nature astronomy

REVIEW ARTICLE

DOI: 10.1038/s41550-017-0233-y

Extragalactic radio continuum surveys and the transformation of radio astronomy

Ray P. Norris[1,2]

Next-generation radio surveys are about to transform radio astronomy by discovering and studying tens of millions of previously unknown radio sources. These surveys will provide fresh insights for understanding the evolution of galaxies, measuring the evolution of the cosmic star-formation rate, and rivalling traditional techniques in the measurement of fundamental cosmological parameters. By observing a new volume of observational parameter space, they are also likely to discover unexpected phenomena. This Review traces the evolution of extragalactic radio continuum surveys from the earliest days of radio astronomy to the present, and identifies the challenges that must be overcome to achieve this transformational change.

A human observing a clear night sky sees only starlight. Most of this starlight comes from visible stars, including those in distant galaxies, plus objects such as the Moon and planets that are illuminated by our star, the Sun. To an observer with eyes sensitive to radio rather than visible light, stars would be relatively faint. Instead, the sky would be dominated by diffuse radio synchrotron emission from our own Galaxy, plus many pairs of compact objects, typically billions of light years away. These pairs are the twin lobes of radio galaxies, illustrated in Fig. 1, caused by a supermassive black hole (SMBH) in the nucleus of some galaxies, termed active galactic nuclei (AGN). Stars and normal galaxies are far weaker at radio wavelengths than these exotic radio galaxies.

The problem facing the first radio astronomers was that these radio galaxies are often very faint at optical wavelengths, so that optical and radio surveys largely sampled two different populations of objects, with few objects in common. A few normal low-redshift star-forming galaxies were found to emit diffuse synchrotron radiation at radio wavelengths, analogous to that from our own Galaxy, but this was much weaker than the emission from radio-loud AGN. Of those few AGN that could be identified, most seemed to be either low-redshift elliptical galaxies or high-redshift radio-loud quasars. It was therefore widely thought that all radio galaxies were elliptical galaxies.

It is now known that there is a continuum of galaxy properties, ranging from pure star-forming galaxies, such as our own Galaxy, whose radio output is dominated by stellar evolution processes, to the radio-loud objects whose radio emission is dominated by AGN. There is also an important class of composite galaxies in which the radio emission has comparable contributions from AGN and stellar evolution components.

Fortunately, as the sensitivity of both radio and optical telescopes has increased, the overlap between optical and radio surveys has grown to the point where many optical galaxies are detectable in the radio regime, and vice versa. Radio surveys are no longer dominated by exotic objects — of little interest to those studying the galaxies seen at optical wavelengths — but are taking their place as a window to provide new information regarding the majority of classes of objects in the sky. Radio surveys are therefore a key tool in understanding the evolution of galaxies over cosmic time.

This Review attempts to chart the changing nature of extragalactic radio continuum surveys, highlight the successes and challenges of this task, and describe the 'next generation' radio continuum surveys that will soon dominate the field. For conciseness, this Review does not include Galactic, spectral line or polarization surveys, nor experiments to detect and measure the cosmic microwave background or the epoch of reionization. Figures 2 and 3 compare the performance and historical context of all major extragalactic radio continuum surveys. A list of the most significant radio continuum surveys, which was used to compile these figures, can be found in the Supplementary Information.

History

Radio astronomy began in December 1932 when Karl Jansky[1] found that a component of short-wave 'static' came from a fixed position in the sky, which he subsequently found to be the centre of our Galaxy[2]. However, this discovery attracted little attention in the astronomical community. The first systematic surveys of radio sources[3–5] quickly found that most of the emission was from the Milky Way. Reber[3] also reported a tentative (but incorrect) detection of M31, and the first true extragalactic source (Cygnus A)[4], which was first detected as a discrete source by Hey et al.[6] and first resolved using the Australian sea-cliff interferometer in 1948[7]. The first extragalactic identifications of radio sources were made in 1949[8], although Cygnus A was not identified as an extragalactic source until 1954[9].

The end of the Second World War saw a surge of activity in radio astronomy, led mainly by ex-radar scientists in Cambridge, Manchester and Sydney. By 1950, there were 67 known radio sources, although only 7 had been identified[10], including M31[11]. Most of the work focused on measuring their angular size and position, to enable cross-identification. Meanwhile, three groups (Ryle at Cambridge, and Mills and Bolton in Sydney) produced catalogues of sources to explore their range of properties. By 1954, when Bolton[12] produced the first catalogue with more than 100 sources, they were still regarded as 'Galactic' sources.

In 1950, the strong radio emission from our Galaxy was attributed[13] to synchrotron emission by cosmic rays accelerated by supernova shocks. It was deduced that other normal galaxies should also exhibit this emission, which would be far weaker than that of powerful radio galaxies. Few normal galaxies were therefore detected in early surveys.

The first large (>1,000 sources) radio survey, published in 1955, was the 2C survey at Cambridge[14], which catalogued 1,936 discrete

[1]Western Sydney University, Locked Bag 1797, Penrith South, NSW 1797, Australia. [2]CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia. e-mail: r.norris@westernsydney.edu.au

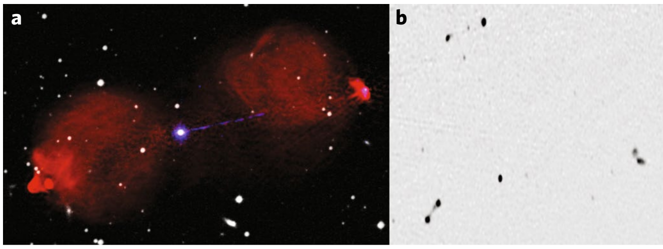

Fig. 1 | Typical sources in the radio sky. a, Composite image of a radio galaxy (Pictor A) with radio in red, optical in white and X-ray in blue. An X-ray jet emanates from the environs of a SMBH at the centre, powering two diffuse lobes (shown in red) of radio emission, which dominate the appearance at radio wavelengths. Image courtesy of Emil Lenc[118]. **b**, Sample of a typical deep radio survey[87]. Many of the radio sources are grouped into pairs or triplets, which are probably similar to the radio galaxy shown in **a**, but much fainter and more distant. Panel **a** adapted from ref. [118], Wiley.

radio sources at 81 MHz. The distribution of flux densities in the 2C catalogue was inconsistent with a Euclidean distribution of standard candles, and was claimed[15] to rule out the 'steady state' theory, favouring instead a 'Big Bang' model. However, the 2C survey was subsequently found to contain many spurious sources caused by strong radio sources detected in the outer sidelobes of the telescope point-spread function[16]. Nevertheless, the statistical properties of the noise below the detection threshold[17] still favoured the Big Bang model. The first major survey without significant errors, published in 1957–1958, was made with the Mills Cross interferometer[18,19] near Sydney, whose 85 MHz catalogue showed a distribution of flux densities only slightly steeper than that predicted by a Euclidean model.

Subsequent surveys at Cambridge, notably the 3C in 1959[20], 3CR in 1962[21] and 4C in 1961[22], agreed with the Sydney surveys, but showed strong evolution of radio sources, from which it was successfully argued that the steady state theory was incorrect.

These early successes stimulated the development of radio astronomy groups in The Netherlands, where the Dwingeloo telescope was completed in 1956, the United States, where the Owens Valley Radio Observatory was built in 1958, and Italy, where the construction of the Northern Cross telescope started in 1960, resulting in the Bologna B2 survey[23].

In 1969, the first large single-dish survey with the new Parkes telescope was published[24], and included spectral and polarization information, as well as optical identifications. Successive single-dish multifrequency surveys continued with the Parkes telescope for two decades, with a final consolidated catalogue published in 1991[25]. These surveys resulted in a growing understanding of the properties of AGN, and the physical processes driving them.

The many continuum surveys since then are listed in Supplementary Table 1 and shown in Fig. 2. From 1990 to 2004, new technology enabled the construction of higher sensitivity telescopes, resulting in a hundred-fold increase in the total number of known radio sources. This enormous change was dominated by the following four surveys.

The Westerbork Northern Sky Survey (WENSS)[26] surveyed a large area of the northern sky between 1991 and 1996 at 327 MHz, producing a catalogue of about 230,000 sources.

The National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS) surveyed the northern sky at 1.4 GHz between 1993 and 1996, producing a catalogue of about 1.8 million sources. The NVSS is still the largest radio survey, and its survey paper[27] is the second most highly cited paper in radio astronomy.

The complementary Faint Images of the Radio Sky at Twenty-Centimeters (FIRST)[28] surveyed a smaller area between 1993 and 2004 with higher resolution and greater sensitivity to yield a catalogue of about 800,000 sources. It found many sources that are not present in the NVSS catalogue, but is insensitive to some extended NVSS sources.

The lack of a corresponding Southern Hemisphere survey was rectified by the Sydney University Molonglo Sky Survey (SUMSS)[29,30], which used the upgraded 'Molonglo Cross' telescope to survey the southern sky at 843 MHz from 1997 to 2003, producing a catalogue of around 211,000 sources.

Figure 2 shows that survey sizes subsequently plateaued for almost two decades. Surveys during this time focused on covering smaller areas very deeply, presumably because another large, shallow survey could not be justified until the technology enabled an order-of-magnitude improvement over the earlier surveys, particularly NVSS.

The radio sky

The twin-lobed radio galaxies that dominated early surveys are caused by the synchrotron radiation from relativistic plasma ejected from material falling towards a SMBH. Sometimes a third component is found between them, at the position of the host, marking the start of the jet of relativistic electrons powering the double lobes. These sources naturally fall into two groups[31]: Fanaroff–Riley class II (FRII), which are very luminous sources dominated by edge-brightened lobes; and the less luminous Fanaroff–Riley class I sources, in which the peak brightness occurs closer to the host.

Orientation can dramatically change the appearance of a radio source and its host — an effect that is sometimes called 'the unified model'[32]. For example, relativistic beaming in the jets causes sources with jets along the line of sight to have a much brighter nucleus (known as core-dominated sources) than those with jets pointed elsewhere[33].

The central broad-line region of most radio galaxies is obscured by dust, but when the jet is oriented close to the line of sight, the broad-line region is visible, giving the galaxy a 'stellar' appearance at visible wavelengths. Such radio galaxies are classed as quasars.

Quasars were originally discovered[34] based on their radio properties, and, by definition, are radio-loud. A corresponding class of radio-quiet objects were called quasi-stellar objects at the time of their discovery[35] but are now normally called radio-quiet quasars (RQQs). The difference between radio-quiet and radio-loud objects cannot be explained by orientation, but must be an intrinsic property of the host. The hosts of RQQs are also found to emit weak radio emission, which is sometimes ascribed to the star-formation processes of the host[36,37], but in at least some cases the RQQ shows radio emission from weak AGN[38,39]. More generally, it is now recognized that there is a class of low-luminosity AGN, typified by RQQs and Seyfert galaxies, that appear mainly in radio survey images as faint unresolved sources.

While the strongest radio sources are AGN, sensitive surveys with sufficient resolution can detect synchrotron emission from normal star-forming galaxies.

These classes of radio source can be seen in Fig. 4. At high flux densities, the source counts are dominated by radio-loud AGN, and follow a smooth power law distribution down to about 1 mJy. The source counts flatten below 1 mJy, which suggests an additional population of low-luminosity AGN, star-forming galaxies and composite galaxies. It is remarkably difficult to distinguish between low-luminosity AGN and star-forming galaxies, but there is evidence that the density of star-forming sources approaches that of AGN at a flux density level of about 200 μJy (ref. [40]).

Scientific motivation

Radio surveys are an important astrophysical tool to provide large samples of galaxies for studying cosmology or galaxy evolution. These surveys also reveal rare but important stages of galaxy

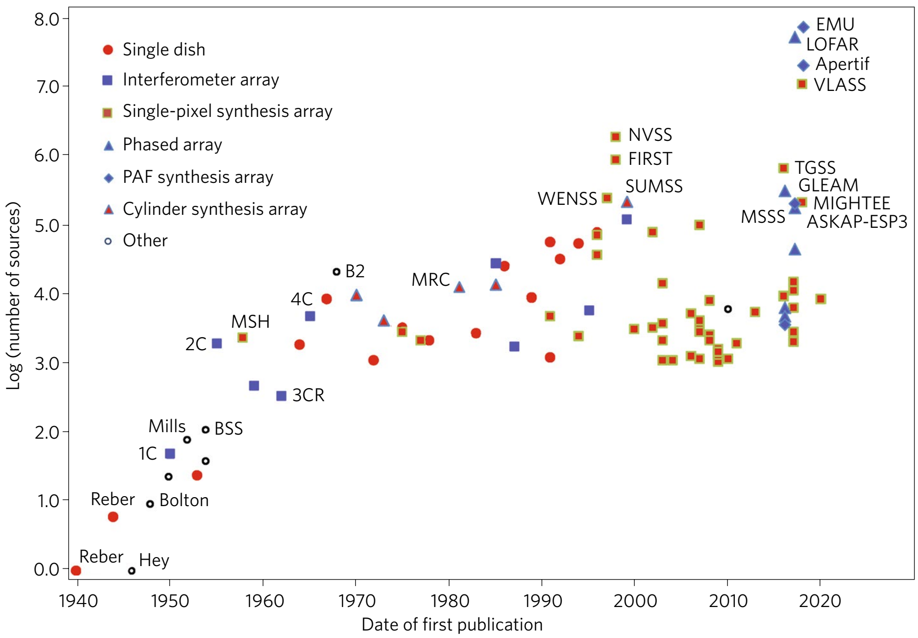

Fig. 2 | Number of known extragalactic radio sources detected in surveys as a function of time. Plot shows the increase in the number of radio sources detected by extragalactic radio surveys, from the birth of radio astronomy to the next-generation surveys. Surveys with fewer than 1,000 sources are omitted, except for those in the early days of radio astronomy. The symbols indicate the type of telescope used to make the survey: red circle, single dish; blue square, non-synthesis interferometer array; red square, conventional synthesis array; blue triangle, phased array; blue diamond, synthesis array using phased-array feeds (PAFs); red triangle, cylindrical telescope; open circle, anything else. Details of individual surveys are given in Supplementary Table 1.

evolution and expand the volume of observed parameter space, thereby increasing the likelihood of making unexpected discoveries[41]. This section outlines some of the science that drives these surveys. More detailed discussions can be found elsewhere[40,42,43].

The evolution of star formation. Only a small fraction of radio sources found in the early radio surveys were star-forming galaxies, but increasingly sensitive observations enabled their study at radio wavelengths. Star-forming galaxies are expected to represent about half of the sources in next-generation surveys.

The cosmic star-formation rate density (SFRD) of the Universe started at zero, reached a broad maximum about seven billion years ago, and has since declined by around an order of magnitude to the present day[44]. However, the shape of the curve is poorly defined, particularly at high redshifts, where different star-formation indicators give different values[45,46], largely because of poorly known extinction corrections. The contribution of different classes of galaxy to the overall rate is poorly determined, although it is known that the SFRD at low redshift is dominated by lower-mass galaxies in low-density environments, whereas the SFRD at high redshift is dominated by high-mass galaxies in high-density environments that rapidly exhaust their fuel, and are the progenitors of the brightest early-type galaxies at low redshift.

The radio emission from star-forming galaxies is dominated by synchrotron emission generated by cosmic ray electrons that have been accelerated by supernova shocks, and is proportional[47] to the far-infrared (FIR) emission, and therefore to the star-formation rate. This correlation is now known to be accurate over several orders of magnitude[48], and to extend beyond redshift $z = 2$ (ref. [49]). A plausible explanation[50] is that young stars not only heat the dust, thereby causing the FIR emission, but also explode in supernovae, causing shocks that accelerate the electrons, although this model is unable to explain the observations in detail[51,52]. Nevertheless, measuring the FIR-radio correlation is a valuable empirical method for distinguishing between star-forming galaxies and radio-loud AGN.

As radio waves are unaffected by dust extinction, radio measurements of the synchrotron emission are found to give an accurate measure of the star-formation rate. In the future, high-frequency surveys, which are sensitive to free–free emission, will also be important[53]. Whereas FIR luminosity is also a good measure of star-formation rate, next-generation radio surveys will detect more star-forming galaxies per square degree than FIR surveys, thus giving larger sample sizes. Radio continuum surveys therefore provide an important tool for measuring the cosmic star-formation history of the Universe. However, radio measurements of star-formation rate require redshifts, and better ways of detecting contributions from radio-luminous AGN that might corrupt the measurement.

Provided these challenges are met, next-generation radio surveys will measure the evolution of the cosmic star-formation rate to an unprecedented accuracy at high redshift, with a large enough sample size to examine the contributions from different classes of galaxy.

The evolution of AGN. One of the major unsolved problems in radio astronomy is to understand the difference between radio-loud and radio-quiet sources[36]. Although low-redshift radio-loud AGN are predominantly hosted by elliptical galaxies[54], the probability of a high-redshift galaxy or quasar possessing a radio-loud AGN seems to depend primarily on the mass of the host[55]. Several factors, such as black hole spin, have been suggested as the cause of this dichotomy[56]. The existence of 'restarted' radio galaxies[57] suggests that radio-loudness — or AGN activity — may be an episodic phenomenon, with a quasar spending maybe 10% of its time in a radio-loud mode, perhaps on timescales as short as 10^5 years[58].

Simulations of galaxy formation cannot reproduce the observed mass spectrum of galaxies; they typically produce too many small galaxies and too few large galaxies. This discrepancy is thought to be caused by feedback mechanisms in which the energy from supernovae and AGN limit the star-formation rate of a galaxy[59].

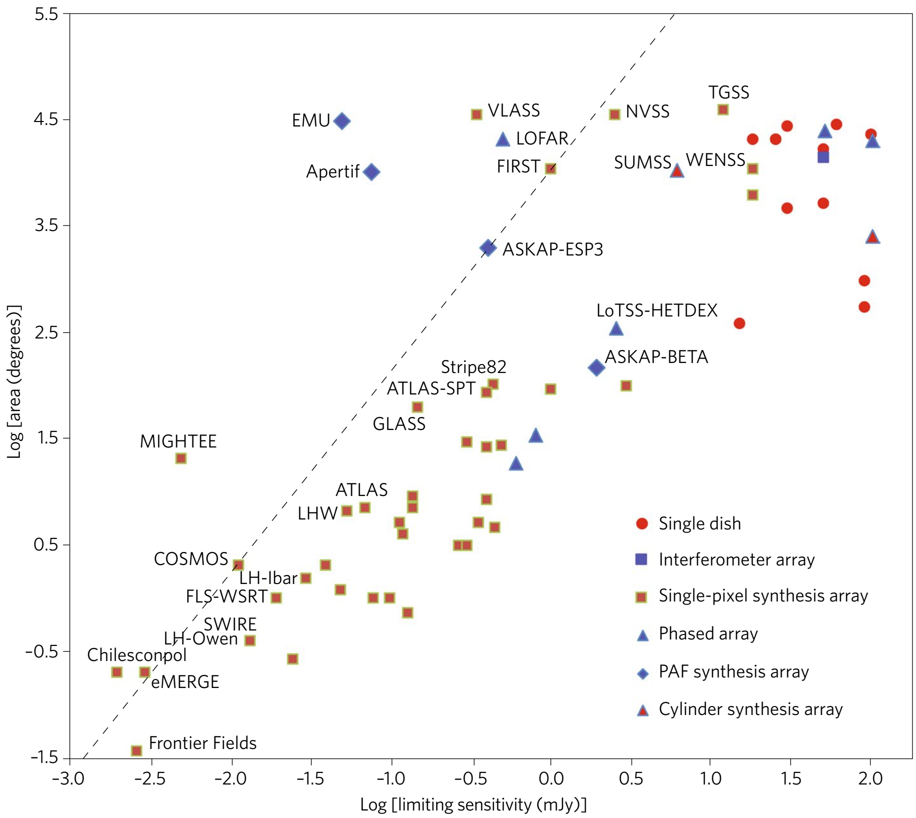

Fig. 3 | Sky area versus sensitivity of modern radio surveys. Sensitivity is either the quoted detection limit or five times the quoted r.m.s. noise level. The dashed line marks the boundary of existing surveys, and roughly corresponds to a few months of observing time on one of the leading international radio telescopes. Symbols are the same as in Fig. 2.

Two modes of accretion onto the SMBH are recognized. In cold-mode accretion — the dominant accretion mode at high redshift — cold gas fuels a SMBH with high efficiency, but the resulting AGN activity disrupts the infalling gas, thus limiting the accretion rate. In hot-mode accretion, typically seen in low-redshift elliptical galaxies, the cool gas has either been used up, heated, or expelled from the galaxy, and the remaining hot gas accretes onto the SMBH with low efficiency[60,61]. These mechanisms result in the changing space density[62] and luminosity functions[63] of radio sources. AGN activity peaks in the redshift range $z = 1–2$, closely following the evolution of cosmic star-formation rate, and suggesting that they are linked, perhaps by AGN feedback.

Future radio surveys will help us understand the links between AGN evolution and star-formation evolution, the role and redshift distribution of low-luminosity AGN, and the mechanisms of, and differences between, different classes of radio AGN, and how they are related to the accretion modes.

Clusters of galaxies. Galaxy clusters are the most massive bound objects in the Universe, consisting of galaxies in a cloud of intergalactic gas located at the intersections of filaments and sheets of the cosmic web. Clusters are rich in dynamics, shocks, interactions, and, at high redshift, even molecular gas[64]. The radio emission from clusters consists of three elements: (1) the radio emission from constituent galaxies, including bent-tail galaxies that are interacting with the intracluster gas; (2) diffuse elongated objects, known as 'relics', caused by shock-excited electrons[65]; and (3) a large diffuse 'halo' sometimes found centred on the cluster core. Our understanding of these elements has been hampered by insufficient radio data. For example, most of the ~60 known radio halos[66,67] have been found in clusters detected first at X-ray wavelengths, and our knowledge may therefore be biased by selection effects. Next-generation radio surveys will discover hundreds of diffuse radio haloes and thousands of bent-tail galaxies. Radio emission in clusters is therefore likely to become an important tool both for studying clusters themselves and for detecting large numbers of clusters to study cosmology and trace large-scale structural formation.

Cosmology. Since the early use of surveys to argue against the steady state theory, there have been many attempts to use radio surveys to measure cosmological parameters, with some successes such as the measurement of the cosmic dipole[68]. However, only now are radio continuum surveys approaching the size and depth necessary to rival other wavelengths at the precision measurement of cosmological parameters. One technique, for measuring the distortion of the images of radio sources by weak gravitational lensing[69], will probably not be feasible until the advent of large surveys with the Square Kilometre Array. Other techniques[70] use three indicators of the statistical properties of catalogues of radio surveys, via the angular power spectrum, cosmic magnification and the integrated Sachs–Wolfe effect. Even if no redshifts are available, next-generation surveys will yield independent measurements of cosmological parameters[70] to complement those from dedicated projects such as Euclid[71] and the Dark Energy Survey[72]. However, even without accurate individual redshifts, statistical redshifts[40], in which objects are assigned to a small number of redshift bins, can significantly increase the accuracy of radio-derived cosmological parameters, making them likely to become important cosmological tools[73].

Discovering the unexpected. While science resulting from well-defined scientific goals is important, experience shows that most major discoveries in astronomy are unexpected, often when technical

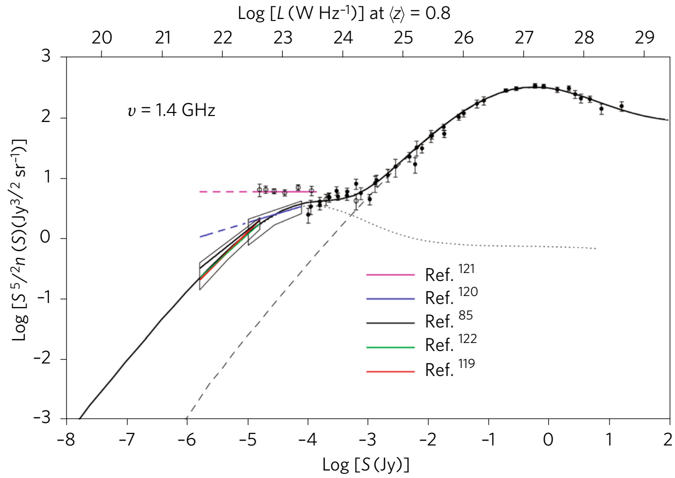

Fig. 4 | The number of radio sources as a function of flux density, plotted as a Euclidean-normalized differential source count plot at 1.4 GHz. The filled points at log[S(Jy)] > −3 are from refs [119,120]. The open data points indicate the source count[121]. The dashed black line is the contribution from radio-loud AGN, and the dotted black line is the contribution from star-forming galaxies and low-luminosity AGN. Polygons shows error boxes for the data from refs [85,120]. Coloured lines show possible extrapolations. Figure reproduced from ref. [85], IOP.

innovation enables a new part of the observational parameter space to be observed[74]. Figure 3 shows that next-generation radio surveys explore a new part of parameter space, and so should yield unexpected discoveries, provided they are equipped to do so. However, the complexity of the telescopes and the large volumes of data involved mean that it may be difficult for a human to make these discoveries. Instead, most science will be extracted from the large survey datasets by querying the data with specific questions, thereby resulting in specific answers. To discover the unexpected, we must develop algorithms[41] that can mine the data for the unexpected, such as identifying 'weird' galaxies in the Sloan Digital Sky Survey data by looking for abnormal spectra[75].

Technical challenges

Technical innovation is a major driver of radio astronomy, and significant discoveries often follow the adoption of new technologies[74]. While technology continues to increase the sensitivity and bandwidth of telescopes, new analysis techniques such as compressive sampling[76] and machine learning[77] compete with traditional techniques.

Perhaps the greatest challenge facing next-generation radio telescopes is radiofrequency interference. This issue will be best minimized by locating future telescopes at radio-quiet sites, such as those chosen for the Square Kilometre Array[78] in Australia and South Africa. However, these sites, although orders of magnitude better than urban sites in this respect, are still susceptible to satellites, aircraft and even terrestrial interference reflected from the Moon[79], which has itself been suggested as a future radio observatory site[80]. A promising avenue is the development of active interference mitigation techniques, such as the use of null beams that track an interfering signal for subsequent subtraction from the data[81].

Early radio continuum surveys utilized low frequencies owing to technical limitations, and because most radio sources are stronger at low frequency. Unfortunately, radiofrequency interference is often worse at low frequencies. Higher frequencies offer a higher resolution, positional accuracy and dynamic range. These factors determine a 'sweet spot' of 1–3 GHz chosen by most current large radio continuum surveys, although the Murchison Widefield Array[82] and the Low Frequency Array (LOFAR)[83] use low frequencies, and the Australia Telescope 20-GHz (AT20G) survey[84] uses high frequencies, to optimize the detection of different physical mechanisms.

Confusion, in which the beam size fails to distinguish between neighbouring sources, represents a fundamental limit to surveys. For example, a sea of faint unresolved sources limits the sensitivity of contemporary 20 cm surveys to a few μJy per beam[85], although techniques are being explored[86] to use the statistical properties of noise to probe the astrophysics of faint sources. Confusion caused by strong sources in the sidelobes of the telescope may be overcome by techniques such as constructing an a priori model of strong sources in the radio sky, which is subtracted from the observed data before imaging.

Cross-matching radio sources with optical/infrared catalogues is essential but difficult. About 90% (ref. [87]) of sub-mJy radio sources are simple unresolved sources at arcsec resolution, and can be reliably matched using traditional techniques such as the likelihood ratio[88]. However, the remaining 10% are complex sources that consist of several radio components. For example, two nearby unresolved radio components might be either the two lobes of an FRII radio source, in which case the optical host lies near their midpoint, or the radio emission from two unassociated star-forming galaxies. Distinguishing between these two cases is difficult, but techniques are being developed to address this challenge, including estimating the probabilities of competing hypotheses about a particular source[89], training a convolutional neural network on a set of sources that have been classified manually[41,90], or using the classification abilities of thousands of citizen scientists in projects such as Radio Galaxy Zoo[91].

Redshifts are important for many of the scientific goals of radio continuum surveys. In most cases, redshifts will be obtained from optical/infrared surveys, or from H I surveys such as WALLABY[92], LADUMA[93] and APERTIF[94]. Spectroscopic redshifts are currently impractical for surveys comprising tens of millions of sources, so photometric redshifts must be used. Because of strong AGN evolution, traditional template-based photometric redshifts are not well-matched to the high-redshift AGN found in radio surveys, nor do they exploit the available radio photometry. Empirical methods, such as machine learning, have the advantage of being able to use other available data, such as radio morphology and polarization[95], and can use training sets from deep multiwavelength surveys. Furthermore, the wide fractional bandwidth of modern surveys has shown that a source's radio spectrum is often not a simple, featureless power law, but instead has an intrinsic rest-frame spectral energy distribution containing features[96–98] that may eventually enable the estimation of redshifts using radio photometric data alone.

Next-generation continuum surveys

Since the transformational period in 1990–2000 when WENSS, NVSS, FIRST and SUMSS increased the number of known radio sources from tens of thousands to around 2.5 million, there have been many important deep surveys, but none have had the transformational power of those four. However, radio astronomy is now embarking on another transformational period with the advent of seven major continuum surveys, each based on a new or radically upgraded telescope. These surveys not only have enormously increased sensitivity, but are also transformational in their polarization capability and bandwidth. Over the next few years, these surveys will increase the number of known radio sources by a factor of about 40. The areas of sky where they overlap with each other or with other multiwavelength surveys will be particularly important.

The Australian SKA Pathfinder (ASKAP)[99] is a new radio telescope approaching completion in Western Australia that has a maximum baseline of 6 km, operating at 700–1,800 MHz. Each of its 36 antennas is equipped with a phased-array feed[100] for a 30 deg^2 field-of-view, resulting in a high survey speed. The telescope is currently in an 'early science' phase[101], with full operation expected to start in early 2018. ASKAP's continuum survey is the Evolutionary Map of the Universe (EMU)[102], which plans to survey the entire visible sky to a root mean square (r.m.s.) sensitivity of 10 μJy beam^{-1}. EMU is expected to generate a catalogue of about 70 million galaxies at 1,100 MHz, with spectral shapes and all polarization products (courtesy of the POSSUM project[103]) across a 300 MHz band.

The Giant Metrewave Radio Telescope (GMRT)[104] is a synthesis array in India with 30 antennas spanning 25 km, operating over the frequency range 150–1,500 MHz. Formally opened in 2001, it is currently undergoing a major upgrade to extend its sensitivity, reliability and frequency coverage. A large all-sky survey at 150 MHz called the Tata Institute of Fundamental Research (TIFR) Giant Metrewave Radio Telescope (GMRT) Sky Survey (TGSS) was started in 2009. However, processing the data has proved more challenging than expected, and only a small fraction of the survey has been published. A reanalysis of the raw archived data[105] has yielded a catalogue of 0.63 million sources, reaching an r.m.s. noise below 5 mJy beam^{-1}. The upgraded GMRT is expected to host even larger surveys.

LOFAR[83] is a newly completed phased-array telescope, operating at 10–240 MHz, that spans a diameter of 100 km in The Netherlands, with additional stations located in Germany, the United Kingdom, Sweden, France and Poland. Each station is an array of antennas that form many beams simultaneously on the sky. The Multifrequency Snapshot Sky Survey[106] first used LOFAR to make a shallow first-pass of the northern sky, cataloguing over 150,000 sources. The main LOFAR continuum survey, the LOFAR Two-Metre Sky Survey[107–109] consists of three tiers: tier 1 is a shallow wide-field survey that is expected to detect 50 million radio sources; tier 2 is a deep survey over 500 deg^2 targeted at deep fields, clusters and nearby galaxies; and tier 3 includes five single deep pointings at 150 MHz to reach the confusion level of 5 μJy beam^{-1} r.m.s.

MeerKAT[110], the South African SKA pathfinder telescope, is nearing completion in the Karoo region. Its 64 antennas span an area 8 km in diameter. MeerKAT continuum surveys are still being planned, but will probably include the MIGHTEE survey[111], which will survey 20 deg^2 at about 1.4 GHz to the confusion level of around 1 μJy beam^{-1}, thereby detecting about 200,000 sources. Polarized sources should be detectable significantly below this, and statistical techniques may provide astrophysical information at even deeper levels[86].

The Murchison Widefield Array[82] is a low-frequency synthesis telescope in Western Australia, located adjacent to ASKAP. It currently consists of 128 'tiles' of dipoles operating in the 80–300 MHz frequency range, over an area of 3 km in diameter. It is currently being upgraded with longer baselines and more tiles. The main continuum survey is GLEAM[112], which has produced a catalogue[113] containing over 300,000 sources at a typical r.m.s. of 9 mJy beam^{-1}. Further data releases will reach lower flux densities with higher resolution and will include the Galactic Plane and other areas omitted from the initial catalogue.

The VLA is a versatile 27-antenna synthesis array with a maximum baseline of 35 km operating in the frequency range 0.074–50 GHz, and has been in operation since 1980. It has been responsible for several of the leading radio surveys shown in Fig. 3, including the NVSS, which is currently the largest radio survey. It was upgraded in 2011 to become the Karl G. Jansky Very Large Array[114], with major increases in sensitivity, bandwidth and operating flexibility. A new radio continuum survey has started, called the VLA Sky Survey[115], which will survey declinations from −40 to +90° at 2–4 GHz. The survey is expected to reach an r.m.s. of 70 μJy beam^{-1} in 2023, producing a catalogue of around 10 million sources.

The Westerbork Synthesis Radio Telescope is a 14-antenna array with a maximum baseline of 2.7 km that has been in operation since 1970. The recent APERTIF upgrade[94] installed phased-array feed receiver systems operating over a frequency range of 1.0–1.7 GHz. The APERTIF continuum surveys are still being planned, but will probably include the WODAN survey[116], which will survey the northern cap of the sky that is inaccessible to ASKAP, to a target r.m.s. sensitivity of 15 μJy beam^{-1}. It is also planned to observe a deeper tier to a target r.m.s. of about 5 μJy beam^{-1} to cover 20 deg^2 being surveyed by the LOFAR tier 3 survey.

The future

Radio continuum surveys have a proud history of generating major breakthroughs in our understanding of the Universe. The next-generation surveys now starting will probe unexplored areas of observational parameter space, and history suggests that we can expect revolutionary discoveries as a result.

These surveys will also change the nature of radio astronomy. Existing radio measurements are not as intrinsically deep as existing optical data, and so >99% of objects studied at optical wavelengths have no radio data. Next-generation surveys are crossing a sensitivity threshold below which most galaxies detected in radio surveys are normal star-forming galaxies, and many galaxies found in optical/infrared surveys will have radio photometry. About 20% of galaxies detected by surveys such as the Sloan Digital Sky Survey and the Wide-field Infrared Survey Explorer will be detected by the new radio surveys, and radio astronomical measurements will become an indispensable part of every astronomer's toolkit.

The numbers of galaxies detected in these surveys are increasing to tens of millions, which suggests that new approaches will be needed to generate the science from the data. These surveys are likely to differ from the previous generation in three ways: (1) next-generation surveys will routinely generate polarization and spectral shape measurements that were previously available for only a few radio sources; (2) techniques for extracting the science from the data will change, with an increasing emphasis on empirical techniques such as machine learning; and (3) the approaches for interpreting the science from the data will change from studying features of individual galaxies to studying the statistical properties of subsamples. We can view the surveys as sampling the many stages, and many byways, of the evolutionary paths of galaxies from soon after the Big Bang through to the present day. The challenge will be to identify the several evolutionary threads and place the surveyed galaxies in their time and place on this web of evolutionary sequences.

This Review has said little about the Square Kilometre Array (SKA)[78], whose greatest strength will be to make extremely deep observations over small areas of sky. Phase 1 of the SKA, which is scheduled to be completed about 2023, may conduct even larger surveys than those discussed here, although specific plans are still being debated. A decade further on will hopefully see the construction of SKA phase 2, which is planned to outperform current telescopes by at least an order of magnitude, and will revolutionize radio astronomy yet again.

Radio continuum surveys are at a watershed. Behind us are the first tentative steps of discovery, followed by the gradual realization of the vast diversity of radio sources. Ahead of us is the data-driven era in which we apply ingenuity to devising the key questions with which to mine samples of tens of millions of galaxies. Radio astronomy is about to take its place in the toolbox of every astronomer, opening a new window of radio photometry on many objects studied at other wavelengths. Above all, we are opening up new tracts of unexplored parameter space, in which history tells us we are likely to make completely unexpected discoveries, provided we have the tools and insight to do so.

Received: 8 December 2016; Accepted: 28 July 2017
Published online: 18 September 2017

References

1. Jansky, K. G. Radio waves from outside the solar system. *Nature* **132**, 66 (1933).
2. Sullivan, W. T. *The Early Years of Radio Astronomy* (Cambridge Univ. Press, Cambridge, 1984).
3. Reber, G. Notes: cosmic static. *Astrophys. J.* **91**, 621–624 (1940).
4. Reber, G. Cosmic static. *Astrophys. J.* **100**, 279–287 (1944).
5. Hey, J. S., Phillips, J. W. & Parsons, S. J. Cosmic radiations at 5 metres wave-length. *Nature* **157**, 296–297 (1946).
6. Hey, J. S., Parsons, S. J. & Phillips, J. W. Fluctuations in cosmic radiation at radio-frequencies. *Nature* **158**, 234 (1946).
7. Bolton, J. G. & Stanley, G. J. Variable source of radio frequency radiation in the constellation of Cygnus. *Nature* **161**, 312–313 (1948).
8. Bolton, J. G., Stanley, G. J. & Slee, O. B. Positions of three discrete sources of galactic radio-frequency radiation. *Nature* **164**, 101–102 (1949).
9. Baade, W. A. & Minkowski, R. L. Identification of the radio sources in Cassiopeia, Cygnus A, and Puppis A. *Astrophys. J.* **119**, 206–214 (1954).
10. Greenstein, J. L. In *The Early Years of Radio Astronomy* (ed. Sullivan, W. T. III) 67–81 (Cambridge Univ. Press, Cambridge, 1984).
11. Brown, R. H. & Hazard, C. Radio-frequency radiation from the great nebula in Andromeda (M.31). *Nature* **166**, 901–902 (1950).
12. Bolton, J. G., Stanley, G. J. & Slee, O. B. Galactic radiation at radio frequencies. VIII. Discrete sources at 100 Mc/s between declinations +50° and −50°. *Aust. J. Phys.* **7**, 110–129 (1954).
13. Kiepenheuer, K. O. Cosmic rays as the source of general galactic radio emission. *Phys. Rev.* **79**, 738–739 (1950).
14. Shakeshaft, J. R., Ryle, M., Baldwin, J. E., Elsmore, B. & Thomson, J. H. A survey of radio sources between declinations −38° and +83°. *Mem. R. Astr. Soc.* **67**, 106–153 (1955).
15. Ryle, M. & Scheuer, P. A. G. The spatial distribution and the nature of radio stars. *Proc. R. Soc. Lond. Ser. A* **230**, 448–462 (1955).
16. Mills, B. Y. In *The Early Years of Radio Astronomy* (ed. Sullivan, W. T. III) 147–166 (Cambridge Univ. Press, Cambridge, 1984).
17. Scheuer, P. A. G. A statistical method for analysing observations of faint radio stars. *Proc. Camb. Phil. Soc.* **53**, 764–773 (1957).
18. Mills, B. Y. & Slee, O. B. A preliminary survey of radio sources in a limited region of the sky at the wavelength of 3.5 m. *Aust. J. Phys.* **10**, 162–194 (1957).
19. Mills, B. Y., Slee, O. B. & Hill, E. R. A catalogue of radio sources between declinations +10° and −20°. *Aust. J. Phys.* **11**, 360–387 (1958).
20. Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E. & Archer, S. A survey of radio sources at a frequency of 159 Mc/s. *Mem. R. Astron. Soc.* **68**, 37–60 (1959).
21. Bennett, A. S. The revised 3C catalogue of radio sources. *Mem. R. Astron. Soc.* **68**, 163–172 (1962).
22. Scott, P. F. & Ryle, M. The number-flux density relation for radio sources away from the Galactic Plane. *Mon. Not. R. Astron. Soc.* **122**, 389–397 (1961).
23. Colla, G. et al. The B2 catalogue of radio sources — third part. *Astron. Astrophys. Supp.* **1**, 281–317 (1973).
24. Ekers, J. A. The Parkes catalogue of radio sources, declination zone +20° to −90°. *Aust. J. Phys. Astrop. Suppl.* **7**, 3–75 (1969).
25. Otrupcek, R. E. & Wright, A. E. PKSCAT90 — the southern radio source database. *Pub. Astron. Soc. Aust.* **9**, 170 (1991).
26. Rengelink, R. et al. The Westerbork Northern Sky Survey (WENSS). I. A 570 square degree mini-survey around the North Ecliptic Pole. *Astron. Astrophys. Supp.* **124**, 259–280 (1997).
27. Condon, J. J. et al. The NRAO VLA Sky Survey. *Astron. J.* **115**, 1693–1716 (1998).
28. Becker, R. H., White, R. L. & Helfand, D. J. The FIRST survey: Faint Images of the Radio Sky at Twenty centimeters. *Astrophys. J.* **450**, 559–577 (1995).
29. Bock, D., Large, M. I. & Sadler, E. M. SUMSS: a wide-field radio imaging survey of the southern sky. I. Science goals, survey design, and instrumentation. *Astron. J.* **117**, 1578–1593 (1999).
30. Mauch, T. et al. SUMSS: A wide-field radio imaging survey of the southern sky. II. The source catalogue. *Mon. Not. R. Astron. Soc.* **342**, 1117–1130 (2003).
31. Fanaroff, B. L. & Riley, J. M. The morphology of extragalactic radio sources of high and low luminosity. *Mon. Not. R. Astron. Soc.* **167**, 31P–36P (1974).
32. Barthel, P. D. Is every quasar beamed? *Astrophys. J.* **336**, 606–611 (1989).
33. Orr, M. J. L. & Browne, I. W. A. Relativistic beaming and quasar statistics. *Mon. Not. R. Astron. Soc.* **200**, 1067–1080 (1982).
34. Kellermann, K. I. The discovery of quasars and its aftermath. *J. Ast. Hist. Heritage* **17**, 267–282 (2014).
35. Sandage, A. The existence of a major new constituent of the Universe: the quasi-stellar galaxies. *Astrophys. J.* **141**, 1560–1578 (1965).
36. Kellermann, K. I., Condon, J. J., Kimball, A. E., Perley, R. A. & Ivezic, V. Radio-loud and radio-quiet QSOs. *Astrophys. J.* **831**, 168–180 (2016).
37. Bonzini, M. et al. Star formation properties of sub-mJy radio sources. *Mon. Not. R. Astron. Soc.* **453**, 1079–1094 (2015).
38. Herrera Ruiz, N., Middelberg, E., Norris, R. P. & Maini, A. Unveiling the origin of the radio emission in radio-quiet quasars. *Astron. Astrophys.* **589**, L2 (2016).
39. Maini, A., Prandoni, I., Norris, R. P., Giovannini, G. & Spitler, L. R. Compact radio cores in radio-quiet active galactic nuclei. *Astron. Astrophys.* **589**, L3 (2016).
40. Norris, R. P. et al. Radio continuum surveys with square kilometre array pathfinders. *Pub. Astron. Soc. Aust.* **30**, e020 (2013).
41. Norris, R. P. Discovering the unexpected in astronomical survey data. *Pub. Astron. Soc. Aust.* **34**, e007 (2017).
42. Prandoni, I. & Seymour, N. Revealing the physics and evolution of galaxies and galaxy clusters with SKA continuum surveys. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)* 67 (2015).
43. Padovani, P. The faint radio sky: radio astronomy becomes mainstream. *Astron. Astrophys. Rev.* **24**, 13 (2016).
44. Hopkins, A. M. & Beacom, J. F. On the normalization of the cosmic star formation history. *Astrophys. J.* **651**, 142–154 (2006).
45. Bouwens, R. J., Illingworth, G. D., Franx, M. & Ford, H. $z \sim 7$–10 galaxies in the HUDF and GOODS fields: UV luminosity functions. *Astrophys. J.* **686**, 230–250 (2008).
46. Kistler, M. D. et al. The star formation rate in the reionization era as indicated by gamma-ray bursts. *Astrophys. J.* **705**, L104–L108 (2009).
47. van der Kruit, P. C. Observations of core sources in Seyfert and normal galaxies with the Westerbork synthesis radio telescope at 1415 MHz. *Astron. Astrophys.* **15**, 110–122 (1971).
48. Condon, J. J., Anderson, M. L. & Helou, G. Correlations between the far-infrared, radio, and blue luminosities of spiral galaxies. *Astrophys. J.* **376**, 95–103 (1991).
49. Mao, M. Y. et al. No evidence for evolution in the far-infrared-radio correlation out to $z \sim 2$ in the extended Chandra deep field south. *Astrophys. J.* **731**, 79 (2011).
50. Harwit, M. & Pacini, F. Infrared galaxies — evolutionary stages of massive star formation. *Astrophys. J.* **200**, L127–L129 (1975).
51. Murphy, E. J. The far-infrared-radio correlation at high redshifts: physical considerations and prospects for the square kilometer array. *Astrophys. J.* **706**, 482–496 (2009).
52. Lacki, B. C., Thompson, T. A. & Quataert, E. The physics of the far-infrared-radio correlation. I. Calorimetry, conspiracy, and implications. *Astrophys. J.* **717**, 196–208 (2010).
53. Murphy, E. et al. The astrophysics of star formation across cosmic time at >10 GHz with the square kilometre array. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)* 85 (2015).
54. Best, P. N. & Heckman, T. M. On the fundamental dichotomy in the local radio-AGN population: accretion, evolution and host galaxy properties. *Mon. Not. R. Astron. Soc.* **421**, 1569–1582 (2012).
55. Rees, G. A. et al. Radio galaxies in ZFOURGE/NMBS: no difference in the properties of massive galaxies with and without radio-AGN out to $z = 2.25$. *Mon. Not. R. Astron. Soc.* **455**, 2731–2744 (2016).
56. Heckman, T. M. & Best, P. N. The coevolution of galaxies and supermassive black holes: insights from surveys of the contemporary Universe. *Astron. Astrophys.* **52**, 589–660 (2014).
57. Saripalli, L., Subrahmanyan, R. & Udaya Shankar, N. Renewed activity in the radio galaxy PKS B1545−321: twin edge-brightened beams within diffuse radio lobes. *Astrophys. J.* **590**, 181–191 (2003).
58. Schawinski, K., Koss, M., Berney, S. & Sartori, L. F. Active galactic nuclei flicker: an observational estimate of the duration of black hole growth phases of 10^5 yr. *Mon. Not. R. Astron. Soc.* **451**, 2517–2523 (2015).
59. Silk, J. Feedback in galaxy formation. Tracing the ancestry of galaxies. *Proc. IAU Symp.* **277**, 273–281 (2011).
60. Croton, D. J. et al. The many lives of active galactic nuclei: cooling flows, black holes and the luminosities and colours of galaxies. *Mon. Not. R. Astron. Soc.* **365**, 11–28 (2006).
61. Hardcastle, M. J., Evans, D. A. & Croston, J. H. Hot and cold gas accretion and feedback in radio-loud active galaxies. *Mon. Not. R. Astron. Soc.* **376**, 1849–1856 (2007).
62. Wall, J. V., Jackson, C. A., Shaver, P. A., Hook, I. M. & Kellermann, K. I. The Parkes quarter-Jansky flat-spectrum sample. III. Space density and evolution of QSOs. *Astron. Astrophys.* **434**, 133–148 (2005).
63. Mauch, T. & Sadler, E. M. Radio sources in the 6dFGS: local luminosity functions at 1.4GHz for star-forming galaxies and radio-loud AGN. *Mon. Not. R. Astron. Soc.* **375**, 931–950 (2007).
64. Emonts, B. H. C. et al. Molecular gas in the halo fuels the growth of a massive cluster galaxy at high redshift. *Science* **354**, 1128–1130 (2016).
65. van Weeren, R. J. et al. The case for electron re-acceleration at galaxy cluster shocks. *Nat. Astron.* **1**, 0005 (2017).
66. Cassano, R. et al. Radio halos in future surveys in the radio continuum. *Astron. Astrophys.* **548**, A100 (2012).
67. Brunetti, G. & Jones, T. W. Cosmic rays in galaxy clusters and their interaction with magnetic fields. *Astrophys. Space Sci.* **407**, 557–598 (2015).

68. Blake, C. & Wall, J. A velocity dipole in the distribution of radio galaxies. *Nature* **416**, 150–152 (2002).
69. Brown, M. et al. Weak gravitational lensing with the square kilometre array. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)* 23 (2015).
70. Raccanelli, A. et al. Cosmological measurements with forthcoming radio continuum surveys. *Mon. Not. R. Astron. Soc.* **424**, 801–819 (2012).
71. Sartoris, B. et al. Next generation cosmology: constraints from the Euclid galaxy cluster survey. *Mon. Not. R. Astron. Soc.* **459**, 1764–1780 (2016).
72. Dark Energy Survey Collaboration. The dark energy survey: more than dark energy — an overview. *Mon. Not. R. Astron. Soc.* **460**, 1270–1299 (2016).
73. Camera, S. et al. Impact of redshift information on cosmological applications with next-generation radio surveys. *Mon. Not. R. Astron. Soc.* **427**, 2079–2088 (2012).
74. Harwit, M. *Cosmic Discovery*. (MIT Press, Cambridge, 1984).
75. Baron, D. & Poznanski, D. The weirdest SDSS galaxies: results from an outlier detection algorithm. *Mon. Not. R. Astron. Soc.* **465**, 4530–4555 (2017).
76. Dabbech, A. et al. MORESANE: MOdel REconstruction by Synthesis-ANalysis Estimators. A sparse deconvolution algorithm for radio interferometric imaging. *Astron. Astrophys.* **576**, A7 (2015).
77. Ball, N. M. & Brunner, R. J. Data mining and machine learning in astronomy. *Int. J. Mod. Phys. D.* **19**, 1049–1106 (2010).
78. Dewdney, P. E., Hall, P. J., Schilizzi, R. T. & Lazio, T. J. L. W. The square kilometre array. *Proc. IEEE* **97**, 1482–1496 (2009).
79. McKinley, B. et al. Low-frequency observations of the Moon with the Murchison widefield array. *Astron. J.* **145**, 23 (2013).
80. Lazio, J., Carilli, C., Hewitt, J., Furlanetto, S. & Burns, J. The lunar radio array (LRA). *Proc. SPIE* **7436**, 74360I (2009).
81. Offringa, A. R. et al. The low-frequency environment of the Murchison widefield array: radio-frequency interference analysis and mitigation. *Pub. Astron. Soc. Aust.* **32**, e008 (2015).
82. Tingay, S. J. et al. The Murchison widefield array: the square kilometre array precursor at low radio frequencies. *Pub. Astron. Soc. Aust.* **30**, e007 (2012).
83. van Haarlem, M. P. et al. LOFAR: The LOw-Frequency ARray. *Astron. Astrophys.* **556**, A2 (2013).
84. Massardi, M. et al. The Australia Telescope 20-GHz (AT20G) survey: the bright source sample. *Mon. Not. R. Astron. Soc.* **384**, 775–802 (2008).
85. Condon, J. J. et al. Resolving the radio source background: deeper understanding through confusion. *Astrophys. J.* **758**, 23 (2012).
86. Zwart, J. et al. Astronomy below the survey threshold in the SKA era. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)* 172 (2015).
87. Norris, R. P. et al. Deep ATLAS radio observations of the Chandra deep field-south/spitzer wide-area infrared extragalactic field. *Astron. J.* **132**, 2409–2423 (2006).
88. Sutherland, W. & Saunders, W. On the likelihood ratio for source identification. *Mon. Not. R. Astron. Soc.* **259**, 413–420 (1992).
89. Fan, D., Budavari, T., Norris, R. P. & Hopkins, A. M. Matching radio catalogues with realistic geometry: application to SWIRE and ATLAS. *Mon. Not. R. Astron. Soc.* **451**, 1299–1305 (2015).
90. Aniyan, A. & Thorat, K. Classifying radio galaxies with convolutional neural network. *Astrophys. J. Supp. Ser.* **230**, 20 (2017).
91. Banfield, J. K. et al. Radio Galaxy Zoo: host galaxies and radio morphologies derived from visual inspection. *Mon. Not. R. Astron. Soc.* **453**, 2326–2340 (2015).
92. Koribalski, B. S. The local Universe: galaxies in 3D. *IAU Symp.* **309**, 39–46 (2015).
93. Holwerda, B. W., Blyth, S.-L. & Baker, A. J. Looking at the distant Universe with the MeerKAT array (LADUMA). *IAU Symp.* **284**, 496–499 (2012).
94. Oosterloo, T. et al. Apertif — the focal-plane array system for the WSRT. In *Wide Field Astronomy Technology for the Square Kilometre Array (SKADS 2009)* 70 (2009).
95. Bonnett, C. Using neural networks to estimate redshift distributions. An application to CFHTLenS. *Mon. Not. R. Astron. Soc.* **449**, 1043–1056 (2015).
96. Callingham, J. R. et al. Extragalactic peaked-spectrum radio sources at low frequencies. *Astrophys. J.* **836**, 174 (2017).
97. O'Dea, C. P. The compact steep-spectrum and gigahertz peaked-spectrum radio sources. *Proc. Astr. Soc. Pacific* **110**, 493–532 (1998).
98. Carilli, C. L. & Yun, M. S. The radio-to-submillimeter spectral index as a redshift indicator. *Astrophys. J.* **513**, L13–L16 (1999).
99. Johnston, S. et al. Science with ASKAP. The Australian square-kilometre-array pathfinder. *Exp. Astron.* **22**, 151–273 (2008).
100. Bunton, J. D. & Hay, S. G. Achievable field of view of chequerboard phased array feed. *Int. Conf. Electromagnetics Adv. Applications (ICEAA)* 728 (2010).
101. McConnell, D. et al. The Australian square kilometre array pathfinder: performance of the Boolardy engineering test array. *Pub. Astron. Soc. Aust.* **33**, 42 (2016).
102. Norris, R. P. et al. EMU: Evolutionary Map of the Universe. *Pub. Astron. Soc. Aust.* **28**, 215–248 (2011).
103. Gaensler, B. M., Landecker, T. L. & Taylor, A. R. Collaboration survey science with ASKAP: polarization sky survey of the Universe's magnetism (POSSUM). *Bull. Amer. Astron. Soc.* **42**, 515 (2010).
104. Swarup, G. Giant metrewave radio telescope (GMRT). *Astr. Soc. Pacific Conf.* **19**, 376–380 (1991).
105. Intema, H. T., Jagannathan, P., Mooley, K. P. & Frail, D. A. The GMRT 150 MHz all-sky radio survey. First alternative data release TGSS ADR1. *Astron. Astrophys.* **598**, A78 (2017).
106. Heald, G. H. et al. The LOFAR multifrequency snapshot sky survey (MSSS). I. Survey description and first results. *Astron. Astrophys.* **582**, A123 (2015).
107. Williams, W. L. et al. LOFAR 150-MHz observations of the Bootes field: catalogue and source counts. *Mon. Not. R. Astron. Soc.* **460**, 2385–2412 (2016).
108. Röttgering, H. LOFAR and the low frequency Universe. Probing the formation and evolution of massive galaxies, AGN and clusters. In *International SKA Forum 2010 (ISKAF2010)* 50 (2010).
109. Shimwell, T. W. et al. The LOFAR two-metre sky survey. I. Survey description and preliminary data release. *Astron. Astrophys.* **598**, A104 (2017).
110. Jonas, J. L. MeerKAT — The South African array with composite dishes and wide-band single pixel feeds. *Proc. IEEE* **97**, 1522–1530 (2009).
111. Jarvis, M. J. & Taylor, A. R. The MeerKAT international GHz trailblazing extragalactic exploration (MIGHTEE) survey. In *MeerKAT Science: On the Pathway to the SKA (MeerKAT2016)* 6 (2017).
112. Wayth, R. B. et al. GLEAM: the galactic and extragalactic all-sky MWA survey. *Pub. Astron. Soc. Aust.* **32**, 25 (2015).
113. Hurley-Walker, N. et al. Galactic and extragalactic all-sky Murchison widefield array (GLEAM) survey. I. A low-frequency extragalactic catalogue. *Mon. Not. R. Astron. Soc.* **464**, 1146–1167 (2017).
114. Napier, P. J. The EVLA project: ten times more capability for the VLA. *Astr. Soc. Pacific Conf.* **356**, 65–71 (2006).
115. Murphy, E. & VLASS Survey Science Group. The VLA sky survey. In *The Many Facets of Extragalactic Radio Surveys: Towards New Scientific Challenges (EXTRA-RADSUR2015)* 6 (2015).
116. Röttgering, H. et al. LOFAR and APERTIF surveys of the radio sky: probing shocks and magnetic fields in galaxy clusters. *J. Astrop. Ast.* **32**, 557–566 (2011).
117. Andernach H. In *Astronomy from Large Data Bases* (eds Heck, A. & Murtagh, F.) 185–190 (ESO, Garching, 1992).
118. Wilson, W. E. et al. The Australia telescope compact array broad-band backend: description and first results. *Mon. Not. R. Astron. Soc.* **416**, 832–856 (2011).
119. Condon, J. J. Cosmological evolution of radio sources found at 1.4 GHz. *Astrophys. J.* **284**, 44–53 (1984).
120. Mitchell, K. J. & Condon, J. J. A confusion-limited 1.49-GHz VLA survey centered on alpha = 13 h 00 m 37 s, delta = +30 deg 34 arcmin. *Astron. J.* **90**, 1957–1966 (1985).
121. Owen, F. N. & Morrison, G. E. The deep swire field. I. 20 cm continuum radio observations: a crowded sky. *Astron. J.* **136**, 1889–1900 (2008).
122. Wilman, R. J. et al. A semi-empirical simulation of the extragalactic radio continuum sky for next generation radio telescopes. *Mon. Not. R. Astron. Soc.* **388**, 1335–1348 (2008).

Acknowledgements

Some of the information in Supplementary Table 1 was taken from tables kindly shared by H. Andernach[117], I. Prandoni and J. Callingham. I thank the following for contributing to or commenting on an early draft of this Review: H. Andernach, J. Callingham, C. Chandler, J. Condon, E. de Blok, R. Ekers, M. Filipovic, C. Hales, G. Heald, N. Hurley-Walker, A. Kimball, R. Kothes, M. Lacy, E. Lenc, T. Muxlow, E. Murphy, T. Oosterloo, I. Prandoni, H. Röttgering, N. Seymour, V. Smolcic, R. Taylor and R. Wayth.

Competing interests

The author declares no competing financial interests.

Additional information

Supplementary information is available for this paper at doi:10.1038/s41550-017-0233-y.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to R.P.N.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.