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Perspective

Very large radio surveys of the sky

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Recent advances in electronics and computing have made possible a new generation of large radio surveys of the sky that yield an order-of-magnitude higher sensitivity and positional accuracy. Combined with the unique properties of the radio universe, these quantitative improvements open up qualitatively different and exciting new scientific applications of radio surveys.

Radio astronomy always has been a science of the unexpected. Pulsars, powerful radio galaxies, quasars, and gravitational lenses are serendipitous discoveries of radio sky surveys (1). Even the earliest surveys revealed a radio universe quite unlike the familiar optical one. None of the nearby stars that dominate the visible sky were detected at radio wavelengths. Most radio sources are extragalactic and surprisingly distant. Even the brighter ones have a median redshift of ≈0.8; thus, the radio radiation received today was emitted when the universe was less than half its present age. In a spatially homogeneous universe, the excess of distant over nearby extragalactic radio sources implies strong evolution of such sources on cosmological time scales. The radio universe we see now looks like a hollow shell dominated by the distant glow from active galactic nuclei, which were far more common 5×10^9 to 10×10^9 years ago.

The Big Picture

The distribution of these remote radio sources on the sky reflects the structure of the observable universe on the largest possible scales. The top half of Fig. 1 shows the locations of the 4×10^4 strongest [flux density $S > 140$ milliJansky (mJy) at 1,400 MHz, where 1 Jy = 10^{-26} W·m^{-2}·Hz^{-1}] radio sources visible from the northern hemisphere. The north celestial pole is at the center of this equal-area projection, and declination $\delta = -40°$ marks the edge. The curved streak at the left is caused by sources near the center of our own galaxy, but isotropically distributed extragalactic sources dominate elsewhere. The bottom half of Fig. 1 focuses on the 4×10^4 sources stronger than $S = 2.5$ mJy in the representative small area within 15° of the north celestial pole. Galaxies cluster strongly on scales up to $\approx 10^7$ parsec (1 parsec $\simeq 3.09 \times 10^{16}$ m $\simeq$ 3 light years); however, radio sources in both of these flux-limited samples are so distant that the typical spacing between nearest neighbors is $>10^7$ parsecs, and the clustering of radio sources can be detected only by sensitive statistical tests (2).

The assumption that the universe is spatially homogeneous on larger scales (the "cosmological principle") is the basis for today's standard cosmological models and implies that the sky distribution of distant sources should be nearly isotropic (3). The isotropy of the cosmic microwave background is the strongest evidence supporting the cosmological principle in the early universe (redshift > 1,000), and the isotropy of radio sources is the strongest evidence that the universe of galaxies still obeys the cosmological principle. In fact, the largest departure from isotropy expected in samples containing $>10^6$ radio sources is actually the dipole anisotropy caused by earth's motion relative to distant galaxies (4), just as the dipole anisotropy in the cosmic microwave background is produced by the earth's motion with respect to the big bang.

Earlier radio surveys easily found many luminous (radio powers up to 10^{38} W) active galactic nuclei at cosmological distances, but most have two serious limitations. (*i*) Although these surveys produce images and catalogs specifying the flux densities, positions, and angular sizes of radio sources on the sky, such data are of limited use, unless the corresponding optical objects can be identified. Optical identifications distinguish radio galaxies from quasars or other objects, and optical spectra yield the redshifts and distances from which observables, such as flux density and angular size, can be converted to intrinsic source parameters, such as luminosity and linear size. The faint optical counterparts of most radio sources cannot be distinguished reliably from unrelated objects nearby on the sky, unless the radio positions have

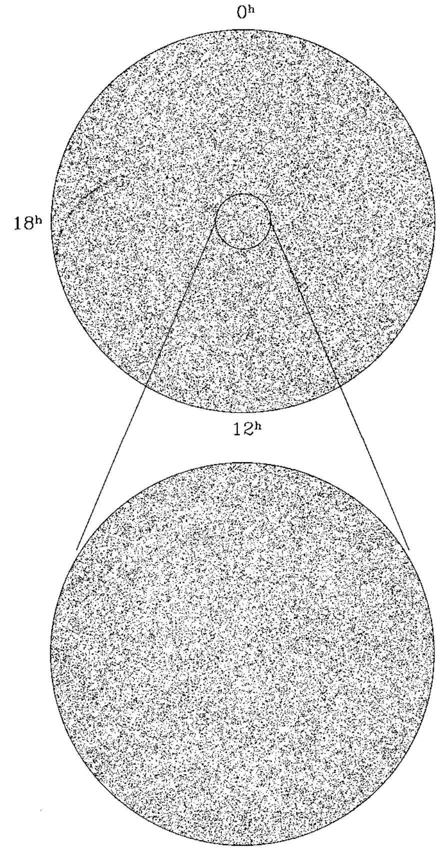

FIG. 1. Even the brightest radio sources are at cosmological distances. Dots in the upper part of the figure show the positions of the brightest 4×10^4 radio sources visible from the northern hemisphere, and the lower figure shows a comparable number of fainter sources within 15° of the north pole. Their isotropic distribution on the sky confirms that the universe becomes spatially homogeneous on the largest scales.

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FIG. 2. The NRAO VLA is located on the Plains of San Agustin west of Socorro, NM. It has the angular resolution of a single filled aperture whose radius equals the length of each array arm, but its sensitivity is only that of 27 25-m telescopes. The individual telescopes can be moved to synthesize aperture diameters from 1 km to 36 km.

rms errors less than 2–3 arc seconds (arcsec). Unfortunately, most radio surveys cannot produce such accurate positions, and slow follow-up observations are needed to secure these identifications. (*ii*) Radio surveys have been limited by sensitivity, resolution, or sky coverage to being able to detect relatively small numbers of sources, nearly all of which are the extremely distant and luminous active galactic nuclei difficult to study at optical or other (e.g., infrared or x-ray) wavelengths. Very few sources in flux-limited samples are produced by nearby objects for which multiwavelength data are available. For example, nearly all of the 10^4 brightest galaxies in the northern sky are nearer than $\approx$200 megaparsecs, yet they account for $<$0.1% of the 5×10^4 strongest radio sources (5). The consequence of these two limitations is that most of the known radio sources have never been identified with individual astronomical objects, and most of the objects studied by astronomers cannot be found in published radio catalogs.

These limitations have been overcome largely by the latest generation of radio surveys, which have the sensitivity (several mJy) required to detect statistically useable samples of nearby sources and the positional accuracy (2–3 arcsec) needed to identify their optical counterparts. The new surveys were made with arrays of telescopes connected electronically to yield the angular resolution of a single dish whose diameter equals the largest spacing between the individual telescopes. For example, one survey was made with 45-arcsec resolution by the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) of 27 25-m telescopes in a configuration 1 km in diameter (Fig. 2). With such an aperture-synthesis array, positional accuracy is not limited by the large mechanical pointing errors of individual telescopes.

Imaging the data from such an array is computationally expensive, and large aperture-synthesis surveys of the sky were not practical until the early 1990s. Also, the sensitivity of an array is proportional only to the total geometric area of its component telescopes. Very sensitive receivers are needed to exploit the power of the aperture-synthesis technique, and the installation of such receivers on the VLA was completed in 1993. Unfortunately, the same advances in electronics and computing that made large radio surveys practical also threaten future ones. Sensitive surveys require bandwidths much wider than the protected radio astronomy bands and are vulnerable to growing interference from broadcast, navigation, and communication satellites. Our new window on the universe may be closed in the near future.

The VLA telescopes can be moved to form larger configurations with higher angular resolution. The choice of survey resolution is constrained by two conflicting scientific goals: good sensitivity to extended sources with low surface brightness and high positional accuracy for weak sources. Survey images and catalogs are sensitivity-limited in apparent brightness (units of Kelvin or milliJansky beam^{-1}), but catalogs complete to some fixed flux density (units of mJy) are needed to construct unbiased source samples. Surveys discriminate against faint sources larger than the image point-source response and can miss even nearby sources with low surface brightness. For example, the median disk brightness of spiral galaxies similar to our own is $\approx$1 K at 1,400 MHz. Only the smallest configuration of the VLA forms a large enough beam (resolution $\theta \approx 45$ arcsec) to detect such galaxies in brief observations. On the other hand, the rms positional errors (σ_P) caused by noise are proportional to this beam width, reaching $\sigma_P \approx \theta/10$ for the faintest detectable sources (about five times the rms noise level). Beam widths smaller than $\theta \approx 20$ arcsec are needed to make reliable optical identifications of the weakest detected sources with faint optical objects. No single survey can satisfy both of these incompatible astronomical constraints—the fault lies not in us but in our stars. The only solution to this dilemma is to make two or more surveys spanning a range of resolving powers.

The new generation of large radio surveys has four members: the Westerbork Northern Sky Survey (WENSS; ref. 6; see also www.strw.LeidenUniv.nl/%7Edpf/wenss/), the Sydney University Molonglo Sky Survey (SUMSS; ref. 7; see also www.astrop.physics.usyd.edu.au/SUMSS/index.html), the Faint Images of the Radio Sky at Twenty cm survey (FIRST; ref. 8; see also sundog.stsci.edu), and the NRAO VLA Sky Survey (NVSS; ref. 9; see also www.nrao.edu). Table 1 lists the main survey parameters. The WENSS is characterized by its ability to image complex sources accurately and by its relatively low frequency, which enable it to be used in conjunction with the NVSS to measure source spectra. The NVSS images cover 82% of the celestial sphere and contain nearly 2×10^6 radio sources. The southern-hemisphere SUMSS, which started recently, is comparable with the NVSS in sensitivity and resolution and complements the NVSS by completing the southern-sky coverage. The ongoing FIRST survey covers a growing area centered on the north galactic pole. It is being made by the VLA in the 10-km configuration, which is distinguished by its uniquely high angular resolution and positional accuracy. Indeed, the resolution that can be achieved by the 10-km configuration is sufficient to make optical identifications of radio sources efficiently (10), even with objects as faint as those galaxies that will be detected by the optical Sloan Digital Sky Survey.

The variety of objects detected in the new surveys is illustrated by Fig. 3, which shows NVSS 1,400-MHz radio-brightness contours superimposed on optical gray-scale images. For the first time, representative samples of radio stars can be examined. HD

Table 1. Large radio surveys

					Sensitivity, (5σ)		
Survey	Frequency, MHz	Sky coverage	Area, deg^2	Resolution, arcsec	K	mJy beam^{-1}	Sources per deg^2
WENSS	325	$\delta > +30°$	10,300	54×54 cosec $\lvert\delta\rvert$	60	15	21
SUMSS	843	$\delta < -30°$	10,300	43×43 cosec $\lvert\delta\rvert$	4.7	5	37
FIRST	1,400	NGP	>5,000	5	25	1	90
NVSS	1,400	$\delta > -40°$	33,900	45	0.8	2.5	54

NGP, north galactic pole.

23478 is a B star whose ionized stellar wind is a thermal radio source. Young x-ray-emitting dwarfs with deep convective envelopes, RS Canis Venaticorum binaries, Algol-type stars, and cataclysmic variables also were found. The time-averaged continuum emission of 79 known pulsars, such as PSR J0628-2800, was detected (11). Pulsars have exceptionally steep power-law spectral slopes: $\alpha = -d \ln S / d \ln \nu$, where α = spectral slope, S = flux density, and ν = frequency. Selecting sources with $\alpha > 1.5$ from the NVSS uncovered no new pulsars but seems to have found a number of luminous extragalactic objects with remarkably steep spectra and small angular sizes (<0.2 arcsec). Some of these can be identified with extremely faint galaxies or groups of galaxies, but we do not yet understand why they have such steep spectra. Most of the $\approx 10^3$ known planetary nebulae in our galaxy were detected (12), G118.8-74.7 being a nearby example. These ionized remnants of low-mass (0.8–8 solar masses) stars are potentially powerful tracers of galactic star-formation history. Because dust extinction strongly biases optically selected samples of planetary nebulae, the NVSS has been used with far-infrared data from the Infrared Astronomic satellite (IRAS) to generate a large extinction-free sample of planetary nebulae (13).

About half of the stronger (>0.1 counts per s^{-1}) extragalactic x-ray sources in the ROSAT (Röntgensatellit) all-sky survey are detectable radio sources. The sky density of NVSS sources is much less than that of candidate optical identifications; thus, x-ray sources having relatively large positional uncertainties (the x-ray position of J002041.8-254307 and its uncertainty are indicated by the open cross-hairs in Fig. 3) can be identified with radio sources whose accurate positions determine unambiguous optical identifications. The majority of optically bright galaxies in the *Uppsala General Catalogue of Galaxies* (14) were detected by the NVSS. The new radio surveys are nearly as sensitive as IRAS to galaxies whose far-infrared and radio emissions are powered by short-lived massive stars and their supernova remnants. Thus, most extragalactic sources found by the IRAS were detected by the NVSS. Faint infrared sources like IRAS F00022+2750 have large position error ellipses, and the smaller radio positional uncertainties can support identifications with optically faint galaxies. Furthermore, the ratio of far-infrared to radio flux densities is a useful diagnostic tool for detecting dust-shrouded active galactic nuclei in these objects.

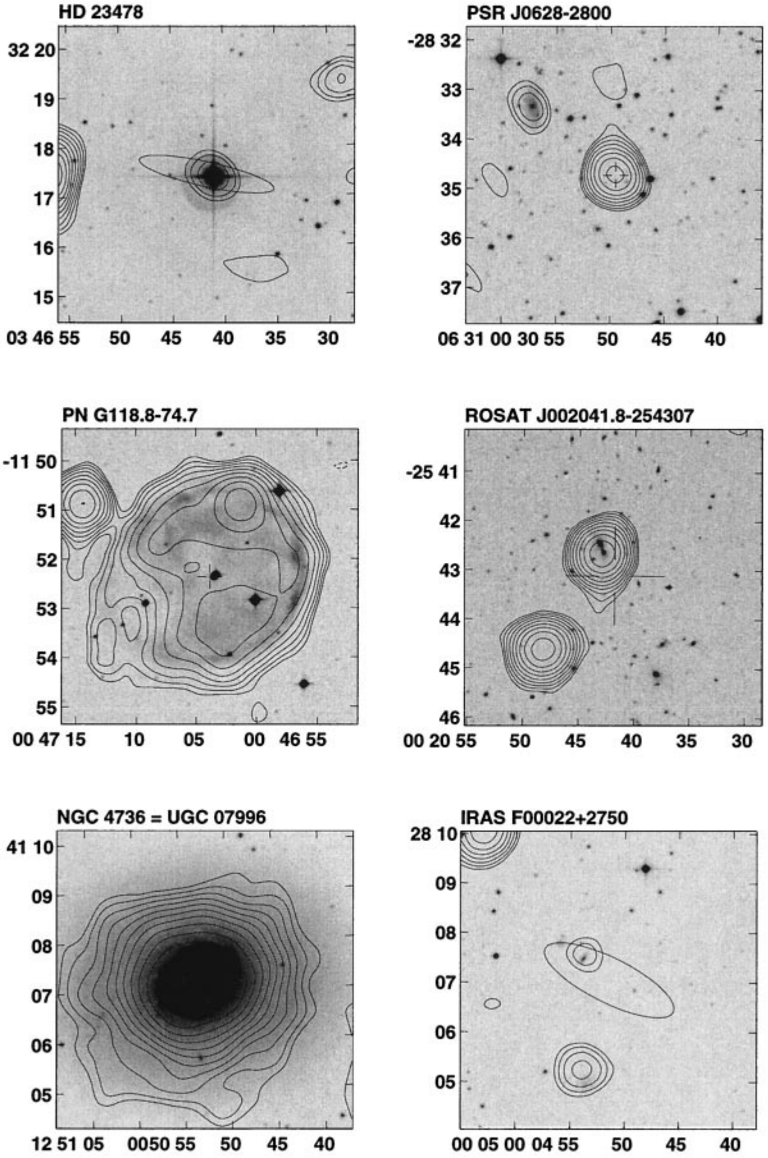

FIG. 3. Representative objects detected by the NVSS: the star HD 23478, the pulsar PSR J0628-2800, the planetary nebula PN G118.8-74.7, the x-ray galaxy ROSAT J002041.8-254307, the nearby spiral galaxy NGC 4736, and the distant infrared galaxy IRAS F00022+2750. In all panels, the 1,400-MHz radio-brightness contours ∓ 1 mJy beam$^{-1} \times \mp 2^0, 2^{1/2}, 2^1, 2^{3/2}$, etc. are shown over gray-scale optical images.

It is clear that these large radio surveys have detected rich and diverse samples of radio sources with many more scientific applications than their survey teams can exploit. Therefore, the survey data have been released on the web sites listed throughout, and all astronomers are encouraged to use them for their own research.

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