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The Sydney University Molonglo Sky Survey (SUMSS) and optical redshift surveys of the southern sky

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Abstract. The Sydney University Molonglo Sky Survey (SUMSS) is a radio imaging survey at 843 MHz of the whole sky south of declination -30°. With a beamwidth of $43'' \times 43''$ cosec $|\delta|$ and an rms noise level of ~ 1 mJy/beam, SUMSS has similar sensitivity and resolution to the northern NRAO VLA Sky Survey (NVSS). Here, we present some results from the first two years of SUMSS and also show what can be done by combining radio data from SUMSS and NVSS with the new generation of large optical redshift surveys (including the 2dF Galaxy Redshift Survey and 6dF Galaxy Survey) now becoming available in the southern hemisphere.

1. Introduction

Sensitive low–frequency radio continuum surveys can detect large numbers of galaxies over a wide range in redshift and are unaffected by dust obscuration, so they are ideal tools for studying the evolution of active and star–forming galaxies from the local to the distant universe. Observations at radio frequencies below $\sim$1 GHz, where extended emission from the radio lobes dominates over the core emission, also sample the full range of active galaxy orientations in an unbiased way (Orr & Browne 1982), and the radio power emitted by an active galaxy at these frequencies appears to be a sensitive indicator of the central black hole mass, at least in the local universe (Francescini et al. 1998).

The Molonglo Radio Observatory, located near Canberra in south–eastern Australia, has a long history of radio survey work. The original telescope (the 408 MHz Molonglo Cross) had a resolution of 2.8 arcmin, and its achievements included the Molonglo Reference Catalogue of radio sources (MRC: Large et al. 1981, 1991), an imaging survey of the Galactic plane (Green 1974), and the discovery of 186 pulsars (Manchester et al. 1978). The Molonglo Cross was closed in 1978 and its east–west arm was used to construct the Molonglo Observatory Synthesis Telescope (MOST), a 1.6 km imaging radio telescope operating at 843 MHz with a 43 arcsec synthesized beam. With a collecting area of 18,000 m^2, this is the largest radio telescope in the southern hemisphere.

During 1993–96, the MOST was upgraded and its field of view increased from 1 to 5 square degrees. Details of the upgrade are given by Bock, Large, & Sadler (1999), and the main properties of the upgraded MOST are summarized in Table 1. The good sensitivity (rms noise level $\sim$1 mJy/beam), wide field of view (see Figure 1) and stable configuration make the upgraded MOST a

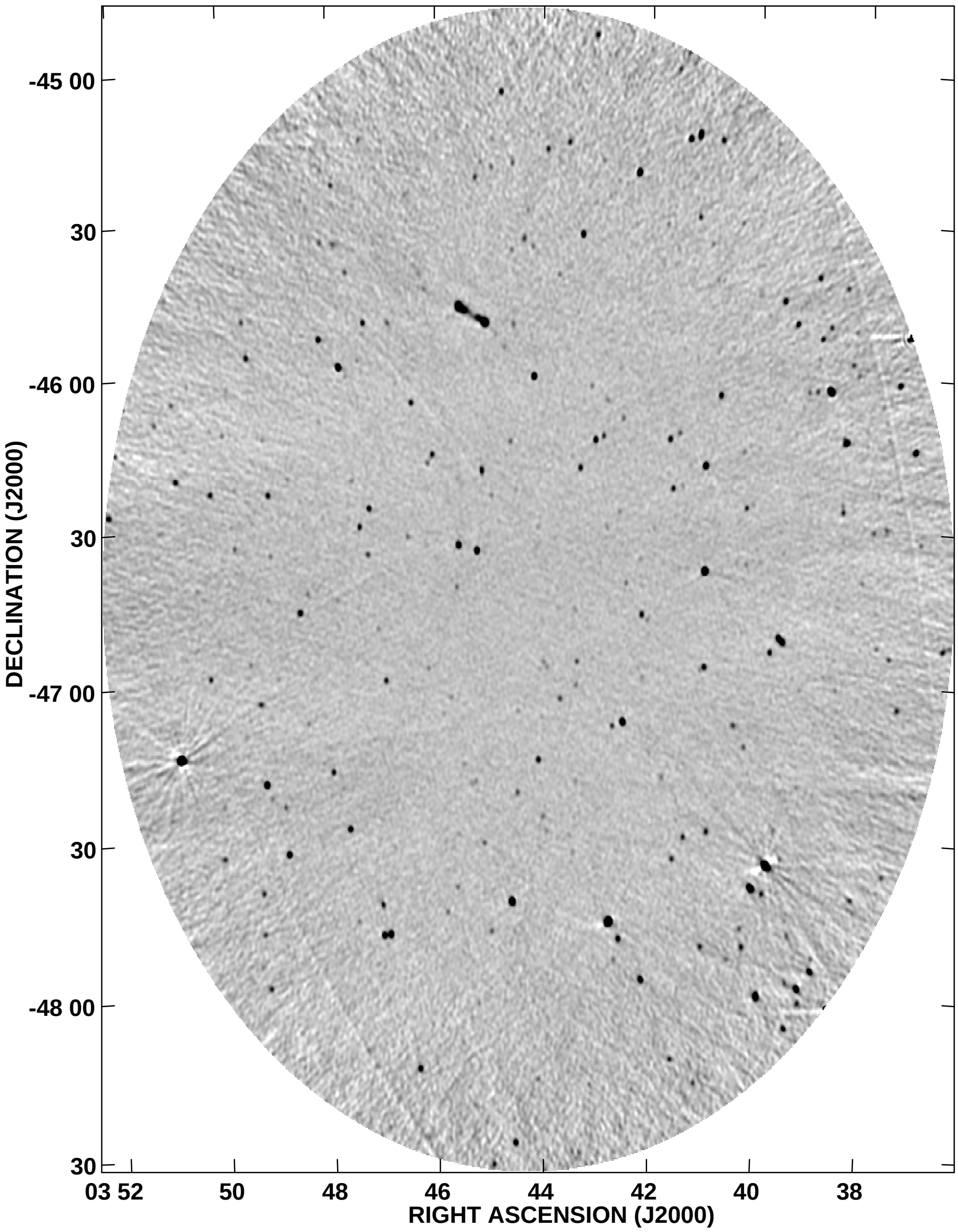


Figure 1. A single 12–hour wide–field radio image at 843 MHz from the MOST, covering field SGP 889 of the 2dF Galaxy Redshift Survey (2dFGRS). The rms noise in this image is 1.3 mJy/beam and the double source in the north of the field is the radio galaxy PKS B0343–459.

particularly powerful tool for carrying out a large–area radio imaging survey, and the telescope is currently surveying the southern sky to faint limits at a rate of ~1500 square degrees per year.

Table 1. Properties of the MOST in its wide–field mode

Parameter	Value
Frequency	843 MHz
Bandwidth	3 MHz
Declination range (12 hr synthesis)	$-90° \leq \delta < -30°$
Maximum field size (RA×Dec)	Elliptical, $163' \times 163'$cosec $\|\delta\|$
rms noise level (1σ)	1–2 mJy beam^{-1}
Resolution (FWHM)	$43'' \times 43''$cosec$\|\delta\|$
Polarization	Right circular (IEEE)

In the Northern Hemisphere, sub–arcminute radio imaging surveys have been completed, or are well advanced, with the VLA (NVSS: Condon et al. 1998, and FIRST: Becker et al. 1995) and Westerbork (WENSS: Rengelink et al. 1997). Table 2 compares these surveys with SUMSS, which has similar sensitivity and resolution to NVSS and covers regions of sky inaccessible to northern telescopes.

Table 2. Comparison of SUMSS with 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	$\delta > -40°$	$\delta < -30°$	$\delta > +30°$
Sources/deg^2	90	60	37	21

Particular strengths of SUMSS include (i) the excellent sensitivity of the MOST to diffuse and low–surface brightness radio emission (see §2), (ii) the potential for multiwavelength studies and radio spectral index measurements to identify rare and interesting radio source populations (§3), and (iii) the overlap with current and planned large optical redshift surveys in the southern hemisphere (§4), which will soon yield spectra and redshift measurements for over 10,000 radio galaxies — by far the largest and most homogeneous set of radio–galaxy spectra ever obtained. In this paper we describe some results from the first two years of SUMSS, and from a project aimed at identifying radio–emitting galaxies in the 2dF Galaxy Redshift Survey.

2. Diffuse and giant radio galaxies

A unique advantage of the MOST over multiple–dish interferometers like the VLA is its sensitivity to extended, low-surface-brightness radio emission. This is because the MOST, as a filled interferometer, has continuous $u - v$ coverage on baselines from 15 to 1576 m (Bock et al. 1999). Figure 2, a recent SUMSS image of the radio galaxy Fornax A, shows how well the telescope can image complex radio structures of large angular size.

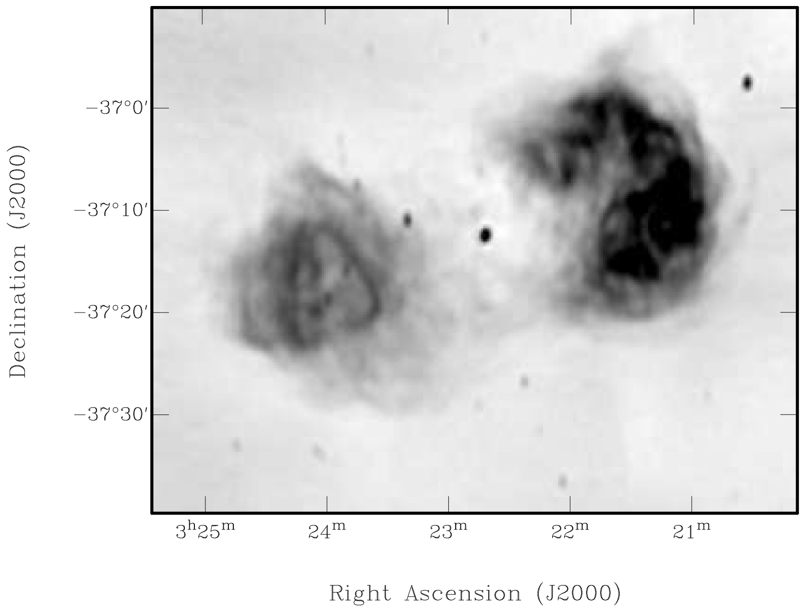


Figure 2. SUMSS image of the nearby radio galaxy Fornax A at 843 MHz, after maximum entropy cleaning. Note the filamentary lobe structures and the bridging low surface–brightness radio emission.

This sensitivity to radio sources of large angular size and low radio surface brightness makes SUMSS well–suited to the detection of giant radio galaxies (GRGs). These are defined to be radio galaxies with projected linear sizes $\geq$1 Mpc (e.g. Ishwara–Chandra & Saikia 1999) — they represent the last stages of radio galaxy evolution and provide unique probes of the intergalactic medium (Subrahmanyan & Saripalli 1993; Cotter, Rawlings & Saunders 1996). Based on our experience so far, the surface density of GRG candidates in SUMSS is about one per 50–60 deg^2 so that we expect to find up to 150 such objects in the whole SUMSS area. For an angular size $\theta \geq 5'$ most should have $z < 0.2$. Figure 3 shows two GRG candidates recently discovered by SUMSS.

Once the central AGN turns off, the lobes of a radio galaxy continue to radiate for up to 10^8 years (Komissarov & Gubanov 1994), leaving a pair of diffuse, fading radio sources with a gradually–steepening radio spectral index. SUMSS images also reveal nearby galaxies with extended, low-surface-brightness emission which may correspond to these last stages of radio source evolution, and two examples are shown in Figure 4.

3. Radio spectral index measurements and multiwavelength studies

By combining SUMSS data with radio surveys at other frequencies, we can measure spectral indices for large numbers of radio sources. This will allow us both to select rare objects such as those with ultra–steep radio spectra, and to

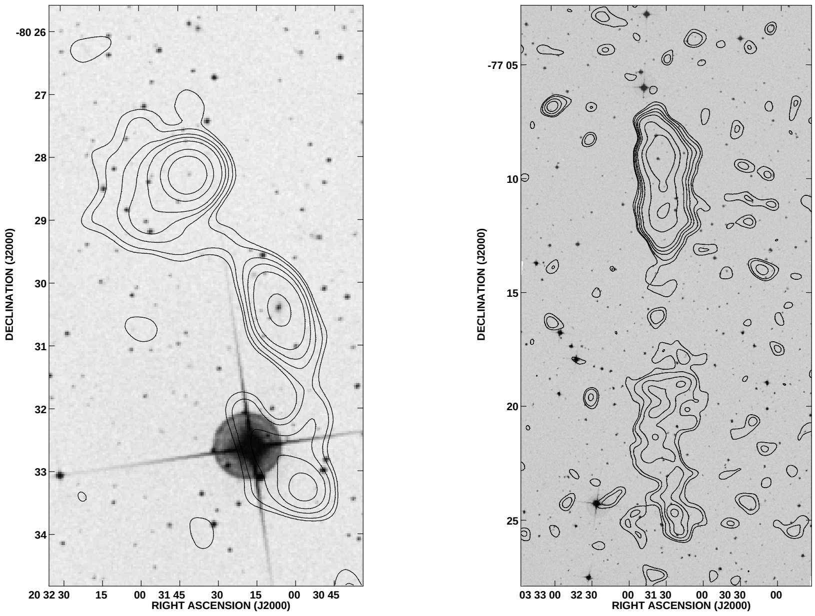


Figure 3. *Left:* The giant radio galaxy SUMSS J2031–80, which has an angular size of about 8 arcmin. Radio contours at 2, 3, 5, 7, 10, 20 and 30 mJy/beam are superimposed on an optical image from the DSS. The host galaxy is an 18th magnitude elliptical for which we measure a redshift of $z = 0.13$, so that the radio source is about 1.6 Mpc in extent (for $H_0 = 50$ km/s/Mpc). *Right:* A candidate giant radio galaxy, SUMSS J0331–77, with a total angular size of about 20 arcmin. The radio contour levels are the same as for SUMSS J2031–80. We are currently making follow–up radio observations of this object at higher frequency in an attempt to pinpoint the radio core and hence identify the host galaxy.

determine accurate radio and optical luminosity functions for flat and steep–spectrum radio source populations separately. When SUMSS is complete, we will have spectral indices and accurate positions for 16,000 southern–hemisphere radio sources from the PMN catalogue at 5 GHz (Griffith & Wright 1993), and at least 30,000 sources observed at 1.4 GHz by NVSS in the overlap zone at declination $-30°$ to $-40°$. Most of the sources cross-matched with PMN will have flat radio spectra ($\alpha > -0.5$, where $S_\nu \propto \nu^\alpha$), while about 25% of the NVSS/SUMSS matches will have flat spectra and around 5% will be ultra–steep spectrum sources ($\alpha < -1.5$), many of which will lie at high redshift.

An important tool for identifying star-forming galaxies is the remarkably tight correlation between radio and far-infrared (FIR) luminosities (e.g. Wunderlich et al. 1987, Condon et al. 1991). For spiral galaxies observed by SUMSS, we find $S_{60\mu\mathrm{m}} \sim 100\, S_{843\,\mathrm{MHz}}$, so that nearly all the galaxies in the IRAS Faint Source Catalog (with a limiting flux density of $S_{60\mu\mathrm{m}} = 0.28$ Jy; Moshir et al. 1992) are detected as radio sources by SUMSS. The surface density of star–

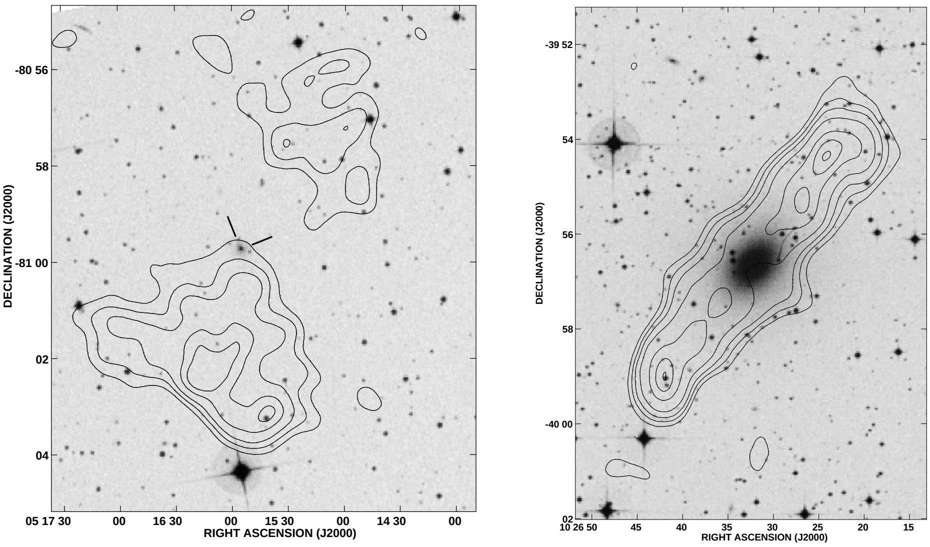


Figure 4. *Left:* The giant radio galaxy SUMSS J0515–80, which is about 1.6 Mpc in extent and has very diffuse radio emission. The 843 MHz contours are at 3, 5, 7, 10 and 12 mJy/beam. This source (associated with a 17th magnitude elliptical galaxy whose position is marked, and for which we measure $z = 0.104$) has similar radio power and morphology to Fornax A, but is significantly larger in size. *Right:* NGC 3250 is a nearby (v = 2824 km/s), 12th mag elliptical galaxy which has diffuse radio emission 8 arcmin in extent and no detectable radio core (Slee et al. 1994). The radio contours levels are 3, 5, 7, 10, 15, 18 and 20 mJy/beam, and the radio spectral index is -1.05 between 843 MHz and 2.7 GHz. Although the total radio power is low ($10^{22.5}$ W/Hz), the edge–brightened FR-II morphology suggests that this may be the ageing remains of a once-powerful radio galaxy.

forming galaxies detected in this way is about 1 per square degree, or 4–5 galaxies per SUMSS field.

We can also identify radio–loud X–ray sources by cross–matching SUMSS with the ROSAT All-Sky Survey (Voges et al. 1999), and expect to identify about 600–800 such objects in the whole SUMSS area. These should be a local population with median redshift around $z = 0.1$ (Bauer et al. 1999), but only about 10% of them appear to be associated with galaxies brighter than $b_J = 19.5$, based on our early work with the 2dFGRS. The remainder will be mainly radio–loud QSOs and BL Lacs (Caccianiga et al. 1999), making this an important sample for testing unified models of radio source populations.

4. Combining radio surveys with optical redshift surveys (2dFGRS and 6dFGS)

The scientific return from large radio surveys is enormously increased if the optical counterparts of the radio sources can be identified, their optical spectra classified (as AGN, star-forming galaxy, etc.) and their redshifts measured. In the past, however, this was a slow and tedious process which could only be carried out for relatively small samples.

Now, new fibre–fed optical spectrographs make it possible to carry out spectroscopy of complete samples of hundreds of thousands of galaxies in the local universe. 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 in the 2dF Galaxy Redshift Survey (2dFGRS; www.mso.anu.edu.au/2dFGRS). A Six–degree Field (6dF) spectrograph will be commissioned on the AAO's Schmidt Telescope in late 2000, with 150 fibres over a 6°-diameter field. This will carry out a major optical redshift survey of the entire southern sky, the 6dF Galaxy Survey (6dFGS; msowww.anu.edu.au/~colless/6dF). The relevant properties of the 2dFGRS and 6dFGS are summarized in Table 3.

Table 3. Large redshift surveys in progress in Australia

	2dFGRS	6dFGS
Survey area	1700 deg^2	17,000 deg^2
Limiting mag.	b_J=19.4 mag	K=13 mag ($b_J \sim 17$ mag)
To be completed	late 2001	late 2003
Redshift range	$z < 0.3$	$z < 0.1$
Radio detections	4000 (1.6%)	8000 (9%)
Population mix	60% AGN	35% AGN
	40% star–forming	65% star–forming

Cross–matching radio source surveys with the new generation of optical redshift surveys can provide redshift and spectroscopic data for tens of thousands of local radio–emitting galaxies rather than the few hundred available at present, and the radio–source positions from SUMSS and NVSS are accurate enough that we can make unambiguous optical identifications from the 2dFGRS and 6dF target lists (see Fig. 5).

Two recent studies show the potential of combining low–frequency radio data with the new optical redshift surveys. Machalski & Condon (1999) identified 1157 galaxies in the Las Campanas Redshift Survey (LCRS) with NVSS radio sources above 2.5 mJy at 1.4 GHz. They attempted to determine the radio and infrared properties of galaxies in the LCRS redshift range of z = 0.05–0.2, but had difficulties because the LCRS was sparsely sampled, with optical spectra only being taken for about one galaxy in three. Sadler et al. (1999) cross–matched the NVSS radio catalogue with the first thirty fields (100 deg^2) observed in the 2dFGRS, and found that it was usually straightforward to tell from the optical spectra whether the radio emission arose from star formation or an AGN (unlike LCRS, the 2dFGRS has a spectroscopic completeness of 95%). AGN have either a pure absorption–line spectrum like that of a giant elliptical galaxy, or a stellar continuum plus nebular emission lines of [OII] and [OIII] which are strong compared with any Balmer–line emission. Star–forming galaxies have strong, narrow emission lines of Hα and (usually) Hβ.

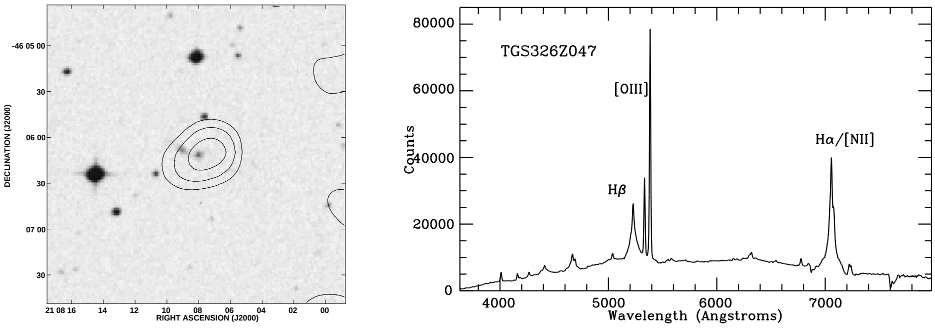


Figure 5. *Left*: SUMSS contours overlaid on the DSS image of the star–forming 2dFGRS galaxy TGS876Z654, which appears to be interacting with a neighbour. The radio contours are at 3, 4 and 5 mJy/beam, and the galaxy is clearly detected with a peak flux density of 5.4 mJy. *Right*: 2dF spectrum of the active galaxy TGS326Z047, which was detected at both radio and X–ray wavelengths.

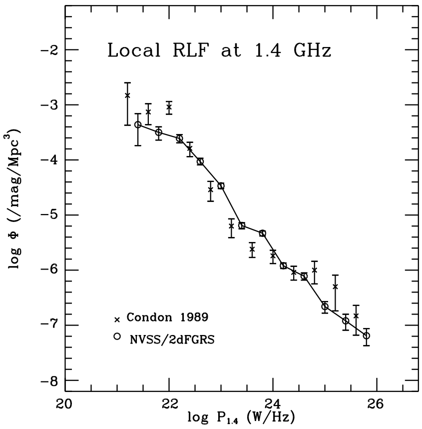
5. Results so far

We have now cross–matched the NVSS source catalogue with 2dFGRS spectra observed up to May 1999, when the 2dFGRS was about 20% complete[1]. This yielded a sample of 903 2dFGRS spectra of radio-emitting galaxies of which about 35% have HII region–like spectra associated with star–forming galaxies, 54% are AGN (i.e., with spectra typical of radio galaxies), 2% are Galactic stars and 9% have spectra with low S/N which are difficult to classify.

Figure 6(a) shows the local radio luminosity function at 1.4 GHz derived from the 2dFGRS/NVSS data. This agrees well with the earlier determination by Condon (1989), but has smaller error bars. Another advantage of the new data set is that the entire LRLF shown in Figure 6 has been derived from one radio survey and one homogeneous set of optical data, without the need to patch together measurements from several different sources. Figure 6(b) shows the RLFs for AGN and starburst galaxies separately. The star–forming galaxies span a wide range in star formation rate, from nearby spiral galaxies to distant ultra–luminous IRAS galaxies (ULIRGs).

We stress, however, that only about 5% of SUMSS and NVSS radio sources are associated with an optical galaxy brighter than $b_J = 19.4$ mag, the faint limit of the 2dFGRS. About 30% have an optical counterpart bright enough to be seen on the Digitised Sky Survey (DSS; Lasker 1994), i.e., b_J brighter than about 22 mag, and 70% are 'blank fields'. Ideally we would like to know the characteristic redshift distribution of all SUMSS/NVSS radio sources as a function of flux density, which would allow us both to measure the evolution of the radio luminosity function with redshift and to quantify the three–dimensional clustering of radio sources. This, however, is still a distant goal. The most

[1]Almost all these early 2dFGRS spectra are from the region north of declination $-30°$ which is not covered by SUMSS, but we will soon be able to make a similar analysis combining 2dFGRS spectra with radio data from both NVSS and SUMSS.



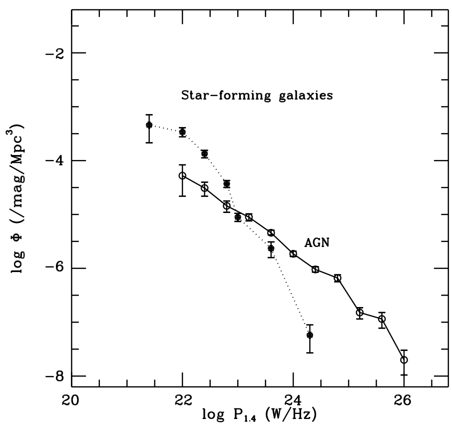


Figure 6. *Left:* The local radio luminosity function at 1.4 GHz from 2dFGRS and NVSS data, assuming $H_0 = 50$ km/s/Mpc and $q_0 = 0.5$ (open circles). Crosses show the earlier determination by Condon (1989). *Right:* The RLF split into star–forming galaxies and AGN, based on our classification of the optical spectra from the 2dFGRS.

promising approach for the future appears to be the use of large–area multi–colour optical and infrared imaging surveys to measure photometric redshifts down to faint optical magnitudes.

6. Summary

SUMSS is imaging the southern radio sky at 843 MHz, with similar resolution and sensitivity to NVSS. The survey was 35% complete at the end of 1999, and data are being released publicly (see www.physics.usyd.edu.au/astrop/SUMSS) as the survey proceeds. The continuous $u-v$ coverage of the MOST means that SUMSS is particularly well–suited to detecting large and diffuse radio sources, including giant radio galaxies. The combination of NVSS/SUMSS with optical spectra from the 2dF and 6dF redshift surveys provides a powerful tool for studying local radio sources to $z = 0.3$–0.4 as a benchmark for more distant populations. By the end of 2003, we should have optical spectra for over 12,000 radio galaxies to $z = 0.3$, by far the largest and most homogeneous set of radio galaxy spectra yet obtained.

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