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SUMSS: Wide–field radio imaging of the southern sky

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Abstract. The Sydney University Molonglo Sky Survey (SUMSS) is a sensitive radio imaging survey at 843 MHz of the whole sky south of declination $-30°$. With a resolution of $43'' \times 43''$ cosec $|\delta|$ and an rms noise level of ~ 1 mJy/beam, SUMSS has similar resolution and sensitivity to the northern NRAO VLA Sky Survey (NVSS). Here, we present some results from the first three years of SUMSS, and show how the combination of NVSS/SUMSS with optical spectra from the 2dF and 6dF (AAO) redshift surveys provides a powerful tool for studying local radio sources out to $z = 0.3$–0.4 as a benchmark for more distant populations. By the end of 2003, we expect to have optical spectra for over 12,000 radio galaxies out to $z = 0.3$, by far the largest and most homogeneous set of radio galaxy spectra yet obtained.

1. Introduction

Radio surveys are among the most powerful probes of the distant universe, since luminous radio galaxies act as 'beacons' which can be seen over a wide range in redshift. A new generation of sensitive radio imaging surveys at centimetre wavelengths now provides a wide–field view of the sky which is unobscured by dust and extends to very early cosmic epochs ($z > 5$). Radio surveys are also a very efficient way of identifying star–forming galaxies in the local universe and beyond, and are particularly powerful when combined with data from large–area optical/IR imaging and redshift surveys.

The Molonglo Observatory Synthesis Telescope (MOST; see Figure 1), located near Canberra in south–east Australia, is a 1.6 km east–west filled array which operates at 843 MHz with a 43 arcsec synthesized beam. The MOST's collecting area of 18,000 m^2 makes it the largest radio telescope in the southern hemisphere. In 1996, the telescope was upgraded to give it a 2.7° diameter field of view, making it possible to begin a sensitive radio imaging survey of the entire southern sky. Details of the upgrade, and the general properties of the telescope, are given by Bock, Large & Sadler (1999).

The Sydney University Molonglo Sky Survey (SUMSS) began in March 1997, and is covering the sky at a rate of $\sim$1500 deg^2 per year. At the time of writing (November 2000), SUMSS is almost 50% complete. Table 1 compares SUMSS with the three radio imaging surveys carried out with northern telescopes: FIRST (Becker et al. 1995), NVSS (Condon et al. 1998) and WENSS (Rengelink et al. 1997). Here, we describe some results from the first three years

Figure 1. The Molonglo Observatory Synthesis Telescope (MOST).

Table 1. Comparison of SUMSS with three northern surveys

	FIRST	NVSS	**SUMSS**	WENSS
Frequency (MHz)	1400	1400	843	325
Area (deg^2)	10,000	33,700	8,000	10,100
Resolution	$5''$	$45''$	$43''$	$54''$
Detection limit	1 mJy	2.5 mJy	5 mJy	15 mJy
Coverage	NGP	$\delta > -40^\circ$	$\delta < -30^\circ$	$\delta > +30^\circ$
Sources/deg^2	90	60	37	21

of SUMSS, and from a project aimed at identifying radio–emitting galaxies in the 2dF Galaxy Redshift Survey (2dFGRS; Colless 1999).

2. Science goals of SUMSS

SUMSS will detect up to 300,000 new radio sources, most of which will be very distant — only about 30% of SUMSS sources have an optical ID brighter than $B \sim 22$, the limit of the digitised sky surveys. While almost all the stronger SUMSS sources (>100 mJy) are radio galaxies or quasars, starburst galaxies start to contribute significantly below 10 mJy (e.g. Jackson & Wall 1999). Thus SUMSS detects significant numbers of both AGN and star–forming galaxies.

The main science goals of the survey include:

- Identification and statistical studies of diffuse and giant radio sources (see §3).
- Measurement of the large–scale (100–500 Mpc) clustering of faint radio sources.
- Radio spectral index measurements for ~30,000 NVSS radio sources in the overlap zone at declination -30° to -40°, and selection of objects with flat or ultra–steep radio spectra.
- Radio studies of southern optical/FIR–selected samples (e.g. nearby galaxies; 2dFGRS and 6dF galaxies to $z \sim 0.4$; QSOs; IRAS galaxies).

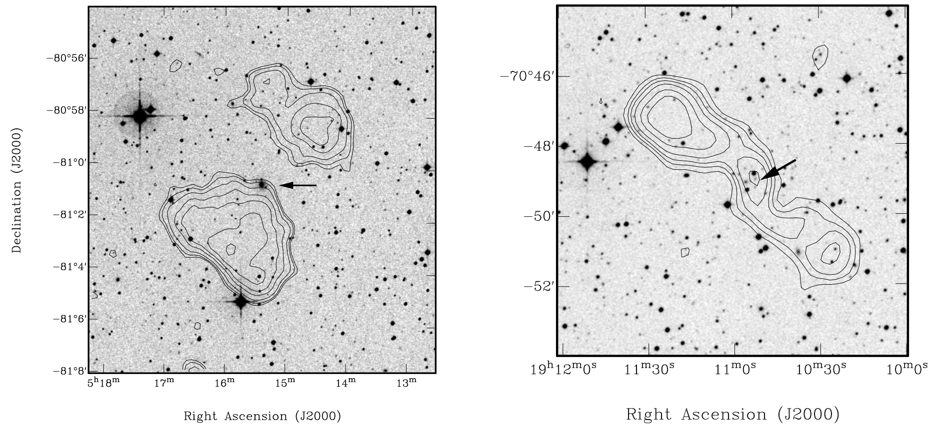

Figure 2. Radio contours overlaid on DSS images for two giant radio galaxies discovered by SUMSS (Boyce 2000): *(Left)* J0515−810, for which the host galaxy is a 17 mag E (arrowed) with $z = 0.104$. The radio source has a linear size of 1.3 Mpc (for $H_0 = 50$ km s^{-1} Mpc^{-1}). *(Right)* J1911−708, identified with a 20 mag galaxy (arrowed). The redshift is estimated as $z \sim 0.36$, giving a linear size of 2.5 Mpc for the radio source. Contour levels are 1.5, 2, 3, 5, 7, 10 and 15 mJy/beam for J0515−810 and 5, 7, 10, 15, 20 and 30 mJy/beam for J1911−708.

• Identification of radio–loud X–ray sources by cross–matching SUMSS with the ROSAT All-Sky Survey (Voges et al. 1999).
• Measurement of the local radio luminosity function of AGN and starburst galaxies, and its evolution with redshift (see §4).

3. Giant and diffuse radio galaxies

A particular strength of the MOST is its excellent sensitivity to diffuse and low–surface-brightness (LSB) radio emission. This is because the MOST (unlike the VLA and the ATCA) is a filled interferometer with continuous u–v coverage on baselines from 15 to 1576 m. As a result, SUMSS detects many sources with extended, LSB radio emission, analogous to the LSB optical objects discovered on deep Schmidt plates (e.g. Froebrich & Meusinger 2000). These include giant radio galaxies, and cluster relic sources (see Figure 3).

Giant radio galaxies (GRGs) — defined to have projected linear sizes greater than 1 Mpc (e.g. Ishwara–Chandra & Saikia 1999) — represent the last stages of radio galaxy evolution and provide unique probes of the intergalactic medium (Subrahmanyan & Saripalli 1993; Cotter, Rawlings & Saunders 1996). The surface density of GRG candidates in SUMSS is about one per 50–60 deg^2.

4. Combining radio surveys and optical redshift surveys

Radio positions from SUMSS and NVSS are accurate enough (typical errors of 1–2 arcsec) that unambiguous optical identifications can be made down to

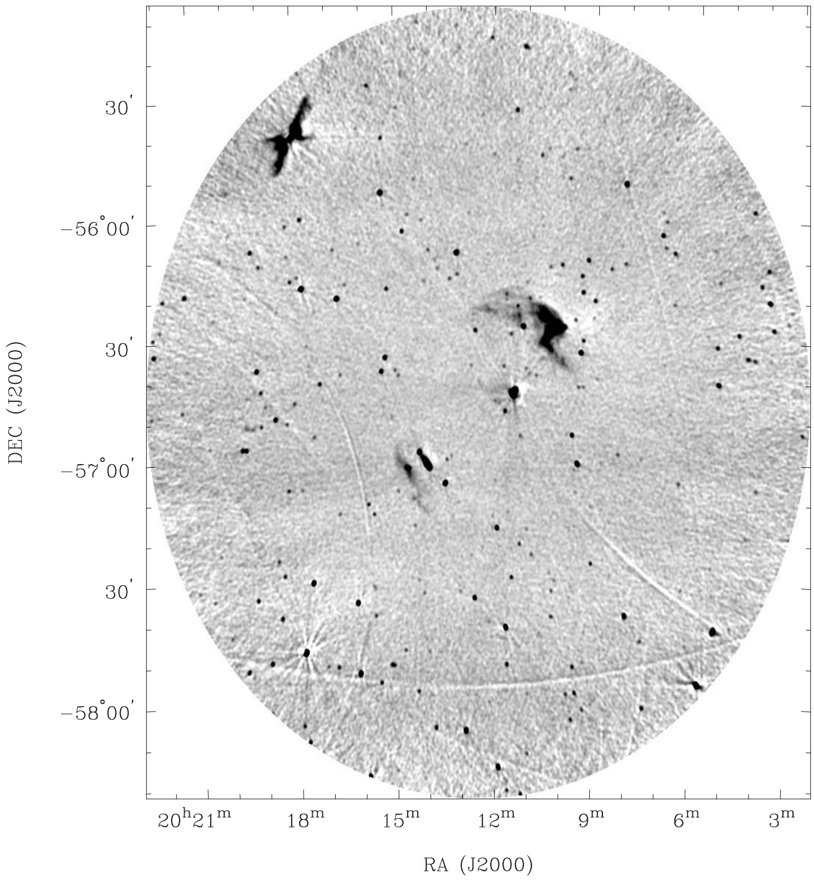

Figure 3. A single wide–field radio image at 843 MHz from the MOST. Near the centre of this particular field are two extended, diffuse radio sources associated with the galaxy cluster Abell 3667 (Röttgering et al. 1997). The strong source to the north-east is the FR I radio galaxy PKS B2014–55.

$B = 20$. Cross–matching with the new generation of optical redshift surveys can then provide redshift and spectroscopic data for tens of thousands of local radio–emitting galaxies rather than the few hundred available up to now. In the southern hemisphere, the Anglo–Australian Observatory's Two–degree Field (2dF) spectrograph can observe up to 400 galaxies simultaneously over a $2°$ diameter region of sky and is currently being used to carry out the 2dF Galaxy Redshift Survey (2dFGRS). A Six–degree Field (6dF) spectrograph will be commissioned on the AAO's Schmidt Telescope early in 2001, with 150 fibres over a $6°$ diameter field. This will carry out a redshift survey of the entire southern sky, the 6dF Galaxy Survey (6dFGS; F. Watson, this meeting).

The 2dFGRS area overlaps both NVSS and SUMSS, and about 1.5% of 2dFGRS galaxies are detected as radio sources to a limit of $\sim$2.5 mJy (Sadler et al. 1999). It is usually straightforward to tell from the 2dFGRS spectra whether the radio emission arises from star formation or from an active nucleus (AGN)

— see Figure 4. Most of the star–forming galaxies are also detected at 60μm by IRAS (the detection limits of NVSS/SUMSS and the IRAS Faint Source Catalogue are very similar for star–forming galaxies).

When complete, the 2dFGRS will yield high–quality optical spectra of more than 4000 radio–emitting galaxies in the redshift range $0 < z < 0.4$, by far the largest and most homogeneous set of radio–galaxy spectra ever obtained. The 6dFGS will add about 8000 further spectra of radio–emitting galaxies out to $z \sim 0.2$. Such data sets will be large enough to contain AGN at all stages of their evolution and over the whole range of viewing angles. This will enable us to disentangle the effects of age, luminosity and orientation, and to establish a detailed local benchmark from which to study the cosmic evolution of both AGN and star–forming galaxies.

We have already made a new determination of the local radio luminosity function at 1.4 GHz (Figure 4), based on about 900 2dFGRS spectra of NVSS radio sources, or about 20% of the final 2dFGRS sample. There is good agreement with the earlier determination by Condon (1989) and the recent work of Machalski & Godlowski (2000).

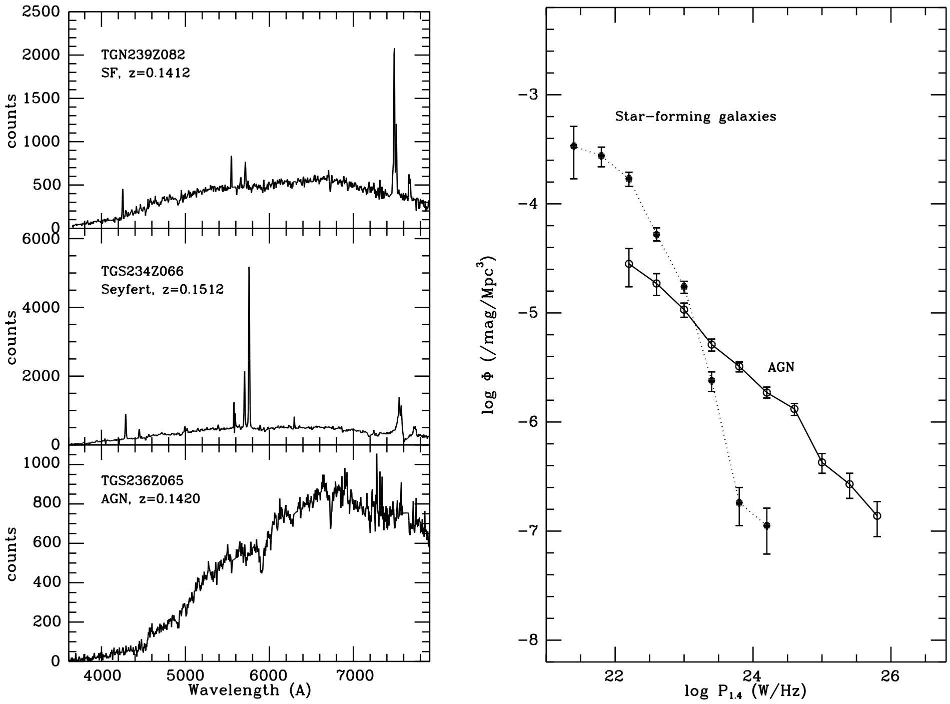

Figure 4. *(Left)* Typical radio–source spectra for three galaxies at $z \sim 0.15$ from the 2dFGRS (Sadler et al. 1999). The top panel shows a star–forming galaxy (40% of 2dFGRS radio sources), the middle panel an emission–line AGN/Seyfert (10% of 2dFGRS radio sources) and the lower panel a radio galaxy (AGN) with no obvious emission lines (50% of 2dFGRS radio sources). *(Right)* The local radio luminosity function at 1.4 GHz for AGN and star–forming galaxies, derived from NVSS radio sources with 2dFGRS redshifts.

The 6dF Galaxy Survey will cover ten times the area of the 2dFGRS, and because the target galaxies are closer on average (median $z \sim 0.1$) the radio detection rate will be around 10% rather than 1.5% for the more distant 2dFGRS galaxies. The 6dF data will pin down the low–luminosity end of the local radio luminosity function, and allow us to determine the local star–formation density as a function of Hubble type.

5. SUMSS data release

Individual SUMSS images are combined to form $4° \times 4°$ mosaics on the same field centres as the NVSS mosaics (Condon et al. 1998). Completed mosaics, and details of the survey's progress, are available from the SUMSS website (www.physics.usyd.edu.au/astrop/SUMSS), and SUMSS images can also be accessed through NASA's SkyView Virtual Observatory (skyview.gsfc.nasa.gov). Preparation of a SUMSS source catalogue is in progress, with a first release planned for early 2001.

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