Chapter 1
Future Observations of Cosmic Magnetic Fields with LOFAR, SKA and Its Precursors

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Abstract Polarization observations with the forthcoming large radio telescopes will open a new era in the observation of magnetic fields and should help to understand their origin. Low-frequency radio synchrotron emission from the Milky Way, galaxies and galaxy clusters, observed with the new Low Frequency Array (LOFAR) and the planned Square Kilometre Array (SKA), traces low-energy cosmic ray electrons and allows us to map the structure of weak magnetic fields in the outer regions and halos of galaxies, in halos and relics of clusters and in the Milky Way. Polarization at higher frequencies (1–10 GHz), to be observed with the SKA and its precursors Australia SKA Pathfinder (ASKAP) and the South African MeerKAT telescopes, will trace magnetic fields in the disks and central regions of galaxies and in cluster relics in unprecedented detail. All-sky surveys of Faraday rotation measures towards a dense grid of polarized background sources with ASKAP (project POSSUM) and the SKA are dedicated to measure magnetic fields in intervening galaxies, clusters and intergalactic filaments, and will be used to model the overall structure and strength of magnetic fields in the Milky Way. Cosmic magnetism is "key science" for LOFAR, ASKAP and the SKA.

1.1 Prospects of Future Magnetic Field Observations

1.1.1 Diffuse Polarized Emission

Synchrotron radiation and Faraday rotation (see also Chap. 3) revealed magnetic fields in our Milky Way, nearby spiral galaxies and in galaxy clusters (see also Chaps.18 and 20), while little is known about magnetic fields in the intergalactic medium. Furthermore, the origin and evolution of galactic magnetic fields are still mostly unknown. The next-generation radio telescopes will widen the range of observable magnetic phenomena. SKA (Sect. 1.4) and its precursor telescopes ASKAP and MeerKAT (Sect. 1.5) will measure diffuse synchrotron emission from

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the Milky Way, nearby galaxies and nearby clusters of galaxies. As Faraday depolarization increases towards lower frequencies, polarized emission can hardly be detected from the star-forming disks of galaxies at frequencies below about 300 MHz (Arshakian et al. 2011). On the other hand, polarized and unpolarized synchrotron emission at low frequencies should be observable from aging, low-energy electrons that have propagated far away from their places of origin. Hence, LOFAR (Sect. 1.3) is a suitable instrument to search for weak magnetic fields in outer galaxy disks, galaxy halos and halos of galaxy clusters (Anderson et al. 2012). "Relics" in galaxy clusters, probably signatures of huge shock fronts, have steep radio spectra and may become prominent in LOFAR's frequency range (Brunetti et al. 2008).

Deep high-resolution observations at high frequencies, where Faraday effects are small, require a major increase in sensitivity of continuum observations, which can be achieved by the SKA. In this way the detailed structure of the magnetic fields in the ISM of galaxies, in galaxy halos, cluster halos and cluster relics can be observed and the magnetic power spectra measured (Vogt and Enßlin 2005). Direct insight into the interaction between gas and magnetic fields in these objects will become possible. The SKA will also allow measurement of the Zeeman effect of weak magnetic fields in the Milky Way and in nearby galaxies.

Detection of polarized emission from distant, unresolved galaxies can reveal large-scale ordered fields (Stil et al. 2009), to be compared with the predictions of dynamo theory (Arshakian et al. 2009). The SKA should be able to detect Milky-Way type galaxies out to $z \leq 1.5$ (Fig. 1.1) and their polarized emission out to $z \leq 0.5$ (assuming 10 % polarization). Cluster "relics" are highly polarized (van Weeren et al. 2010) and will be detectable at large redshifts.

Bright starburst galaxies are not expected to host ordered fields. Unpolarized synchrotron emission from starburst galaxies, signature of turbulent magnetic fields, should be detected with the SKA out to large redshifts, depending on luminosity and magnetic field strength (Fig. 1.1), and from cluster halos. However, for fields

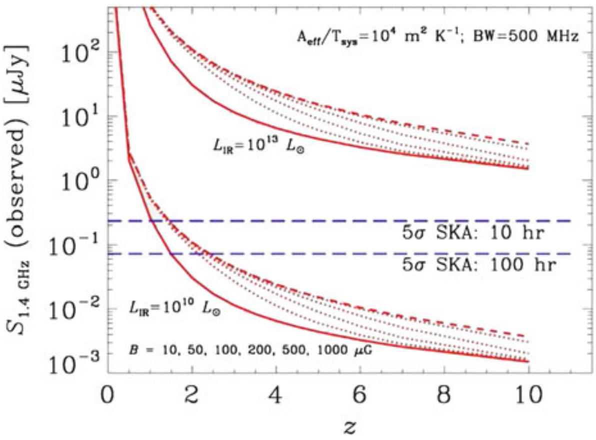

Fig. 1.1 Total synchrotron emission of galaxies at 1.4 GHz as a function of redshift z and magnetic field strength B, and the 5σ detection limits for 10 and 100 h integration time with the SKA (Murphy 2009)

weaker than 3.25 μG $(1+z)^2$, energy loss of cosmic-ray electrons is dominated by the inverse Compton effect with CMB photons, so that the energy appears mostly in X-rays, not in the radio range. On the other hand, for strong fields the energy range of the electrons emitting at a 1.4 GHz drops to low energies, where ionization and bremsstrahlung losses become dominant (Murphy 2009). In summary, the mere detection of synchrotron emission of galaxies at high redshifts would constrain the range of allowed magnetic field strengths.

1.1.2 Rotation Measure Grids

Faraday rotation is another powerful tool to detect cosmic magnetic fields. The Faraday rotation angle $\Delta\chi$ of the polarization plane is proportional to the *Faraday depth (FD)*, defined as the line-of-sight integral over the product of the plasma density and the strength of the field component along the line of sight. If the rotating region is located in front of the emitting region (*Faraday screen*), *RM* and *FD* are identical. Multiple emitting and rotating regions located along the line of sight generate a spectrum of FD components. In such cases, RM Synthesis is needed (Sect. 1.2 and Chap. 3).

If diffuse polarized emission is too weak to be detected, the method of *RM grids* towards background QSOs can still be applied and allows us to determine the field strength and pattern in the intervening objects, such as distant spiral galaxies, clusters and intergalactic filaments. Because the Faraday rotation angle increases with the square of wavelength, low frequencies are also ideal to search for small Faraday rotation measures from weak interstellar and intergalactic fields.

This method can be applied to distances of very distant QSOs ($z \simeq 5$). Regular fields of several μG strength were already detected in distant, intervening galaxies (Bernet et al. 2008, 2013; Kronberg et al. 2008). Mean-field dynamo theory predicts RMs from evolving regular fields with increasing coherence scale at $z \leq 3$ (Arshakian et al. 2009). A reliable model for the field structure of nearby galaxies, cluster halos and cluster relics needs RM values from a large number of polarized background sources, hence large sensitivity and high survey speed (Krause et al. 2009). As the observed RM values are reduced by the redshift dilution factor of $(1+z)^{-2}$, high precision of RM measurements is required (Sect. 1.2).

The *POSSUM* all-sky survey at 1.1–1.4 GHz with the ASKAP telescope (Sect. 1.5) with about 30 deg^2 field of view is expected to measure about 100 RMs of extragalactic sources per square degree within 10 h integration time.

The *SKA Magnetism Key Science Project* plans to observe a wide-field survey (at least 10^4 deg^2) around 1 GHz with 1 h integration per field which should detect sources of 0.5–1 μJy flux density and measure at least 1500 RMs deg^{-2}, or a total of at least 1.5×10^7 RMs from compact polarized extragalactic sources at a mean spacing of $\simeq 90''$ (Gaensler et al. 2004). This survey will be used to model the structure and strength of the magnetic fields in the Milky Way, in intervening

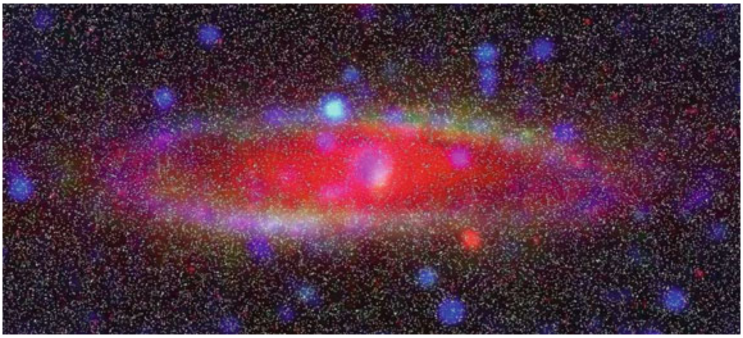

Fig. 1.2 Simulation of RMs towards background sources (*white points*) in the region of M 31 observable with the SKA within 1 h. Optical emission from M 31 is shown in *red*, diffuse radio continuum intensity in *blue* and diffuse polarized intensity in *green* (from Gaensler, priv. comm.)

galaxies and clusters and in the intergalactic medium (Beck and Gaensler 2004). More than 10,000 RM values are expected in the area of the galaxy M 31 and will allow the detailed reconstruction of the 3-D field structure (Fig. 1.2). Simple patterns of regular fields can be recognized out to distances of about 100 Mpc (Stepanov et al. 2008) where the polarized emission is far too low to be mapped. The evolution of field strength in cluster halos can be measured by the RM grid method to redshifts of about one (Krause et al. 2009).

1.1.3 Magnetic Fields of the Milky Way

LOFAR will detect almost all pulsars within 2 kpc of the Sun and discover about 1,000 new nearby pulsars, especially at high latitudes (van Leeuwen and Stappers 2010). Most of these are expected to emit strong, linearly polarized signals at low frequencies. This should allows us to measure their RMs and to derive the Milky Way's magnetic field structure near to the Sun. The SKA pulsar survey should find about 20,000 new pulsars which will mostly be polarized and reveal RMs (Fig. 1.3), suited to map the Milky Way's magnetic field with even higher precision.

The SKA and its precursor telescopes will also map out magnetic fields in gas clouds, HII regions, planetary nebulae and supernova remnants, in the Milky Way, via the Zeeman effect, polarized emission and Faraday rotation.

1.1.4 Intergalactic Filaments

If the filaments of the local Cosmic Web outside clusters contain a magnetic field (Ryu et al. 2008), possibly enhanced by IGM shocks, we hope to detect this field by

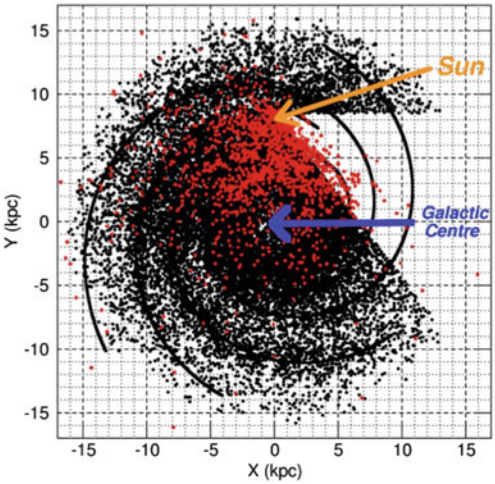

Fig. 1.3 Known pulsars in the Milky Way (*red*) and pulsars expected with the SKA (*black*). Simulation: Michael Kramer, MPIfR Bonn

direct observation of its total synchrotron emission (Keshet et al. 2004) and possibly its polarization, or by Faraday rotation towards background sources. For fields of $\approx 10^{-8}$–10^{-7} G with 1 Mpc coherence length and $n_e \approx 10^{-5}\,\mathrm{cm}^{-3}$ electron density, Faraday rotation measures between 0.1 and $1\,\mathrm{rad\,m}^{-2}$ are expected which will be challenging to detect even with LOFAR. Promising is a statistical analysis like the measurement of the power spectrum of the magnetic field of the Cosmic Web (Kolatt 1998) or the cross-correlation with other large-scale structure indicators like the galaxy density field (Stasyszyn et al. 2010).

If an overall IGM field with a coherence length of a few Mpc existed in the early Universe and its strength varied proportional to $(1 + z)^2$, its signature may become evident at redshifts of $z > 3$. Averaging over a large number of RMs is required to unravel the IGM signal. The goal is to detect an IGM magnetic field of 0.1 nG, which needs an RM density of $\approx$ 1,000 sources deg^{-2} (Kolatt 1998), achievable with the SKA. Detection of a general IGM field, or placing stringent upper limits on it, would provide powerful observational constraints on the origin of cosmic magnetism.

1.2 Faraday Rotation Measure Synthesis

Modern radio telescopes are equipped with digital correlators that allow us to record a large number of spectral channels. While radio spectroscopy in total intensity is well-developed, the possibilities of spectropolarimetry in radio continuum have been explored for only a few years. The fundamentals were presented by Burn (1966), the first application to multi-channel polarization data (data cubes) by Brentjens et al. (2005). If the medium has a relatively simple structure, the 3-D structure of the magnetized interstellar medium can be determined (*Faraday tomography*).

Faraday Rotation Measure Synthesis ("RM Synthesis") Fourier-transforms the observed polarized intensity the "Faraday dispersion into function" or, in short, the "Faraday spectrum" $F(\phi)$, which is the (complex-valued) polarized intensity spectrum as a function of "Faraday depth" ϕ (see Chap. 3). As in classical spectroscopy, the interpretation of this spectrum is not straightforward. In particular, there is no simple relation between Faraday depth and geometrical depth. Furthermore, the Faraday spectrum suffers from sidelobes of the main components caused by limited coverage of the wavelength space.

RM Synthesis is characterized by four basic parameters (Beck et al. 2012; Brentjens et al. 2005):

- The resolution $\delta\phi$ in Faraday space, which is inversely proportional to the coverage $\Delta\lambda^2$ in wavelength (λ^2) space;
- the maximum observable $|\phi_{max}|$ of point-like sources in Faraday space, which is inversely proportional to the width of a single frequency channel;
- the maximum width $|\Delta\phi_{max}|$ of extended structures in Faraday space (Faraday-rotating *and* synchrotron-emitting regions), which is inversely proportional to the square of the minimum observation wavelength. Wide-band observations at long wavelengths yield high resolution in Faraday space but cannot detect extended structures;
- the ratio of maximum to minimum wavelengths which is crucial to recognize a range of different scales in Faraday space.

Table 1.1 summarizes the properties of the present-day and future radio telescopes. The highest resolution in Faraday space (largest $\Delta\lambda^2$) and hence the highest precision to measure FD components is achieved by LOFAR and SKA, while

Table 1.1 Spectral ranges of various radio telescopes and parameters crucial for RM synthesis

Telescope	λ (m)	$\Delta\lambda^2$ (m^2)	$\|\delta\phi\|$ (rad/m^2)	$\|\Delta\phi_{max}\|$ (rad/m^2)	$(\lambda_{max}/\lambda_{min})^2$
LOFAR highband	1.25–2.73	5.9	0.59	2.8	4.8
Westerbork (WSRT) (Netherlands)	0.17–0.23 + 0.77–0.97	0.91[a]	3.8	110	33
GMRT (India)	0.21–0.30 + 0.47–0.52 + 0.87–0.98	0.92[a]	3.8	71	22
DRAO, Parkes, Effelsberg (GMIMS survey)	0.17–0.23 + 0.33–1.0	0.97	3.6	110	35
Parkes (S-PASS survey)	0.12–0.14	0.004	870	220	1.4
Arecibo (GALFACTS)	0.20–0.24	0.021	165	79	1.4
JVLA (USA)	0.025–0.30	0.089	39	5,000	144
ATCA (Australia)	0.03–0.27	0.072	48	3,500	81
ASKAP (POSSUM)	0.21–0.27	0.026	130	71	1.6
SKA	0.021–6	36	0.10	7,100	82,000

[a]High sidelobes in Faraday spectrum expected owing to the large gaps in wavelength coverage

Australia Telescope Compact Array (ATCA), Jansky VLA (JLVA) and SKA provide the largest range of scales in Faraday space (largest $(\lambda_{max}/\lambda_{min})^2$). Until the SKA, the ideal "Faraday telescope", becomes operational, data from telescopes operating in different frequency ranges should be combined to obtain an excellent frequency coverage and hence allow high-precision investigations of cosmic magnetism.

1.3 Low Frequency Array

The meter-wave radio telescope LOFAR (Low Frequency Array), designed by ASTRON, the Netherlands Institute for Radio Astronomy, is the largest connected radio telescope ever built (van Haarlem et al. 2013). LOFAR is a software telescope with no moving parts, steered solely by electronic phase delays. It has a large field of view and can observe towards several directions simultaneously. LOFAR is an interferometric array using about 20,000 small antennas of two different designs, one for the wavelength range 10–80 MHz ("lowband") and one for 110–240 MHz ("highband"). The antennas are aggregated in at least 49 stations with baselines up to more than 1,000 km across Europe. Forty of these stations are distributed across the Netherlands, six stations in Germany, one each in Great Britain, France and Sweden, which are jointly operated as the International LOFAR Telescope (ILT). Another three stations are planned in Poland and further stations may be built in other European countries. The core stations are located about 3 km north of the village of Exloo in the Netherlands (Fig. 1.4). The total effective collecting area is up to approximately 300,000 m^2, depending on frequency and antenna configuration. The angular resolution is between 2″ (at 240 MHz) and 30″ (at 15 MHz) for the

Fig. 1.4 The LOFAR core near Exloo/Netherlands (photo: ASTRON)

Fig. 1.5 International LOFAR station near Tautenburg/Germany. *Left*: dense array of dipole "tiles" for frequencies of 110–240 MHz, *right*: sparse dipole array for 10–80 MHz; *top*: optical Schmidt telescope (copyright: Michael Pluto, Thüringer Landessternwarte)

Dutch stations (up to about 100 km baselines) and can further be improved by about 10x if the international baselines are included (Fig. 1.5). Digital beam forming allows observation towards several directions simultaneously. The data processing is performed by a supercomputer situated at the University of Groningen/Netherlands.

The sensitivities and spatial resolutions attainable with LOFAR will allow several fundamental new studies:

- Search for the signature of the reionization of neutral hydrogen in the distant Universe ($6 < z < 10$), making use of the shift of the 21 cm line into the LOFAR observing window;
- detect the most distant massive galaxies and study the processes of formation of the earliest structures in the Universe: galaxies, galaxy clusters and active galactic nuclei;
- discover about 1,000 new pulsars within a few kiloparsecs from the Sun;
- detect flashes of low-frequency radiation from pulsars and short-lived transient events produced by events such as stellar mergers or black hole accretion, and search for bursts from Jupiter-like extrasolar planets;
- detect ultra-high energy cosmic rays entering the Earth's atmosphere;
- detect coronal mass ejections from the sun and provide large-scale maps of the solar wind;
- map the three-dimensional distribution of magnetic fields in our own and nearby galaxies, in galaxy clusters and in the intergalactic medium (see Sect. 1.1).
- By exploring a new spectral window, LOFAR is likely to make unexpected "serendipitous" discoveries.

First science results of LOFAR were presented in Beck et al. (2013), de Gasperin et al. (2012), van Haarlem et al. (2013), and van Weeren et al. (2012).

1.4 Square Kilometre Array

The Square Kilometre Array (SKA) is the most ambitious radio telescope ever planned. With a collecting area of about one square kilometer, the SKA will be about ten times more sensitive than the largest single dish telescope (305 m diameter) at Arecibo (Puerto Rico), and about 50 times more sensitive than the currently most powerful interferometers. The SKA will continuously cover most of the frequency range accessible from ground, from about 50 MHz to at least 14 GHz. The third major improvement is the enormously wide field of view, ranging from about 100 square degrees at 50 MHz to at least 1 square degree at 1.4 GHz. The speed to survey a large part of the sky, particularly at the lower frequencies, will hence be ten thousand to a million times faster than what is possible today. The SKA is dedicated to constrain fundamental physics on the dark energy, gravitation and magnetism.

1.4.1 Technical Design and Development of the SKA

The SKA will be a radio interferometer and consist of many antennas which are spread over a large area to obtain high the resolving power. The SKA core regions of about 5 km diameter each will contain about 50 % of the total collecting area and comprise dish antennas and aperture arrays. The mid-region out to about 180 km radius from the core comprises dishes (Fig. 1.7) and sparse aperture array antennas (Fig. 1.6) aggregated into stations distributed on a spiral arm pattern. Remote stations with about 20 dish antennas each will spread out to distances of 3,000 km or more from the core and located on continuations of the spiral arm pattern. The overall extent of the array determines the angular resolution, which will be about $0.1''$ at 100 MHz and $0.001''$ at 10 GHz.

The frequency range spanning more than two decades cannot be realized with one single antenna design, so this will be achieved with a combination of different types of antennas. Under investigation are the following technical designs:

1. SKA-low: An aperture array of dipole antennas with wide spacings (a “sparse aperture array”) for the low-frequency range (about 50–350 MHz) (Fig. 1.6). This software telescope is an improved version of the LOFAR lowband antennas and also has a large field of view.
2. SKA-mid: An extended array of parabolic dishes of 15 m diameter each for the medium-frequency range, each equipped with a wide-bandwidth single-pixel “feed” and several receiving systems covering about 350 MHz–14 GHz

Fig. 1.6 SKA sparse aperture array station of dipole elements for low frequencies of about 50–350 MHz. Graphics: Swinburne Astronomy Productions and SKA Project Office (SPO)

Fig. 1.7 SKA parabolic dishes for medium frequencies of about 350 MHz–14 GHz. Graphics: Swinburne Astronomy Productions and SPO

(Fig. 1.7). The surface accuracy of these dishes will allow a later receiver upgrade to higher frequencies.

3. SKA-survey: A compact array of parabolic dishes of 12–15 m diameter each for the medium-frequency range, each equipped with a multi-beam, phased-array feed with a huge field of view and several receiving systems covering about 350 MHz–4 GHz. This array will allow fast surveys of the sky.

An additional technology for substantially enhancing the field of view in the 500–1,000 MHz range is under development: aperture arrays of antenna "tiles" with dense spacings, forming an almost circular station 60 m across (Fig. 1.8), similar to the LOFAR highband antennas.

Fig. 1.8 SKA dense aperture array station made up of 3 m x 3 m "tiles" for medium frequencies of about 500 MHz–1 GHz. Graphics: Swinburne Astronomy Productions and SPO

The data from all stations have to be transmitted to a central computer and processed online. Compared to LOFAR with a data rate of about 150 Gb per second and a central processing power of 27 Tflops, the SKA will produce much more data and need much more processing power—by a factor of at least 100. Following "Moore's law" of increasing computing power, a processor with sufficient power should be available by the next decade.

1.4.2 SKA Key Science Projects

Apart from the expected technological spin-offs, five main science questions (Key Science Projects) drive the SKA (Carilli and Rawlings 2004):

- Probing the dark ages: The SKA will use the emission of neutral hydrogen to observe the most distant objects in the Universe and map the detailed structures formed during the Epoch or Reionization out to a redshift of about 27.
- Galaxy evolution, cosmology and dark energy: A deep all-sky SKA survey will detect hydrogen emission from Milky Way-like galaxies out to redshifts of about one, reveal a comprehensive picture of the Universe's expansion history and hence help to distinguish between the various explanations of "dark matter". The same data set will give us unique information about the evolution of galaxies.
- Tests of General Relativity and detection of gravitational waves: Almost all pulsars in the Milky Way will be detected with the SKA (Fig. 1.3) plus several 100 bright pulsars in nearby galaxies. The SKA will search for a radio pulsar orbiting around a black hole, measure time delays in extremely curved space with much higher precision than with laboratory experiments and hence probe the limits of General Relativity. Regular high-precision observations with the

SKA of a network of pulsars with periods of milliseconds opens the way to detect gravitational waves with wavelengths of many parsecs.
- The cradle of life: The SKA will be able to detect the thermal radio emission from centimeter-sized "pebbles" in protoplanetary systems which are thought to be the first step in assembling Earth-like planets. Biomolecules are also observable in the radio range. Finally, the SETI (Search for Extra Terrestrial Intelligence) project will use the SKA to find hints of technological activities.
- Origin and evolution of cosmic magnetism (see Sect. 1.1).

From the five Key Science Projects two major science goals have been identified that drive the technical specifications for the first phase (SKA1):

- Origins: Understanding the history and role of neutral hydrogen in the Universe from the dark ages to the present-day.
- Fundamental Physics: Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity.

1.4.3 SKA Timeline

The detailed design for low and mid frequencies is ready in 2015. Construction of the SKA is planned to start in 2018. In the first phase (until 2020) about 10 % of the SKA will be erected (SKA1) (Garrett et al. 2010), with completion of construction at the low and mid frequency bands by about 2025 (SKA2), followed by construction at the high band.

The members of the SKA Organisation agreed on a dual site solution for the SKA with two candidate sites fulfilling the scientific and logistical requirements: Southern Africa, extending from South Africa, with a core in the Karoo desert, eastward to Madagascar and Mauritius and northward into the continent, and Australia, with the core in Western Australia. The dishes of SKA1 will be built in South Africa, combined with the MeerKAT telescope. Further dishes for the SKA1-survey array will be added to the Australian SKA Pathfinder (ASKAP) array in Australia. All the dishes and the mid-frequency dense aperture array for SKA2 will be built in Southern Africa. The low-frequency sparse aperture array of dipole antennas for SKA1 and SKA2 will be built in Australia.

1.5 SKA Pathfinder and Precursor Telescopes

Two SKA "pathfinder" telescopes provide examples of low frequency arrays, the European LOFAR (Sect. 1.3) and the Long Wavelength Array (LWA) in the USA. These long-wavelength telescopes are software telescopes steered by electronic phase delays (phased aperture array). Examples of dishes with a single-pixel feed are under development in South Africa (Karoo Array Telescope, MeerKAT).

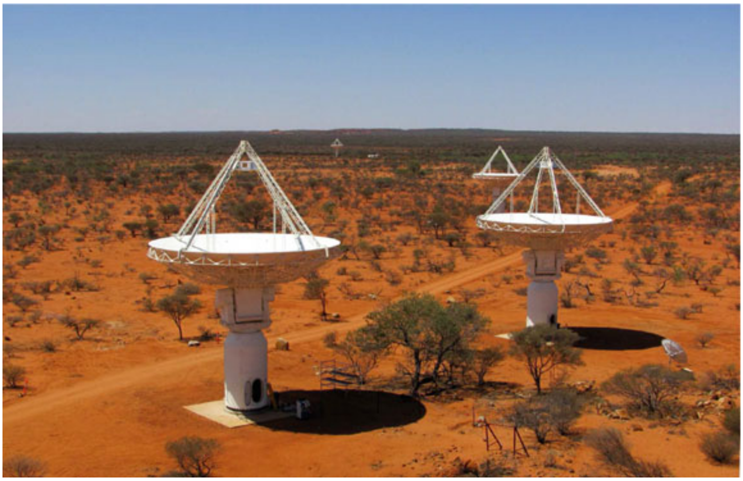

Fig. 1.9 ASKAP antennas (photo: Anthony Schinckel, CSIRO)

Dense aperture arrays comprise up to millions of receiving elements in planar arrays on the ground (Fig. 1.8) which can be phased together to point in any direction on the sky. Due to the large reception pattern of the basic elements, the field of view can be up to 250 square degrees. This technology can also be adapted to the focal plane of parabolic dishes. Prototypes of such wide-field cameras are under construction in Australia (ASKAP), the Netherlands (APERTIF) and in Canada (PHAD).

The Australian SKA Pathfinder (ASKAP), MeerKAT and the Murchison Wide-field Array (MWA) in Australia are SKA "precursor" telescopes at the selected SKA sites and will become part of the SKA array. ASKAP is made up of 36 antennas, each 12 m in diameter (Fig. 1.9) and equipped with a receiving system covering the frequency range 700 MHz–1.8 GHz. ASKAP is currently under construction at the Murchison Radio Astronomy Observatory in Western Australia and started early operations in 2013.

MeerKAT, currently taking shape in South Africa's Karoo region, will consist of 64 dishes of 13.5 m diameter each with an offset Gregorian configuration and equipped with three receiving systems covering the frequency range 580 MHz–14.5 GHz. The KAT-7 precursor array with seven dishes (Fig. 1.10) has been constructed and is being used as an engineering and science prototype. MeerKAT itself will be delivered in three phases. The commissioning will take place in 2014 and 2015, with the array coming online for science operations in 2016.

Fig. 1.10 Antennas of the KAT-7 array (photo: Maik Wolleben, SKA Project South Africa)

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