Part 1

Radio Source Surveys and Cosmology

The Universe at Low Radio Frequencies
IAU Symposium, Vol. 199, 2002
A. Pramesh Rao, G. Swarup and Gopal-Krishna, eds.

Radio Source Surveys

J. J. Condon

National Radio Astronomy Observatory[1]*, 520 Edgemont Road,*
Charlottesville, VA 22903 USA

Abstract. The primary goal of radio source surveys is to generate flux-limited samples. Sources selected at very low frequencies are dominated by unbeamed emission and give the only unbiased view of the parent populations used by "unification" models to account for the diversity of sources seen at high frequencies. Low-frequency surveys favor sources with exceptionally steep spectra. They include radio galaxies at high redshifts, radio halos of nearby galaxies, relic radio sources, diffuse cluster emission, pulsars that may be missed by traditional pulse searches, and a new class of unidentified compact sources. Flux densities from low-frequency surveys extend the spectra of known source populations to frequencies at which free-free and synchrotron absorption become significant and constrain basic source parameters. Finally, telescope fields-of-view scale $\propto \lambda^2$, so gridded surveys can be more efficient than directed observations of individual targets. This review covers recent and proposed low-frequency source surveys and their astronomical uses.

1. Introduction

Recent advances in electronics and computing have made possible a new generation of large surveys (see `http://www.cv.nrao.edu/~jcondon/nvss.html` for links to these surveys and Condon et al. (1998) for a description of the NVSS) with much higher sensitivity, resolution, and positional accuracy. Combined with the unique properties of the radio universe, these quantitative gains open up qualitatively different and exciting new scientific applications of radio surveys. In particular, the new surveys detect large samples of astronomically interesting objects besides the ubiquitous radio-loud AGNs: radio stars, planetary nebulae, pulsars, nearby "normal" galaxies, and starburst galaxies. Surveys are especially relevant at low frequencies because the primary-beam solid angle Ω_b is proportional to λ^2, so nearly all surveys have been made at relatively low frequencies ($\nu \leq 5$ GHz). At the longest wavelengths, the number $4\pi/\Omega_b$ of fields in the sky may be much smaller than the number of objects to be studied, and making gridded surveys becomes the most efficient observing technique (Baldwin 1990).

---

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

The principal scientific applications of source surveys depend on the current state of astronomy and on the technical parameters of the surveys. The first is finding unexpected classes of astronomical objects, especially those from which we learn new astrophysics. Early radio surveys discovered radio galaxies, quasars, BL Lac objects, pulsars, and gravitational lenses. Next came the construction of complete samples of source populations, from which their statistical properties (e.g., cosmological evolution) could be inferred. Recent sensitive large-scale surveys have been used to find radio emission from intrinsically rare objects in radio samples, such as gravitational lenses or, remarkably, nearby galaxies. Finally, the accurate radio positions of sources in high-resolution surveys yield reliable optical identifications without the need for slow follow-up observations.

2. An overview of the radio sky

Almost all radio sources are extragalactic. Their cosmological evolution is so strong that most are very distant AGNs whose distribution in the universe can be approximated by a hollow shell at $\langle z \rangle \approx 1$. Since the mean separation between nearest neighbors is larger than the 10 Mpc galaxy clustering correlation length, radio sources have a nearly isotropic distribution on the sky (Figure 1), providing the strongest evidence that the universe of galaxies obeys the "cosmological principle."

Advantages of radio surveys for studying the large-scale distribution of galaxies include uniform photometry unaffected by interstellar dust and negligible confusion by Galactic stars. Even the Earth's motion relative to the frame defined by distant galaxies may be measureable (Ellis & Baldwin 1984) via its dipole signal proportional to $(1 + v/c)(3 + \alpha)$, almost 4 times greater for $\langle \alpha \rangle = +0.7$ radio sources than for the $\alpha = -2$ microwave background. Still, the low space density of sources makes the clustering signal at $\langle z \rangle \approx 1$ weak, and it may be confused by nearby sources (Cress & Kamionkowski 1998).

The remoteness of most radio sources has been both a blessing and a curse for radio astronomy. Even early radio surveys could detect extremely distant galaxies, discover quasars and BL Lac objects, and demonstrate that the universe evolves over time. Unfortunately, few radio sources are close enough to be studied easily in other wavelength ranges—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. There is nothing more useless than another unidentified radio source!

Thus surveys with both high sensitivity and extensive sky coverage are needed to yield useful numbers of nearby sources as well as rare source types (e.g., sources with spectra steeper than $\alpha = 1.5$). Almost as important as finding these sources is identifying them with astronomical objects seen in the optical and other wavebands. Unfortunately, radio sources have conspired to make these two aims mutually incompatible. Most scientific applications need samples complete above some *flux-density* (mJy) limit, but all surveys produce images which are *brightness* (mJy/beam or K) limited. Complete surveys should be made with low enough resolution ($\sim 1'$) that most sources are unresolved, but higher resolution ($\leq 15''$) is necessary to identify the optical counterparts

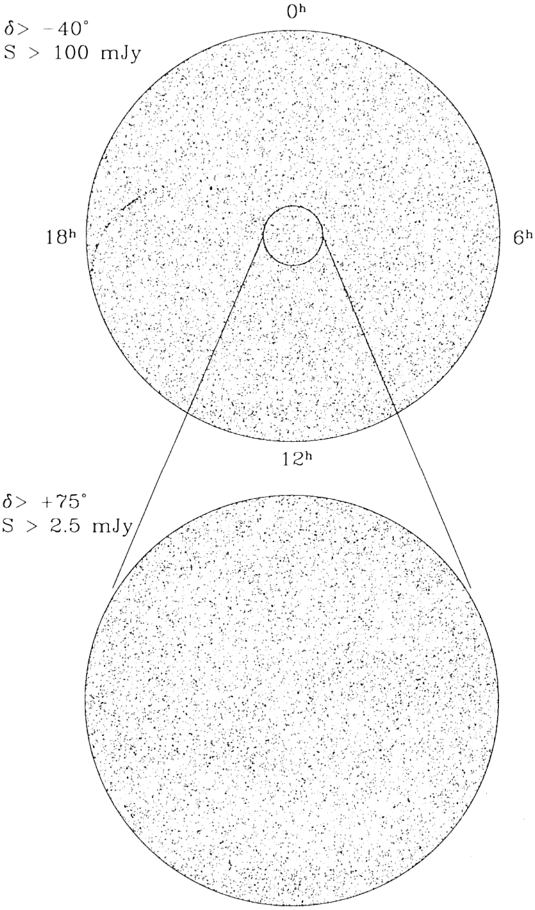

Figure 1. Most radio sources are extragalactic and very distant, so their distribution on the sky is quite uniform. The top figure shows the strongest 4×10^4 NVSS sources on an equal-area projection; the Galactic plane is just visible as a band near the Galactic center ($\alpha \sim 18^h$. The bottom figure shows a similar number of faint NVSS sources north of $\delta = +75°$.

of faint, distant radio sources reliably. Clearly, no single survey can satisfy both requirements.

3. Low-frequency surveys

The radio window covers several decades in frequency, so surveys at different frequencies select quite different spectral populations. Low-frequency surveys favor steep-spectrum sources, but discovering "new" sources at low frequencies remains difficult because low-frequency surveys are usually less sensitive than those at $\nu \approx 1$ GHz, owing to confusion (by both strong sources in the sidelobes of the primary beam and faint sources in the synthesized beam), high sky temperatures, and the narrow bandwidths available. For example, any sources in the proposed VLA 4MASS survey (Section 4) stronger than 400 mJy at 74 MHz that are not in the 1400 MHz NVSS must have $\alpha(74, 1400) > 1.7$. More importantly, new low-frequency surveys will provide the flux densities we need to *recognize* the rare ultra-steep spectrum sources in existing samples as well as to reveal spectral changes caused by physical effects like synchrotron self-absorption, free-free absorption, and energy-dependent losses from synchrotron and inverse-Compton radiation. For example, the free-free absorption coefficient κ of an H II region is

$$\left(\frac{\kappa}{\mathrm{pc}^{-1}}\right) \approx 3.3 \times 10^{-7}\left(\frac{n_\mathrm{e}}{\mathrm{cm}^{-3}}\right)^{2}\left(\frac{T_\mathrm{e}}{10^4\ \mathrm{K}}\right)^{-1.35}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1} . \tag{1}$$

A normal spiral galaxy like our own has a face-on brightness temperature $T_\mathrm{b} \approx 1$ K at $\nu = 1.4$ GHz and should become optically thick below a few MHz. Starburst galaxies become opaque even at higher frequencies ($\nu \approx 1$ GHz for the edge-on M82, several GHz for compact ultraluminous galaxies like Arp 220). Israel & Mahoney (1990) found that the 57.5 MHz flux densities of nearby spiral galaxies are generally lower than extrapolations from higher frequencies and that the deficit is greater for edge-on galaxies. They suggested that free-free absorption in a cold ($T_\mathrm{e} < 1000$ K) plasma is responsible. Hummel (1991) has confirmed the spectral flattening but not the dependence on inclination, so the cause might also be a flattening of the cosmic-ray energy distribution at low energies.

There are several known populations of sources with very steep spectra: (1) Pulsars, especially millisecond pulsars, have the steepest known spectra and are conspicuous continuum sources in low-frequency surveys (Erickson & Mahoney 1985; Erickson et al. 1987). (2) About 2% of extragalactic sources have extremely steep spectra at very low frequencies: $\alpha(38, 178) > 1.2$ (Baldwin & Scott 1973). Most are found in nearby rich clusters of galaxies and have only moderate radio luminosities ($L \approx 10^{25}$ W Hz^{-1} sr^{-1} at 178 MHz); they are probably evolved powerful double sources confined for $\approx 10^9$ yr by the hot ICM (Slingo 1974). (3) Sources having steep spectra at frequencies above 178 MHz tend to be exceptionally luminous and distant radio galaxies (Blumenthal & Miley 1979). The extensive Leiden project (Röttgering et al. 1997) based on the criterion $\alpha(178, 1400) > 1$ has been very efficient at selecting high-redshift galaxies from the 3C and 4C samples, and a new program (De Breuck et al. 1998) using the WENSS and NVSS surveys to detect weaker sources with $\alpha(327, 1400) > 1.3$ has already uncovered a radio galaxy with $z = 5.19$ (van Breugel et al. 1999). (4) "Relic" or "dead" radio sources no longer being supplied with relativistic electrons can have arbitrarily steep spectra. If scattering keeps the electron pitch angle distribution isotropic, the radio spectrum will fall exponentially above the frequency

$$\left(\frac{\nu_{\rm c}}{\rm GHz}\right) \approx \left(\frac{H}{\mu{\rm G}}\right)^{-3} \left(\frac{t}{\rm Gyr}\right)^{-2} . \tag{2}$$

Kaplan et al. (2000) isolated 74 of the steepest-spectrum ($\alpha > 1.5$) sources by comparing fluxes in the Texas 365 MHz survey catalog and the NVSS 1400 MHz catalog. Only 4 sources with $\alpha > 2.5$ were found, although all sources with $S_{365\ \rm MHz} > 200$ mJy and $\alpha < 3.2$ are above the 2.5 mJy NVSS limit. Although six known pulsars were easily recognized, no new pulsars were found that might have been missed by traditional pulse searches: those with high dispersion measures, < 1.5 mS periods, high acceleration (in tight binaries), or little intrinsic modulation. One known $z = 3.79$ galaxy was rediscovered, but most of the steep-spectrum sources are "new." They are not clustered near the galactic plane and so appear to be extragalactic. High-resolution VLA observations at 1.4 and 5 GHz resolve about two-thirds of the new sources; the rest are smaller than about $0\farcs2$ in size. The new unresolved sources are also distinguishable from known pulsars by their low linear and circular polarizations. Their optical counterparts are all very faint or invisible.

Finally, samples of AGN selected at very low frequencies are important because they represent the unbeamed "parent" populations used in "unified" models to explain the differences between AGN in terms of relativistic beaming (Wall and Jackson 1997). Samples selected at $\nu \leq 74$ MHz are completely dominated by isotropic radio emission, unlike those found at higher frequencies—even 3CR has a 10% contamination by beamed sources. They give the only unbiased view of the parent populations used in "unification" models to account for the diverse source populations observed at higher frequencies.

4. A 4-Meter All-Sky Survey (4MASS)

Perley et al. (1999) recently proposed to make a 74 MHz ($\lambda = 4$ m) continuum survey covering the 10.3 sr of sky with $\delta > -40°$ using the VLA BnA and B configurations. The principal data products will be a set of images with $\theta = 80''$ FWHM resolution and a catalog of sources brighter than $S_{\rm p} \approx 400\,{\rm mJy\ beam}^{-1}$. A test survey covering the north polar cap has been made.

The main scientific goals of 4MASS are:

(1) To construct the largest flux-limited sample of sources at a very low frequency. If the median spectral index of sources between 74 and 1400 MHz is $\langle\alpha\rangle \approx 0.7$, then there should be $N \approx 1.3 \times 10^5$ sources in $\Omega = 10.3\,{\rm sr}$ (Condon 1984). The 4MASS will yield statistically usable samples ($N > 10^2$ members) of relatively rare but important radio sources such as normal galaxies (cf. Condon et al. 1991).

(2) To generate large samples of steep-spectrum sources. The 4MASS should detect $\sim 10^2$ pulsars. The survey will find and image steep-spectrum radio halos surrounding nearby radio galaxies. Fossil or relic radio sources are diffuse steep-spectrum sources not obviously identified with any galaxy (cf. Goss et al. 1987).

X-ray emission from inverse-Compton scattering of their synchrotron electrons can be used to estimate the magnetic field strengths of clusters containing fossil sources (Bagchi et al. 1998). High-redshift radio galaxies are efficiently discovered by their steep radio spectra. The low-frequency sky is almost completely unexplored at the proposed sensitivity and resolution, so serendipidous discoveries are likely.
(3) To extend the radio spectra of known source populations to 74 MHz, where free-free absorption and synchrotron self-absorption become increasingly important. Evidence for free-free absorption within the first two galactic supernova remnants (SNRs) imaged by the VLA at 74 MHz (Kassim et al. 1995; Bietenholz et al. 1997) suggests that 4MASS will find many more cases. The Cas A result (Kassim et al. 1995) provides only the second direct case for cool, unshocked ejecta interior to the reverse shock in a young SNR.
(4) To disentangle the superposition of sources along complex lines of sight in our Galaxy via the contrast between nonthermal emitters and free-free absorbing H II regions. This technique has been applied to H II regions in and around the W30 SNR complex (Kassim & Weiler 1990) and placed the thermal galactic center source Sgr A West in front of the nonthermal Sgr A East (Pedlar et al. 1989). In addition, the intervening interstellar medium affects the continuum spectra of many SNRs, and the measured optical depths will constrain its properties and distribution (Kassim 1989).
(5) To image extended (up to $30'$) steep-spectrum sources such as galactic SNRs and the halos and tails of nearby radio galaxies. The multiscan (u, v)-plane coverage of 4MASS will greatly surpass previous single-snapshot VLA surveys.

The 4MASS scientific goals largely determine the survey design. Many steep-spectrum sources are likely to be larger at 74 MHz than at 1400 MHz (Perley & Erickson 1979), and even the 1400 MHz angular-size distribution (cf. Condon et al. 1998) indicates that the B configuration ($\theta \approx 80''$ FWHM resolution) is the largest able to generate complete flux-limited samples. The faintest detectable sources ($S \approx 5\sigma$) have rms positional uncertainties $\sigma \approx \theta/10$ owing to noise alone, so most 4MASS positions will not be good enough for making reliable optical identifications with faint galaxies. However, even the faintest sources with spectra flatter than $\alpha = 1.7$ should have NVSS counterparts with $\sigma \geq 1''$ positions. Supplementing a B-configuration survey with NVSS positions yields good positional accuracy without sacrificing completeness.

Nearly uniform sensitivity is essential for generating flux-limited source samples, so 4MASS will cover the sky north of $\delta = -40°$ with a hexagonal grid of 571 fields (Figure 2). The partially overlapping images will be weighted and combined to produce the final sky images as described by Condon et al. (1998). Each field will be observed with six ten-minute snapshots spread over several hours centered on transit. This gives the filled (u, v)-plane coverage needed to image sources as large as $30'$ in diameter while minimizing the "w-term" delays that make wide-field imaging computationally expensive. Test observations indicate that the rms noise is $\sigma \leq 80\tau^{-1/2}\,\mathrm{mJy\,beam^{-1}}$ for total integration times $0.25 < \tau < 10$ hours on relatively cold sky. The system temperature is dominated by sky noise and will be higher in the galactic plane. With $\tau \approx 1$ hour plus overhead for calibration, slewing, and repeating observations corrupted by severe ionospheric disturbances the 5σ detection limit is $S_\mathrm{p} \approx 400\,\mathrm{mJy\,beam^{-1}}$.

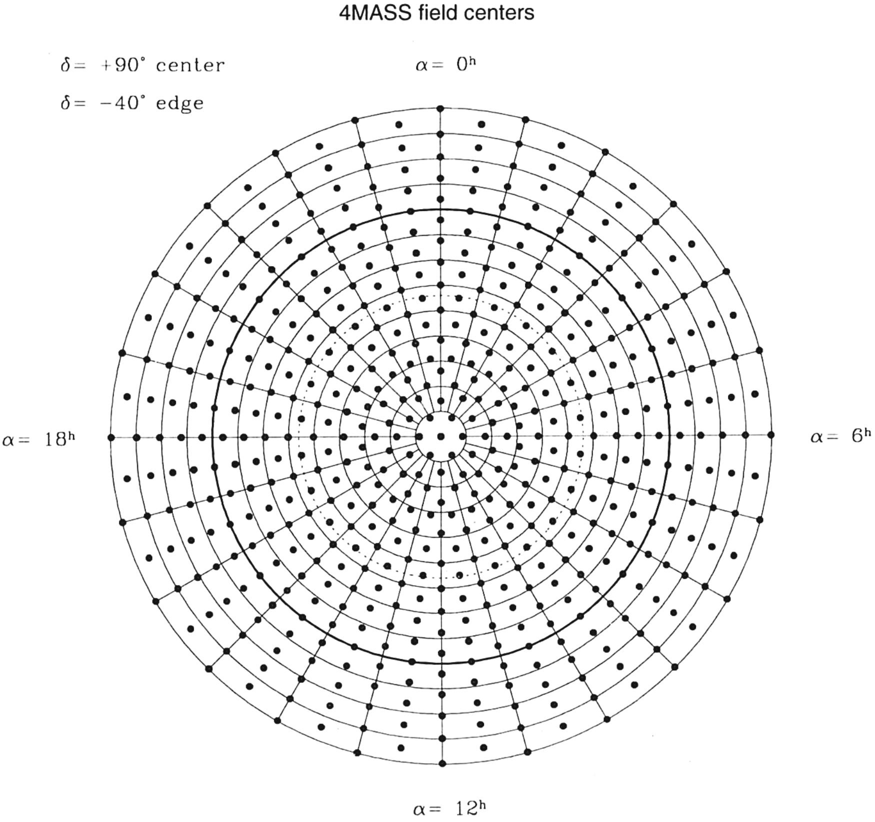

Figure 2. At $\lambda = 4$ m the VLA primary beamwidth is 11.5° FWHM, so only 571 fields are needed to cover $\delta > -40°$ with uniform sensitivity, and a gridded sky survey is more efficient than observing many target sources.

References

Bagchi, J., Pislar, V., & Lima Neto, G. B. 1998, MNRAS, 296, L23

Baldwin, J. E. 1990, in Low Frequency Astrophysics from Space, ed. N. E. Kassim & K. W. Weiler (Springer Verlag Lecture Notes in Physics 362), 195

Baldwin, J. E., & Scott, P. F. 1973, MNRAS, 165, 259

Bietenholz, M. F., Kassim, N., Frail, D. A., Perley, R. A., Erickson, W. C., & Hajian, A. R. 1997, ApJ, 490, 291

Blumenthal, G., & Miley, G. K. 1979, A&A, 80, 13

Condon, J. J. 1984, ApJ, 287, 461

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693 (NVSS)

Condon, J. J., Frayer, D. T., & Broderick, J. J. 1991, AJ, 101, 362

Cress, C. M., & Kamionowski, M. 1998, MNRAS, 297, 486

De Breuck, C., Brotherton, M. S., Tran, H. D., van Breugel, W., & Röttgering, H. J. A. 1998, AJ, 116, 13

Ellis, G. F. R., & Baldwin, J. E. 1984, MNRAS, 206, 377

Erickson, W. C., & Mahoney, M. J. 1985, ApJ, 299, L29

Erickson, W. C., Mahoney, M. J., Becker, R. H., & Helfand, D. J. 1987, ApJ, 314, L45

Goss, W. M., McAdam, W. B., Wellington, K. J., & Ekers, R. D. 1987, MNRAS, 226, 979

Hummel, E. 1991, A&A, 251, 442

Israel, F. P., & Mahoney, M. J. 1990, ApJ, 352, 30

Kaplan, D. L., Cordes, J. M., Condon, J. J., & Djorgovski, S. G. 2000, ApJ, in press

Kassim, N. E. 1989, ApJ, 347, 915

Kassim, N. E., Perley, R. A., Dwarakanath, K. S., & Erickson, W. C. 1995, ApJ, 455, L59

Kassim, N. E., & Weiler, K. W. 1990, ApJ, 360, 184

Pedlar, A., Anantharamaiah, K. R., Ekers, R. D., Goss, W. M., van Gorkom, J. H., Schwarz, U. J., & Zhao, J.-H. 1989, ApJ, 342, 769

Perley, R. A., Condon, J. J., Cotton, W. D., Yin, Q. F., Wall, J. V., Kassim, N. E., & Erickson, W. C. 1999, VLA proposal AP-390 (4MASS)

Perley, R. A., & Erickson, W. C. 1979, ApJS, 41, 131

Röttgering, H. J. A., van Ojik, R., Miley, G. K., Chambers, K. C., van Breugel, W. J. M., & de Koff, S. 1997, A&A, 326, 505

Slingo, A. 1974, MNRAS, 168, 307

van Breugel, W., De Breuck, C., Stanford, S. A., Stern, D., Röttgering, H., & Miley, G. 1999, ApJ, 518, L61

Wall, J. V., & Jackson, C. A. 1997, MNRAS, 290, L17