 21 cm line. Currently, surveys using Arecibo with its L-band feed array are probing cosmological volumes in the local universe z~0 for the first time and are demonstrating the capability to detect field galaxies with > 10^9 solar masses of HI out to redshifts of 0.3. Various combinations of collecting area, field of view, spectroscopic capability and survey strategy will allow exploration of the HI content at higher redshifts.

While mapping the 3-D spatial distribution of 10^9 galaxies to a redshift z~1 will require the full Square Kilometer Array, it is possible that intensity mapping of the unresolved HI line emission over a range of redshifts can be used to measure the kinematics of the cosmic expansion and hence the role of dark energy. An Intensity Mapping Project (Chang et al. 2008, Physical Review Letters, vol. 100, Issue 9, 091303) will place constraints on the evolution of the dark energy equation of state, which will be competitive with all Stage III dark energy experiments. The Project aims at detecting Baryon Acoustic Oscillations (BAO) in the large-scale distribution of neutral hydrogen in the universe in the redshift interval $0.5 < z < 2$, without actually resolving individual galaxies, but treating neutral hydrogen as a tracer of large scale structure. A modest collecting area (1% of SKA) should be sufficient for detecting several BAO peaks in the power spectrum of hydrogen distribution. The success of the Intensity Mapping Project is crucially dependent on the ability to distinguish spectroscopically a fluctuating cosmic signal from a smooth but much larger foreground contamination. These challenges are qualitatively and quantitatively similar to the challenges faced by the reionization 21cm experiments.

2.1.3 B-Mode Polarization on Large Angular Scales – the Quest for the Energy Scale of Inflation

It is now widely believed that the universe went through a period of very rapid inflation about 10^{-36} sec after the Big Bang. This inflationary epoch could explain a number of curious features of the universe, such as why the geometry is almost flat, why the isotropy of the CMB extends over regions much larger than those that could otherwise have been in causal contact, and the absence of magnetic monopoles. Thus, establishing whether or not such an inflationary epoch occurred and, if so, when it occurred, *i.e* , at what energy, are of critical importance to the foundation of our cosmological theories. In an inflationary epoch quantum fluctuations would be stretched to large scales, providing the primordial density variations that are the seeds of large scale structure, and also gravitational waves on all scales. The long wavelength gravitational waves would subsequently interact with the CMB to produce B-mode polarization on large angular scales in the CMB. The observation of the large-scale B-mode polarization is extraordinarily difficult because even the most optimistic estimates of the strength of the signal require sensitivities on the order of 10^{-8} K, and galactic foreground B-mode signals due to synchrotron radiation and/or dust emission exceed the most optimistic estimates over almost all of the sky. Nevertheless a number of experiments are in progress to measure the B-mode signal. These experiments are being fielded now and the first results are expected within the next few years.

2.2 How do galaxies assemble and evolve?

Thanks largely to the Sloan Digital Sky Survey, we have found a few very luminous galaxies and quasars at redshifts $z > 6$, at a time well before most galaxies had formed and the universe was emerging from the "Dark Ages." The quest to find and understand the earliest galaxies through infrared imaging and spectrometry is a major goal driving the development of the James Webb Space Telescope and ground-based optical/infrared telescopes having apertures > 25m.

At the same time that astronomers were finding these early galaxies with OIR telescopes, they were also discovering submillimeter galaxies (SMGs), sources of powerful dust continuum emission matching the brightest QSOs in luminosity. The relationship of the SMGs to other categories of high redshift galaxies remains elusive. Overall, SMGs appear to be ultraluminous, massive galaxies which cluster strongly. Some have no optical counterparts. We are challenged to understand the nature of these sources, the origin of their luminosities, their non-thermal components and their clustering properties. Once discovered and catalogued by future submm/mm instruments with sufficiently low confusion limits, subsets will be mapped in detail by ALMA and investigated spectroscopically by the large OIR telescopes and the EVLA (and eventually the SKA) will locate their non-thermal counterparts. A combination of SED sampling, angular resolution, sensitivity and spectroscopic capability offered by the suite of future instruments across the E-M spectrum will be necessary to provide a full picture of the population of earliest luminous galaxies.

The first galaxies and accreting black holes act to ionize the neutral intergalactic medium (IGM). Observations of Gunn-Peterson absorption and of the large scale polarization of the CMB indicate that the "epoch of reionization" likely commenced around $z \sim 14$ and removed the last vestiges of the neutral IGM by $z \sim 6$ (Fan, Carilli, Keating 2006, ARAA, 4, 415).

A major enterprise of optical astronomy today is the mapping of large scale structures in the distribution of galaxies and clusters of galaxies. We see a quantitative correspondence between the morphology and statistical properties of the observed clustering of galaxies and the same properties measured from numerical simulations beginning with the primordial $\sim 10^{-4}$ fluctuations seen in the microwave background. However, the simulations employ *ad hoc* recipes to describe the ratio of luminous matter to the condensations of dark matter that drive the dynamics of large scale structure formation. The baryonic matter is less than 20% of the dark matter, and the fraction of the baryonic matter that is optically luminous is substantially less than that. What factors determine the "bias" of light to dark matter and its dependence on mass and cosmic time?

Our understanding of galaxy formation and evolution is limited by the complex nonlinear interplay between various physical processes that shape a galaxy. We understand that galaxies develop their morphologies through gravitational encounters and mergers, and probably also by accretion of intergalactic gas, but we don't know the relative importance of these processes as a function of cosmic time. We know that most of the stars in the bulges of galaxies must have formed at times corresponding to redshifts $z > 1$.

During the past decade, astronomers have also found evidence that supermassive black holes may play a substantial role in regulating galaxy formation, both in the remarkable correlation of black hole mass with the mass of galactic bulges, and also in radio and X-ray imaging observations showing that AGNs have large-scale influence on the hydrodynamics of intergalactic gas in clusters, where most of the baryonic mass resides.

The roles of RMS observations:

A major goal of future RMS observations is to measure directly the evolution of the spatial structure of intergalactic HI during the epoch of reionization ($z \sim 14 - 6$). Such measurements are only possible with low-frequency radio observations of redshifted 21-cm emission. At the relevant wavelengths (1.5 – 4 m), the principal astronomical challenge is detecting small fluctuations (both in intensity, $\Delta T/T \sim 10^{-5}$, and angle, ~1') against the dominant synchrotron background. The current pathfinder experiments such as MWA, PAPER, and LOFAR will test the technology and the algorithms for statistical detection of the HI signal. A more powerful probe is redshifted 21cm tomography of the *Epoch of Reionizaton* (EoR), which is likely to require significantly more collecting areas than any of these arrays. Nonetheless, the results of these pathfinder arrays will likely inform the design for a low-frequency SKA. In the more distant future, a low frequency radio array on the far side of the Moon might permit us to avoid interference generated by terrestrial transmitters and ionospheric radiation and may probe even deeper ($z \sim 50$) into the dark ages.

Galaxies at their peak of star formation are likely to be heavily enshrouded at optical and near-infrared wavelength bands. But observations at RMS wavelengths are immune to this obscuration and can provide a wealth of information on their internal structure, dynamics, and evolution. For example:

- 21-cm observations measure the total mass of atomic gas in the galaxy and the dynamical mass of the galaxy.
- Atomic fine structure lines, such as [CII] 158μm and [OI] 63, 146 μm measure the cooling rate of atomic gas. The Herschel observatory will measure these lines for relatively nearby galaxies, while sub-mm telescopes can observe these lines from galaxies at high redshifts.
- Observations of rotational emission lines from CO provide estimates of the total molecular mass of molecular gas in galaxies and its temperature distribution.
- Observations of emission from molecules having higher dipole moments, such as HCN and HCO^+, trace the dense ($> 10^5$ cm^{-3}) gas directly associated with star-forming clouds.
- The radio continuum emission from star-forming galaxies provides a dust-unbiased estimate of the massive star formation rate.

- The sub-mm thermal continuum emission from warm dust provides an estimate of the dust temperature and dust mass, while the total far-infrared (FIR) luminosity provides a bolometric measure of the starlight that is absorbed by interstellar dust.
- Imaging spectroscopy at sub-kpc resolution of the molecular gas and fine structure lines in distant galaxies traces galaxy dynamics, and hence the gravitating mass distribution within the galaxies.

The power of radio observations of the most distant galaxies is demonstrated by recent results on the study of the host galaxy of the most distant QSO known, SDSS J1148+5251 at z = 6.42, a luminous AGN with a supermassive black hole of 2×10^9 M_{Sun}. The host galaxy has been detected in thermal dust, non-thermal radio continuum, and CO line emission, with an implied molecular gas mass of 2×10^{10} M_{Sun}, and a dust mass of 7×10^8 M_{Sun}. The radio through FIR spectral energy distribution is consistent with a star-forming galaxy having dust temperature ~ 50K. High resolution VLA imaging shows that the molecular gas in 1148+5251 is extended by about 6 kpc (Figure 2.2.1). These observations also provide an estimate of the galaxy dynamical mass of 4×10^{10} M_{Sun} within a radius of 3 kpc. Most recently, the [CII] 158 μm line has been detected with the Plateau de Bure Interferometer (Figure 2.2.1) with an implied star formation rate comparable to that inferred from the radio to FIR spectral energy distribution. The fact that the [CII] line emission is extended over the same spatial scale as the molecular gas implies that star formation is distributed over 6 kpc in the host galaxy.

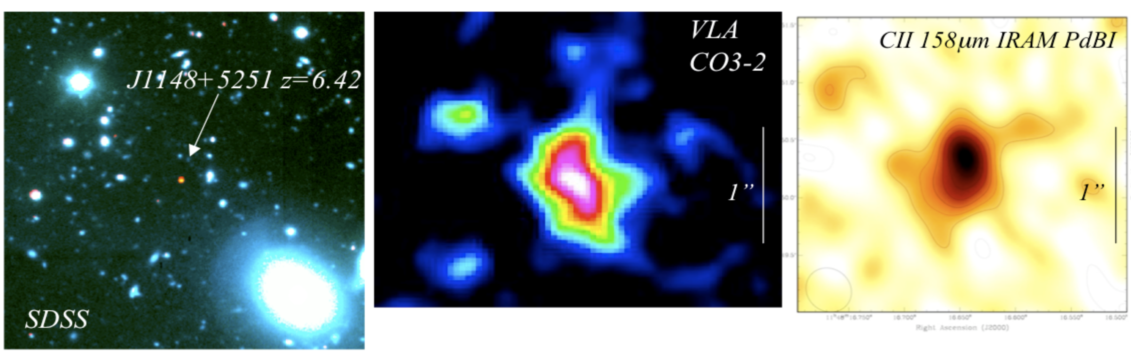

Figure 2.2.1: Left is the optical SDSS image of the z=6.42 quasar J1148+5251. Center is the VLA CO image showing a resolved molecular gas cloud on a scale of 6 kpc (Walter et al 2003). Left is the [CII] 158 μm emission observed by the Plateau de Bure Interferometer, also showing a resolved structure on the same scale as the molecular gas (Walter et al. 2004, ApJ, 615, L17; Maiolino et al. 2005, A&A 440, L51; Walter et al. 2008 in prep).

These observations of J1148+5251 demonstrate that large reservoirs of dust- and metal-enriched atomic and molecular gas can exist in galaxies within 870 Myr of the Big Bang. These results, and results on other z ~ 6 quasar host galaxies, are consistent with coeval galaxy-supermassive black hole formation at the earliest epochs. These systems are probably destined to become giant elliptical galaxies at the centers of rich clusters.

Current centimeter and millimeter instruments are limited to the study of rare, extreme luminosity objects at z > 6. Fortunately, the one to two orders of magnitude increase in sensitivity afforded by ALMA and the EVLA, and eventually the SKA, will push observational capabilities into the regime of normal star-forming galaxies.

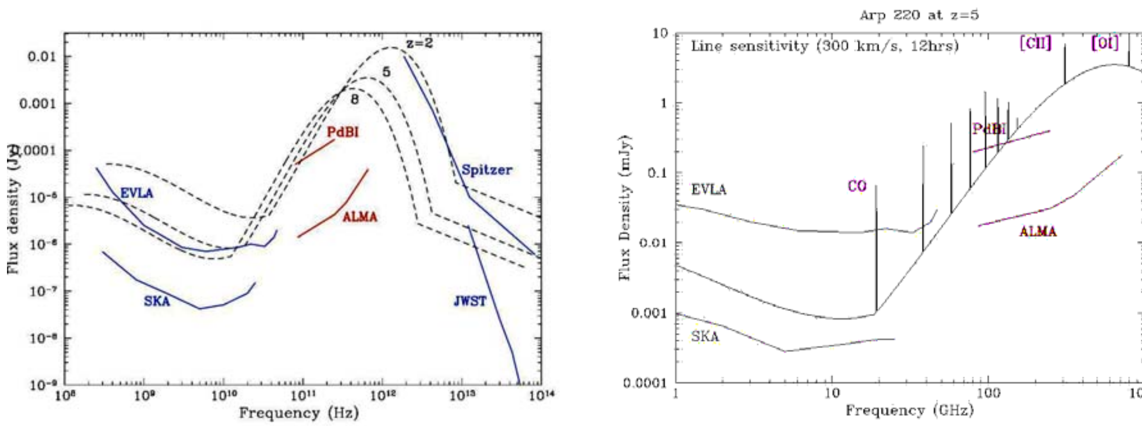

Figure 2.2.2: Left shows the continuum sensitivities, plus the observed continuum spectrum of an active star forming galaxy (e.g. Arp 220) at three redshifts. Also shown is the sensitivity of current and future telescopes. Right shows the observed spectrum of Arp 220 at z=5, including the CO lines and some of the fine structure lines.

Figure 2.2.2 (left) shows the continuum sensitivities of current and future telescopes, along with the radio through near-IR SED of an active star forming galaxy, Arp 220 at z = 2, 5, and 8. Current telescopes, such as Spitzer, the Plateau de Bure, and, soon, the EVLA, are able to detect such active star forming galaxies into the epoch of reionization. The increased sensitivity of JWST, ALMA, and ultimately the SKA will push down to galaxies having star formation rates ~ 10 Msun/year.

Figure 2.2.2 (right) shows the line intensity of Arp 220 at z = 5, along with the rms line sensitivity of current and future radio telescopes. The EVLA will detect the low order molecular line transitions, while telescopes such as the Plateau de Bure and CARMA can study the higher order transitions. ALMA will open up the study of both higher-order molecular line transitions and the atomic fine structure lines from normal galaxies. All these telescopes will be capable of sub-kpc resolution imaging of the gas distribution and dynamics.

With instruments such as SCUBA, astronomers have discovered galaxies that are extremely luminous at sub-mm wavelengths but have no optical counterparts. Wide field surveys with more sensitive cameras having broad fields of view are likely to turn up many more such sources, which may be responsible for most of the star formation that has occurred in the universe. The challenge will then be to measure the spectra of these sources to determine redshifts and other indicators of star formation activity.

It is clear from these examples that RMS observations spanning a broad range of wavelengths and redshifts, in combination with infrared, optical, and X-ray observations, will play a major role in elucidating the physical processes involved in the formation and evolution of galaxies and supermassive black holes. Panchromatic surveys will be needed to identify patterns and evolutionary sequences among galaxies.

2.3 How do stars and planetary systems form?

2.3.1 Star Formation

This question has intrigued astronomers for centuries. Stars form in dark dust clouds from which no optical light emerges, and star formation involves complex interaction of many physical processes operating over many orders of magnitude of distance scale. Consequently, our understanding of star formation lags behind our understanding of cosmic evolution and structure formation. For example, we still lack a quantitative theory to explain some of the most basic observational consequences of the star formation process, such as: the efficiency of conversion of gas in molecular clouds to stars; the initial mass function; and the frequency of binary stars. Today, however, we see rapid progress in elucidating the physics of star formation, largely as a result of advances in instrumentation to observe star-forming regions in infrared, submillimeter, and radio bands as well as dramatic advances in computational techniques.

The roles of RMS observations:

Likewise, we can expect rapid progress in our understanding of the formation of stars and planetary systems thanks to new observatories on the ground and in space, which will observe these systems at infrared, sub-mm and radio wavelengths with unprecedented angular and spectral resolution. Here we describe three examples.

Figure 2.3.1 shows part of a 1.1 mm continuum survey of 150 square degrees of the Milky Way taken with the Bolocam array on the Caltech Submillimeter Observatory overlaid with 8 μm emission from Spitzer and 20 cm continuum emission from the VLA. At an angular resolution of 30 arcsec, the Bolocam survey has detected emission from cold dust grains in several thousand dense cloud cores, many of which are seen to be active sites of star formation. By observing the 1.3 cm emission lines from NH_3 molecules in these cloud cores with the GBT, one can infer the distances of the cores (through the Galactic rotation curve) and their gas temperatures, which should be roughly equal to the dust temperatures. Then, assuming a constant gas/dust ratio, one can infer the distribution function of cloud core masses ranging from 1 to 1000 solar masses. This procedure yields the remarkable result that this distribution is a power law with slope ~ -2.3, similar to the initial mass function of stars. But this coincidence remains puzzling, especially since the low-mass cores show no evidence of star formation.

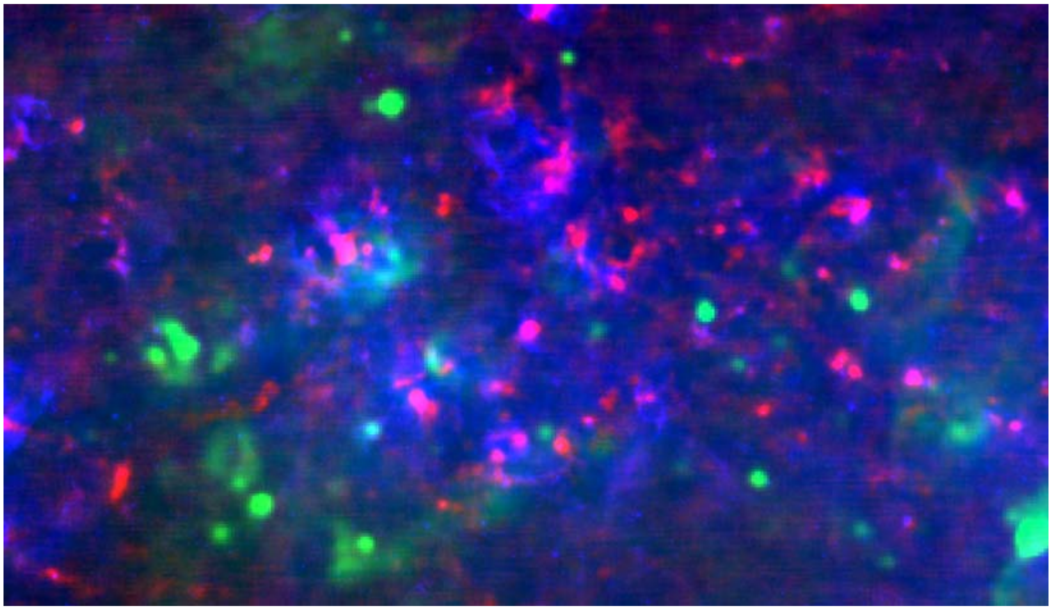

Figure 2.3.1: A region of active star formation in the Galactic Plane ($23.65^o < l < 25.35^o$, $-0.5^o < b < 0.5^o$) in three different wavelength bands. Red represents 1.1 mm continuum emission seen by the Bolocam Galactic Plane Survey (PI: John Bally), blue is 8 μm emission seen by the Spitzer IRAC camera taken as part of the GLIMPSE Legacy survey (PI: Ed Churchwell), and green is 20 cm continuum from the VLA Galactic Plane Survey (Stil et al. 2006, AJ 132, 1158). The nearly pure red regions in the image are infrared dark clouds (IRDCs), where molecular gas is condensing into the youngest stars. The blue regions represent stars nearing the main sequence (point-like objects) and warm dust heated by starlight. Regions showing both 1.1 mm and 8 μm emission appear pink or violet in this image. The green regions represent 20 cm continuum emission by ionized gas around massive star clusters.

Star formation involves further fragmentation of these cloud cores, so we need to observe them at higher resolution to see how this fragmentation proceeds to protostar formation. Soon it will be possible to image these cores at 1 arcsec resolution with the CARMA array at 1 mm and with the EVLA at 1.3 cm. The Herschel Observatory will obtain far-infrared continuum spectra of the cool dust that will enable more accurate inference of the dust mass from the mm observations. Herschel will also observe emission lines from OI 63 μm and CII 158 μm responsible for cooling of the condensations. Then, a few years later, it should become possible with ALMA to image the cores at ~10 mas resolution in both continuum and molecular emission lines. Statistical analysis of these images and their radio, mm, and sub-mm spectra, combined with infrared images and spectra from the JWST of protostars in these cores, should provide an empirical foundation for the theory of star formation, much as the Hertzsprung-Russell diagram provided a foundation for the theory of stellar structure about a century ago.

2.3.2 The Chemistry of Star Formation

Molecular lines in the millimeter and sub-millimeter spectra of star-forming regions provide valuable information on dynamics, physical conditions, and chemical abundances.

The past decade has seen rapid progress in understanding the chemical depletion of heavy elements from the gas phase onto dust grains. Depletion is particularly noticeable for CO and its isotopologues, as well as most other carbon-bearing species such as CS and HCO^+. It is also believed to be responsible for the H_2O vapor deficiency in interstellar clouds found by the SWAS mission (Bergin & Snell 2002, ApJ, 581, L105). By contrast, nitrogen-bearing species appear relatively resistant to depletion, although even these may deplete in the coldest and densest regions. Cold temperatures and CO depletion also increase the abundance of deuterated species such as H_2D^+ and N_2D^+ by many orders of magnitude. The sensitivity of both depletion and deuteration to environmental conditions implies that they are excellent probes of the earliest stages of star formation.

Of central importance is the molecular ion H_3^+, which along with its deuterated isotopologues (chiefly H_2D^+) may be the dominant charge carrier in the coldest, densest regions where heavy elements are severely depleted. However, H_3^+ is difficult to observe (except in absorption) because it lacks a permanent dipole moment. As a result, H_2D^+ may be the only detectable ion in the innermost parts of dense cores (Caselli et al. 2003, A&A, 403, L37) and in the shielded regions of circumstellar disks near the midplane (Ceccarelli et al. 2004, ApJ, 607, L51). Observations of H_2D^+ from the ground are difficult, because the only accessible transition at 372 GHz lies close to an atmospheric band. Pioneering observations have been made with the Caltech Submillimeter Observatory (see Figure 2.3.2), but the significant improvement in sensitivity and resolution promised by ALMA will allow much more detailed mapping of its distribution and motions. At the same time, mm/sub-mm continuum observations are essential to derive the density and temperature profiles needed to interpret measurements of H_2D^+.

The abundances of ions like H_2D^+ have implications for the physics of star formation – for example, in constraining the role of ambipolar diffusion (AD) in determining the rate and efficiency of star formation. The effectiveness of AD, which retards collapse because of the strong binding of ions to magnetic field lines, depends largely on the ionization degree deep within a molecular cloud, which should be reflected in the abundances of H_2D^+ and H_3^+. The ionization degree is also an important constraint on models of protoplanetary disks, because ions couple the gas to the magnetic field, which may in turn control angular momentum transport in the disk via the magneto-rotational instability (Balbus & Hawley 1991, ApJ, 376, 214). These types of studies are highly complementary to studies of magnetic field strengths in molecular clouds, which are also best accomplished with RMS facilities.

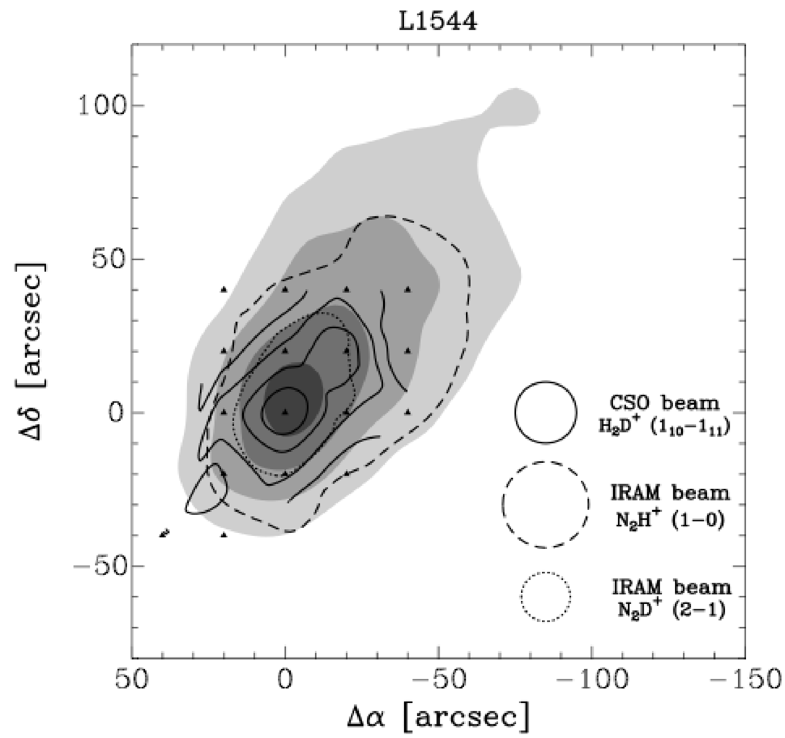

Figure 2.3.2: Integrated intensity maps of H_2D^+ ($1_{1,0} – 1_{1,1}$), N_2H^+ (1 – 0), and N_2D^+(2 – 1) superposed on the 1.3 continuum emission map of the prestellar core L1544.

2.3.3 Formation of Planetary Systems

At the time of the last decadal survey, about three dozen extrasolar planets had been detected. Today, more than 300 planetary systems have been detected, approximately 10% of which are known to contain two or more planets. Most extrasolar planets have been discovered through stellar radial velocity searches, but planets have also been discovered photometrically by transits, through gravitational microlensing events, and through pulsar timing. Up to now, the list of known planets has a lower mass limit of approximately 4 Earth masses (except for one of the planets orbiting the pulsar PSR 1257+12). Within a decade, we expect both the number of known planetary systems to increase to several thousand as a result of photometric searches with the COROT and Kepler missions and both photometric and astrometric searches with the GAIA mission. We can also expect that the diversity of known planetary systems will continue to increase and that we will begin to sample the terrestrial planet mass range.

In the 18th Century, Kant and Laplace proposed that stars and planetary systems are formed in disks of gas and dust. Optical observations with HST and radio and infrared observations both from the ground and space have provided ample evidence of disks of gas and dust orbiting protostars and young stars, but many basic questions remain unanswered. For example, we do not know whether giant planets are formed during the protostellar phase or afterwards in circumstellar disks. We do not have an adequate understanding of the environment and processes leading to grain growth and accretion into planetesimals. Planetary compositions (solids, ices, gas) certainly depend on the composition and temperature of the protoplanetary disks, which may vary greatly with radius. Newly formed planets will strongly perturb the dynamics of these disks, while interactions with the disk and other planets will cause their orbits to evolve.

The roles of RMS observations:

Radio observations play a crucial role in the study of the early phases of planet formation, through imaging of the dust and gas in protoplanetary disks. These observations can probe deep into dusty disks and down to AU scales. Such observations complement the studies of proplyds, or the dusty shadows of protoplanetary disks, as imaged in the optical, and the IR studies of dust spectra.

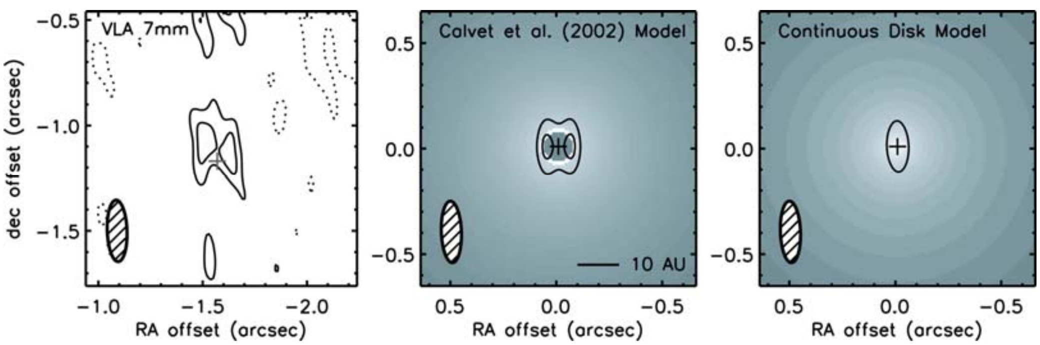

Figure 2.3.3: Left is the VLA image of the protoplanetary disk TW Hya at 40mas resolution (Hughes et al. 2007, ApJ, 664, 536). The VLA beam is N-S due to a low declination. The middle image is a model based on a disk with a gap at 4AU. The right image is a continuous disk model.

We highlight one recent study of the protoplanetary disk in the nearby (50 pc) star, TW Hya. This system is considered a prime example of a pre-solar nebula, with a young star of 0.8 Msun with an age of about 5 to 10 Myr. Studies of the broad band spectral energy distribution (SED) by Hughes et al. *(2007, ApJ, 664, 536)* show a deficit in the mid-IR which has been interpreted as being the result of a gap in a dusty disk around the star at about 4AU radius (*Calvet et al. 2002. ApJ, 568, 1008*), apparently created during the formation of a protoplanet. Radio studies of the SED have revealed a fairly shallow slope for the cm emission, implying a broad spectrum of grain sizes extending to cm scales, i.e, the formation of pebble sized grains, the first step from interstellar dust to planetesimals, and then on to planets themselves.

VLA imaging of TW Hya (Hughes et al. 2002) at 7mm with a resolution of 40mas (Figure 2.3.1) show an extended structure on 10 AU scales which can be modeled reasonably by a disk with the 4AU gap proposed by Calvet et al. While these observations provide an important confirmation of the inference of a disk gap induced by planet formation, they are still insufficient to properly resolve the disk system.

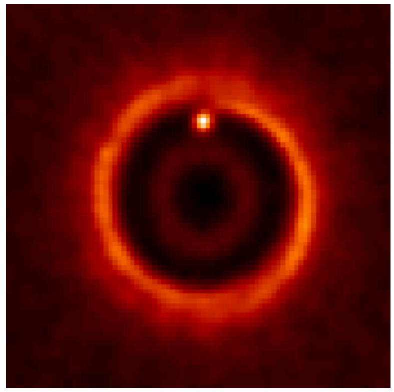

Figure 2.3.4: A simulation of the TW Hya disk plus gap and hot protoplanet as seen by ALMA at 0.35 mm with 20mas resolution (Wolfe & D'Angelo 2005, ApJ, 619, 1114).

Figure 2.3.4 shows how this system might appear to ALMA. The simulated image clearly shows a disk with AU-scale gap containing a hot protoplanet. Such high resolution images of protoplanetary systems will be complemented by spectroscopic studies ranging from mid-IR to cm wavelength to elucidate the complex physical, chemical, and dynamical processes involved in the formation of planetary systems. The infrared – sub-mm spectrum is rich with molecular emission lines that will provide information on the distributions of composition, temperature, density, and column density in the protoplanetary disk.

2.4 How do space-time, matter, and radiation behave in extreme environments?

Astronomical observations have a long history of both illuminating and testing fundamental physical theories. Notable historical examples include Tycho's observations of planetary motions and Eddington's observations of the 1919 solar eclipse, both of which were vital to the development of our current understanding of gravity. Modern terrestrial laboratories are able to make measurements in which relative uncertainties approach 1 part in 10^{10}, and observations within the solar system can approach similar uncertainties.

The roles of RMS observations:

Astronomical observations, especially those at RMS wavelengths, continue to play an important role in probing fundamental physical theories because they measure extreme environments having characteristic masses and densities that are orders of magnitude greater than those found within the solar system. For example:

- Combined radio, millimeter, and infrared astrometric observations show that Sgr A*, the central radio source in the Milky Way, has a mass density approaching that expected for a supermassive black hole with a mass ~ 4 x 10^6 solar masses.

- Precision measurements of the times of arrival of radio pulses from pulsars in double neutron star systems routinely show that their orbits are decaying, consistent with the systems emitting gravitational waves which then carry away energy and angular momentum.
- Both radio and X-ray observations indicate that the interiors of neutron stars have supra-nuclear densities. X-ray observations of some X-ray binaries hint that their accretion process involves compact objects without solid surfaces, tantalizing evidence for black holes with event horizons, as predicted by general relativity.
- Multiwavelength observations show that some neutron stars, magnetars, have magnetic field strengths sufficiently high that quantum mechanical effects are likely to be important in their magnetospheres.

Centimeter- and meter-wavelength observations have already contributed to a number of these tests of fundamental physical theories, and future observations with centimeter and sub-millimeter telescopes will be integral to studying extreme physics, in some cases obtaining unique probes. The questions that these observations will address include both probing the strong-field limit of gravity and the state of matter in extreme conditions.

2.4.1 Probing the Spacetime Environment of the Galactic Center

Infrared observations of stars in elliptical orbits about the position of Sgr A* *(Shoedel et al. 2002, Nature, 419, 694; Ghez et al. 2005, ApJ, 620, 744; Ghez et al 2008, arXive:0808.2870)* demonstrate conclusively that there is an unseen mass of 4×10^6 solar masses close to the position of Sgr A*. Infrared, X-ray, and millimeter observations of Sgr A* show flares, perhaps tracing the last stages of accretion of material into a central supermassive black hole. Detailed models of the gas orbiting within a few gravitational radii of Sgr A* have been produced, including simulations of its "image" at sub-millimeter wavelengths. Radiation emitted by gas within the immediate environs of the black hole should manifest severe bending and lensing effects that depend on the black hole's spin. Comparison of the observed and modeled images would then probe the environment within a few gravitational radii of Sgr A* and potentially determine the black hole's spin.

The apparent angular diameter of a non-rotating $4 \times 10^6\ M_{Sun}$ black hole at the distance of Sgr A* is of order 50 microarcseconds (including a factor 2.6 to account for gravitational focusing). Recent VLBI observations between antennas in Hawaii and the mainland U.S. have detected fringes from Sgr A* that indicate structure on scales < 40 microarcseconds at a wavelength of 1.3 mm (*Doeleman et al 2008, Nature, in press; arXiv:0809.2442v1*). Producing an image of this supermassive black hole is likely to require only continued improvements in existing antennas, such as increased bandwidth for their receivers and improved oscillator stability, which will yield considerable sensitivity enhancements. Further, image quality is improved by using as many antennas as possible; if even a subset of ALMA antennas were to have a VLBI capability, they would add substantial sensitivity and improve the image quality.

A complementary probe would be to find pulsars orbiting the Galactic Center. While likely to be at larger distances than the gas that would be imaged with sub-mm VLBI, a pulsar would be a clock in the gravitational potential of Sgr A* (*Pfahl & Loeb, ApJ, 615, 253*). The high timing precision capable with modern instrumentation would be able to measure a variety of post-Keplerian parameters, akin to the manner in which they are measured routinely in pulsars in double neutron star binaries. Infrared observations reveal many young, massive stars near Sgr A*. Over the course of the Galaxy's history, successive episodes of star formation should have resulted in a large population of neutron stars in orbit about Sgr A*.

As yet, no radio pulsar has been found near the Galactic center, primarily because of the pulse broadening caused by intense interstellar turbulence along the line of sight to Sgr A*. Mitigation of these effects requires searches at wavelengths < 3 cm, wavelengths not traditionally employed in searching for pulsars because of their typically steep radio spectra. Nonetheless, searches using the GBT are already underway, exploiting its relatively high sensitivity at short wavelengths. The EVLA will be a powerful instrument for such a search. However, the GBT and EVLA will probably be sensitive enough to detect only the most luminous fraction of the pulsar population in the Galactic center. Telescopes of greater collecting area will be required to realize the full promise of this technique.

2.4.2 Pulsars as tests of Theories of Gravity

With normalized gravitational fields $GM/Rc^2 \sim 0.2$, as compared to about 10^{-6} for the Sun and 10^{-10} for the Earth, pulsars in binary systems present an opportunity to probe gravity in a regime qualitatively different than that within the solar system. A spectacular example is the precise timing at Arecibo of PSR B1913+16 (the Hulse-Taylor binary, 1993 Nobel Prize in Physics), which demonstrates that it is in a binary with another neutron star and that its orbit is decaying in a manner consistent with the emission of gravitational wave radiation from the system (Figure 2.4.1), a test widely seen as confirming an important prediction of General Relativity. A number of other neutron star-neutron star binaries are now known, including one pulsar-pulsar binary PSR J0737−3039, and relativistic effects are measured routinely.

Broadly, pulsar tests of theories of gravity fall into two categories, either tests of the equivalence principle (e.g., *Stairs et al. 2005, ApJ, 632, 1060*) or strong-field tests of theories of gravity (e.g., *Kramer et al. 2006, Science, 314, 97*). In both cases, one characterizes the spacetime environment of the pulsar by considering it as a clock and monitoring the arrival times of its pulses. This approach presents a natural framework for considering not only GR, but classes of theories, of which GR is a particular manifestation, e.g., a parameterized post-Newtonian (PPN) formalism. Quantitatively, pulsar tests are providing limits on deviations from GR that are comparable to or even beginning to surpass solar system tests, in addition to being in a qualitatively different regime. Because pulsars are relatively faint objects, both Arecibo and GBT have been instrumental in establishing many of the current pulsar limits on theories of gravity, and continued exploitation of this method requires long-term pulsar timing programs to be sustained.

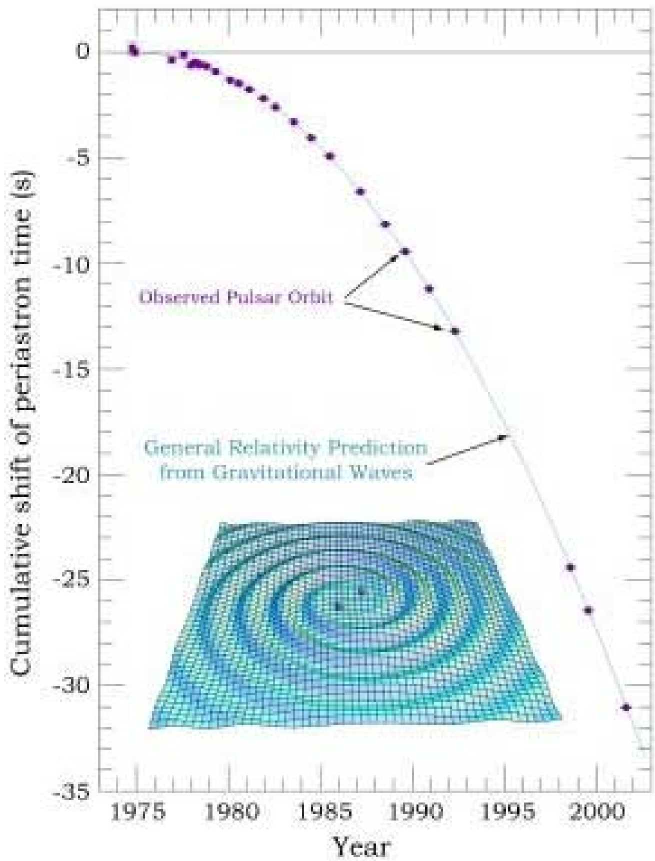

Figure 2.4.1. The long-term decay of the orbit of PSR B1913+16 (solid dots) from Arecibo timing data and the prediction of the orbital decay assuming that the system emits gravitational waves in accord with General Relativity. Uncertainties on the data are plotted, but are smaller than the symbols.

There is no reason to expect that PSR J0737-3039 is the most compact neutron star-neutron star binary in the Galaxy, and evolutionary models suggest that there should also be a small population of neutron star-black hole binaries in the Galaxy. The discovery of a pulsar-black hole binary would allow unprecedented tests of gravity, such as measuring the spin of the black hole. A long-term timing program could extract the signature of the coupling between the black hole spin and the orbital angular momentum in the system, from which the black hole spin could be inferred.

Until recently, there have been severe selection effects against detecting relativistic binaries. Computational challenges result from the need to analyze pulse data over time spans comparable to the orbital period in order to obtain adequate timing precision. The combination of improved algorithms and increased computational power are now rendering this problem tractable. Interstellar propagation effects are important, especially at long wavelengths (> 20 cm). Dispersion smearing can be mitigated in post-processing, but pulse broadening cannot. However, since interstellar propagation effects diminish rapidly with decreasing wavelengths, sensitive searches at wavelengths < 20 cm promise to discover pulsars undetectable at longer wavelengths.

Determining the number of such ultra-relativistic binaries in the Galaxy is an important calibration datum for LIGO and similar gravitational wave observatories, which should be able to detect the signal of the final merging of such systems.

2.4.3 Detecting Gravitational Waves with a Pulsar Timing Array

All modern gravitational wave observatories operate on essentially the same principle: deviations in the path length between point masses indicate the passage of gravitational waves. For terrestrial detectors, such as LIGO, and space-borne detectors, i.e., LISA, a phase shift between laser light propagating along different paths serves as the marker of a gravitational wave passing through the detector. Similarly, a network of millisecond radio pulsars, widely distributed about the sky, can serve as the "arms" of a gravitational wave observatory (a Pulsar Timing Array, or PTA). As gravitational waves pass through the Galaxy, they distort the spacetime metric between radio pulsars and the Earth. In turn, these distortions produce deviations in the pulse arrival times from the various pulsars in the PTA.

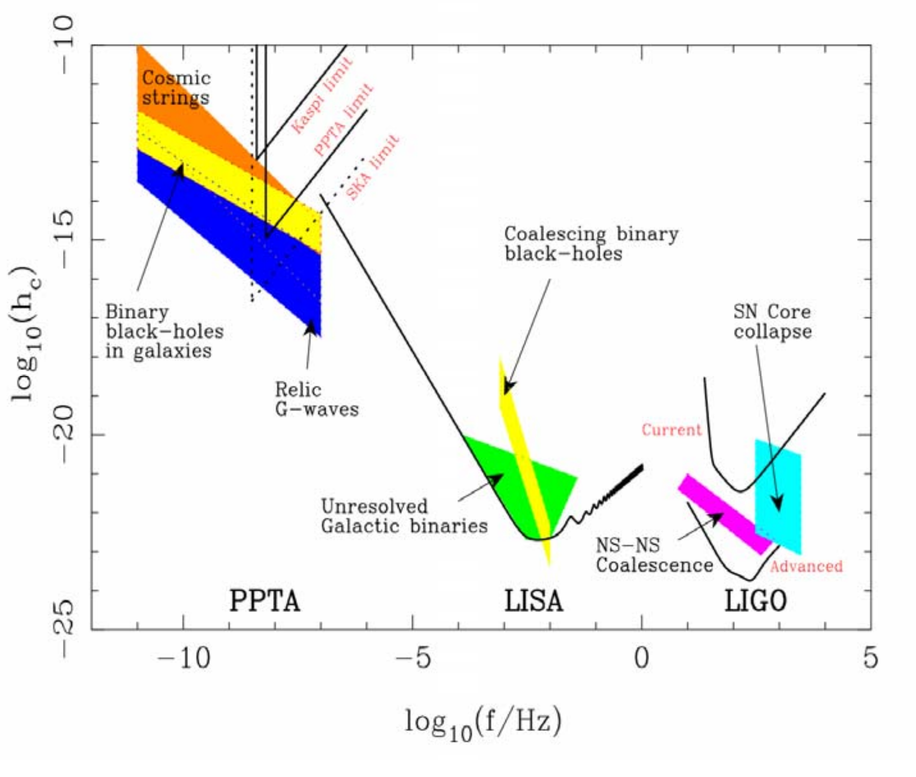

Figure 2.4.2. The expected gravitational wave signal vs. frequency, along with the expected sensitivity of future gravity wave telescopes. The Pulsar Timing Array is sensitive to low frequency gravity waves from massive black hole binaries (Manchester, 2007, in "40 Years of Pulsars: Millisecond Pulsars, Magnetars, and More." AIP Conference Proceedings, 983, 584, 2008).

The goal of a PTA is to detect the stochastic background of gravitational waves at nHz frequencies. Such a background can arise from binary supermassive black holes in yearly orbits, as well as from possible backgrounds of cosmic strings and relic G-waves from the early universe. Searches for gravitational waves with a PTA complement those using optical interferometers, such as LIGO, and eventually, LISA, which measure the gravitational wave background at much higher frequencies (a few Hertz), due to, for example, Galactic binary black holes or SN core collapse. Figure 2.4.2 shows the relative frequencies and sensitivities of these different gravity wave "telescopes" highlighting the complementary aspects of the different programs to open a new window on the Universe through gravitational radiation.

As Figure 2.4.2 shows, the current upper limits on detection of nanoHz gravitational waves through a PTA are above the estimated background, but observations currently underway with GBT, Arecibo, and Parkes are expected to reduce these limits by nearly two orders of magnitude. The challenge will be to find some 20 to 40 millisecond pulsars and track them with 100 nsec accuracy over 5 to 10 years. With more sensitive facilities such as the proposed SKA, it should be possible to gain further orders of magnitude in sensitivity.

2.4.4 Matter at Extreme Densities Matter at the center of neutron stars is at supra-nuclear densities, for which the equation of state is poorly constrained. As a result, the mass-radius relationship and the upper mass limit of neutron stars are not well determined. Precision timing of pulsars in binaries can measure their masses. To date, almost all of these mass determinations are consistent with a value near 1.4 solar masses, the classical Chandrasekhar limit. The timing of a millisecond pulsar in a highly eccentric orbit discovered by the Arecibo PALFA survey has given a very well-determined mass for the neutron star of 1.7 solar masses (*Champion et al. 2008, Science 320, 1309*). This mass places constraints on the viable equations of state and measurements of even higher masses would provide additional contraints (*Lattimer & Prakash 2007, Phys. Rev., 442 109*).

Another approach to constraining the nuclear equation of state follows from the measured pulse periods of millisecond pulsars. The minimum rotation period of a spinning neutron star places a limit on its equatorial radius. Hessels et al. (*2006, Science, 311, 1901*) used the GBT to discover the millisecond binary pulsar (PSR J1748-2446ad) in the globular cluster Terzan 5. With a pulse frequency 716 Hz, it is the fastest-spinning pulsar known, breaking the nearly 25-year record held by the 642 Hz pulsar B1937+21. The discovery of a shorter period millisecond pulsar would further constrain the nuclear equation of state, likely ruling out several currently viable equations of state.

2.5 How are high energy particles accelerated by compact objects?

The advent of radio astronomy, more than half a century ago, put astronomers on notice that high energy physics was an essential part of their portfolio. Since then, evidence has accumulated relentlessly to show that cosmic explosions of all types accelerate particles to relativistic energies. Moreover, compact objects, ranging in mass from more than 10^9 M_{Sun} in AGNs down to a few M_{Sun} in gamma ray bursts (GRBs) and "microquasars", typically produce narrowly collimated jets of relativistic particles. Understanding the mechanisms for the acceleration and collimation of particles in these jets remains a major challenge to astrophysics today.

Beginning in the 1970s, astrophysics gained new windows on the high energy cosmos with the launch of orbiting X-ray and gamma ray observatories. X-ray observatories detected most of the known galactic and extragalactic radio sources and discovered new classes of sources, such as accreting neutron star and black hole binaries. Gamma ray observatories mapped diffuse emission in the Milky Way due to relativistic particle interactions with interstellar gas, detected rapidly variable AGNs ("blazars"), and discovered new classes of objects such as magnetars and GRBs. With few exceptions, the compact X-ray and gamma ray sources are highly variable, on timescales ranging from milliseconds (for black hole binaries and GRBs) to days and years (for AGNs).

The pace of discovery in high energy astrophysics is accelerating with the successful operation of X-ray observatories such as Chandra and XMM, new high energy gamma ray observatories such as Fermi (formerly GLAST), ground-based TeV gamma ray observatories such as HESS and VERITAS, and high energy cosmic ray telescopes such as Auger. Air showers due to high energy cosmic rays also produce low-frequency radio flashes that can be detected by instruments such as LOPES. Observations at many wavelength bands are necessary to elucidate the physics of the high energy sources. For example, optical and radio observations played a critical role in demonstrating that GRBs were at cosmological distances and that some GRBs were associated with supernovae. The value of being able to identify and track transient high energy sources simultaneously at wavelengths ranging from optical to gamma rays has been amply demonstrated by the successful operation of the Swift Observatory.

The roles of RMS observations:

Non-thermal radio emission has been detected from all types of X-ray and gamma ray sources, and radio observations have unique power to elucidate their physics. For example, only radio observations have the angular resolution to probe the jets near their compact sources. The main challenge to radio astronomy is to develop the capabilities to observe the high energy sky with sufficient time resolution and sky coverage so that we can detect these transient sources and track their variability in several wavelength bands and polarization modes.

2.5.1. How are jets collimated and accelerated?

Recent VLBA monitoring and observations of TeV gamma rays from blazars show that their jets flow with Lorentz factors of order 30-50 (Cohen et al. 2007, ApJ 658, 232, Begelman, Fabian, & Rees 2008, MNRAS 384, 19) and imply acceleration of particles to at least TeV energies. We do not understand how these jets are accelerated and collimated, but we believe that the acceleration takes place near the event horizon of a supermassive black hole, and that accretion disks and magnetic fields play fundamental roles.

FERMI is expected to detect approximately 5,000 blazars (AGN with relativistic jets beamed nearly directly at us). The origin of the high-energy gamma-rays is still uncertain; they may be produced by Compton up-scattering of synchrotron photons from the relativistic jet, accretion disk or broad-line region, or by high-energy particle cascades. Since FERMI cannot image the gamma rays, VLBI observations will be required to image the jets on sub-milliarcsecond scales and to locate the site of gamma-ray emission by correlating gamma-ray time series with morphological changes in the jets.

The potential of this approach was demonstrated by the recent multi-wavelength study of BL-Lacertae (Marsher et al. 2008, Nature 452, 966), one of the prototypical relativistically beamed jet sources. Their VLBA observations show signs of bulk acceleration as well as rotating polarization vectors as the radio emission brightens in response to a gamma-ray flare, hinting at the underlying dynamics of the flow.

Multi-epoch radio imaging at VLBI resolution offers the unique ability to constrain the relativistic kinematics of the jets and to map the polarization of the radio emission. Such observations will provide critical tests of relativistic simulations of jet formation that will be realized in the coming decade.

This approach is perhaps best illustrated by one of the most promising targets for high-resolution radio observations, the M87 jet. Observations by the HESS array show that M87 contains a source of high energy (> 730 GeV) gamma rays that varies on timescales of days (Aharonian et al. 2006, Science, 314, 1424), comparable to the light travel time across the central supermassive black hole. Cheung et al. (2007, ApJL, 663, L65) observed the M87 jet with the VLBA at 20 cm and found evidence for a highly variable compact superluminal feature located more than 100 pc downstream from the central object, coincident with the optical/X-ray feature known as HST-1. Kovalev et al. (2007, ApJL, 668, 27), working at 2 cm, has observed an apparent limb brightening, characteristic of a two layer jet containing a fast central spine and a slower surrounding sheath (Fig 2.5.1). Currently, VLBI observations at 3mm can probe scales of 20 Schwarzschild radii of the supermassive black hole (Krichbaum et al. 2007, Journal of Physics, Conference Series, Volume 54, 328) and VSOP-2 will improve the resolution limit by another factor of 2.

Spectro-polarimetric imaging at VLBI resolution can not only detect the intrinsic magnetic field orientation of the jet (thus probing the geometry of the accelerating field) but also foreground Faraday rotation and conversion in the sheath of plasma surrounding the jet. In a pioneering study of the complex multi-frequency imaging polarimetry of VLBI jets, Gabuzda et al. (2008, MNRAS 384, 1003) provide evidence that the sense of circular polarization in jets might be linked to the sense of helicity in the field, which could provide a potentially powerful tool to study the conditions of the frame-dragging ergosphere of spinning black holes (Ensslin 2003, A&A 401, 499). The intrinsically weak fractional circular polarization implies that this approach requires large collecting areas combined with long baselines.

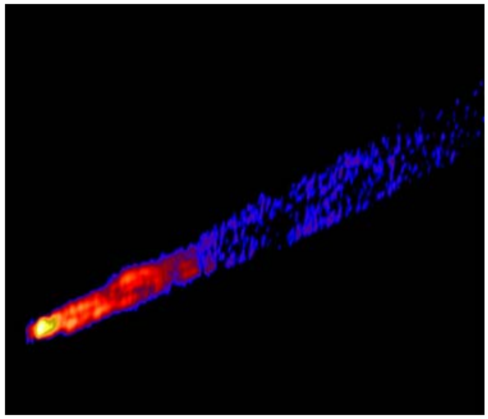

Figure 2.5.1. Inner 10 parsecs of M87 jet observed with the VLBA at 2 cm. The resolution of this VLBA image is 0.001 arcsec or 0.08 pc. (*Kovalev et al. 2007, ApJL, 668, 27*)

2.5.2. What is the nature of gamma ray burst sources?

Understanding the physics of gamma-ray bursts (GRBs), the brightest objects in the universe, is one of the outstanding challenges of high energy astrophysics. We now know that GRBs reside in galaxies, and that they can be seen at redshifts comparable to those of the most distant known galaxies and quasars (the current record holder, GRB 050904, has $z = 6.29$). Models to explain the brightness of GRBs require that the sources are highly beamed, with Lorentz factors ~ 10^2 (Figure 2.5.2).

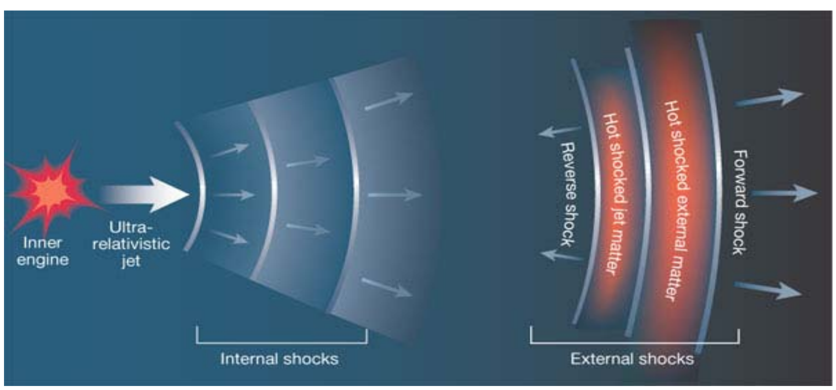

Figure 2.5.2. Model for gamma ray burst source (*Piran 2003, Nature 422, 268*). Highly beamed gamma rays are produced by internal shocks in the ultra-relativistic jet, while the more isotropic afterglows are produced by the external shocks.

It follows that for every observed GRB, there must be hundreds of such sources that we do not detect because the beams are not aimed toward Earth. We also know that at least some GRBs are associated with massive star supernovae, but that GRBs are rare events compared to supernovae, even allowing for the beaming.

The gamma ray bursts last only seconds to minutes, but the events have afterglows seen at longer wavelengths. The optical afterglows decay on timescales ~ days, but the radio afterglows persist much longer, rising and falling on characteristic timescales ~ months. We believe that the radio afterglows are the result of relativistic particle acceleration due to shock interaction of the relativistic jets with circumstellar matter, and that the radio reaches its peak after the jet has transferred most of its energy into a nearly spherical blast wave. Thus, the radio afterglow is expected to be nearly isotropic and one can infer the total burst energy from its brightness (*Berger et al. 2004, ApJ 612, 973*).

Moreover, radio observations have the unique capability to measure the angular (hence physical) size of the GRB radio afterglows. By observing the decay with time of interplanetary scintillation of the radio sources, Waxman et al (*1998 ApJ 497, 288*) inferred that one such source had an angular size ~ 3 microarcsec. Taylor et al. (*2004 ApJL 609, L1*) have used VLBI techniques to measure the expansion rate of the afterglow of the relatively nearby GRB 030329.

If the afterglow model is correct, then for every observed GRB there should be hundreds of radio/optical "orphan afterglows", whose gamma ray signals elude detection. Detection of these orphan afterglows, and of the prompt radio emission that is predicted by many models of GRBs, will provide powerful constraints of such models, especially when combined with deep synoptic surveys that are planned with proposed optical telescopes such as PanSTARRS, LSST, and JDEM. For example, the observed ratio of orphan afterglows to GRBs will constrain the gamma ray beam size. Even more important, the combined radio/optical surveys will give much better statistics on the relationship of gamma ray burst sources to supernovae of various types.

Detection of orphan afterglows at radio wavelengths will require sensitive wide-angle synoptic surveys. Rossi et al (*2008, MNRAS, in press; archiv. 0711.4096*) estimate that the VLA-FIRST project, which surveyed roughly three steradians of the sky at 20 cm continuum to a sensitivity limit ~ 1 mJy, should have detected ~ 7 such orphan afterglows. But the FIRST survey took roughly 3200 hours of VLA observing time. It would be necessary to repeat the FIRST survey on roughly a one month cadence to pick out the variable sources among the ~ 10^6 sources in the FIRST database. Synoptic surveys will be enabled with the EVLA, which will be able to repeat the FIRST survey in less than 1/10 the time that was required by the VLA, and with ASKAP, which will be able to reproduce the NVSS data set in a single day of observing.

But such a synoptic continuum survey with EVLA or other proposed radio facilities is likely to turn up far more variable sources than the orphan afterglows of GRBs, including radio blazars and radio supernovae. A strategy to search for near-coincidence events through synoptic surveys in multiple wavelength bands will be required to classify the many variable objects that will be detected by the surveys and to identify prime targets for pointed observations.

Even more intriguing is the possibility of finding entirely new classes of sources as more variability parameter space is opened up with such surveys, as demonstrated by the detection of a bright radio burst of 5ms duration. The large dispersion measure of this burst indicates an extragalactic origin (Lorimer et al. 2007, Science 318, 777), possibly related to the stellar collapse or mergers of compact objects. The possibility of using such radio bursts as a coincidence filter illustrates the importance of radio surveys for gravitational wave observatories.

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3. The Technical Agenda

3.1 Introduction

In Chapter 2 we gave examples of how RMS facilities play a role in addressing several overarching questions driving research in astrophysics. Here we discuss the technical capabilities that will be needed to achieve these goals. We briefly describe some of the major RMS facilities in the world, both existing and planned, and we discuss advances in technologies that will enable progress within the next decade.

In general, the scientific capabilities of RMS facilities can be characterized by the following figures of merit:

- Sensitivity (flux density and/or intensity)
- Angular resolution
- Spectral range
- Instantaneous bandwidth
- Spectral resolution
- Temporal resolution
- Polarimetric capability
- Field of view
- Commensal observing opportunity

The flux density sensitivity of radio telescopes and arrays is proportional to the net collecting area of the telescopes. The intensity sensitivity (brightness temperature) further depends on array scale and observing frequency. Sensitivity is a major motivation to build facilities having a collecting area of order one square kilometer. Indeed, the international Square Kilometer Array program aims to develop such a facility in the mid-frequency (500 MHz to 10 GHz) range. In the US, the Allen Telescope Array (ATA) is an SKA mid-frequency precursor. Major efforts are underway to develop mid-frequency SKA precursors in both Australia (ASKAP) and South Africa (MeerKAT). The EVLA is a precursor to a high frequency SKA. In the low-frequency range (10-300 MHz) the coming decade will see a transformation in access to the skies by a number of facilities and experiments led by US (MWA, PAPER, LWA) and European (LOFAR) collaborations. The SKA has the goal of reaching frequencies as low as 100 MHz, motivated largely by epoch of reionization (EoR) studies. Full exploitation of the EoR will require about 1 km^2. These SKA precursors have much broader fields of view than current large facilities, and so will have vastly increased capabilities for surveying the sky.

Significant advances in the capabilities of existing telescopes may be realized by retrofitting with advanced instrumentation. Take sensitivity, for example. By retrofitting the VLA antenna array with new receivers, correlators, and electronics, NRAO is transforming the array into the EVLA, which will have bandwidth increased by a factor of 80 and continuum source sensitivity by a factor of 5-20.

Historically, single-telescope instrumentation has been limited to single-pixel devices. However, recent advances in array receiver technology at meter to submillimeter wavelengths have revolutionized the survey capabilities of radio telescopes. For example, by installing a 13-element receiver array on the Parkes 64m telescope, the Australia Telescope National Facility has discovered more pulsars than any other observatory. The most impressive example to date of a focal plane array is the SCUBA2 dual 5120-pixel camera that is currently being installed on the JCMT and will result in a gain by a factor ~100 in the speed of the JCMT to survey the sky at sub-mm wavelengths.

As we discuss in Sections 3.2 and 3.3, we believe that the rapidly advancing ability of astronomers to survey the sky in several wavelength bands has great discovery potential and is transforming the way many astronomers carry out their research. Then, we describe existing and planned facilities for RMS astronomy and the opportunities that will be enabled by emerging technologies.

3.2 Multi-wavelength Enabling Technology

3.2.1 Surveys, Multiwavelength, and Synoptic Astronomy

From the time of Hipparcos, surveys of large areas of the sky have provided a rich yield of discovery. The modern era began in the late 1950's with the completion of the Palomar Observatory Sky Survey and the 3C catalogue of radio sources.

Surveys at RMS wavelengths have led to discovery of many new classes of astrophysical phenomena, such as: supernova remnants, radio galaxies, quasars, gravitational lensing, interplanetary scintillation, pulsars, millisecond pulsars, pulsar planets, interstellar scattering, dozens of interstellar molecular lines, and submm galaxies.

The discovery potential of modern surveys is greatly enhanced by the increasingly multiwavelength suite of complementary surveys (e.g., NVSS, FIRST, VLSS, SDSS, IRAS, 2MASS, Spitzer, GALEX, ROSAT). Correlating the data of objects taken in several wavelength bands has proven to be a powerful technique to study patterns among large numbers of related objects and to identify rare phenomena.

For the same reasons, deep surveys of selected regions of the sky with large telescopes are making major contributions to our understanding of cosmic evolution. For example, the COSMOS survey employs the VLA, Spitzer, Keck, Subaru, VLT, HST, Chandra, and XMM telescopes to map 2 square degrees of the extragalactic sky in many wavelength bands from radio to X-ray wavelengths, and including spectroscopic information for redshifts and other physical source properties. Similar panchromatic surveys are being undertaken for several smaller but much deeper "cosmological" fields. Likewise, deep surveys of the Milky Way (GALFA and PALFA at Arecibo and the International IGPS) are yielding new insights into the formation of stars and planetary systems, the structure of the interstellar medium, the physics of pulsars, and many other topics.

Synoptic surveys to detect variable objects have demonstrated great potential for discovering new phenomena. The most obvious examples are surveys for radio pulsars and X-ray and gamma ray astronomy, for which almost every source (except diffuse hot interstellar and intergalactic gas) is seen to vary wildly on timescales ranging from milliseconds to years. Beginning with UHURU and followed later by ROSAT, high energy surveys have kept the study of black holes, neutron stars, and gamma ray bursts at the forefront of astrophysical research. More recently, the MACHO and OGLE projects have found not only gravitational microlensing events, but also extra-solar planets through planetary transits as well as in the lensing events themselves. With optical telescopes equipped with large format detector arrays, astronomers have increased the rate of supernova discovery by more than an order of magnitude. This advance led to the discovery that the cosmic expansion is accelerating.

Many of the world's greatest telescopes have narrow fields of view and are not well suited for carrying out surveys of large areas of the sky. *But such large-aperture telescopes are empowered by surveys,* through which one can identify phenomena that merit intensive study through pointed observations. This is true, for example, with HST and Chandra, and it will be the case for some of most powerful RMS facilities under development, such as VLBI arrays and ALMA.

Recognizing the scientific impact of surveys, astronomers today are planning and developing new instruments to survey broad areas of the sky in many wavelength bands to greater sensitivity, angular resolution, spectral resolution, and cadence. From space, we anticipate:

- **FERMI**, successfully launched on June 11, 2008, will survey the gamma ray sky with sensitivity and angular resolution far better than those of the Compton Gamma Ray Observatory;
- **Planck,** scheduled for launch in December 2008, will survey the sky in 9 channels ranging from 0.3 mm to 1 cm with angular resolution ~ 5 arcmin.
- **WISE**, scheduled for launch in late 2009, will survey the infrared sky with sensitivity 500 times that of the IRAS satellite;
- **e-ROSITA**, a German-Russian mission with an anticipated launch in November 2011, will survey the X-ray sky with sensitivity, angular resolution, and spectral range substantially exceeding those of the ROSAT satellite.

The pressure to increase the survey and synoptic capability at optical/IR wavelengths has driven the development of wide-field cameras and multi-object spectrographs on existing telescopes, as well as plans for new wide field ground-based telescopes such as the proposed LSST and PANSTARRS II telescopes and the proposed JDEM space mission.

Surveys with RMS facilities play essential roles in addressing every scientific topic discussed in Chapter 2 of this report. As we shall describe in more detail in Sections 3.3 – 3.5, new technologies can greatly advance the capabilities of both existing and planned facilities to carry out surveys of the RMS sky.

3.2.2 The impact of information technology

The scientific strategies and facilities described above – large surveys including those exploring the time domain, large format detectors, and analysis of multiwavelength data bases – are possible only as a result of the dramatic advance of information technology. For example: the SDSS database is greater than 10 terabytes; pulsar surveys routinely generate data sets of tens to hundreds of terabytes; and the VLBA database is greater than 30 terabytes. Databases of substantially greater size will be generated by planned facilities operating at optical, infrared and RMS wavelength bands.

Moreover, enormous progress is being made in developing resources to enable astronomers efficiently to retrieve and analyze information from these databases via the web. An important example is the "National Virtual Observatory" project supported by the NSF, NASA, and DoE, which in turn is part of a larger international effort, the International Virtual Observatory.

The rapid development of information technology is creating cultural changes in the way astronomers do their work. The Space Telescope Science Institute led the way in ensuring that archived, fully calibrated data from the HST were made accessible to the public after a short proprietary period, and this principle has now become standard practice for all major astronomical facilities supported by NASA, NSF, and DOE. Indeed, in some instances, such as the NRAO VLA Sky Survey (NVSS) and FIRST survey, and the Spitzer Legacy Program, the data are made available to the public as soon as technically possible, with no proprietary period.

As astronomers have become used to mining astronomical databases, they can no longer be pigeonholed according to the wavelength band in which they do their research. This trend toward multi-wavelength astronomy research is accelerated by the fact that almost all observations with space observatories and an increasing fraction of observations with ground-based observatories are carried out remotely through queue scheduling.

The rapid growth of astronomical databases and the tools to access them has a democratizing influence on the field. A couple of decades ago, much of the most valuable data for astronomical research were available only to astronomers residing at institutions managing the major observational facilities. Today, an astronomer or student anywhere in the world can retrieve and analyze relatively fresh data from the world's greatest observatories using only an inexpensive PC.

Although excellent science can be done in this mode, training that includes exposure to the fundamental capability of instruments will remain essential to the vitality of the next generation of astronomers.

The growth of multiwavelength astronomy is also accelerating the internationalization of astronomy. It is now relatively easy for astronomers to collaborate internationally through the web. For example, the Sloan (SDSS) team consists of 150 scientists at 25 institutions in 7 countries while the extragalactic ALFA (Arecibo) consortium is 105 scientists from 15 countries.

3.3 RMS Science and Technology

We find it convenient to organize our discussion into three wavelength bands: > 1 m (Sec. 3.3.1), 1 cm – 1m (Sec. 3.3.2), and < 1 cm (Sec. 3.3.3).

3.3.1 Meter-Wave Science and Technology

The recognition that the Universe could be observed at wavelengths other than those in the visual spectrum began with Jansky's discovery of celestial radio emission at a wavelength of 14.6 m (20.5 MHz), and the Nobel prize in physics was awarded for work at meter wavelengths (the discovery of pulsars and the development of aperture synthesis). Meter wavelength observations of a binary pulsar ushered in the dawn of gravitational wave astronomy.

At wavelengths greater than one meter, the radio emission from the sky is dominated by non-thermal continuum processes, such as synchrotron emission from the Galaxy and radio galaxies, AGNs, and pulsars. More recently, astronomers have been motivated to build large and sensitive meter-wave facilities by the exciting possibility of observing structure in highly redshifted intergalactic HI 21-cm emission at the epoch of reionization, as described in Chapter 2. As the discovery of pulsars (at 81 MHz) illustrates, low frequency radio arrays can also detect transients, with recent interest generated in detecting pulses of coherent synchrotron emission by extensive air showers from ultrahigh energy cosmic rays.

At meter wavelengths, parabolic antennas can become impractically large, and broadband dipoles are a more suitable option for obtaining collecting area. Dipoles have a number of additional advantages. Their collecting area scales as λ^2 while the temperature of the Galactic background scales approximately as $\lambda^{2.6}$, so that to first order they provide approximate wavelength-independent sensitivity. Moreover, dipoles are intrinsically low cost, suggesting that a substantial collecting area can be obtained relatively inexpensively, and they provide a naturally wide field of view.

For computational reasons, all of the dipole-based arrays under development employ "stations" or "tiles," consisting of phased arrays of 16-256 dipoles each. One can think of the stations as replacing individual dishes, except that every station can view large fractions of the sky at once depending on the complexity of the beam-forming electronics.

The technical challenges presented by these arrays include very wide-field imaging, calibration of the ionospheric phase perturbations, excision of interference, and real-time calibration/imaging required by the immense data flow through large number of correlations. The opportunity for multiple (commensal) observations with independent beams formed at the stations both enhances the scientific throughput and challenges the design optimization.

Major current and future (planned or under development) facilities for meter-wave astronomy are listed in Table 3.1.

Table 3.1. Major Meter-Wave Facilities

Telescope	Antennas[1]	Diameter (m)	Focal Plane Elements Or beams	Wavelength range (m)	Area[2] (m^2)	Max Baseline (km)	Angular resolution (arcsec)[3]	Field of View[4] (deg)
Currently Operating								
GMRT	30	45	1	0.21 - 6	6 x10^4	25	8 @ 300 MHz	3 @ 300 MHz
Future Facilities								
LWA	~50*256	--	4	3.75 – 15	10^6	400	2 @ 80 MHz	8 @ 80 MHz
LOFAR	40*60	--	--	1.25 - 10	2 x 10^5	100+	21 @ 30 MHz	10 @ 30 MHz
MWA	500*16	--	--	1 – 3.75	8000	1.5	275 @ 150 MHz	15 @ 150 MHz
PAPER	256*1	--	--	1.5 - 3	1800	1.2	345@150 MHz	60 @150 MHz

[1]In the case of GMRT, the number of parabolic dishes: in the case of other facilities, we list (number of stations)*(number of dipole antennas/station)
[2]Net effective collecting area.
[3]Scales as λ
[4]Scales as λ^{-1}

GMRT: Giant Metrewave Radio Telescope (GMRT) in Pune, India, currently the largest operating array dedicated primarily to observations in this band. The design of the GMRT array resembles that of the VLA. Its field of view is determined by the diffraction limit of one 45-m antenna.

LWA: Long Wavelength Array, currently under development to be deployed in New Mexico.

LOFAR: Low Frequency Array, the largest project for low-frequency astronomy, currently under construction. The LOFAR project is a European collaboration led by The Netherlands.

MWA: Murchison Wide Field Array, a US-Australia-India collaboration currently under construction in Western Australia.

PAPER: Precision Array to Probe the Epoch of Reionization, a US-Australian collaboration currently under construction in Western Australia with test site in Green Bank, WV.

3.3.2 Centimeter-Wave Science and Technology

As Chapter 2 illustrates the scientific agenda for centimeter wave facilities includes both continuum studies of a wide variety of thermal and non-thermal sources, studies of relativity and gravitational physics through pulsars, and spectroscopic studies of atomic and molecular line emission from diffuse interstellar gas and star-forming regions in the Milky Way and other galaxies.

Table 3.2 lists major existing and future facilities for centimeter-wave astronomy and estimates of observing parameters at nominal wavelength 21 cm. The table is not intended to compare the capabilities of the various facilities, which depend greatly on observing wavelength. Indeed, several of the facilities listed will not operate at wavelengths < 4 cm. Rather, it is meant to give a rough census of the worldwide capabilities of cm-wave telescopes, and to illustrate the dramatic advances that are imminent. As we discuss below, such advances will occur not only with new facilities, but also with existing facilities, which are always "under development".

Table 3.2. Major Centimeter-Wave Facilities

Telescope	Antennas	Illuminated Diameter (m)	Focal Plane Elements	System Temperature (K)	Wavelength range (cm)	Bandpass (MHz)[1]	Area (m^2)	Max Baseline (km)	Angular resolution[2] (arcsec)	Field of View[3] ($arcmin^2$)
Currently Operating Single Telescopes										
Effelsberg	1	100	7	23	0.3 – 73	100	7800	--	430	300
Parkes	1	64	13	23.5	1.3 – 70	300	3200		670	1300
Arecibo	1	225	7	30	4 – 200	300	4×10^4	--	200	60
GBT	1	100	1	20	0.3 – 200	650	7,800	--	430	40
Currently Operating Array Telescopes										
MOST	88	11.6 x 17.7	1	300	36	3	1.8×10^4	1.57	45	1800
ATCA	6	22	1	32	0.3 – 25	256	2300	6	7	850
VLBA	10	25	1	28	0.3 – 100	32	4900	8000	0.005	650
ATA-42	42	6.1	1	45	3 – 60	200	1200	0.3	144	1.1×10^4
Future Facilities										
EVLA	27	25	1	35	0.6 – 30	1000	1.3×10^4	35	1.4	650
WSRT/ APERTIF	14	25	25	50	3.6– 260	150	6900	2.7	16	1.6×10^4
e-Merlin	7	25 – 76	1	40	1.25 – 100	800	7900	217	0.17	650
FAST	1	~250	19	30	10 – 400	300	2×10^5	--	150	90
MeerKAT	80	15	1	30	12 - 60	512	1.4×10^4	5	9	1800
ASKAP	30	12	~30	50	17 - 43	~1000	5100	8	5	8.5×10^4

[1]At nominal wavelength $\lambda = 21$ cm; scales roughly as λ^{-1}. Except MOST, for which $\lambda = 36$ cm

[2]At nominal wavelength $\lambda = 21$ cm; scales as λ.

[3]Solid angle viewed by a single dish determined by diffraction limit of a single telescope, times number of focal plane elements. Listed for nominal wavelength $\lambda = 21$ cm; scales as λ^{-2}, except ~ λ^0 for ASKAP.

Arecibo: With an effective aperture of 225 m at 21 cm, Arecibo is currently the world's largest-aperture radio telescope. The 7-element ALFA receiver array has opened up dramatic new capabilities in wide field HI 21cm line, CMB foreground polarization, and pulsar surveys. Multiple back ends enable simultaneous recording of signals by different science programs. Design of a larger number (up to 40) of array beams is being explored.

GBT: Green Bank Telescope – the world's largest fully steerable radio telescope – has broad capabilities, including studies of pulsars, extragalactic masers, and Galactic HI. The capability of GBT for deep surveys will be greatly enhanced by focal plane arrays under development, including a 7-element array operating at K-band (1.1 – 1.7 cm) for wide field surveys of ammonia, water, and other molecules and a 64-element bolometer camera for 3-mm continuum observations. A 61-element K-band focal plane array is in the planning phase.

WSRT: Westerbork Synthesis Radio Telescope. The APERTIF project is developing a beam-forming focal plane array that could increase the effective field of view, hence the mapping speed, of WSRT by a factor ~ 25.

MOST: MOST: The Molonglo Observatory Synthesis Telescope is the largest radio telescope in the southern hemisphere, and has recently completed a sensitive continuum survey of the entire southern sky. The MOST is now in the process of being upgraded into the Square Kilometre Array Molonglo Prototype (SKAMP), a wide-field facility which will have similar survey capabilities to the ATA-42 in the wavelength range 21-42cm. SKAMP will search for redshifted HI from distant galaxies, map the sky for radio transients, and measure Faraday rotation measures to tens of thousands of background sources.

ATCA: The Australia Telescope Compact Array is capable of observing in seven bands between 25 cm and 3mm, and can be rapidly reconfigured into many different array configurations. From 2009, the ATCA will be equipped with the new CABB correlator, which will provide 4 GHz of instantaneous bandwidth. This will provide a dramatic improvement in continuum sensitivity, and will allow simultaneous observations of up to 16 widely separated spectral lines.

VLA: The VLA is currently the world's most sensitive aperture synthesis array. It is currently being upgraded into the Expanded VLA (EVLA), scheduled for completion by 2012. The EVLA will achieve an order of magnitude improvement in continuum sensitivity over the VLA, full frequency coverage from 1 to 50 GHz, and dramatically improved spectral capabilities, enabling study of thermal objects at sub-arcsecond resolution at centimeter wavelengths.

ATA: The Allen Telescope Array is producing science with a 42-element array, with plans to expand to 350 elements. This is the first working prototype for the next-generation Square Kilometer Array (see below). The ATA has a wide field of view, and, when completed, will be the fastest wide-field survey telescope at wavelengths > 3 cm.

The multi-frequency and multi-beam capabilities of the ATA allow multiple simultaneous (commensal) observing programs.

VLBA: The VLBA produces the highest angular resolution observations available in astronomy, including sub-milliarcsecond imaging and microarcsecond astrometry. By including Arecibo, the GBT, Effelsberg, and the VLA, one can double the effective area of the array to achieve imaging with mJy sensitivity. It would be possible to increase the sensitivity of the existing array for continuum observations by another factor ~16 by increasing the data recording rate, and hence the bandwidth.

FAST: Under development in China, FAST is planned to be the world's largest single-dish antenna. FAST is planned to have an effective aperture ~ 250 m at 21 cm and a 19-element focal plane array

The International SKA Project aims to develop an array of telescopes with net effective area ~ 1 square kilometer. Several facilities under construction can be considered as SKA pathfinders, and two specific ones are under development at potential SKA sites in Australia and South Africa:

MeerKAT: The Karoo Array Telescope is a technology demonstrator for the SKA under development in South Africa. The MeerKAT project will study, among other items, parabolic dish design and construction. MeerKAT is currently under construction in South Africa and is scheduled for completion in 2012.

ASKAP: Australian Square Kilometer Array Pathfinder. ASKAP is an international collaboration with Australia (CSIRO), and Canada (NRC) to build an array of dishes capable of high dynamic range imaging. Each telescope will be equipped with a wide-field-of-view phased receiver array capable of forming ~ 30 independent beams at 1400 MHz. The ASKAP design has a fixed field of view independent of wavelength and an octave or slightly larger bandpass. ASKAP is currently under construction in Western Australia and is scheduled for completion in 2012.

As discussed in Chapter 2, there are great scientific opportunities for telescopes which can map the galactic and extragalactic sky at wavelengths < 3 cm, where key molecular lines (e.g., H_2O masers, NH_3 and CO) are found. Both the ATA and the EVLA are pathfinders in the development of a short wavelength (1 cm to 10 cm) Square Kilometer Array, in terms of both the technology (antennas, receivers, IF electronics and data transmission...), and the science targets (microJy radio sources, protoplanetary disks, etc.). VLBA is currently the only facility that can serve as a pathfinder for the highest resolution goals of the SKA project.

For optical astronomy, the speed at which a telescope can map the sky is proportional to the "etendue", defined as the product of the telescope area and field of view, $A\Delta\Omega$. Because the flux-density sensitivity of a radio receiver is limited by system noise, the mapping speed is proportional instead to $(A/T)^2\Delta\Omega(\Delta\nu/\nu)$, where T is the system temperature and $\Delta\nu/\nu$ is the fractional bandpass. In Figure 3.1 we plot the mapping speeds of the centimeter-wave facilities listed in Table 3.2 vs. angular resolution at a nominal wavelength 21 cm. Note that for imaging arrays composed of diffraction-limited, single-pixel antennas, $\Delta\Omega$ is proportional to λ^2/A and so the mapping speed is proportional to $A\lambda^2$. Brightness temperature (intensity) mapping speeds differ in that they depend on array size.

We emphasize that Figure 3.1 is only intended to illustrate the gains in mapping speed that may be expected in facilities under development, and not to compare the scientific capabilities of the facilities. The relative performances would be very different at shorter wavelengths.

Figure 3.1 and Table 3.2 illustrate the orders-of-magnitude gains in mapping speed which are possible as a result of increasing the field of view of the telescopes through focal plane receiver arrays. For example, note the resulting gains in mapping speed of the Parkes, Effelsberg, and Arecibo telescopes. As we have mentioned, the GBT will soon gain a factor of 7 in mapping speed (at 22 GHz) when a new 7-element multi-beam receiver array is installed.

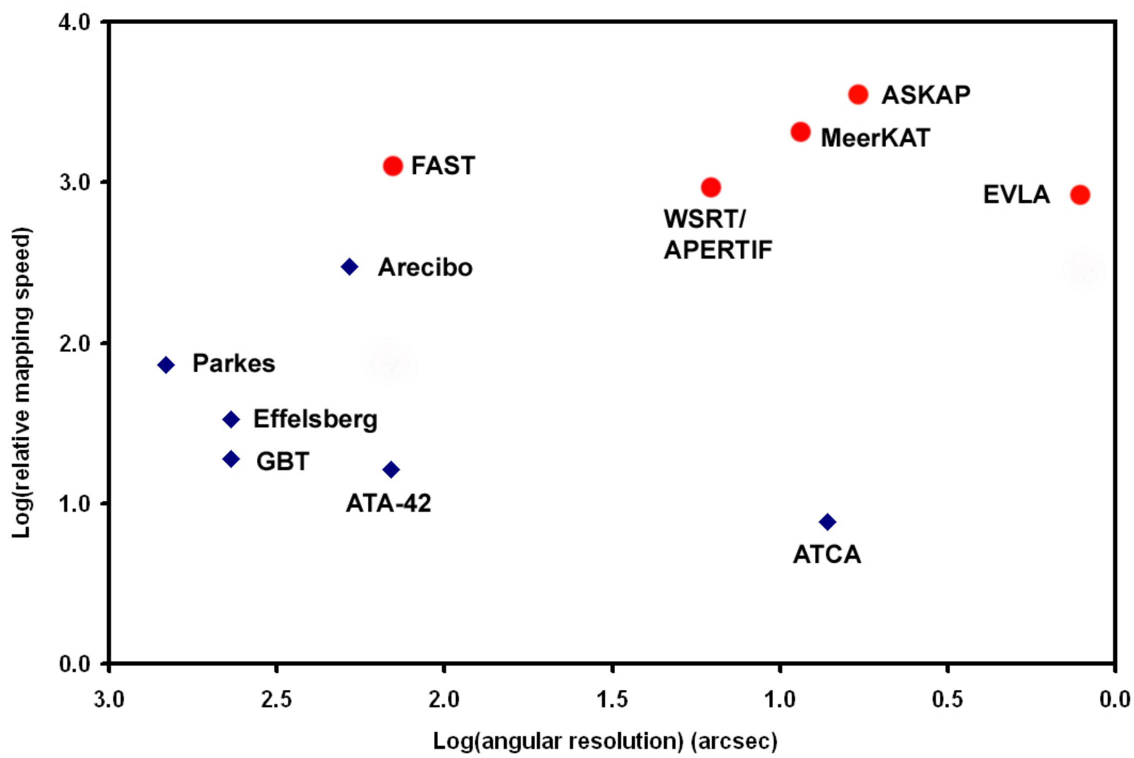

Figure 3.1. Comparison of mapping speeds and angular resolutions of various existing and planned cm-wave telescopes and arrays at nominal wavelength 21 cm. Blue diamonds indicate actual performance of existing instrumentation; red dots indicate performance goals for facilities under development.

The other approach to achieving high mapping speed is to employ an array of large numbers of relatively small dishes. The advantage of this approach for mapping has been demonstrated by the 42-element ATA. Even greater gains are possible by employing arrays of relatively small dishes, each of which is equipped with a multi-beam focal plane array of receivers. This is the strategy that will be employed by the SKA precursor ASKAP. As one can see from Figure 3.1, these facilities will have mapping speeds exceeding any existing cm-wave facility by more than an order of magnitude.

Of course, increased ability for surveys is only one part of a balanced strategy for radio astronomy. Telescopes with large area and relatively small fields of view will always be more effective for making deep observations of relatively compact sources.

Technical Opportunities for Cm-wave Astronomy

Centimeter-wave astronomy has reached, or is near, the practical limits of many observational parameters that determine its sensitivity and accuracy: system temperature, instantaneous bandwidth and resolution, frequency coverage, and angular resolution. The two parameters that can be improved further are collecting area and field of view. Exploiting this parameter space at an affordable cost requires a long-term research and development horizon. High time resolution is a further area of interest owing to new attention to the transient emission.

Two concrete examples of goals that will address the field-of-view problem are beam-forming focal-plane arrays and small, lightweight, low-noise receiver packages that are compatible with reflectors in the six- to ten-meter class. These require significant research in the areas such as cryogenic insulation, refrigeration, antenna mutual coupling, antenna-amplifier integration and low-cost manufacturing techniques. The payoff for success in either of these goals will be substantial. Both are relevant to the SKA, and to enhanced capabilities of current telescopes such as the GBT and ATA. Many details remain to be addressed before cost estimates can be considered realistic. Current instruments are not terribly far from optimum cost solutions for the given frequency coverage and collecting area/system temperature quotient. Collecting area is expensive no matter how you build it, so very low system temperature is going to be of paramount importance to the success of SKA. Moreover, receiver or feed array development cannot be done in isolation from other parts of a radio telescope.

The success of the new centimeter-wavelength telescopes is strongly dependent on powerful and agile digital signal processing -- correlators, beam-formers, spectrometers, pulsar signal analyzers and real-time calibration and imaging. Open source platforms -- hardware, firmware, and software -- have emerged in recent years suggesting a new paradigm for rapid, modular and scalable developments. The boundary between how early in the signal path one converts from analog to digital is shifting driven by cost, agility and performance. Similarly the boundary between online and offline processing is shifting driven by the large data rates in raw data vs. that in sky-based images. The boundary between signal processing in FPGA-based hardware vs. software in computing clusters, which may be assisted by co-processors like GPUs, is shifting. Finally the complexity of the required signal processing leads design engineers to raise the priority of attention to power consumption -- operations per watt.

3.3.3 Millimeter and Sub-mm Science and Technology

As described in Chapter 2, observations at mm/sub-mm wavelength bands are important for cosmology through continuum observations of CMB fluctuations and polarization and for the evolution of cosmic structure through observations of the S-Z effect. Moreover, mm/sub-mm observations are powerful tools for probing galaxy formation, star formation, and formation of planetary systems, both through continuum observations of dust emission and through observations of spectral lines that provide a 3D view of kinematics and, in cases, dynamics. The mm/sub-mm spectra of many cosmic sources are rich in emission lines from many molecular species, and mm/sub-mm spectroscopy of such sources is highly synergistic with IR spectroscopy using future infrared/sub-mm facilities such as Herschel, SOFIA, and JWST. Moreover, mm/sub-mm VLBI will achieve the highest angular resolution in astronomy, and offers the tantalizing prospect of measuring phenomena close to the event horizons of supermassive black holes and possibly the black hole spin.

Table 3.3 Major Millimeter/Submillimeter Facilities

Telescope	Instrument[1]	Antennas	Diameter (m)	number pixels[2]	Wavelength (mm)	Area (m^2)	Max Baseline (km)	Angular resolution[3] (arcsec)
Currently operating single dishes								
CSO	Bolocam	1	10.4	115	0.35/1.1/2.1	85	--	20
SMT	MPIfR	1	10	19	0.6 – 3	79	--	20
JCMT	SCUBA-2	1	15	5120	0.45/0.85	177	--	14
APEX	LABOCA	1	12	295	0.35 – 0.87	113	--	17
ASTE	AzTEC	1	10	144	1.1	79	--	21
IRAM	MAMBO II	1	30	117	0.11 – 3.75	707	--	7
SPT	--	1	10	330	0.2 – 3	79	--	20
Currently operating arrays								
Plateau du Bure	Heterodyne	6	15	1	1 – 3	1060	0.76	0.3
CARMA	Heterodyne	6+9+8	10/6/3.5	1	1.3 – 3	725	2	0.1
SMA	Heterodyne	8	6	1	0.3 – 1.7	226	0.6	0.35
Future facilities								
ALMA	Heterodyne	54[4]	12	1	0.3 – 3	6560	15	0.014
LMT	AzTEC	1	50	144	1.1 – 2.1	1963	--	4
CCAT	LWC	1	25	10^4	0.2 – 2.0	491	--	8

[1]Primary instrument for observations @ ~ 1 mm
[2]Number of independent beams may be less (some focal plane arrays are oversampled)
[3]At nominal wavelength $\lambda = 1$ mm; scales as λ.
[4]ALMA also includes a subarray of 12 7-meter antennas.

Table 3.3 lists major existing and future facilities for mm/sub-mm astronomy, some of which we describe in more detail below.

SMT: Submillimeter Telescope, located on Mt. Graham in Arizona.

CSO: Caltech Submillimeter Observatory, located on Mauna Kea, Hawaii. Current instrumentation includes a bank of heterodyne detectors operating over the range 0.3 – 1.6 mm, the 115 pixel BoloCAM bolometer camera operating at 1.1 and 2.1 mm, the 384 pixel SHARCII camera operating at .35 - .85 mm, and two grating spectrometers, ZSPEC and ZEUS, operating at 1 – 1.6 mm and 0.35 – 0.46 mm, respectively.

JCMT: James Clark Maxwell Telescope, located on Mauna Kea, currently the fastest telescope for mapping the sub-mm sky. The SCUBA-2 camera, currently being installed, contains a beam-splitter that illuminates two 5120-pixel bolometer arrays simultaneously at 0.45 and 0.85 microns.

APEX: Atacama Pathfinder Experiment. APEX is a copy of an ALMA prototype dish operated by the Max-Planck Institute for Radio Astronomy at the ALMA site. Instruments include LABOCA, a 300-pixel bolometer array operating at 0.87 mm, and CHAMP, a 16-pixel heterodyne array operating at 0.65 mm.

ASTE: Atacama Submm Telescope Experiment (Japan), a 10m dish currently operating at 0.87 mm.

ACT: Atacama Cosmology Telescope, located at altitude 5190 meters. ACT employs three bolometer arrays, each with 1024 pixels, to observe the cosmic microwave background at 1.07, 1.4, and 2.06 mm.

CARMA: A hybrid interferometer array consisting of six 10.4-m dishes, nine 6.1-m dishes, and eight 3.5-m dishes. CARMA will dramatically improve our ability to image cosmic molecular gas and dust clouds and to study star and galaxy formation.

SMA: The Submillimeter Array, located on Mauna Kea, has begun to explore the sub-mm sky at sub-arcsecond resolution for the first time, demonstrating key pathfinder science and technology for ALMA.

ALMA: The Atacama Large Millimeter Array is the most ambitious ground-based telescope project ever undertaken and represents the largest single advance in astronomical capabilities at a given waveband in history. ALMA will provide up to two orders of magnitude improvement in all aspects of millimeter and submillimeter interferometry, including sensitivity, resolution, and spectral coverage. These capabilities are enabled by large collecting area, many dishes, the suite of receivers, and the remarkable quality of the high (5000 m) site in Chile. ALMA will provide exquisitely detailed images of thermal objects throughout the universe, from Galactic star-forming regions to the first galaxies.

The scientific agenda for ALMA will be greatly enriched by large-scale surveys of the southern sky at mm/sub-mm wavelengths. ALMA's capability for such surveys is limited by its relatively narrow field-of-view. Fortunately, two large millimeter and submillimeter antennas are being developed to carry out such surveys:

LMT: The Large Millimeter Telescope, a collaboration between the University of Massachusetts and Mexico, is located at 4,600 m on Volcan Sierra Negra near Puebla, Mexico. LMT is currently being commissioned with a 30-m diameter surface. When completed, it will have a 50-m diameter surface and will be the world's largest single-dish millimeter telescope.

CCAT: The Cornell-Caltech Atacama Telescope, currently in the planning stage, will be located near the ALMA site at an altitude of 5612 m. ALMA and CCAT are highly complementary. ALMA will have roughly 400 times the angular resolution of CCAT. But CCAT, equipped with large-format detector arrays, will have a continuum mapping speed more than 100 times that of ALMA.

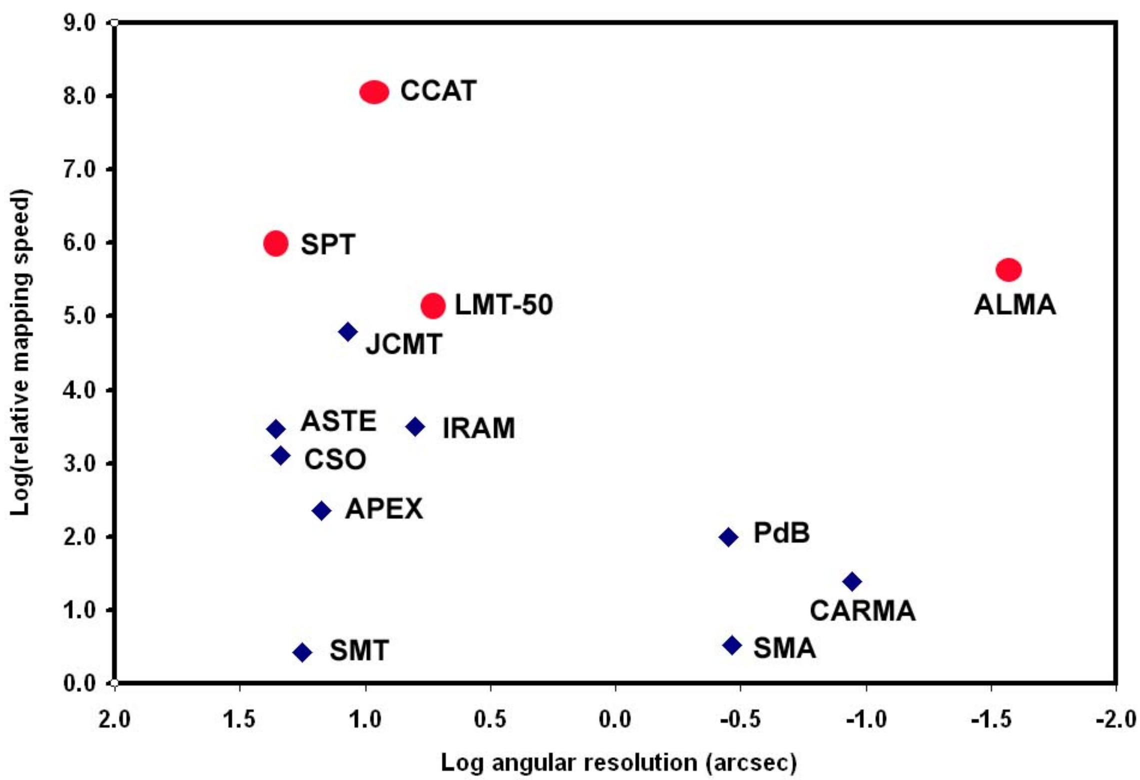

Figure 3.2. Comparison of continuum mapping speeds (at wavelength ~ 1 mm) and angular resolutions of various existing and planned mm/sub-mm-wave telescopes and arrays. Blue diamonds denote existing instruments; red dots denote planned receivers.

Figure 3.2 is the analogue of Figure 3.1 for mm/sub-mm telescopes. As with Figure 3.1, Figure 3.2 is not meant to compare the overall scientific capabilities of the facilities, but only to illustrate the rapid progress that is occurring as a result of advances in instrumentation. In fact, the scientific capabilities of mm/sub-mm telescopes depend on many factors besides continuum mapping speed. For example, heterodyne systems typically have lower continuum mapping speeds than bolometer cameras but are often far more powerful for mapping emission line sources. Moreover, the mapping speeds displayed in Figure 3.2 have been estimated for ideal observing conditions. The frequency of occurrence of such conditions depends greatly on the location of the telescope, especially for observations at sub-mm wavelengths.

Even so, Figure 3.2 shows that our ability to study the cosmos at mm/sub-mm wavelengths is about to advance by orders of magnitude. It also illustrates the complementarity of single-dish telescopes equipped with large-format array detectors and interferometric arrays such as ALMA.

Technical Opportunities for Mm/sub-mm Astronomy

Detector technology at mm/sub-mm wavelengths continues to advance rapidly. Mm/sub-mm detectors employ two distinct and complementary technologies. Coherent detectors resemble receivers operating at longer wavelengths. They have narrow intrinsic bandwidths and can be used for interferometry. Incoherent detectors – bolometers – have intrinsically broad bandwidths and high sensitivity for continuum observations. Instruments employing bolometers resemble those on infrared and optical telescopes. For example, spectral resolution can be achieved with instruments employing diffraction gratings and bolometer arrays.

Detectors and optical elements for mm/sub-mm instruments are naturally smaller (comparable to the wavelength observed) than those at longer wavelengths. Consequently, it is possible to pack a greater number of detector elements at the focal plane of the telescope. Therefore many single-dish antennas employ focal plane cameras containing hundreds or even thousands of pixels.

Monolithic Microwave Integrated Circuit (MMIC) Arrays of Detectors

Until the last decade all coherent receivers on radio telescopes were single-beam or dual-beam devices, since the complexity and cost of fielding multiple-beam instruments was prohibitive. However the increasing levels of integration in chips has proceeded far enough to enable receiver arrays to be built at reasonable cost and several such instruments have been fielded in the last few years (e.g., at UMass and Parkes). Coherent detectors can be used for the whole gamut of RMS observations: total intensity, polarization, continuum, spectral line from low to high resolution, and interferometry.

There are several fundamental science areas that can be addressed by MMIC arrays covering the frequency range from ~15 GHz to ~300 GHz:

1. B-mode Polarization of the CMB for (a) the quest for the energy scale of inflation, and (b) weak lensing to determine the density distribution along the line of sight to the last scattering region at z~1100. These are specialized instruments and telescopes, which address particular questions.

2. High resolution (~0.1 km/s) spectroscopy of the Milky Way and of nearby galaxies would address a number of critical questions related to star formation and the composition, dynamics, and breakup of the molecular clouds that give rise to star formation. A ~1000-element receiver on the GBT, for example, covering the 80-115 GHz window, would be a very powerful general-purpose instrument that could map the galactic plane in a few months with unprecedented resolution in position and velocity.

The MMIC array revolution has only just begun, but it seems primed to have an immense impact on RMS astronomy. A decade ago a state-of-the-art differential radiometer in the range 20 GHz - 115 GHz would cost about $40k and the size of the radiometer prohibited its use in arrays. This has all changed – the same radiometer can now be incorporated into a tiny module, and the cost is expected to drop by about two orders of magnitude once mass production begins. HEMT-based MMIC devices will be able to achieve noise temperatures only a factor of 2-3 above the quantum limit up to about 150 GHz. MMIC arrays are already being built at 22 GHz, 45 GHz, and 90 GHz, while others are planned at 15 GHz and 30 GHz.

Matching these developments in the RF part of the radiometer, the digital back-end opportunities provided by modern FPGA devices and powerful computing clusters that are relentlessly following Moore's Law will allow construction of enormously powerful and versatile digital back-ends on a reasonable timescale, at reasonable cost and with a reasonable (although challenging) power consumption budget.

Bolometer Arrays:

Millimeter and submillimeter continuum detector – bolometer – arrays are also undergoing a revolution yielding improvements in observational capabilities analogous to the dramatic change enabled by the development of CCDs for optical astronomy in the 1980s. In a couple of decades, submillimeter bolometer cameras have evolved from single-pixel instruments to 10^4 pixels. The rapid growth has resulted from development of fabrication techniques for arrays and large-scale multiplexing enabled by superconducting detectors. Detector sensitivity has routinely reached nearly background-limited performance.

Through the use of superconducting technology the pace of array growth shows no signs of slowing. Conventional bolometer array technology has culminated in the 250 - 500 μm arrays of semiconducting bolometers ("spider web bolometers") for SPIRE on the *Herschel Space Observatory* (to be launched in spring 2009), totaling 337 detectors, and the SHARC-2 350 μm camera on the CSO with 396 Pop-Up bolometers. SCUBA-2 makes use of the state of the art to achieve two 5,120-pixel arrays: superconducting transition-edge sensors (TESs) with superconducting quantum interference device (SQUID) multiplexed readouts.

Even TESs with SQUID readouts, the most significant development of the last decade, are likely to be superseded by imminent technology: microwave kinetic inductance detectors (MKIDs), that will likely make arrays of 10^5 detectors feasible on the timescale of a decade, are one candidate. MKIDs are superconducting, Cooper-pair-breaking resonators with extremely high quality factors (10^5-10^6) with a powerful multiplex advantage – thousands of detectors can be read out with single HEMT amplifiers, with no other cryogenic electronics required.

Each new detector array technology has increased mapping speeds 1-2 orders of magnitude, enabling grand surveys for characterizing star formation on all scales, from dust cores in molecular clouds, to unbiased surveys of the Milky Way, to surveys for star-forming galaxies sensitive to all redshifts. The Galactic observations promise to measure the mass and luminosity functions of star forming regions for comparison to the stellar IMF to help elucidate the transformation from the diffuse interstellar medium, to molecular clouds and cloud cores, to protostars. By virtue of the "negative K-correction" arising from the $T \approx 20 - 60$ K greybody dust spectral energy distributions, deep surveys will detect galaxies with redshifts between 1 and 10 with approximately equal sensitivity, thereby probing the earliest epoch of galaxy formation. Deep, wide-area millimeter-wave observations of the CMB polarization probe the epoch of cosmic inflation; submillimeter, millimeter, and centimeter-wave observations will be necessary because foregrounds, specifically polarized dust emission, produce a significant systematic effect. Observations of secondary CMB anisotropies characterize the formation of galaxy clusters – the most massive structures in the universe, which are therefore extremely sensitive to our cosmology – through gravitation.

4. Summary and Recommendations

4.1 Summary

In this Chapter, we summarize some of the main points we have discussed in the previous Chapters and provide some recommendations regarding the strategy for further development of RMS science during the coming decade.

Multi-wavelength Surveys: As we have described, the overarching scientific themes driving astronomical research today will be addressed not only by RMS facilities, but also by a suite of frontier instruments that spans the entire electromagnetic spectrum. Moreover, systematic surveys of large numbers of sources, including multi-wavelength and synoptic surveys, are becoming an increasingly important and productive strategy for astronomy. Multiwavelength data from such surveys become "virtual skies", often far richer in discovery potential than any single survey or observation by itself. By making such data accessible through the internet, we can provide astronomers anywhere with opportunities to carry out frontier research with only a PC.

Advances in Technology: At the same time, the technology for RMS astronomy facilities is advancing at a breathtaking pace. Advances in the design of telescope arrays and focal plane arrays demonstrate the possibility of gaining orders of magnitude in performance (sky coverage, spectral resolution and bandwidth, sensitivity) over what had been feasible to date. For example: the installation of new focal plane arrays on JCMT and CSO are increasing field of view and spectral resolution of these telescopes by more than an order of magnitude; and the installation of new receivers, fiber optics, and correlators on the VLA are enabling the transformation of this array into the EVLA with gains of more than an order of magnitude increase in bandwidth and sensitivity. Likewise, we can vastly increase the mapping speed of existing telescopes such as Arecibo, GBT, and CARMA by retrofitting them with advanced focal plane arrays.

RMS Discovery Phase Space: We have identified many exciting scientific opportunities that can be addressed with current and future RMS facilities, for example:

- Low frequency arrays currently under construction will perform synoptic surveys of pulsars in the Milky Way, transients of any type, and investigate the feasibility of mapping intergalactic HI during the epoch of reionization (redshifts $7 < z < 20$).
- Mid-frequency SKA precursors such as Arecibo, ASKAP, and MeerKAT will perform systematic surveys of the HI in galaxies in the nearby ($z < 0.5$) universe. But some of the most tantalizing scientific opportunities, such as tracking the assembly and evolution of galaxies with the HI 21cm line at high redshifts, can only be realized by SKA-class arrays.
- VLBI observations allow us to observe cosmic phenomena at angular scales orders of magnitude smaller than any other telescope can see, and have proven their value through such notable discoveries as the discovery and measurement of

the mass of the black hole at the center of NGC 4258 and the demonstration of a technique to measure the distance of galaxies directly through astrometry of such maser sources. The extension of VLBI techniques to millimeter and sub-mm wavelengths promises even higher angular resolution, perhaps sufficient to probe the geometry of space time around a supermassive black hole.

ALMA will be the premier observatory for millimeter and sub-mm science for the foreseeable future. Observations by ALMA, especially in combination with observations at other wavelength bands by EVLA, JWST, and large ground-based optical/infrared telescopes, offer tremendous potential for investigating the formation of stars and planetary systems in the Milky Way and the evolution of galaxies. Early science observations with ALMA are expected to begin in 2010, and full operations in 2013.

The university radio observatories pioneered the technology development that led to ALMA. CSO and CARMA and future facilities such as LMT and CCAT will lay the groundwork for deep systematic surveys by ALMA. In the long run, the performance of ALMA itself may be enhanced substantially as a result of ongoing technology developments at the university radio observatories.

The scientific case for building SKA-class facilities is compelling today[1,2], and will become more so as astronomers probe the Universe with facilities at all bands of the electromagnetic spectrum as well as particle detectors and gravitational wave observatories. Undoubtedly, a substantial fraction of SKA operations will be devoted to surveys, producing databases that will be synergistic with observations obtained at other wavelength bands. Moreover, observations at RMS wavelengths have a history of producing serendipitous discoveries, and the same should be expected with SKA-class facilities.

More than one array will be required to address all the scientific opportunities at centimeter- and meter wavelengths. Like ALMA, SKA-class facilities will require an international effort to be realized. An international consortium of astronomers is devoting considerable effort to developing both the scientific case and technical studies for SKA-class facilities. In the next several years, we can expect considerable progress in refining the science goals/programs, technology, and design of SKA-class facilities.

An emerging international suite of precursor telescopes to SKA-class facilities will test new technologies, clarify issues regarding design and cost, further develop the SKA scientific agenda, and deliver exciting scientific results in their own right. The US is already playing a strong role in the development and construction of several of these precursor telescopes. At meter wavelengths, SKA precursors include MWA, PAPER, LWA, and the Dutch-led LOFAR. At mid-frequencies, SKA precursors include the Allen Telescope Array, the Australian SKA Pathfinder (ASKAP), and the South African MeerKAT array. Finally, the proposed EVLA + VLBA/HSA is a precursor to a high-frequency SKA.

4.2 Recommendations

Our recommendations are based on an assessment of what the landscape of RMS astrophysics might look like ten years from now. Motivated by a compelling science case that addresses the likely key problems in astrophysics for years to come, and cognizant of enabling technologies, this committee identifies four major goals for the US RMS community over the next ten years, and suggests key elements of the strategy to achieve these goals. In making these recommendations we stress the need for a different approach to funding major new initiatives; an approach that allows for the community to respond rapidly to advances in science and RMS technology. The ultimate goal is a strong, balanced program in US RMS astronomy tackling the forefront problems in astrophysics, supported by diverse technological developments and with broad community engagement in both science and technology. Our recommendations are as follows:

The overall goals for RMS science in the US should be:

1. **Maintain a balanced and vigorous program in RMS science and technology development.**
2. **Ensure that the US reaps the scientific benefit of its investment in ALMA.**
3. **Develop technologies for the era of Square Kilometer Array Science**
4. **Nurture partnerships leading to SKA-class facilities**

We address strategies leading to each of these goals in turn.

Goal 1: Maintain a balanced and vigorous program in RMS science and technology development

The strength of US RMS astronomy lies in its breadth in both science and technology, and in the synergism between the national observatories and the university groups, where future generations of astronomers are trained. The elements of a balanced program are:

- **Develop technology and systems for processing, archiving, retrieval, and analysis of large-scale data sets.** The RMS community will be challenged to develop a technical infrastructure that enables astronomers to retrieve and analyze the enormous data sets that will be provided by university radio observatories, and national and international facilities such as EVLA and SKA precursors. The NSF, NASA, and their review committees must ensure that this development is integrated with similar efforts to manage large-scale astronomical data sets at every wavelength band in order to realize the scientific leverage that will result from analysis of multi-wavelength data.
- **Ensure that the broad community is engaged in achieving the scientific goals.** As we move further towards a scientific landscape dominated by large-scale surveys and multi-wavelength science, we must not only provide the community with access to the data products, but we must also nurture broad community involvement in developing and implementing the surveys themselves. There must

also be adequate support for optimizing complementary scientific achievements in theory, computation, and multi-wavelength analysis.

- **Provide adequate and balanced support of forefront facilities used by the community to advance science.** These facilities include the national observatories, the university radio observatories, and smaller, but more focused, experiments such as the ongoing CMB and EoR projects.
- **Upgrade existing forefront facilities with advanced focal plane instrumentation.** If major advances in performance of existing facilities can be achieved by replacing focal plane instrumentation with new receivers, we should do so, provided that the upgraded facilities promise to deliver forefront science for an extended period of time.

Goal 2: Ensure that the US reaps the scientific benefit of its investment in ALMA

With its great sensitivity and angular resolution, ALMA will be the world's forefront observatory for mm/sub-mm astronomy for the coming decade and beyond. Observations with ALMA will greatly advance our understanding of the origin of stars and planetary systems, the evolution of galaxies, and many other cosmic phenomena. The unique capabilities of ALMA are highly complementary with those of other forefront facilities, such as EVLA, JWST, and large ground-based optical/infrared telescopes. To ensure that the US reaps the scientific benefit of its investment in ALMA, we must:

- **Support the development of ALMA pathfinder telescopes.** The scientific effectiveness of ALMA will be greatly enhanced by the programs carried out at the university radio observatories to map the mm/sub-mm sky with telescopes outfitted with focal plane arrays, such as CARMA, LMT and CCAT. We note that both Europe and Japan already have single-dish ALMA pathfinder telescopes at the ALMA site. The US community will need similar access to facilities like LMT and CCAT to effectively utilize ALMA.
- **Support a broad community of US astronomers to use ALMA.** Most ALMA observations will be carried out in a queue-scheduled mode, much as observations are carried out with the NASA Great Observatories. As with those observatories, training and grant support for users to analyze their data will be necessary to nurture and engage a broad community of astronomers in using ALMA.

Goal 3: Develop technologies for the era of Square Kilometer Array science

The construction of SKA-class facilities that deliver transformational capabilities remains a priority of the international RMS community. Our recommended strategy over the next ten years has three essential elements:

- **Undertake precursor observations and programs with existing instruments that explore SKA-class science.** The EVLA is recognized as the global SKA high frequency technological and scientific path finder, and will provide a first look into the sub-μJy radio sky. Likewise, the EVLA, Arecibo, and ATA will perform ground-breaking, wide field surveys in the HI 21cm line, as precursors to the ultra-wide surveys planned for an SKA mid-frequency instrument.

- **Develop, test, prototype, and implement the technologies required to achieve SKA-class science.** This technology development program must be both coordinated and distributed. The core competence in radio science technology that exists in the United States, both in the national radio observatories and in university observatories, should be nurtured and preserved. Moreover, this competence must be extended to include development of technology for data handling, automated data processing, surveys, dealing with data from array feeds, etc. Most critically, we must also ensure the education and training of the next generation of scientists and engineers. The best way to achieve these goals is by carrying out observational programs that address the pressing scientific questions that we have described, which will naturally lead to SKA-class science and technology.
- **Review and assess the progress of the international SKA effort on a continuing basis.** While this Committee was not charged to recommend or prioritize specific facilities, it believes that the international SKA enterprise is extremely important to science. The design, cost and schedule are still under study by the international community.

  The Committee is concerned that the US may be left behind if it is not prepared to join a major SKA-class project when the international community is ready to make such a commitment. The level of international effort and the pace of technology development are such that significant progress is likely across the entire SKA wavelength range in the next several years. If these efforts are fruitful, a significant additional US investment in the SKA Program would be warranted. Since the critical time for such a decision is likely to be out of phase with the traditional decadal timescale, it is important that the NSF monitor the progress of this effort carefully so that the agency is prepared to make such a decision when it is warranted.

Goal 4: Nurture partnerships leading to SKA-class facilities

In the US, the tradition of public/private partnerships has helped to advance RMS astronomy to a point where we can seriously consider the design and construction of ALMA and SKA-class facilities. Facilities of such scale are likely to be realized only through international partnerships. To arrive at the stage where the US is ready to participate in the construction of one or more SKA-class facilities, we should:

- **Support public/private partnerships.** CARMA is a fine example of how public/private partnerships can leverage the development and testing of technologies required for SKA-class facilities. As we advance toward the design of such facilities, the NSF should be prepared to leverage private investments if it becomes clear that the technologies are on the critical path.
- **Participate in international development of SKA-class facilities and precursors.** Continuing NSF support for US astronomers to participate fully in

the international SKA Consortium is critical. US astronomers, at NRAO, NAIC, and at universities, must continue to collaborate with the international SKA consortium in developing technology and planning for SKA-class facilities and their precursors.

- **Support an international "open skies" policy.** The US has led the way in supporting an "open skies" policy, in which access to US radio observatories and the data derived from them are available to astronomers worldwide on the basis of scientific merit, regardless of nationality. This policy has been adopted by many other radio observatories, both privately funded observatories and observatories in other nations. It is the most effective way to ensure that these observatories yield the best possible science and to ensure that the international community of astronomers will cooperate effectively in a worldwide strategy to develop future facilities.

In the era of large international collaborations, the meaning of "open-skies" must be clarified. In the current plans for ALMA, for example, each of the partners is guaranteed a certain percentage of ALMA observing time. If all the partners do not share the open-skies paradigm, astronomers in some regions will have greater access to observing time than those in others. We recommend that the Decadal Survey consider the policies for access to future large facilities.

Likewise, it is important that all data products be archived and become publicly available after some proprietary period. The SKA facilities will operate largely in survey mode, and the archive will become a valuable resource. Just as SKA-class facilities can realize their full scientific potential only with open access to the entire community, an open skies policy for the SKA precursors is essential to a strategy leading to international SKA facilities. To ensure that this happens, the resources required to make the data from such facilities available to the worldwide astronomical community should be included in their development plans. Moreover, US participation in international efforts to develop SKA should be conditioned on the commitment of the international partners to provide open skies access to all data.

Finally, it is important that resources be made available to astronomers to take advantage of the large survey data sets to come. Funding must be made available to US astronomers to analyze ("mine") the large data sets or we risk the payoff being skewed away from the US.

[1] "Science with the Square Kilometre Array", eds: C. Carilli, S. Rawlings, New Astronomy Reviews, Vol.48, Elsevier, December 2004 (http://www.skads-eu.org/p/SKA_SciBook.php)

[2] Schillizi, R. T. et al. 2007, "Draft Specifications for the Square Kilometer Array" (http://www.skatelescope.org/PDF/Draft_specifications_10Sep07.pdf)

5. Facility Names and Selected Other Acronyms

2MASS	Two-Micron All-Sky Survey
ALFA	Arecibo L-band Feed Array
ALMA	Atacama Large Millimeter Array
APEX	Atacama Pathfinder Experiment
ASIC	Application Specific Integrated Circuit
ASKAP	Australian Square Kilometer Array Pathfinder
ASTE	Atacama Submm Telescope Experimnent
ASV	Astronet Science Vision
ATA	Allen Telescope Array
ATCA	Australian Telescope Compact Array
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CCAT	Cornell/CalTech Atacama Telescope
CMB	Cosmic Microwave Background
COROT	COnvection, ROtation & Planetary Transits
COSMOS	Cosmological Evolution Survey
CSIRO	Commonwealth Scientific & Industrial Research Organization (Australia)
CSO	California Submillimeter Observatory
DETF	Dark Energy Task Force
eMERLIN	Multi-Element Radio Linked Interferometer Network
EoR	Epoch of Reionization
e-ROSITA	Extended Roentgen Survey
EVLA	Expanded Very Large Array
FAST	Five-hundred meter Aperture Spherical Radio Telescope
FERMI	*see GLAST*
FIRST	Far Infrared and Submillimeter Telescope
FIRST(VLA)	VLA Survey: Faint Images of the Radio Sky at Twenty-Centimeters
FPA	Focal plane array
FPGA	Field Programmable Gate Array
GAIA	Global Astrometric Interferometer for Astrophysics
GALEX	Galaxy Evolution Explorer
GALFA	Galactic Astronomy w/ Arecibo L-Band Array
GBT	Green Bank Telescope
GLAST	Gamma-ray Large Area Space Telescope
GLIMPSE	Galactic Legacy Infrared Mid-Plane Survey Extraordinaire
GMRT	Giant Meterwave Radio Telescope
HSA	High Sensitivity Array
HEMT	High Electron Mobility Transistor
HERSHEL	*see FIRST*
HESS	High Energy Stereoscopic System
HHT	Heinrich Hertz Submillimeter Telescope Observatory
HST	Hubble Space Telescope
IGPS	International Galactic Plane Survey
IRAC	Infrared Array Camera
IRAM	Institut de Radio Astronomie Millimetrique, operates Plateau de Bure
IRAS	Infrared Astronomical Satellite

JCMT	James Clark Maxwell Telescope
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
LIGO	Laser Interferometer for Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LMT	Large Millimeter Telescope
LOFAR	Low Frequency Array for radio astronomy
LOPES	LOFAR Prototype Station
LSST	Large Synoptic Survey Telescope
LWA	Long Wavelength Array
MACHO	MAssive Compact Halo Objects survey project
MeeRKAT	South African Karoo Array Telescope
MMIC	Monolithic Microwave Integrated Circuit
MOST	Monolithic Microwave Integrated Circuit
MWA	Murchison Widefield Array
NVSS	NRAO VLS Sky Survey
OGLE	Optical Gravitational Lensing Experiment
PALFA	Pulsar (surveys) w/ Arecibo Lband Feed Array
PANSTARRS	Panoramic Survey Telescope & Rapic Response System
PAPER	Precision Array to Probe the Epoch of Reionization
PAST	Primeval Structure Telescope
PTA	Pulsar Timing Array
RMS	Radio millimeter - sub-millimeter
ROSAT	Roentgen SATellite
SCUBA	Submillimetre Common-User Bolometer Array
SDSS	Sloan Digital Sky Survey
SED	Spectral energy distributions
SHARCII	"CCD-style" bolometer array at CSO
SKA	Square Kilometer Array
SKAMP	SKA Molonglo Prototype
SMA	Submillimeter Array
SMT	Submillimeter Telescope
SPIRE	Spectral & Photometric Imaging Receiver on *HERSCHEL*
SPITZER	NASA infrared astronomy great observatory
SPT	South Pole Telescope
SQUID	Superconducting Quantum Interference Device
SWAS	Submillimeter Wave Astronomy Satellite
SWIFT	NASA gamma ray burst observatory
TES	Transition Edge Sensor
UHURU	First dedicated X-ray astronomy observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLSS	VLA Sky Survey
VLT	Very Large Telescope
VSOP	VLBI Space Observatory Programme

WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisortopy Probe
WMCP	Water Maser Cosmology Project
WSRT	Westerbork Synthesis Radio Telescope
XMM	X-ray Multiple Mirror satellite