12 New Technologies for Radio Astronomy

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CONTENTS

INTRODUCTION

In this 400th year since the invention of the optical telescope, and in celebration of the *New Vision 400* conference held in Beijing in 2008,* we discuss how new radio astronomical techniques have led to important discoveries in astronomy. We then describe how further technical developments are leading to new facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA), the largest ground-based astronomical facility now under construction, and to the next-generation radio astronomy facilities, collectively named the Square Kilometre Array (SKA), or the SKA Program.

The advent of new technologies in radio astronomy, ironically, has little to do with the invention of the optical telescope 400 years ago. Developed from techniques of radio broadcasting and communication, and especially propelled by the rapid advancement of radar techniques during World War II, radio astronomy opened up the first electromagnetic window into the Universe beyond the visible wavelengths and transformed a view of the Universe that had previously been based entirely on optical studies of stars and nebulae. The most fundamental discoveries made by radio astronomers involve phenomena not observable in visible light, and four Nobel Prizes in Physics have been awarded for discoveries enabled by radio astronomy techniques.

DISCOVERIES ENABLED BY RADIO ASTRONOMY TECHNIQUES

The advent of new techniques leading to new discoveries in the Universe is a pervading theme in astronomy. The transformation of our understanding of the Universe due to radio astronomy is rather

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* See: http://nv400.uchicago.edu/.

profound. Table 12.1 gives a list of major new astronomical phenomena discovered as a result of new radio astronomy techniques, as well as the resulting new understanding of the Universe.

Radio astronomy from the ground covers a very wide wavelength range: $\lambda \sim 30$ m to ~300 μm, corresponding to a frequency range of ν ~10 MHz to ~1 THz. In radio astronomy, the techniques of reception and detection of the electromagnetic wave are different from those at optical wavelengths. Whereas geometric optics governs the design of optical telescopes, electromagnetic wave theory governs the design of radio telescopes, taking account of the wavelength explicitly because it is no longer negligible compared with the dimensions of the telescope. The detection of radio waves is based on heterodyne detection (or coherent detection) of the electric field $\boldsymbol{E}$, whereas the detection of visible light is via incoherent detection of E^2, the intensity of the electric field—i.e., photon counting. Heterodyne detection of the radio wave involves the use of a nonlinear detector that produces a beat signal between the radio signal and a local oscillator (reference) signal. In a domestic radio receiver, the beat signal is the sound waves we hear. Because the wavelength of radio waves is some millions of times greater than that of light, the diffraction limit of a single-dish radio telescope, λ/D, is typically in the range of degrees to arcminutes, whereas the angular resolution of ground-based optical telescopes without adaptive optics is limited by atmospheric fluctuations to about 0.5 arcsec.

By the 1920s, radio communication techniques were developed to the extent that there were commercial radio broadcasting, a worldwide network of commercial and government radiotelegraphic stations, and extensive use of radiotelegraphy by ships for both commercial purposes and passenger messages. In 1932, Karl Jansky at Bell Laboratories was assigned to investigate the sources of radio

TABLE 12.1

New Astronomical Phenomena Discovered via Radio Astronomy Techniques

Discovery	Impact	Year	Ref.
Milky Way radio noise	Cosmic radio emission exists	1933	1
Solar radio noise	Radio emissions of normal star	1945	2
21 cm line of atomic hydrogen	Interstellar medium important component of galaxies	1951	3
Double nature of radio galaxies	Need for large-scale energy transport from AGNs	1953	4
Cosmic microwave background (CMB)	Remnant heat of Big Bang	1965	5
Pulsars	Neutron stars exist	1968	6
Polyatomic interstellar molecules	Astrochemistry, precursors of life in space	1968	7
Molecular clouds	Birthplaces of stars and planets	1971	8
Superluminal motion in AGNs	Relativistic potential wells in Galactic nuclei	1971	9
Galactic center source Sgr A*	Subparsec-scale structure at center of Milky Way	1974	10
Flat H I rotation curve of M31	Dark matter halos of galaxies	1975	11
Binary pulsar	Gravitational radiation	1975	12
Anisotropy of CMB	Origins of cosmological structure	1989	13
Pulsar companions	Exoplanets	1992	14

References: (1) Jansky (1933); (2) Southworth (1945); Appleton (1945); (3) Ewen and Purcell (1951); (4) Jennison and Das Gupta (1953); (5) Penzias and Wilson (1965); (6) Hewish et al. (1968); (7) Cheung et al. (1968); (8) Buhl (1971); (9) Cohen et al. (1971); (10) Balick and Brown (1974); (11) Roberts and Whitehurst (1975); (12) Hulse and Taylor (1975); (13) Smoot et al. (1992); (14) Wolszczan and Frail (1992).

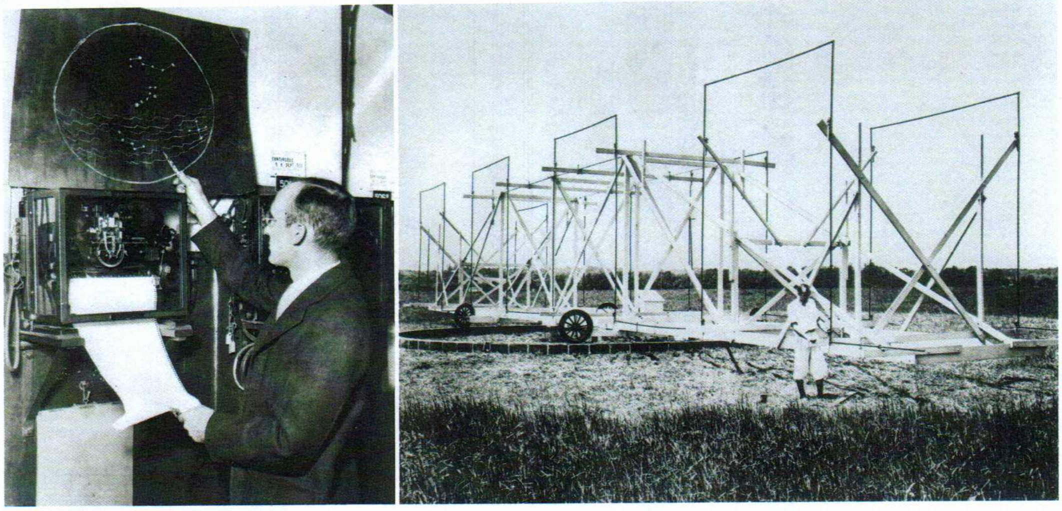

FIGURE 12.1 Karl Jansky (*left*) and the movable dipole array antenna (*right*) with which he discovered cosmic radio noise at Bell Laboratories in 1932. (Courtesy of the NRAO Archives.)

noise that might interfere with transatlantic radio–telephone transmission. He built a directional radio antenna (Figure 12.1) made up of a phased array of vertical dipoles producing a fan beam near the horizon in the direction perpendicular to the length of the antenna so he could locate the sources of interfering radio emissions. His serendipitous discovery of radio emission from the center of the Milky Way (Jansky, 1933) was clearly a case of a new technology unexpectedly matching a natural phenomenon. At that time, radio emission from an astronomical object was unexpected because astronomers had been familiar only with thermal radiation that is very weak in radio wavelengths at stellar temperatures. As a result, the mechanism of astronomical radio emission from beyond the Solar System remained a puzzle for many years.

It was later realized (Ginzburg, 1951; Shklovsky, 1953) that cosmic radio waves could be produced nonthermally by synchrotron radiation (Alfvén and Herlofson, 1950; Kiepenheuer, 1950) from relativistic electrons spiraling in magnetic fields. Astronomers then became aware of the enormous energy reservoirs that must underlie the nonthermal radio emission that occupies volumes hundreds of kiloparsecs in extent (Jennison and Das Gupta, 1953) around radio galaxies (Figure 12.2) and, later, radio-loud quasars. As the most luminous of these extra-Galactic radio sources can be detected at look-back times that are significant fractions of the age of the Universe, their discovery immediately extended the "reach" of observational cosmology. The need to *resolve* these radio structures in order to elucidate the physics of their prodigious energy supply motivated the development of the first high-resolution radio interferometers.

A key innovation at Cambridge University in the 1960s, for which a share of the 1974 Nobel Prize in Physics was awarded to Martin Ryle, was the use of *Earth-rotation aperture synthesis* to make images of the radio sky. Ryle (1962) married techniques from Fourier optics and phase-stable interferometry to then-emerging methods in "fast" digital computing, to realize "synthetic apertures" a few kilometers in diameter D. To obtain still better resolution λ/D, it was necessary to exploit the fact that measurements in radio astronomy are far from being photon-limited. This allows *multi-element* interferometers many kilometers in extent to be used with the principle of *phase closure** (Jennison, 1958) to adaptively correct images for the effects of atmospheric and instrumental

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* The "closure" phase is a quantity derivable from the phases measured for an incoherent source by a *triplet* of Michelson interferometers independently of instrumental errors. Use of closure-phase information underpins many algorithms for removing instrumental and atmospheric effects from sky images made using multi-element interferometers.

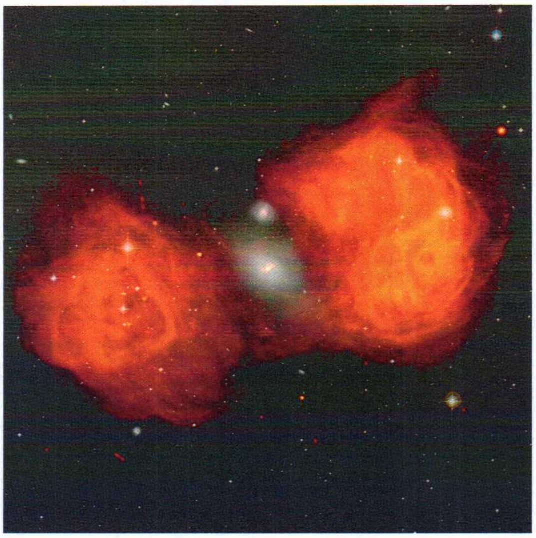

FIGURE 12.2 The radio galaxy Fornax A (1.4 GHz continuum intensity observed with the VLA shown in orange) superposed on an optical (STScI/POSS II) image of a 0.97-degree region around the giant elliptical galaxy NGC 1316. The active nucleus of NGC 1316 has energized two radio "lobes" each ~180 kpc in extent. (From radio data of E.B. Fomalont, R.D. Ekers, W. van Breugel, and K. Ebneter. Image © NRAO/Associated Universities, Inc.)

fluctuations. In the early 1980s, new "self-calibration" algorithms (Pearson and Readhead, 1984) and faster digital computers allowed the 27-element Very Large Array (VLA; Figure 12.3) to surpass the resolving power of the great optical telescopes while making high-quality radio images. Using high-bandwidth data recorders, atomic clocks as local oscillators, and custom-built digital correlators, very long baseline interferometry (VLBI) (Bare et al., 1967; Broten et al., 1967; Moran et al., 1967) extended these methods to synthesize Earth-sized apertures (and larger, using orbiting antennas). VLBI enabled the highest-resolution imaging and the most precise astrometry that has ever been realized for astronomy. These technical advances were used to show that the enormous extra-Galactic radio sources are powered by relativistically moving jets that originate on subparsec scales deep within active galactic nuclei (AGNs). This led to acceptance of the idea that the AGN power source is the extraction of gravitational and rotational energy via accretion of matter (and magnetic fields) into the relativistic potential wells of supermassive black holes (BHs) at the centers of galaxies, as originally proposed by Salpeter (1964) and Lynden-Bell (1969).

Also at Cambridge University, a dipole antenna array designed to study time-variable signals due to interplanetary scintillation of small-diameter radio sources at 81.5 MHz (3.7 m wavelength) came into operation in 1967. Its large (~4.5 acre, i.e., ~18,600 m^2) area collected sufficient signal to detect variability with time constants as short as 0.5 sec. Although aimed at investigating the structure of small-diameter radio sources by studying signal fluctuations caused by irregularities in the solar wind, this array and its instrumentation were ideally suited to detecting short pulses of radio emission spaced ~1.3 sec apart from a previously unknown source, which was fleetingly suspected to be due to extraterrestrial intelligence. Such pulsing sources (Hewish et al., 1968) were subsequently identified with neutron stars (Gold, 1968; Pacini and Salpeter, 1968), whose existence had been theoretically predicted based on supernovae (Baade and Zwicky, 1934). Hewish shared the 1974 Nobel Prize in Physics for the discovery of the "pulsars."

Another exceptionally large antenna, the 305 m (1,000 ft)-diameter spherical reflector at the Arecibo Observatory in Puerto Rico (Figure 12.4), was later used at 430 MHz to detect the first millisecond pulsar in a binary system (Hulse and Taylor, 1975). This discovery opened the way to precise measurements of the merging of the close binary system that are consistent with energy loss by

FIGURE 12.3 The NRAO's VLA on the plains of San Agustin near Socorro, New Mexico. The VLA uses 27 25 m (82 ft) antennas to make images of the radio sky at centimeter wavelengths by Earth-rotation aperture synthesis. (From © NRAO/Associated Universities, Inc.)

gravitational radiation, for which Hulse and Taylor were awarded the 1993 Nobel Prize in Physics. Pulsars, especially millisecond pulsars, which are very accurate clocks, and particularly the 22 ms double pulsar (Burgay et al., 2003) discovered with the 210 ft (64 m) antenna at Parkes, Australia, have become very important for exploring a wide range of fundamental physics issues. These issues include nuclear equations of state, general relativity in the strong-field limit, and the indirect and direct detection of gravitational waves (GWs), primarily based on precise measurements of the arrival time of pulsar pulses with accuracy now achievable near the 100 ns level.

Centimeter-wave and meter-wave astronomy of nonthermal sources at high angular and time resolution thus made relativistic astrophysics an *observational* science by revealing new classes of object whose measurable properties are dominated by effects of special relativity (aberration, beaming) or of general relativity (lensing, gravitational radiation). Equally fundamental progress was made through new techniques applied to observations of thermal emission and to radio spectroscopy.

The detection of the 2.7 K cosmic microwave background radiation (CMBR; Penzias and Wilson, 1965), now accepted as the remnant heat of the Big Bang, was technically achievable owing to the combined use of a highly sensitive maser amplifier receiver and a "horn" antenna designed to minimize stray radiation from the ground (Figure 12.5). Because of the resultant high sensitivity of the antenna-receiver system, the unexplained excess signal was impossible to dismiss and was ultimately identified as the CMBR, resulting in the award of a share of the 1978 Nobel Prize in Physics to Penzias and Wilson. In 1989, the *Cosmic Background Explorer* (*COBE*) satellite documented the precise blackbody spectrum of the CMBR, confirming its interpretation as the residual heat from the primordial explosion of the Big Bang. *COBE* also measured the level of anisotropies in the CMBR that indicate the seeds of structure that evolved into galaxies and clusters of galaxies (Smoot et al.,

FIGURE 12.4 The Arecibo 305 m (1,000 ft) telescope at the National Astronomy and Ionosphere Center in Puerto Rico. (Courtesy of the NAIC–Arecibo Observatory, a facility of the NSF.)

1992). More than 40 years after the initial discovery by Penzias and Wilson, detailed ground-based (Halverson et al., 2002; Mason et al., 2003), balloon-borne (de Bernardis et al., 2000; Hanany et al., 2000), and space-based (Bennett et al., 2003) observations of the anisotropies in the CMBR, for which John Mather and George Smoot shared the 2006 Nobel Prize in Physics, led to a precise determination of all the cosmological parameters, including the age, the curvature, and the energy densities of the various components of the Universe (e.g., Spergel et al., 2007). Perhaps most importantly, when combined with the discovery of the acceleration of the cosmic expansion via the Type

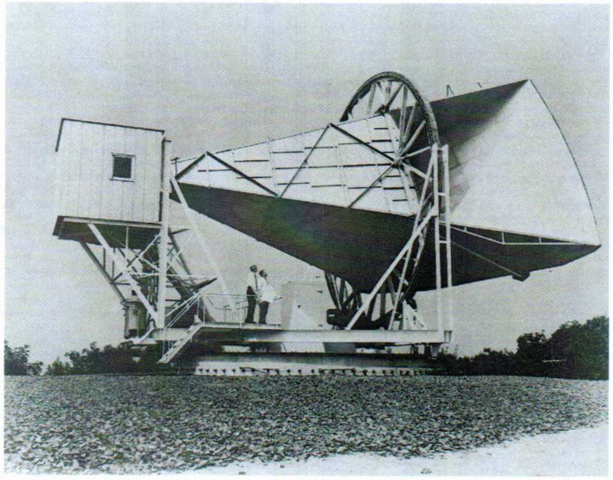

FIGURE 12.5 The horn antenna used by Penzias and Wilson at Bell Laboratories in 1963 to discover the cosmic microwave background. (From NASA photograph.)

Ia supernova Hubble diagram (Knop et al., 2003; Astier et al., 2006; Riess et al., 2007), the CMBR measurements helped to identify dark energy, a term denoting a hitherto completely unknown component of the Universe, making up almost three-quarters of the cosmological energy content.

Another major astronomical discovery made possible by radio techniques was the extensive presence of neutral hydrogen atoms in interstellar space. To begin with, the realization that detecting a radio frequency spectral line would allow its Doppler shift to be used to map motions in the Milky Way led Jan Oort in Leiden to assign his student Hendrik van de Hulst the task of identifying candidate lines for study. This led to the suggestion (van de Hulst, 1945) that the 21 cm hyperfine transition in the ground state of the hydrogen atom might be observable if the lifetime of the upper state is not too great. The detection of this H I line from the Milky Way was accomplished in 1951 (Ewen and Purcell, 1951; Muller and Oort, 1951). Specifically, the novel technique developed by Ewen and Purcell that enabled the detection of the line was "frequency switching," by which the reference local oscillator signal was periodically switched between two frequencies. Frequency switching turned the detection of the line into a differential measurement instead of a much more challenging detection of a weak spectral signal amidst a high background continuum signal.

Subsequent observations demonstrated that atomic hydrogen gas is extensively distributed in the Milky Way and in external galaxies, showing that the interstellar medium (ISM), while dark, is by no means empty, and also providing evidence from Galactic rotation curves for the presence of dark matter halos in galaxies (e.g., Roberts and Whitehurst, 1975).

In the late 1960s and early 1970s, the application of laboratory microwave spectroscopic techniques to astronomy enabled the discovery of inorganic and organic molecules in interstellar space, ushering in the new field of astrochemistry in the ISM, which may yet reveal the pervasive existence of building blocks of life, such as amino acids, in interstellar space. These studies also revealed the extensive existence of molecular clouds in the ISM within the Milky Way and in external galaxies. The technical innovations at that time involved the availability of large high-frequency telescopes (e.g., the National Radio Astronomy Observatory's [NRAO]* 43 m [140 ft]) and high-precision millimeter-wave telescopes (e.g., the NRAO 36 ft [later 12 m] and the University of Texas Millimeter Wave Observatory 5 m [16 ft]); of digital correlator spectrometers (Weinreb, 1963); and of low-noise centimeter-wave amplifiers, such as electron-beam parametric amplifiers (Adler et al., 1959) and maser amplifiers (e.g., Alsop et al., 1959). The invention of sensitive superconductor-insulator-superconductor (SIS) mixer millimeter-wave receivers (Tucker, 1979; Phillips and Dolan, 1982) was also crucial to this field.

ALMA†

The most important astronomical consequence of discovering the significant molecular component of the ISM was the subsequent demonstration that the birth of stars takes place within molecular clouds. Understanding the physical mechanisms of star formation is basic to understanding the formation of stars, planets, and galaxies. The recognition of the importance of studying such processes within molecular clouds in the Milky Way, and in galaxies going back to the epoch of reionization when the first luminous objects were formed, has led to the construction in Chile of what is currently the largest telescope facility for ground-based astronomy—ALMA.

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* The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. (AUI).

† An international astronomy facility, ALMA is a partnership of Europe, North America, and East Asia in cooperation with the Republic of Chile. It is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO); in North America by the US NSF in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC); and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO; on behalf of North America by NRAO, which is managed by AUI; and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning, and operation of ALMA. More information can be found at http://www.nrao.edu/ and http://www.almaobservatory.org/.

When completed by the end of 2012, ALMA will be among the most powerful telescopes ever built. With unprecedented sensitivity, resolution, and imaging capability, it will explore the Universe via millimeter- and submillimeter-wavelength light, one of astronomy's last frontiers. ALMA will open a new window on celestial origins, capturing new information about the very first stars and galaxies in the Universe, and directly imaging the formation of planets. Located at Llano de Chajnantor in the Andes in northern Chile (Figure 12.6), one of the world's best sites for astronomy, ALMA will reside at an elevation of 16,500 ft (5,000 m) above sea level and include at least 66 high-precision submillimeter-wave telescopes. ALMA, an international astronomy facility, is a partnership of Europe, North America, and East Asia in cooperation with the Republic of Chile.

SCIENTIFIC CASE

The primary science goals that have been used to develop the technical specifications of ALMA are (1) the ability to detect spectral line emission from CO or C+ in a normal galaxy, such as the Milky Way at a redshift of $z = 3$, in less than 24 hr of observation; (2) the ability to image the gas kinematics in a solar-mass protoplanetary disk at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation; and (3) the ability to provide precise images at an angular resolution of 0.1 arcsec. Here the term "precise image" means an accurate representation of the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This last requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

To meet these scientific goals, ALMA will have the following superior capabilities:

- at least fifty 12 m (39 ft) submillimeter-wave telescopes for sensitive, high-resolution imaging;
- four additional 12 m (39 ft) telescopes, providing total-power data, and twelve 7 m (23 ft) telescopes making up the ALMA Compact Array (ACA), enhancing the fidelity of wide-field imaging;
- imaging ability in all atmospheric windows from 3.6 to 0.3 mm (84–950 GHz), with coverage down to 10 mm (30 GHz) possible through future receiver development;

FIGURE 12.6 Geographic location of ALMA in Northern Chile. (From © ALMA (ESO/NAOJ/NRAO).)

- array configurations with maximum baselines from approximately 150 m to 15 km;
- ability to image sources many arcminutes across at arcsecond resolution;
- top spatial resolution of 5 mas (better than the VLA and *Hubble Space Telescope* [*HST*]);
- top velocity resolution better than 0.05 km/sec.

ALMA will be a complete astronomical imaging and spectroscopic instrument for the millimeter/submillimeter wavelength range. It will provide scientists with capabilities and wavelength coverage that complement those of other research facilities of its era; under construction, such as the Expanded Very Large Array (EVLA) and the *James Webb Space Telescope* (*JWST*); or being planned, such as the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT), the European Extremely Large Telescope (E-ELT), and SKA. Specifically, ALMA will fill in a crucial scientific gap by providing a sensitive, high-resolution probe of the properties of cold gas and dust in star-forming regions in our Galaxy and other galaxies, as well as in protoplanetary disks. Given that these regions are obscured at visible wavelengths, ALMA will complement shorter-wavelength observations by providing a complete picture of these cold regions in which stars and planets are formed.

TECHNICAL CHALLENGES

ALMA presents many technical challenges, notably the high-precision submillimeter telescopes, the quantum SIS mixers, phase-stable fiberoptic transmission of signals over 15 km, and the pairwise digital correlation of the signals from all the telescopes. The ALMA telescopes are the highest-precision radio telescopes ever built, and they must maintain their accurate shape under the strains of open-air operation on the high-altitude Llano de Chajnantor site near the oasis town of San Pedro de Atacama in northern Chile. This site offers the exceptionally dry and clear sky required to operate at millimeter/submillimeter wavelengths, but it also experiences large diurnal temperature variations and strong midday winds. Other major performance requirements of each antenna are 2 arcsec absolute pointing over the whole sky, 0.6 arcsec ($\sim 10^{-5}$ radian) offset pointing, a 25 μm RMS overall surface accuracy, and the ability to change its pointing over a 2-degree range in less than 1.5 sec and operable under winds up to 30 km/hr. In addition, these telescopes have to preserve their specifications after repeated moves that are needed to reconfigure ALMA and to survive earthquakes up to magnitude ~8. In the early planning stages of ALMA, such requirements posed serious concerns about whether they can be met in practice, and three different prototype telescopes were built to demonstrate the feasibility of constructing the ALMA telescopes.

Receiving systems on the ALMA telescopes will cover the entirety of the electromagnetic spectrum observable from the Earth's surface from 31.3 to 950 GHz (9.6–0.32 mm in wavelength). At the heart of the receiving system are SIS quantum tunnel junction mixers, operating at 4 K (–269°C) with sensitivities below a few times the quantum limit: single sideband $T \leq 6\text{–}10\ h\nu/\mathrm{k}$ for $\nu \leq 1$ THz. Such detectors are not commercially available and can be fabricated only in a handful of laboratories throughout the world, requiring the mastery of the techniques of planar circuit design, thin-film deposition, lithography, and cryogenics. The production of hundreds of such detectors for ALMA at different locations in Europe, North America, and East Asia is technically and logistically very challenging and unprecedented.

All the telescopes of ALMA must operate with constant phase relationship relative to one another. As a result of the unprecedented combination of high observing frequencies (up to 950 GHz) and long baselines (up to 15 km), this poses a particularly difficult challenge. ALMA can be thought of as 66 radio receivers, with the main "tuner" for each of the radios (the source of the reference signal) located in a central technical building. The reference signal to each telescope is transmitted over an optical fiber with lengths up to 15 km. This central "tuner" must tune from 27 to 122 GHz by differencing the frequencies of two very-high-frequency oscillators (lasers!), and the low jitter is achieved by phase-locking the lasers to very low noise microwave references.

However, even if this central "tuner" were a perfect clock, the distribution of the ALMA main tuner (reference) signals must be distributed to the telescopes using fiberoptic transmission with an electrical length maintained to an accuracy of <3.6 μm out of 15 km (corresponding to the RMS phase variation, $\delta\varphi$, to be ≤ 0.55 degree at 119 GHz or a timing error of ≤ 13 fs) for a fractional stability ratio of 2.4×10^{-10}! The approach adopted by ALMA to maintain the phase stability uses a very accurate yardstick—the master laser—to probe the small changes in the fiberoptic delay to each antenna and to use an optoelectronic line-length compensator to continuously correct the small changes in the delay. The master laser accuracy must be better than the required fiber path-length accuracy, and the delivered unit had accuracy better than 10^{-12} fractional stability ratio over timescales of typical ALMA observing periods (1–1,000 sec).

ALMA continuously correlates the signals from all the pairs of telescopes in the array (there are 1,225 antenna pairs in the main 50-telescope array and 66 pairs in the 12-telescope compact array). From each antenna, signals across a bandwidth of 16 GHz will be received from the astronomical object being observed. The electronics will digitize and correlate these signals at a rate of over 1.6×10^{16} operations per second. Astronomical images will then be numerically constructed from the correlation of the signals of all the antenna pairs via Fourier transform after suitable calibration and corrections to the "raw" correlation of the signals.

CURRENT STATUS

JAO in Chile, which operates ALMA on behalf of the three regions (see footnote 4), consists of three components: the Array Operations Site (AOS), the Operations Support Facilities (OSF), and the Central Offices in Santiago. The AOS (Figure 12.7), where the telescopes and technical building (which houses the correlator) are located, is at 5,000 m elevation (16,400 ft). The array will be operated, and maintenance of the telescopes and electronics will be carried out, 33 km from the AOS at the OSF (Figure 12.7), just below 3,000 m (9,800 ft) elevation.

The construction of ALMA is well on its way, having achieved first light and first closure phase with three telescopes (Figure 12.8) by December 2009. Production of the antennas and electronics is proceeding steadily, with more than two dozen telescopes in various stages of assembly in Chile in early 2010 (Figure 12.9). It is planned that ALMA, with at least 50 telescopes, will be inaugurated by the end of 2012.

SKA*

While ALMA is a transformative astronomy facility covering the millimeter- and submillimeter-wavelength range, many astronomical issues require a revolutionary facility covering the meter- and centimeter-wavelength range. Current forefront centimeter- and meter-wave radio telescopes typically have a collecting area A ~10,000 m^2 and receiver system temperature T on the order of 50 K. As the sensitivity of a radio telescope is characterized by A/T and T is nearing the theoretical limit to within a factor of a few, any significant advance of sensitivity must henceforth be obtained by increasing A. In order to carry out scientific explorations far beyond current sensitivities, the SKA (Figure 12.10) aims to achieve a 100-fold sensitivity increase over the current centimeter- and meter-wave telescope facilities by building an array with a collecting area of 1 km^2 or 10^6 m^2, as indicated by the name. Furthermore, the SKA will also be optimized for surveys and therefore designed to achieve a very wide field of view. To achieve the requisite high resolution, the largest dimension of the SKA will reach ~3,000 km. The frequency range will span from ~70 MHz to ~22 GHz (corresponding to a wavelength range of ~4 m to ~1.4 cm).

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* The SKA Program is an international effort; current information about the program can be found at http://www.skatelescope.org/.

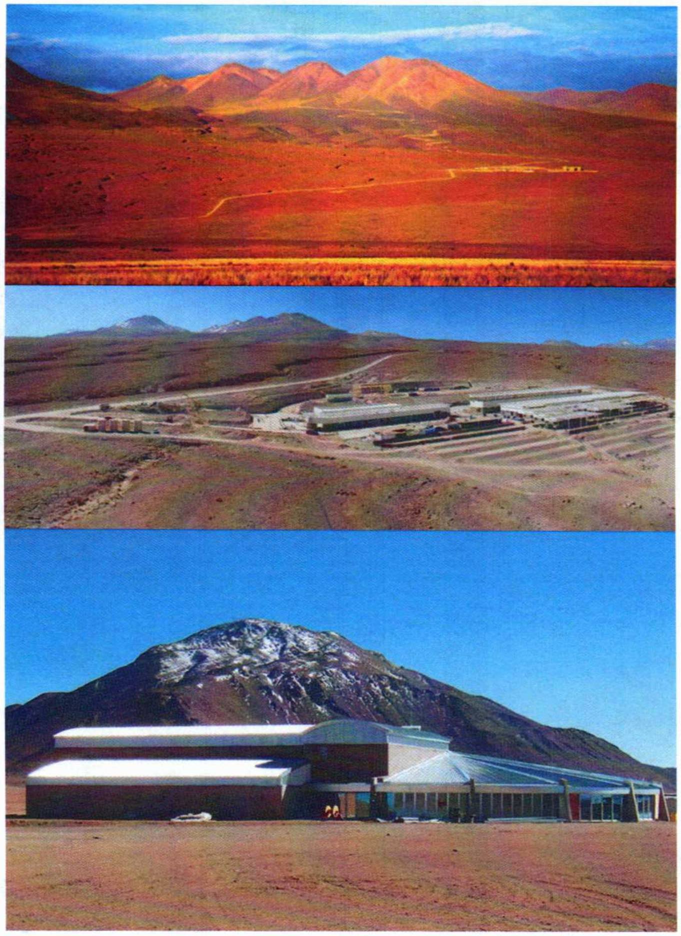

FIGURE 12.7 *Top and middle*: ALMA Operations Support Facilities at the 2,900 m (9,500 ft) level near San Pedro de Atacama. *Bottom*: The Array Operations Site Technical Building at the 5,000 m (16,400 ft) level. (From © ALMA (ESO/NAOJ/NRAO).)

Science Case

The SKA will be one of a suite of new, large telescopes for the 21st century that will be used to probe fundamental physics, the origin and evolution of the Universe, the structure of the Milky Way, the formation and distribution of planets, and astrobiology. The science case for the SKA has been documented in the book *Science with the Square Kilometre Array* (Carilli and Rawlings, 2004) and can be grouped into five themes:

1. *Cradle of life*: Are there Earth-like planets around other stars? Do they host intelligent life? By observing the process of planet building through detection of structure in the dusty disks that form around nearby young stars, the SKA at short-centimeter wavelengths can play a unique role in telling us how Earth-like planets are formed. Its great sensitivity will also open up the possibility of detecting extraterrestrial intelligence via unintentional "leakage" radio transmissions from planets around the closest stars.
2. *Probing the Dark Ages*: The combination of the absorption spectra of quasars at redshift $z > 6$ and the *WMAP* measurement of the surprisingly large electron scattering optical depth to the CMBR implies that the Dark Ages, before the formation of the first luminous

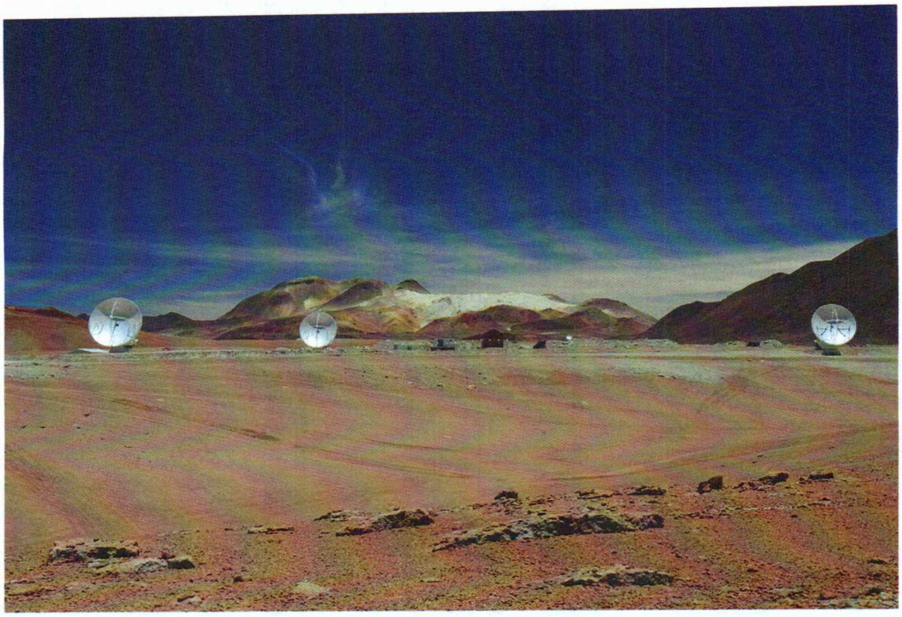

FIGURE 12.8 Phase closure was achieved with these three telescopes at the ALMA Array Operations Site in Chile in December 2009. (From © ALMA (ESO/NAOJ/NRAO).)

objects in the Universe, ends at $z \sim 20$ when the epoch of reionization began. The SKA will provide detailed pictures of structure formation and reionization during this period of Dark Ages and epoch of reionization that ends at $z \sim 6$, through observations of the redshifted 21 cm line of neutral hydrogen. Such observations will allow us to separate the contributions from different redshifts to make fully 3-dimensional maps of the neutral gas in the Universe that will be crucial for studying the time dependence of reionization.

3. *The origin and evolution of cosmic magnetism*: In spite of their importance to the evolution of stars, galaxies, and galaxy clusters, the origin of cosmic magnetic fields is still an open problem in both fundamental physics and astrophysics. Did significant primordial fields exist before the first stars and galaxies were formed? If not, when and how were the magnetic fields of galaxies, stars, and planets subsequently generated, and what now maintains them? The great sensitivity of the SKA will allow it to survey the Faraday rotation of the plane of polarization of radiation from distant polarized extra-Galactic sources. An

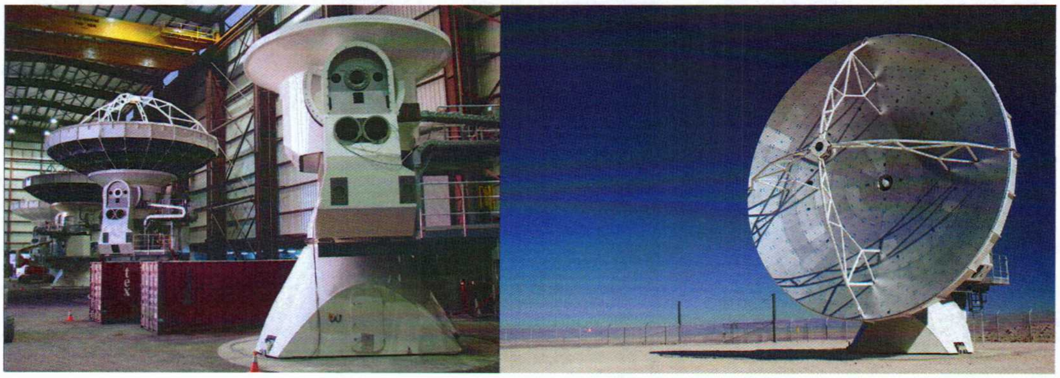

FIGURE 12.9 ALMA Vertex telescopes at various stages of assembly at the Operations Support Facilities. (From © ALMA (ESO/NAOJ/NRAO).)

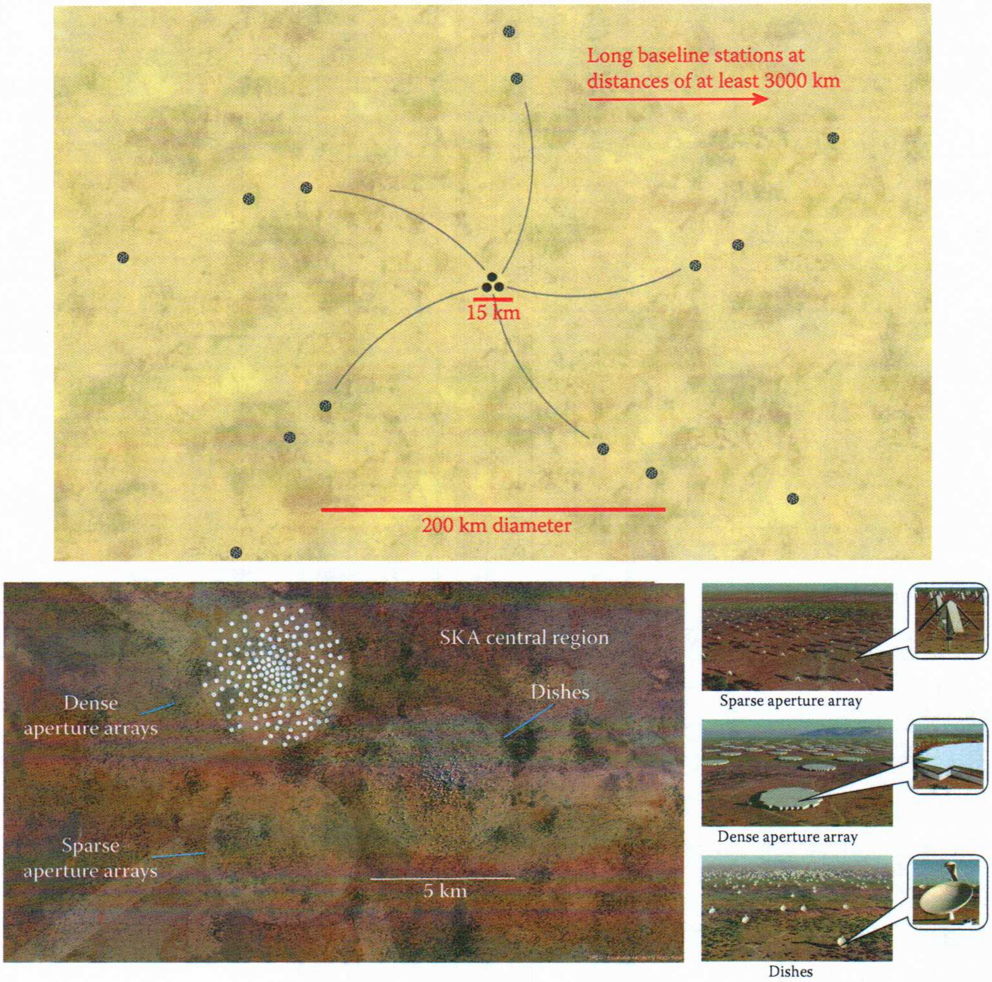

FIGURE 12.10 Artist's renditions of SKA design concepts. *Bottom left*: The central region will be densely packed with stations containing ~50% of the collecting area. *Top*: Other stations will be laid out in a logarithmic spiral pattern extending to the maximum baseline of ~3,000 km (98,400 ft). *Bottom right*: At low frequencies, the array will consist of many phased-aperture arrays, while at high frequencies it will consist of ~3,000 10–15 m-class (33–49 ft) parabolic dishes with new technology feed systems. (From © Swinburne Astronomy Productions and SKA Project Development Office. With permission.)

all-sky Faraday rotation measure survey by the SKA will be a powerful probe for studies of the geometry and evolution of Galactic and intergalactic magnetic fields, to investigate connections between the formation of magnetic fields and the formation of structure in the early Universe, and thus to answer questions about when and how the first magnetic fields in the Universe were generated.

4. *Strong field tests of gravity using pulsars and BHs*: Through its sensitivity, sky coverage, and frequency coverage, the SKA will discover—besides extra-Galactic pulsars—a very large fraction of the pulsars in galaxies. It will also have the sensitivity to time pulsars at the 100 ns precision needed to probe the strong-field realm of gravitational physics and to detect the distortion of spacetime as a result of a stochastic background of *GWs* due to mergers of supermassive BHs or to GWs generated in the inflation era after the Big Bang.

5. *Galaxy evolution, cosmology, and dark energy*: The SKA will enable revolutionary progress in studies of the evolution of galaxies and of large-scale structure in the Universe by tracing the kinematics, merger history, and environments of galaxies at great distances using the 21 cm transition of neutral hydrogen. Once a galaxy has been detected in the 21 cm line, the observed wavelength of the line provides an accurate redshift and locates the object in the 3-dimensional cosmic web. With the SKA, it will be possible to detect the 21 cm line emission from typical galaxies at redshifts $z \sim 3$ in a reasonable integration time and thus to pursue such studies at distances that are almost entirely inaccessible to current instrumentation. The SKA will become the premier machine for surveying the large-scale structure of the Universe and for testing theoretical models for the growth of that structure. Together with CMBR anisotropy data, SKA measurements of the matter power spectrum of galaxies will provide powerful constraints on the equation of state of the dark energy that causes the cosmic expansion to accelerate.

SKA SPECIFICATIONS

The current concept of the SKA Program involves three components:

1. *SKA-low*: Covering a frequency range of roughly ~70 MHz to 0.3 GHz (wavelengths of ~4 m to 1 m) the low-frequency component of the SKA Program will investigate the early Universe and Galactic transient sources such as BH binaries and flare stars.
2. *SKA-mid*: Covering a frequency range of roughly 0.3–3 GHz or higher (~1 m to ~10 cm wavelength), the mid-frequency component will be primarily a survey instrument, exploring the evolution of galaxies, dark energy, transient sources, pulsars, and the realm of strong gravity.
3. *SKA-high*: Covering a frequency range from 3 GHz or higher to 25–50 GHz (~10 to ~1 cm wavelength), the high-frequency component will explore the formation of stars and planets, test strong gravity, and search for extraterrestrial intelligence.

Approximately 50% of the collecting area of the SKA is to be contained within a centrally condensed inner array of 5 km diameter to provide ultrahigh brightness sensitivity at arcsecond-scale resolution for studies of the faint spectral line signatures of structures in the early Universe. Another 25% of the collecting area will be located within a diameter of 150 km, and the remainder out to 3,000 km or more. The nature of the SKA antenna elements will depend on the frequency range. For the lower frequencies, the SKA is currently conceived to be made up of planar aperture arrays that have no moving parts and are pointed electronically. Individual array stations would have a sparse layout of individual elements at the lowest frequencies and denser packing for the mid-frequency range (see Figure 12.10). For high frequencies, the array is envisaged as being made up of ~3,000 10–15 m-class (33–49 ft) dishes with solid or meshed surface, equipped with "smart feeds" (focal-plane arrays or wideband feeds). The final design, including the optimal frequency ranges for using each type of element, will be determined from the outcome of an extensive prototyping exercise that is now under way. The candidate sites for SKA-low and SKA-mid are in western Australia and South Africa, both of which have very low radio frequency interference from artificial sources.

TECHNICAL CHALLENGES AND CURRENT STATUS

Aside from beam-forming array receiver technology (Van Ardenne et al., 2005), the technical requirements of the individual SKA antennas and associated electronics are not particularly difficult. The challenges are primarily due to the scale of the SKA: a large (~3,000) number of antenna elements, broadband signal transmission over long distances, and the processing and storage of an enormous volume of data. Given the expected sensitivity of the SKA, calibration and systematic errors become the technical limits to achieving the theoretical imaging dynamic range (74 db: ~2.5×10^7).

Last but not least, the cost-per-unit-collecting-area of the construction, operation, and maintenance of the SKA has to be significantly lower than that of current facilities in order for it to be affordable. As a reference, the power consumption is estimated to be ~100 MW. Very importantly, attention is now being devoted to the use of solar power as a practical solution to the power requirements, especially given that the potential sites of the SKA are in areas where weather conditions are such that sunshine is abundant. The current cost estimate of the construction of SKA-mid is ~2 billion Euros, and the estimated cost of operations is ~100 million Euros per year.

NOTABLE FACILITIES LEADING UP TO THE SKA

Before the realization of the SKA Program starting in the early 2020s, a number of notable meter- and centimeter-wave facilities that are pathfinders or demonstrators toward the SKA are undergoing construction, nearing completion, or have recently been completed. They include the following:

1. the Giant Meter-wave Radio Telescope (GMRT) in India, an aperture synthesis array with a maximum baseline of 25 km using 30 inexpensive, lightweight 45 m (148 ft) parabolic reflectors formed by stretch mesh attached to rope trusses (SMART), operable from 50 to 1,500 MHz and in use for astronomy since the late 1990s (Rao, 2002);
2. the Allen Telescope Array (ATA-42) in the US, a 42-element pathfinder for the use of large numbers of small-diameter (6 m [20 ft]) paraboloids in a centimeter-wave (0.5–11 GHz) aperture synthesis telescope as envisaged for SKA-high, in use for astronomical surveys and in the Search for Extraterrestrial Intelligence (SETI);
3. the Low-Frequency Array (LOFAR) in Europe, a project to greatly increase sensitivity for imaging at 10–250 MHz using a large number of inexpensive phased arrays of omnidirectional dipole antennas over 1,000 km baselines with digital beam forming as a pathfinder for SKA-low;
4. the Precision Array for Probing the Epoch of Reionization (PAPER), a 128-element interferometer operating from 100 to 200 MHz developed to detect the signal from redshifted H I at the epoch of reionization, to be deployed in South Africa;
5. the Murchison Wide-field Array (MWA), an international (US/Australia/India) SKA-low pathfinder project using a 512-tile array with a maximum baseline of 3 km designed to detect the redshifted H I from the epoch of reionization, to survey the dynamic radio sky at 80 to 300 MHz, and to make measurements of the Sun and heliospheric plasma;
6. the Long Wavelength Array (LWA) in the US, another SKA-low pathfinder, using inexpensive phased arrays of crossed dipoles to achieve Galactic-noise-limited sensitivity from 20 to 80 MHz with baselines up to 400 km for wide-field imaging of both compact and complex sources;
7. the EVLA in the US, greatly improving the sensitivity and expanding the spectroscopic capabilities of the existing 27-element VLA (Figure 12.3) at 1–50 GHz using modern digital wide-bandwidth correlator technology as a pathfinder for SKA-high;
8. the Australian SKA Pathfinder (ASKAP) including field-of-view enhancement by focal-plane phased arrays on new-technology 12 m-class (39 ft) parabolic reflectors to greatly increase survey speed and sensitivity in an SKA-mid-pathfinder at 0.7–1.8 GHz;
9. the Five-hundred meter Astronomical Spherical Telescope (FAST; Figure 12.11) in China, extending the spherical reflector concept used at Arecibo to a larger aperture, increasing sensitivity for single-dish spectroscopy, pulsar, and VLBI observations at 70 MHz to 3 GHz, and as a pathfinder for possible use of extensive karst landforms in an SKA-mid design;

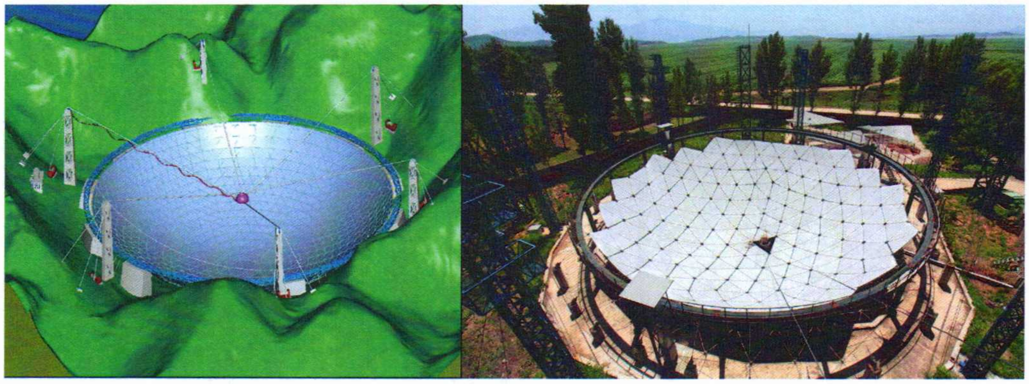

FIGURE 12.11 *Left*: The FAST concept. *Right*: A 50 m (164 ft)-diameter demonstration model built at the Miyun Station of the National Astronomical Observatories, Chinese Academy of Sciences. (Courtesy of the FAST Project Team.)

10. the Karoo Array Telescope (MeerKAT; "meer" means "more" in Afrikaans) in South Africa, a Southern Hemisphere complement to the EVLA using composite, one-piece 12 m (39 ft) reflectors; single-pixel wideband receivers; and low-cost, high-reliability cryogenic systems in an SKA-high precursor that will be optimized for high-fidelity imaging of extended low-brightness emission.

Table 12.2 summarizes the specifications and the status of these facilities, which collectively constitute significant advances in the capabilities of meter/centimeter-wave telescopes and will address many outstanding scientific issues, as well as exploring new antenna, receiver, correlator, and software technologies that will be needed to realize the goals of the SKA Program.

TABLE 12.2

Notable Facilities Leading Up to the SKA

Facility	Date	Country	Frequency Range	Type, Largest Dimension	Ref.
GMRT	1999	India	50 MHz–1.4 GHz	Thirty 45 m antennas, 25 km	1
ATA-42	2007	US	0.5–11.2 GHz	Forty-two 6 m antennas, 300 m	2
LOFAR	2010	Netherlands	10–250 MHz	7,000-element array, 1,500 km	3
PAPER	2010	South Africa	125–200 MHz	128 dipoles	4
MWA	2010	Australia	80–300 MHz	8,192 elements in 512 tiles, 3 km	5
EVLA	2012	US	1–50 GHz	Twenty-seven 25 m antennas, 25 km	6
LWA	2012	US	10–88 MHz	Fifty-three stations, 400 km	7
ASKAP	2013	Australia	700 MHz–1.8 GHz	Thirty-six 12 m antennas, 6 km	8
FAST	2014	China	300 MHz–2 GHz	500 m spherical reflector	9
MeerKAT	2015	South Africa	0.6–14.5 GHz	Eighty-seven 12 m antennas, 60 km	10

Website references: (1) http://www.gmrt.ncra.tifr.res.in/; (2) http://ral.berkeley.edu/ata/; (3) http://www.lofar.org/; (4) http://astro.berkeley.edu/~dbacker/eor/; (5) http://mwatelescope.org/; (6) https://science.nrao.edu/facilities/evla; (7) http://lwa.phys.unm.edu/; (8) http://www.atnf.csiro.au/projects/askap/; (9) http://www.skatelescope.org/publications/; (10) http://www.ska.ac.za/meerkat/.

SUMMARY

Radio astronomy is entering a very exciting era, with many new facilities that embody the latest technologies and make possible the exploration of the latest frontiers of astronomy. At the same time, there are continuing efforts all over the world dedicated to developing novel techniques and technologies needed for the next-generation radio astronomy facilities. Because of the scale of the SKA, collaboration with industry will be essential in the future, changing the way technical development and construction are carried out in the radio astronomy community. The many ambitious projects of radio astronomers, and of astronomers generally, perhaps constitute the best illustration of the essential interplay between the development of new technologies and the unbounded curiosity and imagination of man in the quest to unravel the workings of the Universe.

REFERENCES

Adler, R., Hrbek, G., and Wade, G. (1959). The quadrupole amplifier, a low-noise parametric device. *Proceedings of the Institute of Radio Engineers,* 47: 1713–723.

Alfvén, H. and Herlofson, N. (1950). Cosmic radiation and radio stars. *Physical Review,* 78: 616.

Alsop, L.E., Giordmaine, J.A., Mayer, C.H., et al. (1959). Observations of discrete sources at 3-cm wavelength using a maser. In: R.N. Bracewell (ed.), *Paris Symposium on Radio Astronomy*, IAU Symposium No. 9 and URSI Symposium No. 1, 69–74. Stanford: Stanford University Press.

Appleton, E.V. (1945). Departure of long-wave solar radiation from black-body intensity. *Nature,* 156: 534–35.

Astier, P., Guy, J., Regnault, N., et al. (2006). The Supernova Legacy Survey: Measurement of Ω_M, Ω_Λ and w from the first year data set. *Astronomy and Astrophysics,* 447: 31–48.

Baade, W. and Zwicky, F. (1934). Cosmic rays from super-novae. *Proceedings of the National Academy of Sciences of the USA,* 20: 259–63.

Balick, B. and Brown, R.L. (1974). Intense sub-arcsecond structure in the Galactic center. *Astrophysical Journal,* 194: 265–70.

Bare, C., Clark, B.G., Kellermann, K.I., et al. (1967). Interferometer experiment with independent local oscillators. *Science,* 157: 189–91.

Bennett, C.L., Halpern, M., Hinshaw, G., et al. (2003). First-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations: Preliminary maps and basic results. *Astrophysical Journal Supplement Series,* 148: 1–27.

Broten, N.W., Legg, T.H., Locke, J.L., et al. (1967). Long Base Line Interferometry: A new technique. *Science,* 156: 1592–593.

Buhl, D. (1971). Chemical constituents of interstellar clouds. *Nature,* 234: 332–24.

Burgay, M., D'Amico, N., Possenti, A., et al. (2003). An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system. *Nature,* 426: 531–33.

Carilli, C. and Rawlings, S. (eds.), (2004). *Science with the Square Kilometre Array. New Astronomy Reviews*, Vol. 48. Amsterdam: Elsevier.

Cheung, A.C., Rank, D.M., Townes, C.H., et al. (1968). Detection of NH_3 molecules in the interstellar medium by their microwave emission. *Physical Review Letters,* 21: 1701–705.

Cohen, M.H., Cannon, W., Purcell, G.H., et al. (1971). The small-scale structure of radio galaxies and quasi-stellar sources at 3.8 centimeters. *Astrophysical Journal,* 170: 207–17.

de Bernardis, P., Ade, P.A.R., Bock, J.J., et al. (2000). A flat Universe from high-resolution maps of the cosmic microwave background radiation. *Nature,* 404: 955–59.

Ewen, H.I. and Purcell, E.M. (1951). Observation of a line in the Galactic radio spectrum—radiation from Galactic hydrogen at 1,420 Mc./sec. *Nature,* 168: 356–57.

Ginzburg, V.L. (1951). Kosmicheskie luchi kak istochnik galakticheskogo radioieluениiа (Cosmic rays as the source of galactic radio emission). *Doklady Akademii Nauk SSSR* 76: 377–80.

Gold, T. (1968). Rotating neutron stars as the origin of the pulsating radio sources. *Nature,* 218: 731–32.

Halverson, N.W., Leitch, E.M., Pryke, C., et al. (2002). Degree angular scale interferometer first results: A measurement of the cosmic microwave background angular power spectrum. *Astrophysical Journal,* 568: 38–45.

Hanany, S., Ade, P., Balbi, A., et al. (2000). MAXIMA-1: A measurement of the cosmic microwave background anisotropy on angular scales of 10'-5°. *Astrophysical Journal,* 545: L5–9.

Hewish, A., Bell, S.J., Pilkington, J.D., et al. (1968). Observation of a rapidly pulsating radio source. *Nature,* 217: 709–13.

Hulse, R.A. and Taylor, J.H. (1975). Discovery of a pulsar in a binary system. *Astrophysical Journal,* 195: L51–3.

Jansky, K.G. (1933). Radio waves from outside the solar system. *Nature,* 132: 66.

Jennison, R.C. (1958). A phase sensitive interferometer technique for the measurement of the Fourier transforms of spatial brightness distributions of small angular extent. *Monthly Notices of the Royal Astronomical Society,* 118: 276–84.

Jennison, R.C. and Das Gupta, M.K. (1953). Fine structure of the extra-terrestrial radio source Cygnus 1. *Nature,* 172: 996–97.

Kiepenheuer, K.O. (1950). Cosmic rays as the sources of general Galactic radio emission. *Physical Review,* 79: 738–39.

Knop, R.A., Aldering, G., Amanullah, R., et al. (2003). New constraints on Ω_M, Ω_Λ, and w from an independent set of 11 high-redshift supernovae observed with the *Hubble Space Telescope*. *Astrophysical Journal,* 598: 102–37.

Lynden-Bell, D. (1969). Galactic nuclei as collapsed old quasars. *Nature,* 223: 690–94.

Mason, B.S., Pearson, T.J., Readhead, A.C.S., et al. (2003). The anisotropy of the microwave background to $l = 3500$: Deep field observations with the Cosmic Background Imager. *Astrophysical Journal,* 591: 540–55.

Moran, J., Crowther, P.P., Burke, B.F., et al. (1967). Spectral line interferometry with independent time standards at stations separated by 845 kilometers. *Science,* 157: 676–77.

Muller, C.A. and Oort, J.H. (1951). The interstellar hydrogen line at 1,420 Mc./sec., and an estimate of galactic rotation. *Nature,* 168: 357–58.

Pacini, F. and Salpeter, E.E. (1968). Some models for pulsed radio sources. *Nature,* 218: 733–34.

Pearson, T.J. and Readhead, A.C.S. (1984). Image formation by self-calibration in radio astronomy. *Annual Review of Astronomy and Astrophysics,* 22: 97–130.

Penzias, A.A. and Wilson, R.W. (1965). A measurement of excess antenna temperature at 4080 Mc/s. *Astrophysical Journal,* 142: 419–21.

Phillips, T.G. and Dolan, G.J. (1982). SIS mixers. *Physica B+C,* 110B: 2010–119.

Rao, A.P. (2002). GMRT—current status. In: A.P. Rao, G. Swarup, and Gopal-Krishna (eds.), *The Universe at Low Frequencies*. IAU Symposium No. 199, 439–46.

Riess, A.G., Strolger, L.-G., Casertano, S., et al. (2007). New *Hubble Space Telescope* discoveries of Type Ia supernovae at $z >= 1$: Narrowing constraints on the early behavior of dark energy. *Astrophysical Journal,* 659: 98–121.

Roberts, M.S. and Whitehurst, R.N. (1975). The rotation curve and geometry of M31 at large galactocentric distances. *Astrophysical Journal,* 201: 327–46.

Ryle, M. (1962). The new Cambridge radio telescope. *Nature,* 194: 517–18.

Salpeter, E.E. (1964). Accretion of interstellar matter by massive objects. *Astrophysical Journal,* 140: 796–800.

Shklovsky, I.S. (1953). Problema kosmicheskogo radioizlucheniia (The problem of cosmic radio waves). *Astronomicheskii Zhurnal*, 30: 15–36.

Smoot, G.F., Bennett, C.L., Kogut, A., et al. (1992). Structure in the *COBE* differential microwave radiometer first-year maps. *Astrophysical Journal,* 396: L1–5.

Southworth, G.C. (1945). Microwave radiation from the sun. *Journal of the Franklin Institute,* 239: 285–97.

Spergel, D.N., Bean, R., Doré, O., et al. (2007). Three-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations: Implications for cosmology. *Astrophysical Journal Supplement Series,* 170: 377–408.

Tucker, J. (1979). Quantum limited detection in tunnel junction mixers. *IEEE Journal of Quantum Electronics,* 15: 1234–258.

Van Ardenne, A., Wilkinson, P.N., Patel, P.D., et al. (2005). Electronic Multi-beam Radio Astronomy Concept: EMBRACE a demonstrator for the European SKA Program. *Experimental Astronomy,* 17: 65–77.

van de Hulst, H.C. (1945). Radiogolven uit het wereldrium; herkomst der radiogolven. *Nederlands Tijdschrift voor Natuurkunde* 11: 210–21.

Weinreb, S. (1963). A digital spectral analysis technique and its application to radio astronomy. *M.I.T. Research Lab of Electronics Tech Report*, 412.

Wolszczan, A. and Frail, D. (1992). A planetary system around the millisecond pulsar PSR1257+12. *Nature,* 355: 145–47.