Radio Astronomy in LSST Era

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1. INTRODUCTION

By the middle of next decade, the Large Synoptic Survey Telescope (LSST) will be in the midst of a decade-long sky survey, en route to producing a deep, multicolor view of the sky and generating potentially a million alerts nightly. Radio wavelength observations will provide independent, complementary views of the sky, and they will be crucial for full exploitation of the LSST data products. A community workshop, held by the National Radio Astronomy Observatory in Charlottesville, VA (2013 May 6–8), was held to explore the science themes of time domain radio astronomy and the radio components of multi-wavelength sky surveys, with the aim of identifying emerging scientific and technical capabilities needed for conducting observations in these areas. The focus of this workshop was primarily on centimeter- and meter-wavelength observations (∼30 MHz–50 GHz). This document is intended to capture the key conclusions and recommendations of that community workshop. Section 2 (and Appendix A) summarizes the likely radio astronomy landscape by the middle of next decade, § 3 discusses the complementary nature of radio astronomical observations and LSST observations, § 4 describes radio wavelength surveys and their complementary nature to the LSST survey, and § 5 summarizes other topics of discussion at the workshop. Appendix B summarizes LSST data products, Appendix C describes potential future radio surveys, and Appendix D lists the workshop participants.

2. RADIO ASTRONOMY LANDSCAPE

Observations at centimeter- to meter-wavelengths have been responsible for the discovery of many of the objects and much of the phenomena studied in modern astronomy and have resulted in the awarding of three Nobel Prizes in Physics. Discoveries include the cosmic microwave background (CMB), quasars, pulsars, indirect evidence for gravitational waves, astrophysical masers, cosmic magnetic fields, nonthermal emission mechanisms (specifically synchrotron radiation), and the jets from black holes and other objects. Moreover, the use of aperture synthesis techniques—also recognized by the Nobel committee—has enabled observations at radio wavelengths to reach unprecedented levels of imaging resolution and astrometric precision not attained in any other wavelength band, providing the fuel for further discovery.

Technological developments over the latter half of the 20th Century, often stimulated by commercial considerations, offer a path to substantial improvements in future radio astronomical instrumentation. Among the range of improvements are mass production of centimeter-wavelength antennas, fiber optics for the transmission of large volumes of data, high-speed digital signal processing hardware for the analysis of the signals, and computational improvements leading to massive processing and storage. Applying these new technologies to radio astronomy can open up an enormous expanded volume of discovery space. A vigorous international program of upgrading existing radio telescopes and constructing new ones has been stimulated by the potential of applying these technologies to radio astronomy, a process that is likely to continue at least through the current decade.

While it is difficult to capture the full range of international activity, it spans much of the available parameter space for radio wavelength observations. Various radio telescopes now allow access to frequencies near the ionospheric cutoff (∼20 MHz) and as high as the significant tropospheric oxygen absorption lines (∼50 GHz). Filled aperture radio telescopes are in operation providing significant surface brightness sensitivity, while interferometers, using the technique of very long baseline interferometry (VLBI), routinely obtain submilliarcsecond resolutions. With modern digital signal processing, submicrosecond time resolution has been obtained, and, in conjunction with data...
archives, decade-long light curves of some objects are being produced. Full polarization measurements of the electric field can also be obtained routinely. Even more significant expansions in one or more directions in parameter space will be enabled with future instruments, including the Hydrogen Epoch of Reionization Array (HERA; Backer et al. 2009); the Square Kilometre Array (SKA; Schilizzi et al. 2010; Dewdney et al. 2013); and a high frequency long-baseline standalone U.S. array, possibly a component of the SKA, grown from the Karl G. Jansky Very Large Array (JVLA) and Very Long Baseline Array (VLBA).15

Appendix A provides more quantitative information about radio telescopes likely to become operational before or during the LSST era. In the spirit of this workshop, these summaries of telescope capabilities are intended to provoke thinking about the kinds of radio wavelength observations that could be conducted both now and during the LSST era.

3. TIME DOMAIN ASTRONOMY

Time domain observations at radio wavelengths have a long history, with the initial theoretical prediction for the existence of neutron stars (Baade & Zwicky 1934) being verified by their discovery at a radio telescope that had a fortuitous combination of a wide field of view and high time resolution (Hewish et al. 1968). Since then, it has been recognized that variable and transient emissions—bursts, flares, pulses—mark compact sources or the locations of explosive or dynamic events. As such, radio transient sources offer insight into a variety of fundamental physical and astrophysical questions such as the cosmological star formation history (through observations of supernovae and gamma-ray bursts), the nature of strong gravity (through observations of radio pulsars), and mechanisms for efficient particle acceleration. Considerable recent excitement has been generated by the report of millisecond radio bursts having properties consistent with a cosmological population of sources (Thornton et al. 2013), suggesting that the radio sky may harbor other, yet-to-be-discovered populations of transient sources as well. The wide field of view and cadence of the LSST suggest that it may have a similar discovery potential as some of the early radio telescopes.

Table 1 summarizes various classes of known radio transients, many of which are likely to have LSST counterparts. Many of these classes have visible wavelength counterparts, and there are many classes of transients that are discovered first at shorter wavelengths before being observed at radio wavelengths. Consequently, fully exploiting the LSST data stream, particularly to include understanding new classes of sources that LSST might detect, is likely to require some amount of follow-up radio observations. Moreover, it is possible that a new class of radio transients might be discovered for which LSST observations would be useful in characterizing the class or determining what the visible wavelength counterparts (if any) are.

The intrinsic transient radio emission or variability from astronomical objects can be broadly grouped into four classes, depending upon their location and emission mechanism. Radio transients can be located in the Galaxy or can be extragalactic, and their emission mechanisms can be either incoherent (e.g., synchrotron) or coherent (e.g., masers). For incoherent processes, particles radiate independently (luminosity $L \propto N$, for $N$ radiating particles), which tends to favor centimeter (and shorter) wavelengths by virtue of the Rayleigh-Jeans approximation. For coherent processes, the emission occurs in phase, which can result from stimulated emission, such as occurs in masers, or from collective processes in which the radiating particles are “bunched” within a wavelength (with $L \propto N^2$). The wavelength of maser emission depends upon the transitions (e.g., OH, H$_2$O), but collective processes tend to favor meter wavelengths because the volume within which particles can radiate in phase scales approximately as $\lambda^3$. These classes are not necessarily exclusive, as some kinds of objects could potentially display incoherent and coherent emissions at different times.

Radio signals are also affected by their propagation through a plasma, e.g., interplanetary medium, interstellar medium, or intergalactic medium (Rickett 1990). These propagation effects tend to be strongly wavelength dependent, and are most significant for compact sources, but can produce considerable apparent time variability. In extreme cases, the propagation-induced variability can exceed 100%, producing brightness changes that far exceed any intrinsic variability.

3.1. Transients at Radio Wavelengths

Many examples of coherent and incoherent Galactic radio transients, as well as incoherent extragalactic sources, are well known, as shown in Table 1. However, only recently have examples of coherent radio transients that are potentially located at extragalactic distances been discovered.16 The millisecond durations of the recently-reported fast radio bursts (FRBs; Thornton et al. 2013) require a coherent emission process (Katz 2013) (see also Lorimer et al. [2007] for a potential earlier example of the same phenomenon). The magnitude of various propagation effects is such that they appear to have been generated at cosmological distances. It is not yet clear if they represent a previously unrecognized coherent emission from a known source population or an entirely new class of objects.

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15A concept for such an array, called the North America Array, was presented in a white paper for the 2010 Astronomy & Astrophysics Decadal Survey, http://science.nrao.edu/A2010/rfs/PPP-NAA-edited.pdf.

16While the pulsars known in the Magellanic Clouds are examples of coherent extragalactic sources, we consider them as extensions of a known Galactic population, rather than examples of a coherently emitting radio source detectable even to cosmological distances.
However, Burke-Spolaor et al. (2011) present a cautionary tale about the determination of sources being at cosmological distances by relying solely on propagation effects, and Loeb et al. (2013) present a model for FRBs in which they originate from stars in the Galaxy.

Incoherent synchrotron emitting radio transients and variables span the range from Galactic to cosmological distances, and many have visible wavelength signatures. Notable examples include active galactic nuclei (AGN), gamma ray bursts (GRBs), supernovae (SNe), jetted tidal disruption events (TDEs), X-ray binaries and microquasars, and novae. From the detection of radio wavelength synchrotron emission, it is possible to obtain positional information (potentially with milliarcsecond localization), energy information (e.g., velocity of blast wave or relativistic outflow), beaming constraints, and information on the density of the surrounding medium. While radio emission from these objects has been detected over a broad frequency range, they tend to share a common evolution in frequency, generally peaking earliest at the highest radio frequencies, cascading to lower frequencies, and potentially remaining observable for months to years at the lowest frequencies (Weiler et al. 2002; see also Chevalier 1982a, 1982b, 1998 and Granot et al. 1998). Strikingly, one of the key transient targets for LSST, Type Ia SNe, has never been detected at radio wavelengths (Panagia et al. 2006).

Recent interest in these kinds of objects tends to focus on short GRBs and TDEs. A subset of TDEs was recently discovered to launch relativistic jets, likely in a similar manner to the radio jets in AGNs, allowing probes of the inner environment of a supermassive black hole (Berger et al. 2012). Short GRBs are the leading candidates for an electromagnetic counterpart to gravitational waves by the merging of a compact binary (e.g., neutron stars), but only a few short GRBs have been detected in the radio to date (Fong et al. 2013). Indeed, possible radio counterparts to gravitational wave events may include coherent bursts (e.g., Hansen & Lyutikov 2001; Pshirkov & Postnov 2010) or incoherent emitters (e.g., Berger et al. 2005; Soderberg et al. 2006; Nakar & Piran 2011; Chandra & Frail 2012) or both.

However, there are several challenges in observing gravitational wave counterparts, either at visible or radio wavelengths. The initial source localizations could be poor (tens to hundreds of square degrees; Wen & Chen 2010; Nissanke et al. 2011; Veitch et al. 2012; Nissanke et al. 2013; Aasi et al. 2011; Veitch et al. 2012; Nissanke et al. 2013; Aasi et al. 2013; Kasiwal & Nissanke 2013; Rodriguez et al. 2013) or both.

| Class                              | Object                                      | Timescale          | $\Delta f_{\text{opt}}$ | Frequency Range       |
|------------------------------------|---------------------------------------------|--------------------|--------------------------|-----------------------|
| extragalactic incoherent .......... | SNe, GRBs, TDEs                             | tens of minutes–years | lags by minutes–months, cascading in frequency | $\sim$0.1–50 GHz      |
| AGN                               |                                             | tens of minutes–years | lags                     | $\sim$0.5–50 GHz      |
| gravitational wave event          |                                             | tens of minutes–years | lags(?) by weeks–years, cascading in frequency | $\sim$0.1–50 GHz      |
| extragalactic coherent ........... | fast radio burst?                           | sub-second         | unknown                  | 1.4 GHz?              |
| gravitational wave event?         |                                             | sub-second?        | unknown                  | $\lesssim$1 GHz?      |
| Galactic coherent ................. | circumstellar, interstellar masers          | ??                 | (not applicable)         | $\sim$1.6–22 GHz      |
| neutron stars                     | sub-stellar objects                         | sub-second         | simultaneous, if present | $\sim$0.1–40 GHz      |
| Galactic incoherent .............. | synchrotron flares, late-type stars,        | sub-second–hours   | unknown                  | 0.01–10 GHz           |
| novae, colliding stellar winds     |                                             | minutes–hours      | lags by minutes          | $\sim$1–200 GHz       |
| unknown                            | “Hyman bursters”                            | minutes            | unknown                  | $\lesssim$1 GHz        |
| propagation effects               | affects pulsars, compact extragalactic      | minutes–days (pulsars), | (not applicable)         | $\lesssim$5 GHz       |
| sources                            |                                             | hours–years (AGN)  |                          |                       |

* a See text for references.

* bb The amount by which the radio emission leads or lags the visible wavelength emission.

* c To date, the only published observations of fast radio bursts are at 1.4 GHz.
Incoherent stellar emission is typically in the form of flares generated as part of magnetic reconnection processes. Thus, the phenomenon is applicable to all classes of magnetically active stars. Sensitive time-domain surveys, such as the Kepler mission, have been expanding the stellar types typically thought of for flaring, particularly to A stars (Balona et al. 2012). M dwarfs have the best constraints on their multi-wavelength characteristics (especially radio and visible wavelength) and, with their large space densities, are expected to be a significant contributor to the transient and variable population that LSST will detect. Because of the rapid timescales involved, it is not feasible to make follow-up observations, necessitating cotemporal coverage during coordinated multi-wavelength observations. Examples of processes in stellar coronae that are yet to be understood include the role of particle acceleration in the production of white stellar flares as well as the upper limit on particle acceleration during large stellar reconnection events.

Examples of Galactic coherent radio transients include neutron stars and substellar objects; there may also be coherent prompt emission associated with violent events such as GRBs (Usov & Katz 2000; Sagiv & Waxman 2002) or gravitational wave events (e.g., binary neutron star mergers). In addition to their regular pulsations, radio pulsars have long been known to have intermittent characteristics as well (e.g., “nulling”). The extent and multi-wavelength aspects of their intermittency are just beginning to be appreciated. Radio pulsars have been found to turn off for days to weeks at a time (e.g., Kramer et al. 2006), and a radio “quiet” mode in PSR B0943 + 10 has been found to correlate with a large increase (more than double) in its X-ray emission (Hermes et al. 2013). The extreme of intermittency is exhibited by rotating radio transients (RRATs); neutron stars that produce only sporadic single radio pulses (McLaughlin et al. 2006); some RRATs have been found to have X-ray counterparts as well.

Although coherent radio emitters are not generally considered to have visible wavelength counterparts, this situation may change in the LSST era. For instance, the annual LSST data releases, or the final (10 year) data release, may be deep enough to enable the detection of the visible wavelength emission from neutron stars, which could be identified as such by virtue of their colors and relatively high proper motions (e.g., Bignami et al. 1993). One strategy would be to confirm which, if any, known neutron stars are detected by this approach. Alternatively, any neutron star candidates so identified within the LSST survey could be targeted with a deep radio search. In a similar vein, sub-stellar objects might either be identified from LSST observations or be detected first in the radio then identified in an LSST data release.

As an example of the first method, nearby brown dwarf candidates could be identified in LSST by their red colors, then targeted for radio searches. As an example of the second method, searches of nearby stars for electron cyclotron maser emission, characteristic of planets, could then use LSST data to assess whether there have been intensity (transit) or astrometric variations of those stars.

3.2. Discussion

The workshop highlighted several key points regarding follow-up observations of transients in the LSST era:

1. X- and γ-ray telescopes, like those on Swift and Fermi, have proven invaluable in the detection and localization of various classes of transients. Swift, for example, is capable of surveying roughly 1/3 of the sky instantaneously and rapidly locating a burst to within a few arcseconds. During the LSST era, it is not clear that there will be a comparable U.S. X- or γ-ray capability, though there may be international capability.

2. An all-sky radio survey, similar to NVSS, but either deeper or higher frequency, or both, is invaluable for having a “baseline image” and reference grid for when a transient is discovered.

3. Two-dimensional radio interferometers can provide and are essential for obtaining precise (<1”) positions for optical cross-identifications and redshifts. In contrast, a transient detected by a single dish can be located only within the primary beam, which is usually several arcminutes across and insufficient for localization.

4. Using the knowledge that we have already acquired about the different types of radio transients and their rates and timescales (Table 1) is likely to be an important aspect of the ability to classify LSST alerts and focus on the most unusual or more interesting events.

More broadly, LSST is projected to produce as many as 1–2 million alerts per night. Formally, an “alert” is simply a notification that there has been a difference between images, which may indicate a moving object (e.g., asteroid), a variable, or a transient. In order to ensure that the necessary follow-up resources can be deployed, it is essential that appropriate classifier filters be developed in order to reliably identify those alerts warranting follow-up observations. Specifically, event filters need to be science-defined and have a carefully considered tradeoff between completeness and purity, or between identifying most of a population (completeness) without being overwhelmed by false alarms (purity). The community will need to develop and test appropriate classification engines based on LSST alert data products, a process that can begin now using on-going visible and near-infrared surveys. Even with the most selective filters, the scientifically “interesting” event rate will overwhelm any plausible follow-up resources. Obtaining useful classifier filters will likely be a multi-stage process, requiring a combination of the knowledge of properties of known classes of transients and high quality pre-existing survey catalogs that provide multi-wavelength information. Even after stringent filtering, attempting to follow up on the most interesting tip of the iceberg might still overwhelm available resources. Instead of triage by default, the community and the observatories could consider defining which types, if any, of LSST alerts would
warrant dedicated follow-up programs, as well as defining how such follow-up programs would be conducted.

Given that the LSST Main Survey is expected to have a well-defined cadence and schedule for observing fields, it may be possible to combine this knowledge with knowledge of radio transient time scales to do “pre-observing” or “blind observing.” For instance, if there were to be a class of radio transients for which the radio emission leads the visible wavelength emission, it would be pragmatic to observe LSST fields before the LSST observations. If the rate of such radio transients is sufficiently high, a multi-wavelength study of a transient could be conducted, even if the field in which it would be observed would not be known a priori. A similar strategy has been used, to great effect, in the observations of Type Ia SNe with the Hubble Space Telescope.

4. SURVEYS OF THE SKY

Radio continuum surveys provide an unobscured view of star formation and accretion activity in galaxies out to the highest redshifts as well as a potentially powerful means of constraining cosmological parameters. Nearly all discrete radio sources are extragalactic and are at cosmological distances \( z \gtrsim 1 \), so their distribution on the sky is nearly isotropic. Surveys covering large solid angles are needed to generate statistically useful samples of nearby \( (z \lesssim 0.1) \) radio galaxies or intrinsically rare objects (e.g., the most luminous quasars), and to make sensitive cosmological tests (e.g., constraining dark energy via the Sachs-Wolfe effect). Radio surveys in the much smaller LSST “Deep Drilling Fields” (\( \approx 10 \) deg\(^2\) each, Appendix B) will be sufficient for generating fair samples to study the evolution of AGNs and star-forming galaxies.

The power that radio continuum surveys have to constrain the cosmological model is becoming more apparent, mostly due to the high-redshift tail of the radio source populations, which are difficult to access in optical surveys. To be of maximum value, redshifts of the objects detected in radio continuum surveys are required, but redshifts greater than unity will be difficult to obtain even in the SKA era. The SKA will measure the 21 cm H I line toward gas-rich galaxies, but the weakness of this line means that individual galaxies will be difficult to detect in this line at \( z > 1 \), and it is unlikely to be useful for gas-poor galaxies. Thus, we will continue to rely on redshifts derived from optical and near-infrared instruments. The LSST’s 6-band optical photometry will provide accurate photometric redshifts to \( z \sim 1.5 \) (based on the 4000 Å break spectral feature) and to \( z > 2 \) (based on the Lyman break spectral feature); these photometric redshifts, particularly if combined with complementary near-infrared photometry, will provide much of the key data necessary to derive the evolution of activity in the Universe, as traced by radio emission. The possibility of obtaining a large number of photometric redshifts for the \( z < 2 \) radio source population with the LSST all-sky survey will allow the remaining unidentified sources to be used for probing the largest scales at the highest redshift (e.g., Raccanelli et al. 2012; Camera et al. 2012). Furthermore, LSST’s multiple visits will probe photometric variability to relatively faint magnitudes, providing additional information to aid in determining which objects contain an active nucleus, and can help classify AGN in the deep radio continuum surveys.

The K-correction of optically thin \((\alpha \sim -0.7, S_\nu \propto \nu^\alpha)\) synchrotron radio sources is so large that samples of \( z > 5 \) sources may still be relatively small in number, even with sensitive surveys at traditional frequencies \((\nu \approx 1.4 \) GHz, but also see below). Toward specific targets, deep, targeted observations have been essential in obtaining precise positions, and the enhanced sensitivity of the JVLA improves this capability substantially. Thus, it is now possible to use ultra-deep 1.4 GHz observations of well-studied fields, like the Chandra Deep Field-North (CDF-N), which has both extensive spectroscopy (both visible wavelength and CO) and X-ray imaging data, to find substantial numbers of massive, star-forming galaxies to the highest redshifts. At higher frequencies \((\nu \approx 5–10 \) GHz), the K-correction of free-free emission is more favorable. Surveys at these frequencies could have a high yield of intense star-forming galaxies at \( z > 5 \), for which the (rest-frame) free-free emission would be the direct result of the ionizing activity of massive stars.

Most radio sources stronger than \( S \sim 1 \) mJy at 1.4 GHz are powered by supermassive black holes in AGNs, while star-forming galaxies increasingly dominate the population of fainter sources. The radio emission from a star forming galaxy is roughly coextensive with the star formation region, so the median angular size of faint sources is no more than about 1″. The 1.4 GHz source counts converge rapidly below \( S \sim 10 \) \( \mu \)Jy, the flux density of a normal galaxy at \( z \sim 1 \). Consequently, instrumental confusion declines sharply for surveys with better than 10″ (FWHM) angular resolution (Condon et al. 2012). “Natural” confusion will never limit sensitivity, unless there is a previously unrecognized population of sources at microJansky flux densities.

In addition to discrete sources, at the sensitivity levels of future radio surveys, diffuse sources such as radio relics and halos in clusters of galaxies could be detected. Synchrotron aging within diffuse sources typically results in diffuse sources having steep radio spectra, necessitating a different survey strategy. Relatively lower resolution surveys at frequencies lower than the “standard” of 1.4 GHz will be needed to maintain surface brightness sensitivity. Extended or filamentary structures may also be traced by cross-correlating the radio surveys with the photometric galaxy density from the LSST survey products.

Radio surveys in the LSST era should be designed to match both (1) known source properties and (2) the planned LSST synoptic surveys covering the whole southern hemisphere, plus up to 30 LSST Deep Drilling Fields covering approximately
10 deg² each. Sensitive radio surveys should have detection limits well below the median brightness temperature of star forming galaxies, $T_B \sim 1$ K at 1.4 GHz. For example, the $50 \mu\text{Jy beam}^{-1}$ (5σ) detection limit in the 10″ (FWHM) beam of the proposed Evolutionary Map of the Universe (EMU) survey of the southern sky (Norris et al. 2011) corresponds to $T_B \sim 0.3$ K. The sky density of LSST galaxies with $r < 27.7$ is so high (about one galaxy per 25 square arcseconds) that radio position errors of order $0′′.2$ (rms) in each coordinate will be needed to make complete and reliable position coincidence identifications. Thermal noise alone contributes errors of order $0′′.1$ FWHM for $5\sigma$ sources, so the deepest radio surveys in the Deep Drilling Fields may have to be made with beams as small as approximately 2″ FWHM.

SKA Precursor and pathfinder arrays (e.g., ASKAP, MeerKAT, WSRT/APERTIF, SKA Phase 1; see Appendix A) may attain survey speeds over portions of the radio spectrum (below 10 GHz, in most cases below 2 GHz) superior to those of the JVLA, but the availability of the JVLA opens the possibilities of starting long-term, large-area surveys now that will be complementary to both future radio surveys and LSST surveys. There was considerable discussion of the benefits of such JVLA surveys, such as earlier epochs for synoptic transient surveys, higher frequency measurements, follow-up for the lower frequency Precursor surveys, and radio counterparts for the visible and near-infrared wavelength surveys that exist or are currently underway (e.g., the SDSS, PanSTARRS, the Palomar Transient Factory, Catalina Real Time Survey, Spitzer Extragalactic Representative Volume Survey). Additionally, data processing and imaging techniques can be developed and tested that will be important for enabling future arrays to realize their full potential. Appendix C gives examples of potential surveys that could be performed in the near future with the JVLA and later with the SKA Phase 1, taking advantage of their new capabilities, in preparation for the LSST era.

In the next few years, and complementing the timescale for any JVLA surveys, the Low Frequency Array (LOFAR) will be conducting a series of tiered surveys to explore the radio continuum sky below 300 MHz. The key aims of these surveys are to trace the evolution of activity with the deepest tiers and to constrain the cosmological model through its large-area survey. The frequencies at which LOFAR operates also makes it highly efficient at discovering steep-spectrum radio sources, such as radio halos and relics associated with massive and likely merging clusters of galaxies, and high-redshift radio galaxies, which typically exhibit steep spectral indices (e.g., Chambers et al. 1996; De Breuck et al. 2000; Blundell et al. 1998; Cruz et al. 2007). (However, Roettgering et al. 1994 present a cautionary counterexample.) The low radio-frequencies of the LOFAR surveys should compensate for the large K-correction and could greatly increase the sample of candidate radio sources at $z > 5$ (and possibly into the epoch of re-ionization), though spectroscopic or reliable photometric redshifts will be required for conclusive identifications.

5. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE DEVELOPMENTS

While the workshop was structured around two science themes, there were several topics discussed that were relevant to both. These topics included “co-observing,” probabilistic detection and classification of sources, and the approach toward Deep Drilling Fields. Further, several questions were raised for which either insufficient time for full discussion existed or no consensus was reached.

“Co-observing” was described as a technique for potentially more efficient use of telescopes. The LSST may broadcast its observing schedule, allowing other observatories to know where the LSST will be pointing. In contrast to the current practice of coordinating observations among multiple, independent telescopes, “co-observing” effectively removes a degree of freedom in the coordination, because the LSST schedule can be treated as fixed and known. Radio telescopes could visit LSST fields with the appropriate lag to find certain classes of sources. However, while identified as a possible observing mode, a specific science case or cases that would benefit explicitly from this approach was not identified.

The use of machine learning or artificial intelligence techniques for source detection and classification is not new in astronomy (e.g., Weir et al. 1995; Rohde et al. 2006). There was widespread agreement that such techniques for the probabilistic detection and classification of sources will be essential in the LSST era, if not well before. It may not be possible to determine with complete confidence whether two objects at different wavelengths (e.g., visible and radio) that lie close together on the sky are in fact the same object, particularly if the flux density of one of the sources is near the detection threshold. Similarly, in the early stages of some variable sources, it may not be possible to distinguish between two or more classes of objects.

The locations of the Deep Drilling Fields yet to be selected were of considerable interest. Many workshop participants found the locations of the four selected Deep Drilling Fields17 (in the “extragalactic sky”) to be well-motivated. However, there was concern expressed that the distribution of strong radio sources in or near a Deep Drilling Field may affect the dynamic range of the radio images that could be obtained, thereby limiting the full extent of multi-wavelength data that could be collected for them. (This issue may also affect the recently announced Hubble Frontier Fields18 Further discussion topics

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17 For more information, see http://www.lsst.org/News/enews/deep-drilling-201202.html.
18 For more information, see http://www.stsci.edu/lst/campaigns/frontier-fields.
included the possibility of additional Deep Drilling Fields that have yet to be selected, the need for at least one of these to be optimized for Galactic targets, and the process by which input into the selection of future Deep Drilling Fields could be provided.\footnote{For more information, see https://www.lsstcorp.org/content/whitepapers 32012.}

There was support expressed for interoperability between software tools, such as has been developed in the Virtual Observatory\footnote{Internationally, Virtual Observatory activities are coordinated by the International Virtual Observatory Alliance (IVOA).} (VO) context. Given the multi-wavelength nature of many projects, as stressed in this workshop, the ability to integrate results from multiple surveys or observations will remain essential. Further, for time domain observations, the capability to distribute notices of transients and obtain rapid response to those transients, if needed, requires communication protocols and inter-operability. More generally, the need for a better focus on topics such as long-term data management and archiving was identified. With data volumes continuing to rise, even well before LSST becomes operational, it is increasingly essential that projects take into account how their data can be discovered, accessed, and analyzed.

There was considerable support for the notion that there is groundwork that could be laid now, both in terms of time domain observations and surveys. While there exist mechanisms today for the rapid response of alerts, it is clear neither that these mechanisms have been optimized, nor whether all avenues for rapid response have been identified. Similarly, there will be radio telescopes capable of conducting deep observations or significant surveys well before the LSST becomes operational. Identifying the science case for such surveys, and then executing them, would be important groundwork for future comparisons with LSST images.

Once the LSST is operational, the resulting data set will render unusual events commonplace, and the rarest of events observable. The challenge for the community is to determine how to use the LSST and its major sister facilities to determine how to optimize the follow-up observations that will be necessary to identify, classify, and characterize those events which represent new physics; clearly, given the size of the transient event pool, a set of stringent standards governing access to complementary facilities, both ground and space-based, will be essential to maximize the scientific output of the LSST, and to balance the ongoing operational missions of existing major facilities with time-critical follow-ups.

Meeting this challenge effectively will require establishing and maintaining broad communications channels between the LSST project, its sister institutions, and within the community at a level that appears to have been relatively uncommon to date. Issues which should be addressed might include identifying and setting up appropriate information flows between LSST and the complementary facilities that could be called upon to provide follow-up or concurrent data, developing trigger standards for such observations, making sure that these criteria evolve to reflect ongoing experience as the LSST refines and ramps up its observing programs, and making certain that sister observatories develop and put in place processes to maintain the de facto community ownership of the LSST transient data pool. As an example specific to NRAO, how should observing time on the JVLA be allocated to follow up particularly intriguing events? Should time be granted based on standing trigger proposals (current NRAO practice), or be restricted to first-come/first-serve telescope time allocations only, or should NRAO consider setting aside a fraction of its observing time for follow-up of LSST transient events that satisfy certain community-established criteria, with the data going immediately into the public domain, or some combination of all of the above? While this example is specific to the NRAO and the JVLA, it may have a broader resonance with the entire nature of “target of opportunity” or “rapid response” proposals and the process of time allocation at telescopes.

Finally, there was considerable discussion of future support. In an era of large surveys, with large numbers of people involved, how can individual investigators obtain funding or be recognized for their individual contributions? At least in the U.S., there is unlikely to be any program dedicated to LSST data analysis analogous to a “guest observer” program.\footnote{There is no dedicated program within NSF for analysis of data from the Atacama Large Millimeter/submillimeter Array (ALMA) or any other ground-based NSF facility.} Among the approaches discussed, though no concrete resolution was achieved, was the question of whether it is possible to design a survey in a manner that would make it easier for researchers involved in the survey to obtain funding.

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APPENDIX A.
RADIO ASTRONOMY LANDSCAPE

Tables 2, 3, and 4 highlight radio telescopes either currently operational or in construction and likely to be operational in the LSST era. These tables may not be complete, and, particularly for telescopes still under construction or in commissioning, various aspects of their capabilities may change. Dewdney et al. (2013) have conducted a similar comparison.

We stress that these values should be taken as illustrative of relative performance, but there are many factors that affect the ultimate performance for a given observing program. The observatories that operate most of the telescopes listed maintain up-to-date status documents that should be consulted for the most recent values.

APPENDIX B.
LSST DATA PRODUCTS

LSST will be a large, wide-field ground-based optical telescope system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The current baseline design, with an 8.4 m (6.7 m effective) primary mirror, a 9.6 deg² field of view, and a 3.2 Gigapixel camera, will allow about 10000 deg² of sky to be covered every three hours.

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### TABLE 2
SINGLE DISH RADIO TELESCOPES

| Parameter                        | Arecibo | Effelsberg | GBT | Parkes | FAST |
|----------------------------------|---------|------------|-----|--------|------|
| Aperture (m)                     | 300     | 100        | 100 | 64     | 500  |
| Frequency Range (GHz)            | 0.3–10  | 0.4–86     | 0.2–100 | 0.7, 1.2–1.8, 2.3, 4.8 | 0.07–3 |
|                                  | (ALFA: 1.4 GHz) |           |     | 8.5, 12–15, 16–26 |
| Resolution (@ 1.4 GHz)           | 3.4     | 8'         | 7' | 14.8   | 2.9  |
|                                  | (ALFA: 7 × 3.4) |       |     | (multi-beam: 14.2)       |
| Sensitivity (μJy MHz⁻¹/² hr⁻¹/²) | 45      | 330        | 112 | 500    | 1050 |
| Survey Speed (deg² hr⁻¹)         | 1.8     | 0.5        | 1.1 | 0.76   | 2.5  |
|                                  | (ALFA: 9.0) |       |     | (multi-beam: 4.6)       |
| Location                         | USA     | Germany    | USA | Australia | USA, China |

**NOTE** —FAST = Five hundred metre Aperture Spherical Telescope; GBT = Green Bank Telescope. Telescopes listed in *italic style* are under construction, and the values listed should be considered notional.

*The listed are the current operational parameters of the Green Bank Telescope. As a result of the Portfolio Review conducted by the U.S. National Science Foundation, the operational model for the GBT will change during or before 2017.

*The quoted values are typically at frequencies near 1.4 GHz, are intended to be illustrative of the relative sensitivity of the various telescopes, and assume a 1 MHz processed bandwidth and 1 hr integration time, with the sensitivity scaling as ($\Delta \nu / 1 \text{ MHz}$)($\Delta t / 1 \text{ hr}$)⁻¹/². In practice, the sensitivity is a function of frequency and all of these telescopes will be classically confusion limited in a much shorter duration than 1 hr, but surveys for spectral lines or time domain observations can approach these sensitivity levels.

*The quoted values are at frequencies near 1.4 GHz and are intended to be illustrative of the relative survey speed of the telescopes. The quoted values are the area (in square degrees) that can be surveyed to a flux density $\Delta S$ of 0.1 mJy (rms) in 1 hr, assuming a processed bandwidth $\Delta \nu$ of 100 MHz. The survey speed scales as $\Delta \nu (\Delta S)^2$.

### TABLE 3
METER-WAVELENGTH INTERFEROMETERS

| Parameter                        | LOFAR | LWA1 | LWA-OVRO | MWA | PAPER |
|----------------------------------|-------|------|----------|-----|-------|
| Frequency range (MHz)            | 10–90, 110–250 | 10–88 | 10–88 | 80–300 | 110–180 |
| Angular Resolution              | 10° (@ 60 MHz) | 2.5 ( @ 80 MHz) | 1.3 ( @ 80 MHz) | 3° ( @ 150 MHz) | 0.5°a |
| Field of View                    | 9.77° ( @ 60 MHz)b | 2.5 ( @ 80 MHz) | 135° ( @ 80 MHz) | 25° ( @ 150 MHz) | 60° |
| Location                         | The Netherlands, Europe | USA | USA | Australia | USA, South Africa |

**NOTE** —LOFAR = Low Frequency Array; LWA = Long Wavelength Array; MWA = Murchison Wide-field Array; PAPER = Precision Array to Probe the Epoch of Reionization. Telescopes listed in *italic style* are under construction, and the values listed should be considered notional.

*The listed value is appropriate when PAPER is configured in an imaging configuration.

*The field of view for LOFAR depends upon the antenna stations used. The value listed is the maximal value, and it scales approximately with frequency.
to four nights using pairs of 15 second exposures, with typical 5σ depth for point sources of \( r \sim 24.5 \) (AB). The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The total survey area will include \( \sim 30000 \text{ deg}^2 \) with \( \delta < +34.5^\circ \), and will be imaged multiple times in six bands, \( ugrizy \), covering the wavelength range 320–1050 nm.

The project is scheduled to begin the regular survey operations at the start of next decade. About 90% of the observing time will be devoted to a deep-wide-fast survey mode (“Main Survey”) which will uniformly observe an 18,000 deg\(^2\) region about 1000 times (summed over all six bands) during the anticipated 10 years of operations, and yield a coadded map to \( r \sim 27.5 \). These data will result in catalogs including over 38 billion stars and galaxies that will serve the majority of the primary science programs. The remaining 10% of the observing time will be allocated to special projects such as a Very Deep and Fast time domain survey.\(^{22}\)

LSST Data Management will perform, in an automated fashion, two types of image analyses resulting in two levels (classes) of data products:

1. Analysis of difference images, with the goal of detecting and characterizing astrophysical phenomena revealed by their time-dependent nature. The detection of supernovae superimposed on bright extended galaxies is an example of this analysis. The processing will be done on a nightly or daily basis and result in Level 1 data products. Level 1 products will include difference images, catalogs of sources detected in difference

\(^{22}\)Informally known as “Deep Drilling Fields,” notionally expected to cover approximately 10 deg\(^2\) each.
images, astrophysical objects to which sources in the difference images are associated, and catalogs of orbits of identified Solar System objects. The catalogs will be entered into the Level 1 Database and made available in near real time. Notifications ("alerts") about differences between images will be issued using community-accepted standards. The primary results of analysis of difference images—discovered and characterized sources—will generally be broadcast as event alerts within 60 s of end-of-visit acquisition of a field, allowing for rapid follow up, lest interesting information about a source be lost.

2. Analysis of direct images, with the goal of detecting and characterizing astrophysical objects. Detection of faint galaxies on deep coadds and their subsequent characterization is an example of this analysis. The results are Level 2 data products. These products, generated and released annually, will include the single-epoch images, deep coadds, catalogs of characterized objects (detected on deep coadds as well as individual visits), sources (detections and measurements on individual visits), and forced sources (constrained measurement of flux on individual visits using known source positions). It will also include fully reprocessed Level 1 data products. In contrast to the Level 1 catalog, which is updated in real-time, the data releases will be static and will not change after release. The analysis of science (direct) images is less time sensitive, and will be done as a part of annual data release process.

3. Recognizing the diversity of astronomical community needs, as well as the need for specialized processing not part of the automatically generated Level 1 and 2 products, LSST plans to make its software and APIs available for community use, and to devote 10% of its data management system capabilities to enabling the creation, use, and federation of Level 3 (user-created) data products. Level 3 capabilities will help bridge the gap between LSST Data Products and the science envisioned for LSST, and enable science cases that greatly benefit from colocation of user processing and/or data within the LSST Archive Center.

APPENDIX C.
PROSPECTIVE RADIO SKY SURVEYS

C.1. KARL G. JANSKY VERY LARGE ARRAY

Nearly 20 years ago, the pioneering FIRST and NVSS radio surveys used the Very Large Array for the first time to carry out large wide area, community accessible surveys and data products. With the newly upgraded JVLA construction complete and full science operations underway, the next generation of large JVLA sky surveys is now possible. With expanded radio frequency and correlator bandwidth, the JVLA is 7 to nearly 100 (at 1–2 and 40–48 GHz, respectively) times faster for continuum and line search studies than the classic VLA. An effort is now underway to plan and implement the next large VLA Sky Survey, the spiritual successor to FIRST and NVSS.

Table 5 summarizes the survey speed of the JVLA, defined as the area per unit time (deg$^2$ hr$^{-1}$) that can be imaged in the continuum to a point source (1σ thermal noise) sensitivity of 100 μJy (assuming natural weighting). Examples of possible JVLA Sky Surveys include:

1. An NVSS-style survey (∼30000 deg$^2$) at 2–4 GHz—This survey would require about 1800 hr of integration time to reach 100 μJy in a single epoch and could be conducted so as to provide both high angular resolution and reasonable surface brightness sensitivity (e.g., using A and C configurations to provide an angular resolution approaching 1″ while maintaining sensitivity to scales as large as 90″). For reference, the NVSS (Condon et al. 1998) program took about 2700 hr to reach a level of 450 μJy (rms) at 1.4 GHz with an angular resolution of 45″ (D configuration).

2. A FIRST-style survey (∼10000 deg$^2$) at 4–8 GHz—This survey would require about 1400 hr of integration time to reach 100 μJy in a single epoch and could be repeated every other

| Frequency (RF Band) | Bandwidth (Mode) | $\Delta t_{\text{int}}$ (s) | Field of View (′) | Survey Speed (deg$^2$ hr$^{-1}$) | Mapping Rate (deg min$^{-1}$) |
|--------------------|------------------|---------------------------|------------------|-------------------------------|-------------------------------|
| 1–2 GHz (L) ..........| 0.6 GHz (8 bit)  | 37                        | 30               | 13.9                          | 0.65                          |
| 2–4 GHz (S) ..........| 1.5 GHz (8 bit)  | 7.7                       | 15               | 16.5                          | 1.56                          |
| 4–8 GHz (C) ..........| 1.8 GHz (8 bit)  | 5.5                       | 7.5              | 5.7                           | 1.08                          |
|                    | 3.03 GHz (3 bit) | 4.4                       | 7.5              | 7.2                           | 1.36                          |
| 8–12 GHz (X) ........| 3.50 GHz (3 bit) | 3.9                       | 4.5              | 2.9                           | 0.93                          |
| 12–18 GHz (Ka) ......| 5.25 GHz (3 bit) | 3.5                       | 3                | 1.4                           | 0.68                          |
| 18–26.5 GHz (K) .....| 7 GHz (3 bit)    | 7.1                       | 2.05             | 0.3                           | 0.23                          |
| 26.5–40 GHz (Ka) .....| 7 GHz (3 bit)    | 9.7                       | 1.45             | 0.1                           | 0.12                          |
| 40–50 GHz (Q) ........| 7 GHz (3 bit)    | 50.4                      | 1                | 0.01                          | 0.02                          |

NOTE.—The field of view is defined to be the full width, half maximum of the antenna power pattern, calculated at band center for the effective interference-free frequency “width” for the chosen sampling mode (8-bit or 3-bit). The “Mapping Rate” is the on-the-fly scanning rate (deg min$^{-1}$) needed to reach this depth.
configuration cycle (32 months). The angular resolution could approach 0.5″ (A-configuration, natural weighting). For reference, the 1.4 GHz FIRST survey (Becker et al. 1995) took about 3200 hr to reach a level of 150 μJy (rms) with an angular resolution of 5″ (B configuration).

3. A medium-deep 1000 deg² synoptic survey at 8–12 GHz—This survey would require about 400 hr of integration time to reach 100 μJy and could be repeated every 16 months (corresponding to the time it takes the JVLA to cycle through its configurations). The angular resolution could approach 0.3″ (A-configuration, natural weighting). This combination of angular resolution and sensitivity would be sufficient to resolve some gravitational lenses while the repetition every configuration cycle would allow identification and monitoring of long duration transients such as TDEs (§ 3.1).

4. A 1000 deg² survey at 12–18 GHz—This survey would require 700 hr of integration time and could have an angular resolution approaching 0.2″ (A-configuration), which might be particularly attractive in the crowded Galactic plane.

5. The previously detailed 1000 deg² synoptic surveys could, at little additional effort, include a lower frequency (1–2 GHz or 2–4 GHz) contemporaneous observation.

6. A repeated coordinated campaign to map and monitor the accessible LSST Deep Drilling Fields more deeply in a number of bands could be carried out separately or as part of a larger multi-tiered survey program.

Although the above examples are directed at continuum surveys, the wide spectral bandwidths available would also enable simultaneous line surveys of (for example) H I, redshifted CO, maser emission, or recombination lines. Blind CO surveys may be particularly profitable, especially if made in well studied regions such as the COSMOS field. In addition to the main suite of receivers covering 1–50 GHz, new low-frequency receivers covering 230–470 MHz (P band) and 58–84 MHz ("4-band" or VHF band) are being commissioned for the JVLA. Furthermore, a commensal low frequency observing system (low-band observatory, LOBO) for the JVLA is under discussion. A limited duration, 10-antenna pathfinder (VLA Low Frequency Ionosphere and Transient Experiment, VLITE) is funded and under development in a partnership between NRAO and the U.S. Naval Research Laboratory. If successful and expanded to LOBO, low-frequency observing could be carried out simultaneously with any of the previous examples.

C.2. SQUARE KILOMETER ARRAY PHASE 1

The key requirements for the SKA Phase 1 to push beyond the Pathfinder instruments are the increase in sensitivity (SKA1_Mid) and survey speed (SKA1_Survey), which allow these surveys to be conducted within 2 years of observing time (similar to ASKAP key projects) or less. The proposed longest baselines of 50 km for SKA1_Survey and 200 km for SKA1_Mid should be sufficient to mitigate instrumental confusion. The SKA Organisation released a baseline design for Phase 1 in 2013 March, describing the basic 3-telescope (SKA_Mid, SKA1_Survey and SKA1_Low) model. Although not the final design, the baseline can be used to identify potential continuum and HI surveys with SKA Phase 1.

C.2.1. Ultra-Deep Continuum Survey with SKA1_Mid

An ultra-deep continuum survey would probe galaxy evolution and star-formation over cosmic time, detect AGN to the Epoch of Reionization, and cover a large enough volume to probe clustering of massive galaxies (e.g., Scoville et al. 2013). An ultra-deep survey conducted at 1.4 GHz should reach a 5σ detection limit of at least 250 nJy and cover at least 6 deg². A resolution of ~1″ will mitigate confusion. An imaging dynamic range of 4 × 10⁶ (66 dB) is required, as one 0.1 Jy source is expected in each ~1 deg² field of view.

C.2.2. Medium-Deep Continuum Survey with SKA1_Mid

A medium-deep survey would probe dark matter via weak lensing. Such a survey must cover at least 5000 deg² to be competitive with the Dark Energy Survey (DES, Sánchez et al. 2010), which is expected to be completed by 2017. The SKA1 survey should achieve at least 0.5 μJy rms at 1.4 GHz with 0.5″ resolution, resulting in about 7 resolved radio sources per square arcminute with a median redshift z ∼ 1.6 (Bacon 2013, private communication, using S³ simulations of Wilman et al. 2008).

C.2.3. All-Sky Continuum Survey with SKA1_Survey

An all-sky radio continuum survey would probe cosmology via two important tests: the integrated Sachs-Wolfe effect and cosmic magnification. This survey should cover at least 20,000 deg² to 1 μJy (rms) at 1.4 GHz. A resolution better than 2.5″ is required to mitigate confusion. An imaging dynamic range of order 10⁷ (70 dB) is required, as one 10 Jy source is expected in each ~20 deg² field of view.

C.2.4. All-Sky H I Survey with SKA1_Survey

An all-sky H I survey could be performed commensurately with the all-sky continuum survey in order to probe the evolution of H I and its role in galaxy evolution. A large-area radio spectroscopic survey could also be used to constrain cosmological parameters via the detection of baryonic acoustic oscillations. An all-sky H I survey with SKA1_Survey could reach 85 μJy (rms) in 0.1 MHz channels over 20,000 deg², yielding roughly 7 million galaxy detections.

2For more information, see http://www.darkenergysurvey.org/.
## APPENDIX D.

### PARTICIPANTS

**TABLE 6**

### WORKSHOP PARTICIPANTS

| Name                  | Institution                                      |
|-----------------------|--------------------------------------------------|
| Andrew Baker          | Rutgers, the State University of New Jersey       |
| Amy Barger            | University of Wisconsin                           |
| Tim Bastian           | NRAO                                             |
| Tony Beasley          | NRAO                                             |
| Niel Brandt           | Penn State University                            |
| Dario Carbone         | University of Amsterdam                           |
| Patti Carroll         | University of Washington                         |
| Tzu-Ching Chang       | ASIAA                                            |
| Shami Chatterjee      | Cornell University                               |
| Tracy Clarke          | Naval Research Laboratory                        |
| Jim Condon            | NRAO                                             |
| Anca Constantin       | James Madison University                         |
| Steve Croft           | UC Berkeley/University of Wisconsin-Milwaukee     |
| Sean Cutchin          | NRAO/NRL                                         |
| Bob Dickman           | NRAO                                             |
| Sean Dougherty        | NRC                                             |
| Michael Garrett       | ASTRON                                           |
| Jason Glenn           | University of Colorado                            |
| Gregg Hallinan        | Caltech                                          |
| Robert Hanisch        | STScI/IAO                                        |
| Assaf Horesh          | Caltech                                          |
| Minh Huynh            | University of Western Australia                  |
| Scott Hyman           | Sweet Briar College                               |
| Matt Jarvis           | Oxford University                                 |
| Dayton Jones          | JPL/Caltech                                      |
| Mario Juric           | LSST                                             |
| Namir Kassim          | Naval Research Laboratory                        |
| Ken Kellermann        | NRAO                                             |
| Brian Kent            | NRAO                                             |
| Amy Kimball           | NRAO                                             |
| Mark Lacy             | NRAO                                             |
| Cornelia Lang         | University of Iowa                                |
| Casey Law             | UC Berkeley                                      |
| Joseph Lazio          | Jet Propulsion Laboratory, California Institute of Technology |
| Dana Lehr             | National Science Foundation                      |
| Sam Lindsay           | University of Heriotshire                         |
| Brian Mason           | NRAO                                             |
| Walter Max-Moerbeek   | NRAO                                             |
| Mark McKinnon         | NRAO                                             |
| Kunal Mooley          | California Institute of Technology               |
| Tony Mroczkowski      | Caltech/JPL                                      |
| Steven Myers          | NRAO                                             |
| Bojan Nikolic         | University of Cambridge                          |
| Rachel Osten          | STScI                                            |
| Joshua Peck           | Columbia University                               |
| Phil Puxley           | National Science Foundation                      |
| Peter Quinn           | International Centre for Radio Astronomy Research (ICRAR) |
| Bart Scheers          | UvA/CWI                                          |
| Nigel Sharp           | NSF                                              |
| Ohad Shemmer          | University of North Texas                         |
| Albert Stebbins       | Fermilab                                         |
| Tony Tyson            | UC Davis                                         |
Table 6 lists the participants in the workshop.

| Name                  | Institution   |
|-----------------------|---------------|
| Paul Vanden Bout      | NRAO          |
| Lucianne Walkowicz    | Princeton University |
| Peter Williams        | Harvard       |
| B. Ashley Zauderer    | Harvard       |

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