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Radio Continuum Surveys

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Abstract. Radio continuum surveys in the 1950's and 1960's found unexpected and important properties of cosmic objects that led to the important discoveries of the nature of the universe. In the last ten years, the radio surveys of virtually the entire sky and extremely sensitive radio observations of small regions of sky have led to the determination of the physical properties of a variety of objects, many at cosmologically significant distances. Radio continuum surveys from telescopes that are planned over the next decade will provide a unique glimpse into the far reaches of the universe and data on unprecedentedly large samples of radio sources of many types.

1. The Early Radio Continuum Surveys

The first radio continuum survey was made by Karl Jansky between 1928 and 1933. Using a radio array at 20.7 MHz at the Bell Laboratories in Holmdel, New Jersey, Jansky detected radio noise bursts caused by distant thunderstorms on top of a hiss of unknown origin (Jansky 1933). The maximum amplitude of the hiss repeated every 23 hours and 56 minutes, suggesting that it was caused by something extra-terrestrial in origin. Even with the poor angular resolution of the telescope, it was clear that the radio emission was located near the Galactic center, and thus the science of radio astronomy was born.

The next radio survey was made by Grote Reber, who built a large parabolic antenna in his back yard in Wheaton, Illinois to survey the radio sky at the higher frequencies of 160 and 480 MHz. He confirmed the radio emission near the Galactic plane and then mapped a large portion of the radio sky between 1941 and 1943 (Reber 1944). His maps showed considerable radio emission from the entire Galactic plane with the addition of several bright discrete sources away from the plane. The radio emission was significantly stronger at the lower frequency, so Reber concluded that the emission was nonthermal; that is, not associated with emission from hot objects, but with another radio emission process, called synchrotron emission[2]. Several people had predicted this emission mechanism in the 1950's (Alfvén & Herlofson 1950; Shklovsky 1958), and it was confirmed by Burbidge's interpretation of the jet component in M87 (Burbidge 1944). This type of radiation was also generated in the early accelerators of the 1940's.

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[2] see `http://www.nrao.edu/whatisra/history.shtml`

With the impetus of radar technology in World War II, the science of radio astronomy began in earnest in the late 1940's, mostly in Australia and in England. The brightest discrete radio sources (Cas A, Cyg A, and Tau A) were first identified (Bolton, Stanley, & Slee 1949), and over 50 discrete sources were obtained from the 81 MHz 1C survey (Ryle, Smith, & Elsmore 1950). A more sensitive radio survey—2C (Shakeshaft et al. 1955)—found nearly 2,000 discrete sources. However, many of these sources were found to be blends of several faint radio sources using an Australian array (Mills, Slee, & Hill 1958), and from the next Cambridge survey, the 3C survey at 159 MHz (Edge et al. 1959). These surveys showed that the radio sky was filled with so many discrete sources that much higher resolution—and thus higher-frequency observations—was needed to separate and catalog them. In the 1960's, sensitive and relatively high-resolution radio continuum surveys cataloged many thousands of discrete sources. The most important catalogs were the 3C Revised catalog (Bennett 1962), the Owens Valley catalogs (Kellermann & Read 1965), the Ohio State catalogs (Kraus et al. 1956), the 4C catalog (Pilkington & Scott 1965), and the Parkes catalogs (Bolton & Shimmins 1973).

2. The Surprises of the Radio Sky

These first radio continuum surveys led to extremely important advances in revealing the nature of the universe. First, it was difficult to identify many of the radio sources with optical counterparts, many of which were fainter than 20th magnitude. Although a few sources were apparently associated with supernova remnants in our galaxy (Cas A, Tau A) and some were identified with relatively nearby galaxies such as Cyg A and Vir A, the majority were identified with very faint objects > 20 magnitude or not identified at all. In addition, some of the identifications were associated with faint stellar-like objects and were thought to be distant Galactic stars because of their relatively isotropic distribution on the sky. In the middle 1960's several of the stellar objects were shown to be bright point-like objects with redshifts z well over 0.1 (Schmidt 1963). Hence, most radio sources were at cosmological distances and could be used as probes of the evolution and structure of the universe.

It was clearly realized that the excess numbers of weaker radio sources were incompatible with a simple evenly filled Euclidean universe plus the expected attenuation caused by the redshift. In order to obtain a slope in the count more steep than a Euclidean count, the density and/or luminosity of the sources must increase with cosmological epoch or redshift (Mills, Slee, & Hill 1958; Ryle & Clarke 1961). This alone dealt a severe blow to the steady-state universe model (Hoyle 1969) unless creation of matter was added to the model. The combination of source evolution and the cosmological structure of the universe associated with the expansion of the universe were difficult to disentangle—a problem that remains today.

The second surprise from the early surveys and follow-up observations was that many of the radio sources were very small in angular size. Interferometry using widely spaced antennas (several tens of kilometers) showed that many contained radio emission components less than one arcsecond in size (Allen et al. 1962). Also, observations of sources near the sun showed a twinkling or scintillation that was produced as the emission from radio sources of sub-arcsecond angular size traverse the extended solar corona (Hewish 1964). In 1967 some of these scintillating sources were found to have periodic bursts of emission every second or less (Hewish et al. 1968). After disposing of the "little green men" hypothesis for their origin, astronomers associated these sources with very fast-rotating neutron stars with radio emission produced by a narrow-angle beacon of emission near the surface of the degenerate star (Gold 1968).

Observations in 1964 and 1965 showed that some of the 3C radio sources varied over a period of months and hence were less than one light-month in linear size (Dent 1965). Since many of these sources are at distances of 100 Mpc or more, their angular sizes must be on the order of one milliarcsecond or less. This led to the development of Very Long Baseline Interferometry (VLBI), where radio antennas are separated by many thousands of kilometers in order to reach the resolution necessary to determine the angular sizes of these radio sources (Clark 2003).

Finally, the images of these radio sources made using arrays of many telescopes showed two important properties. The region near the galaxy nucleus often contained a small-diameter radio component (radio core) which suggested that a massive object at the center of the galaxy was a vital component in the generation of the enormous radio energy. In addition, there was often extended emission that could be as large as 1 Mpc in size, much larger than the stellar component in the galaxy. This extended emission was often composed of two symmetrically disposed radio blobs around the core, and sometimes a radio jet emanated from the core region toward one or both of the cores. These observations confirmed the twin-jet model for radio sources (Rees 1971) and led to the investigations of matter falling into a massive central object (perhaps even a black hole). The directionality was produced by the disk-like behavior of the infalling matter and the production of strong magnetic fields that could focus the flow of energy into two narrow beams from the central regions (Blandford 1990).

3. Current Large-Area Sky Surveys

In the 1990's through the present time, radio arrays were constructed to image particular radio sources and to survey a large part of the sky to levels well under 1 mJy, and many millions of discrete sources have now been cataloged. The most comprehensive survey is the NRAO VLA Sky Survey (NVSS) at 1.4 GHz with 45 arcsec resolution, covering the sky north of $\delta > -40^\circ$, complete to 2.5 mJy (Condon et al. 1998). Other surveys are the Westerbork Northern Sky Survey (WENSS) at 0.32 GHz, complete to 18 mJy with 54 arcsec resolution (Rengelink et al. 1997); the VLA Low-Frequency Sky Survey (VLSS) survey at 74 MHz with 90 arcsec resolution, and now in progress (Cohen et al. 2007); the ATCA 20 GHz Survey (AT20G) at 18 GHz with 2 arcsec resolution, complete to 50 mJy (Sadler et al. 2006); the Sydney University Molonglo Sky Survey (SUMMS) at 0.84 GHz with 43 arcsec resolution (Bock et al. 1999); and the Wilkinson Microwave Anisotropy Probe (WMAP) at 23 GHz with 780 arcsec resolution over the entire sky (Page et al. 2007).

Other surveys that cover a significant part of the sky are: Faint Images of the Radio Sky at Twenty cm (FIRST) at 1.4 GHz with 5 arcsec resolution, complete to 1.0 mJy (Becker et al. 1995); the SIRTF First Look (FLS/VLA) survey at 1.4 GHz with 5 arcsec resolution, complete to 0.1 mJy (Condon et al. 2003); the Canadian Galactic Plane Survey (CGPS) at 1.4 GHz with 2 arcmin resolution, down to 50 mJy (Higgs 1989); and the Multi-Array Galactic Plane Image Survey (MAGPIS) at 1.4 GHz and 5 GHz with 4 arcsec resolution (Helfand et al. 2006).

These surveys contain thousands of sources to provide sufficiently large catalogs for statistical studies and to find very unusual objects both within the Galactic plane and above the Galactic plane. These surveys provide sufficiently accurate positions of the radio sources so that identification with optical objects is possible. Some of the properties of radio sources that can be obtained from the above surveys are radio spectral-index distributions, source variability, bright and peculiar quasars, radio structure statistics, radio star detections, radio angular size with redshift (cosmological and evolution studies), clustering scale size of radio sources, finding gravitational lenses, polarization studies to determine Galactic magnetic field structure, removing point-source confusion from cosmic microwave background studies (Tegmark & de Oliveira-Costa 1998), and the correlation of radio properties with a host of other properties of the objects.

4. Current Sensitive, Small-Area Surveys

In order to reach the sensitivity of tens of microJy, long integration times with large arrays on relatively small areas of sky (less than one square degree) are needed. Such surveys between 1973 and 1980 showed that the nature of the faint sources (below about 10 mJy at 1.4 GHz) are significantly different than those of the brightest 5,000 sources (Katgert 1974). The changes are illustrated using Fig. 1. Above about 1 Jy, the excess number of faint sources (density rising with lower flux density), indicative of source evolution, is clearly present. Between about 5 mJy to 500 mJy, the source count does decrease (with respect to the Euclidean normalization), but the drop is caused mainly by the redshift attenuation since many of these sources are at redshift 0.5 or greater. Most sources above 5 mJy are associated with luminous quasars and galaxies that outshine the more numerous fainter galaxies even at their greater distance. Their emission is dominated by a radio core and often with extended radio lobes.

Deeper surveys between 1980 and 1995 (Westerbork at 1.4, 0.6, and 0.3 GHz; Cambridge 5C at 1.4 and 0.4 GHz; VLA at 1.4 GHz) showed a significant change of slope in the source count below about 1 mJy, and the optical identifications showed that many of the galaxies contain strong star formation (Pearson 1975; Condon & Mitchell 1984; Oort 1987). Much of the radio emission in these galaxies is produced by synchrotron radiation associated with supernova remnants and their generated cosmic rays and magnetic fields. Many of these galaxies contain significant amounts of warm dust and are very strong emitters in the infrared.

Since 1995 arrays have probed these sources with emission down to tens of microJy in order to study these star-forming galaxies as a function of their environment and redshift, although there is still a significant component of sources with small-diameter emission from the galaxy nucleus, called AGNs. The ma-

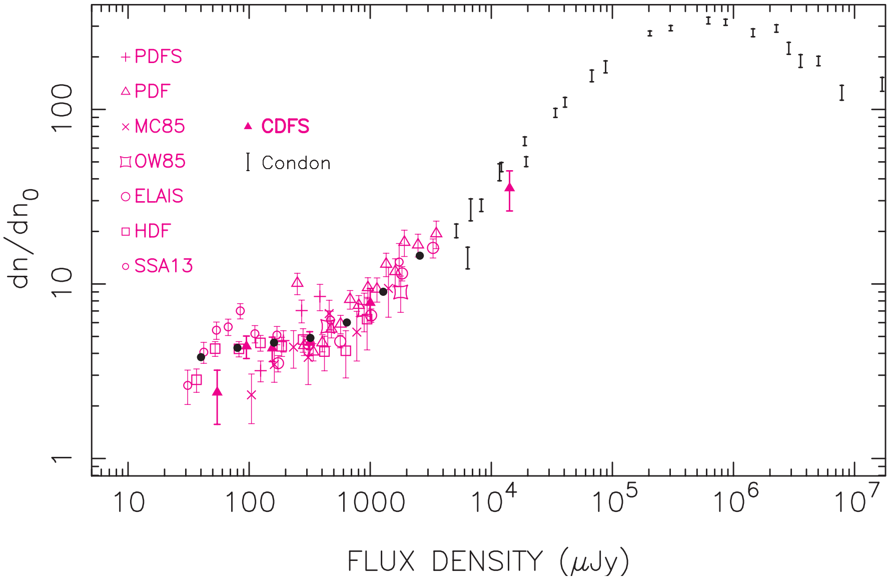

Figure 1. The source count at 1.4 GHz: the plotted points show the differential source counts, dn, normalized to a Euclidean count $dn_0 = 1.0 \times S^{-2.5}$ sources sr^{-1} Jy^{-1}. The references for the counts are given in Kellermann et al. (2008).

jor survey arrays are the VLA at 1.4 GHz with 1 arcsec resolution, needed to separate the high density of sources (Fomalont et al. 2006), GMRT at 0.6 GHz to determine the radio spectral properties of the sources (Bondi et al. 2007), and MERLIN, whose surveys at 1.4 GHz with 0.3 arcsec resolution enable the determination of the source structures since the average angular size for these objects is about 1.5 arcsec (Muxlow et al. 2005). Many radio survey observations are coordinated with regions that have also been imaged at a multitude of wave-bands from the infrared to optical to ultra-violet to X-rays to gamma-rays: e.g., Hubble Deep Field North (Muxlow et al. 2005) and Chandra Deep Field South (Kellermann et al., ApJ, in press).

Details of the radio-source populations are given in the paper by Barger in this volume (Barger 2008). A summary of their properties is:

1. About 5% of the sources are “classic” double sources;
2. Only 2% of the objects are Galactic stars;
3. The typical redshift is ∼ 1;
4. The typical red magnitude is between 20 and 24 mag;
5. Only 5% are unidentified below 25 mag, but many of these are detected in the infrared;
6. Many show strong starburst activity;

7. There is a good radio/FIR correlation in their total flux density;

8. The angular size is between 0.5 arcsec and 2.0 arcsec corresponding to a linear size of ~ 1 kpc;

9. High angular resolution observations show complicated radio structure in about half of the sources (more than a small component at the galaxy core);

10. About 30% have detectable X-ray emission;

11. Modeling shows that there is strong evolution of the sources back to $z = 1.5$.

5. Future Radio Continuum Surveys

Several radio instruments are under construction or planned that will reach even fainter radio sources. While many of the observations will be directed at particular objects, radio surveys will also be made in order to probe the universe at the lowest flux-density levels. The Expanded VLA (EVLA) will improve the sensitivity by a factor of 10 over the existing VLA and will enable fainter sources over a larger region of sky to be detected[3]. Surveys at higher frequency will also become more practical and will lead to accurate determination of the spectral properties of radio sources and may detect distant AGN that tend to be dominant at higher frequencies.

The Atacama Large Millimeter Array (ALMA), now under construction in Chile, will operate at frequencies between 80 and 800 GHz with a resolution a high as 15 milliarcseconds[4]. While most of the observations will concentrate on the detection of spectral-line emission from Galactic objects, ALMA will be an excellent probe of the high-frequency sky and could uncover transient and optically-thick radio continuum sources that may be associated with new phenomena not detectable with the relatively low-frequency arrays that have previously been used.

The Square Kilometer Array (SKA), now under intense investigation, will provide a giant step in the radio sensitivity that can be reached. One can only surmise what new and exciting phenomena will be detected by radio continuum surveys, and some of these have been described in a recent compendium of "Science with the SKA" (Carilli & Rawlings 2004). Some of the chapters associated with radio continuum surveys are:

1. The origin and evolution of cosmic magnetism;

2. Cosmology with the SKA;

3. Sunyaev-Zel'dovich effects;

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[3] see `http://www.aoc.nrao.edu/evla/`

[4] see `http://www.alma.nrao.edu`

4. Searching for intergalactic shocks;
5. Diffuse radio emission from the intra-cluster medium;
6. Magnetic fields in clusters of galaxies;
7. The accretion history of the universe with the SKA;
8. Deep radio continuum studies: evolution of radio AGN population;
9. Surveys of compact extragalactic radio sources;
10. Observations of the magnetic fields in the Milky Way and nearby galaxies;
11. Radio emission from supernovae and gamma-ray bursters;
12. The dynamic radio sky.

With the unprecedented sensitivity of the SKA, it is the exploration of the unknown that will open up new insights into the cosmos. It is reasonable to expect that the unexpected breakthroughs that radio telescope surveys provided in the 1950's and 1960's will be repeated after several years of operation of the SKA.

References

Alfvén, H., & Herlofson, N. 1950, Phys.Rev.A, 78, 616

Allen, L.R., Anderson, B., Conway, R.G., Palmer, H.P., Reddish, V.C., & Rowson, B. 1962, MNRAS, 124, 477

Barger, A.J. 2008, these proceedings, p. 157

Becker, R. H., White, R. L. & Helfand, D. J. 1995, ApJ, 450, 559

Bennett, A.S. 1962 MNRAS, 125, 75

Blandford, R.D. 1990, in *Active Galactic Nuclei*, ed. T.J.-L. Courvoisier & M. Mayor, (Berlin: Springer), p. 161

Bock, R., Large, M. I. & Sadler, E. M. 1999 AJ, 117, 1578

Bolton, J.G., & Shimmins, A.J. 1973, Aust. J. Phys., 30, 1

Bolton, J.G., Stanley, G.J., & Slee, O.B. 1949, Nat, 164, 101

Bondi, M., et al. 2007, A&A, 463, 516

Burbidge, G.R. 1944, ApJ, 124,415

Carilli, C., & Rawlings, S. 2004, *Science with the Square Kilometre Array*, (Amsterdam: Elsevier), New Astronomy Reviews, 48, 979

Clark, B.G. 2003, in *Radio Astronomy at the Fringe*, ed. J.A.Zensus, M.H.Cohen & E.Ros, ASP Conference Series (San Francisco: Astronomical Society of the Pacific), Vol. 300, p. 1

Cohen, A.S., Lane, W.M., Cotton, W.D., Kassim, N.E., Lazio, T.J., Perley, R.A., Condon, J.J., & Erickson, W.C. 2007, AJ, 134, 1245

Condon, J.J., & Mitchell, K.J. 1984, AJ, 89, 610

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

Condon, J.J., Cotton, W.D., Yin, Q.F., Shupe, D.L., Storrie-lombardi, L.J., Helou, G., Soifer, B.T., & Werner, M.W. 2003, AJ, 125, 2411

Dent, W.A. 1965, AJ, 70, 672

Edge, D.O., Shakeshaft, J.R., McAdam, W.B., Baldwin, J.E., & Archer, S. 1959, MmRAS, 68, 37

Fomalont, E.B., Kellermann, K.I., Cowie, L.L, Capak, P, Barger, A.J., Partridge, R.B., Windhorst, R.A., & Richards, E.A. 2006, ApJS, 167, 103

Gold, T. 1968, Nat, 218, 738

Helfand, D.J., Becker, R.H., White, R.L., Fallon, A., & Tuttle, S. 2006, AJ, 131, 2525

Hewish, A. 1964, Nat, 203, 1214

Hewish, A., Bell, S.J., Pilkington, J.D., Scott, P.F., & Collins, R.A. 1968, Nat, 217, 709

Higgs, L.A. 1989, JRASC, 83, 105

Hoyle, F. 1969, Proc.Roy.Astr.Soc., 308, 1

Jansky, K.J. 1933, Proc.IRE, 21, 1387

Katgert, J.K. 1974, A&A, 35, 393

Kellermann, K.I., & Read, R.B. 1965, Publ. Owens Valley Obs., 1, 2

Kellermann, K.I., Fomalont, E.B., Mainieri, V., Padovani, P., Rosati, P., Shaver, P,, Tozzi, P., & Miller, N. 2008, ApJS, in press: `arXiv:0806.0843`

Kraus, J.D., Ko, H.C., Nash, R.T., & Stoutenberg, D.V. 1955, AJ, 61, 182

Mills, B.Y., Slee, O.B., & Hill, E.R. 1958, Aust.J.Phys. 11, 360

Muxlow, T.W.B., et al. 2005, MNRAS, 358, 1159

Oort, M.J.A. 1987, A&AS, 71, 2210

Page, L., et al. 2007, ApJS. 170, 335

Pearson, T.J. 1975, MNRAS, 171, 475

Pilkington, J.D.H., & Scott, P.F. 1965, MmRAS, 69, 183

Reber, G. 1944, ApJ, 100, 279

Rees, M.J. 1971, Nat, 229, 312

Rengelink, R.B., Tang Y., de Bruyn, A.G., Miley, G.K., Bremer, M.N., Röttgering, H.J.A., & Bremer, M.A.R. 1997, A&AS, 124, 259

Ryle, M., & Clarke, R.W. 1961, MNRAS, 122, 349

Ryle, M., Smith, F.G., & Elsmore, B. 1950 MNRAS, 110, 508

Sadler, E.M., et al. 2006, MNRAS, 371, 898

Schmidt, M. 1963, Nature 197, 1040

Shakeshaft, J.R., Ryle, M., Baldwin, J.E., & Thomson, J.H. 1955, MmRAS, 67, 106

Shklovsky, I. S. 1958, Rev. Mod. Phys, 30, 1047

Tegmark, M., & de Oliveira-Costa, A. 1998, ApJ, 500, L83