RADIO SURVEYS

J.J. CONDON
National Radio Astronomy Observatory, Charlottesville

1. Introduction

Radio surveys have an important role in astronomy, one that has changed with technology and scientific requirements. Most objects studied by radio astronomers today are the unexpected discoveries of early surveys. The survey "discovery" phase began with Jansky's detection of Galactic radio emission and Reber's 160 MHz maps showing that this emission is non-thermal. Surveys made just after World War II revealed strong discrete sources which were later identified with supernova remnants, radio galaxies, and quasars. Pulsars were discovered during a sky survey for scintillating sources. BL Lac objects were recognized in early high-frequency surveys. The first gravitationally lensed quasar appeared in the extensive Jodrell Bank 960 MHz survey, and the first measurement of gravitational radiation came from the binary pulsar serendipidously found in a pulsar survey.

2. Cosmological Evolution

The strong cosmological evolution evident in the first samples containing hundreds of extragalactic sources drove the second phase of radio surveying. Most radio sources in flux-limited samples are extragalactic, and evolution dominates their redshift distribution at all flux cutoffs $S_0 < 1$ Jy. Consequently, samples of radio sources are quite different from the local samples of bright galaxies found at optical or infrared wavelengths:
(1) Nearby sources are rare. Less than 1% of the 5×10^4 northern-hemisphere radio sources with $S \geq 25$ mJy at 4.85 GHz are associated with the 10^4 UGC galaxies larger than $\theta = 1'$, most of which are within about 100 Mpc (Condon *et al.* 1991). Similarly, there is $< 1\%$ overlap of this radio sample with the *IRAS* Faint Source Catalog, Version 2 (Moshir *et al.* 1992)

B.J. McLean et al. (eds.), New Horizons from Multi-Wavelength Sky Surveys, 19–25.

galaxies (Condon *et al.* 1995). Unfortunately, disjoint samples discourage multiwavelength cooperation. Optical and near-infrared astronomers generally prefer the nearby galaxies which they can observe well, while radio astronomers concentrate on luminous AGN at the edge of the universe.
(2) The majority of radio galaxies and quasars are found around their median redshift $\langle z \rangle \approx 0.8$, which is nearly independent of S_0 (Condon 1989). In the nearly Euclidean optical universe, faint objects are statistically more distant and have smaller angular sizes, but are intrinsically similar to bright ones. In the hollow-shell radio universe, reducing S_0 does not yield a "deeper" sample; it adds sources with lower absolute luminosities. Characteristic flux densities and angular sizes exist because features in the radio luminosity and linear-size functions are mapped directly onto flux-density and angular-size distributions. For example, there is a transition from classical radio galaxies and quasars to a mixture of starburst galaxies, Seyferts, and "normal" galaxies below $S \approx 1$ mJy at 1.4 GHz.

3. Extragalactic Astronomy

All-sky continuum surveys capable of detecting $\sim 10^5$ sources became practical with multichannel HEMT receivers in the 1980's. The NRAO 7-beam 4.85 GHz receiver was used on the Green Bank 91 m telescope to make the GB6 survey of about 75,000 sources (Gregory *et al.* 1996) stronger than 18 mJy in the northern hemisphere and on the Parkes 64 m to make the PMN surveys of the southern sky (Wright *et al.* 1996). Astronomical applications of such surveys include: (1) Obtaining the first statistically useful ($N > 10^2$) samples of nearby radio sources (*e.g.*, Condon *et al.* 1991, 1995), (2) discovering intrinsically rare objects such as gravitational lenses, and (3) probing the large-scale structure of the universe at redshifts $z \sim 1$.

4. New Large Continuum Surveys

Large aperture-synthesis surveys capable of detecting $\sim 10^6$ sources are possible with modern computing power. Three are under way: the Westerbork Northern Sky Survey (WENSS), the VLA B-configuration Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey, and the NRAO VLA Sky Survey (NVSS) being made with the D and DnC configurations. A fourth, covering $\delta < -30°$, has been proposed (Large *et al.* 1994) for the Molonglo Observatory Synthesis Telescope. They all have significantly higher sensitivity, resolution, and position accuracy than existing single-dish surveys, and the WENSS and NVSS are the first source surveys sensitive to polarization as well as total intensity.

Surveys which can resolve many extragalactic sources face conflicting demands for completeness and position accuracy. Surveys are not flux

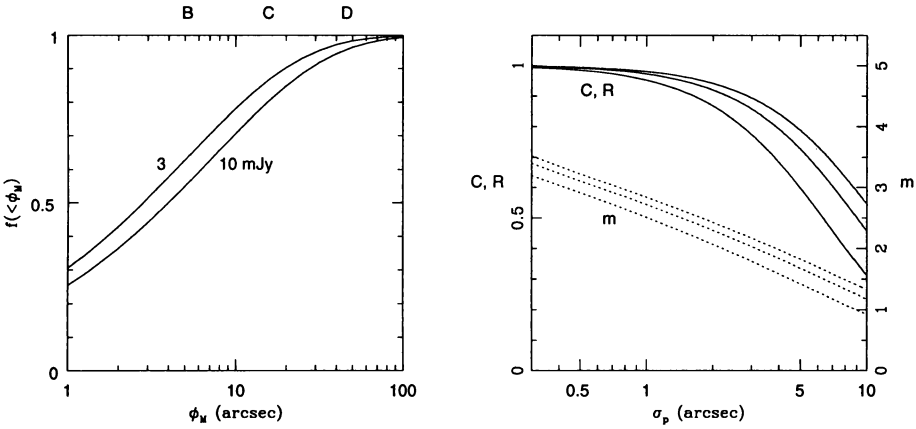

Figure 1. The cumulative fraction $f(< \phi_\mathrm{M})$ of faint sources with angular size ϕ_M is compared with the VLA B-, C-, and D-configuration resolutions in the left panel. The right panel indicates the completness and reliablity (for $C \approx R$ and search radius $r_s = m\sigma_\mathrm{p}$) for optical identifications of sources having rms position uncertainty σ_p with objects brighter than $J = 22.5$ near the Galactic pole (top), at $|b| = 30°$, $|l| = 90°$ (middle), and in the Galactic bulge $|b| \leq 30°$, $|l| \leq 45°$ (bottom).

density (Jy) limited—they are surface-brightness (Jy beam^{-1} or K) limited. For example, the average face-on disk surface brightness of spiral galaxies is ≈ 1 K at 1.4 GHz, so this surface-brightness sensitivity is needed to detect complete samples of spiral galaxies above *any* flux limit S_0. Figure 1a shows the cumulative fractions of extragalactic sources versus angular size at 1.4 GHz flux densities $S = 3$ and 10 mJy. Surveys with resolution $\ll 1'$ miss faint resolved sources. On the other hand, noise limits the rms position uncertainty σ_p of faint sources to $\sigma_\mathrm{p} \geq \sigma\theta/(2S_\mathrm{M})$, where σ is the rms map noise, θ is the FWHM resolution, and S_M is the source peak flux density. At the detection limit $S_\mathrm{M} \approx 5\sigma$ and $\sigma_\mathrm{p} \approx \theta/10$. The desire to make complete and reliable identifications with optically faint objects favors low σ_p and hence low θ. For example, $\sigma_\mathrm{p} \approx 2''.5$ is needed to identify radio sources with $J = 22.5$ (the POSS II limit) objects at galactic latitude $|b| = 30°$ with 90% completeness and reliability (Figure 1b), so $\theta \lesssim 25''$ is needed to make such identifications at the survey limit. The WENSS and NVSS are optimized for completeness and photometric accuracy, FIRST for high position accuracy.

4.1. WENSS

The WENSS (de Bruyn *et al.* 1994) will cover the $\Omega = 3.14$ sr north of $\delta = +30°$ at 325 MHz and about one-third of this area at 610 MHz. Its FWHM resolution is $55'' \times 55''\mathrm{cosec}\delta$ at 325 MHz and $30'' \times 30''\mathrm{cosec}\delta$

https://doi.org/10.1017/S0074180900128177 Published online by Cambridge University Press

at 610 MHz. The 5σ detection limit is about 15 mJy beam^{-1} at both frequencies, and about 3×10^5 sources are expected. The sky is being covered with a mosaic of fields separated by half the primary beamwidth. Every field is observed at 18 different hour angles in each of six array configurations over a period of six weeks. Thus the (u, v)-plane coverage and sensitivity to extended structures is excellent, and the data sample short-term variability at low frequencies. Finally, images in all four Stokes parameters (I, Q, U, and V) will yield polarization information for both discrete sources and diffuse Galactic emission.

Scientific goals of the WENSS include: (1) Selecting sources with extremely steep spectra, such as luminous radio galaxies at high redshifts, relic radio sources in clusters of galaxies, and pulsars. (2) Selecting a large sample of flat-spectrum sources to be used in a search for gravitational lenses. (3) Selecting and studying compact steep-spectrum (CSS) sources. In addition, the WENSS should be effective at finding giant (> 1 Mpc) radio galaxies, low-brightness disk and halo emission from nearby spiral galaxies, and cross-identifying objects found in other wavelength regions.

4.2. FIRST

The 1.4 GHz FIRST is a high-resolution total-intensity survey of the north Galactic cap. It was designed to identify faint galaxies and quasars found by the Sloan Digital Sky Survey (Gunn 1995), detect significant numbers of faint starburst galaxies, and resolve many extended extragalactic sources. The $5''.4$ resolution ensures that the rms position errors are $< 1''$ even at the survey sensitivity limit, ≈ 1 mJy beam$^{-1} \approx 20$ K. A catalog of fitted components from the first 1550 deg^2 observed (≈ 75 sources deg^{-2}) is now available on-line (Becker *et al.* 1995). Unlike the WENSS, both FIRST and NVSS cover each field with a single snapshot, so the (u, v) coverage is poor and the data must be processed carefully to maximize dynamic range.

4.3. NVSS

The 1.4 GHz NVSS is an "all-sky" survey, covering the $\Omega = 10.3$ sr with $\delta \geq -40°$ by a mosaic of 217,446 snapshot observations in the compact D and DnC configurations of the VLA. The principal data products will be (1) a set of 2326 $4° \times 4°$ "cubes" having three planes containing the Stokes I, Q, and U images with $45''$ FHWM resolution and (2) a catalog of almost 2×10^6 discrete sources brighter than 2.5 mJy beam$^{-1} \approx 0.8$ K (≈ 50 sources deg^{-2}). The rms position errors are $< 1''$ for strong sources, $< 2''.5$ for the $\approx 10^6$ sources stronger than 5 mJy, and $\approx 5''$ for the faintest detectable sources. The principal scientific goal of the NVSS is to encourage multiwavelength research by providing complete and reliable samples of sources, especially nearby ones, for use by all astronomers. The NVSS should detect most bright galaxies (*e.g.*, UGC galaxies), most sources in the *IRAS* Faint Source Catalog, and most classical radio galaxies and quasars (*e.g.*, M87 at $z \approx 2$). To guarantee equal access, the NVSS team members have agreed to use only the electronically released results for their own research. Image cubes covering about half of the survey area are currently available on-line, along with a catalog of $\approx 9 \times 10^5$ sources (Condon *et al.* 1996). The NVSS observations will be essentially complete by 1996 October 1.

5. Future Radio Surveys

Imagine a phase space whose axes are survey parameters—sensitivity, frequency, polarization, time resolution, *etc.* (cf. Harwit 1981). Astronomical phenomena are scattered throughout the phase space, some still awaiting discovery. Which regions remain to be explored, which will be scientifically interesting, and how can they be surveyed?

5.1. SPECTROSCOPIC SURVEYS

The first large-scale (survey volume $\approx 10^7$ Mpc$^3 \gg 10^3$ Mpc$^3 \approx$ galaxy correlation volume) spectroscopic survey for galaxies and extragalactic H I clouds was recently proposed (Stavely-Smith *et al.* 1996). A 13-beam receiver on the Parkes 64 m telescope will cover the southern sky to a depth of $140h^{-1}$ Mpc with $14'$ angular resolution. The 5σ sensitivity of 20 mJy in one 14 km s^{-1} channel corresponds to an H I mass detection limit $\approx 10^6 M_\odot (D/\mathrm{Mpc})^2$ for a galaxy with 200 km s^{-1} velocity width. This survey will rediscover known gas-rich galaxies (dwarf galaxies within about 30 Mpc, normal Sc galaxies within about 45 Mpc, and giant gas-rich galaxies such as Malin-1 out to 140 Mpc) and provide data on their H I mass function, space distribution, and group/cluster dynamics. It should discover new galaxies with low optical surface brightness and any isolated H I clouds. If numerous, they may contain a large portion of all H I in the universe.

The longitude range $75° < l < 145°$ of the Galactic plane is being imaged in H I with $\approx 1'$ resolution and in continuum at 408 and 1420 MHz (Normandeau *et al.* 1996). Single-dish data are used to fill the hole in the DRAO (u, v) plane and restore very extended structures.

5.2. $\nu \gg 5$ GHZ CONTINUUM SURVEYS

Continuum surveys now span 30 MHz to 5 GHz. Most known blazars were found in the higher-frequency surveys sensitive to compact sources with flat

https://doi.org/10.1017/S0074180900128177 Published online by Cambridge University Press

radio spectra. Surveys at higher frequencies have been considered in the hope that they might find a "new population" of sources with peaked or inverted spectra, but they are technically difficult. The beam solid angle of a telescope scales as ν^{-2} and system noise generally increases with frequency, so the the time needed to survey a fixed area of sky to a given flux limit rises very rapidly above 5 GHz. For example, the 100 m Green Bank Telescope (GBT) will be capable of making an all-sky survey at $\nu = 15$ GHz with the resolution and sensitivity of the 1.4 GHz NVSS, but it would take five years of continuous observing even with a 7-beam receiver!

This region of phase space may also be empty. Chauvanistic radio astronomers see the IRAS $\lambda = 60$ μm survey as a $\nu = 5000$ GHz radio survey complete to $S = 0.28$ Jy over most of the sky. The hypothetical blazars with spectral peaks between 5 and 5000 GHz should appear in cross-identifications with radio sources stronger than 25 mJy at 5 GHz. Unfortunately, all IRAS blazars in the northern hemisphere are stronger than 250 mJy (or weaker than 25 mJy) at 5 GHz (Condon *et al.* 1995). Their absence in the decade above the radio flux-density limit suggests that few nonthermal sources peak at short cm wavelengths. The only significant new population of "radio" sources found by IRAS is dusty galaxies.

Dusty galaxies at high redshifts remain the best candidates for surveys at the shortest radio wavelengths, in the $\lambda \approx 0.8$ mm atmospheric window. At frequencies below the blackbody peak, the spectra of dusty galaxies and quasars are so steep ($S \sim \nu^3$) that flux density is nearly independent of redshift above $z \approx 1$. Distant galaxies with luminosities near the knee of the evolved luminosity function pile up around $S \approx 1$ mJy, and the source counts near this critical flux density may exceed the Euclidean extrapolation by two orders of magnitude. Blain and Longair (1996) showed that the SCUBA multibeam bolometer mounted on the JCMT could survey about 0.1 deg^{-2} to this level and detect up to 50 galaxies, enough to provide useful constraints on the early evolution of star-forming galaxies.

5.3. SYNOPTIC SURVEYS

Strongly variable and transient radio sources are produced by X-ray binaries, black holes, gamma-sources, radio stars, novae, and other exotic objects in our Galaxy. Some have been discovered serendipidously and a few systematically (Gregory and Taylor 1986), but most remain unrecognized against the background of extragalactic radio sources. Known Galactic variables tend to be weak, have flat or inverted radio spectra, variability time scales ranging from hours to days, and low duty cycles. A systematic survey of this population requires repeated observations with high sensitivity and resolution (to avoid Galactic and extragalactic confusion) at a short

https://doi.org/10.1017/S0074180900128177 Published online by Cambridge University Press

wavelength. A 7-beam $\lambda = 2$ cm receiver could be built for the GBT and scanned parallel to the Galactic plane. At a scan rate of 10° min^{-1} it would make a Nyquist-sampled image covering $|b| \leq 1^\circ$, $350^\circ < l < 260^\circ$ with $45''$ FWHM resolution and 2 mJy rms noise *daily*. Averaging images from N successive days would yield an image with $\sqrt{N}$ lower noise for constant sources and differencing them would eventually detect all transient sources stronger than 10 mJy plus many fainter ones. This is a true "discovery" survey for the new millenium.

References

Becker, R.H., White, R.L., and Helfand, D.J. (1995) The FIRST Survey: Faint Images of the Radio Sky at Twenty Centimeters, Astrophys.J., 450, 559. `http://sundog.stsci.edu`

Blain, A.W., and Longair, M.S. (1996) Observing Strategies for Blank-field Surveys in the Submillimeter Waveband, Mon.Not.R.astron.Soc., 279, 847.

Condon, J.J. (1989) The 1.4 GHz Luminosity Function and Its Evolution, Astrophys.J., 338, 13.

Condon, J.J., Anderson, E., and Broderick, J.J. (1995) Radio Identifications of Extragalactic *IRAS* Sources, Astron.J., 109, 2318.

Condon, J.J., Cotton, W.D., Greisen, E.W., Yin, Q.F., Perley, R.A., Taylor, G.B., and Broderick, J.J. (1996) NRAO VLA Sky Survey, `http://www.cv.nrao.edu/~jcondon/nvss.html`

Condon, J.J., Frayer, D.T., and Broderick, J.J. (1991) UGC Galaxies Stronger Than 25 mJy at 4.85 GHz, Astron.J., 101, 362.

de Bruyn, G., Miley, G., Tang, Y., Bremer, M., Brouw, W., Rengelink, R., Bremer, M., and Röttgering, H. (1994) The WENSS Project, Astron NFRA, August, 4–8 and `http://www.strw.leidenuniv.nl/wenss/`

Gregory, P.C., Scott, W.K., Douglas, K., and Condon, J.J. (1996) The GB6 Catalog of Radio Sources, Astrophys.J.Supp., 103, 427. `http://www.cv.nrao.edu/~jcondon/gb6ftp.html`

Gregory, P.C., and Taylor, A.R. (1986) Radio Patrol of the Northern Milky Way, Astron.J., 92, 371.

Gunn, J.E. (1995) The Sloan Digital Sky Survey, Bull.Am.Astron.Soc., 28, 875

Harwit, M. (1981) *Cosmic Discovery.* Basic Books, New York.

Large, M.I., Campbell-Wilson, D., Cram, L.E., Davison, R.G., and Robertson, J.G. (1994) Increasing the Field Size of the Molonglo Observatory Synthesis Telescope, Proc.ASA, 11, 44.

Moshir, M., *et al.* (1992) Explanatory Supplement to the IRAS Faint Source Survey, Version 2 JPL D-10015 8/92, Jet Propulsion Laboratory, Pasadena.

Normadeau, M., Taylor, A.R., and Dewdney, P.E. (1996) The DRAO Galactic Plane Survey Pilot Project, `http://www.ras.ucalgary.ca/pilot_project.html`

Stavely-Smith, L., *et al.* (1996) The Parkes 21 cm Multibeam Project, `http://wwwatnf.atnf.csiro.au/Research/multibeam/multibeam.html`

Wright, A.E., Griffith, M.R., Hunt, A.J., Troup, E., Burke, B.F., and Ekers, R.D. (1996) The Parkes-MIT-NRAO Surveys, Astrophys.J.Supp., 103, 145. `http://wwwpks.atnf.csiro.au/databases/surveys/pmn/pmn.html`