Maps of the Cosmos
ASP Conference Series, Vol. 216, 2005
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Mapping the Local and Distant Universe with SUMSS

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Abstract. The Sydney University Molonglo Sky Survey (SUMSS) is a radio continuum imaging survey of the southern sky at 843 MHz, with similar sensitivity and resolution to the northern NRAO VLA Sky Survey (NVSS). We have combined radio data from SUMSS and NVSS with optical spectra from the 2dF Galaxy Redshift Survey and 6dF Galaxy Survey to study the space distribution and properties of both AGN and star–forming galaxies in the local universe (redshift range $0 < z < 0.3$). We also discuss new results on radio-source clustering in the more distant universe ($z \sim 1$) and present the first results from a search for the most distant ($z > 3$) southern radio galaxies.

1. Introduction

Surveys of the sky at radio wavelengths detect large numbers of galaxies over a very wide range in redshift, making them potentially powerful tools for mapping structures in both the local and the distant universe. Since galaxy redshifts cannot be measured from radio continuum data alone (though see Carilli & Yun 1999 for a discussion of the 1.4 to 350 GHz radio spectral index as a potential 'photometric redshift' for starburst galaxies), the full power of radio surveys for mapping the cosmos can only be realised by identifying the optical counterparts of faint radio sources and measuring their redshifts. Until recently, this was a slow and laborious process which could only be carried out for relatively small samples of galaxies.

However, large optical redshift surveys such as the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000) can now be combined with a new generation of all-sky radio continuum surveys to assign redshifts to many thousands of radio-emitting

https://doi.org/10.1017/S0074180900196652 Published online by Cambridge University Press

galaxies in the local universe. In the future, deeper redshift surveys should allow this work to be extended to higher and higher redshifts.

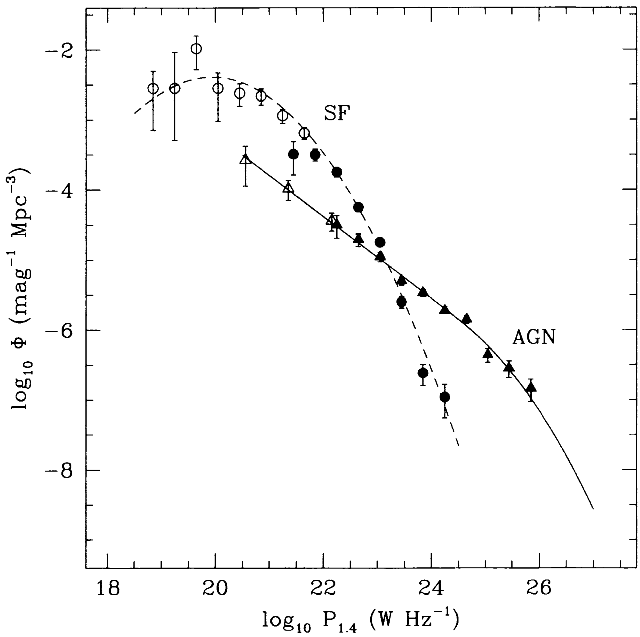

Figure 1. The local ($z < 0.3$) radio luminosity function at 1.4 GHz for AGN and star–forming galaxies in the 2dFGRS, from Sadler et al. (2002).

Radio-emitting galaxies fall into two physically–distinct classes, 'normal' and 'active' galaxies. In normal galaxies, the radio continuum emission arises from processes related to star formation, i.e. synchrotron radiation from relativisitic electrons accelerated in supernova remnants, and thermal (free–free) emission from HII regions (Condon 1992). The radio continuum luminosity of normal galaxies correlates strongly with both their star–formation rate and their luminosity at far–infrared wavelengths (the well–known 'FIR–radio correlation'; Helou, Soifer, & Rowan-Robinson 1985; Devereux & Eales 1989). In active galaxies (AGN), the radio emission arises from synchrotron–emitting relativistic electrons associated with collimated jets of plasma moving outwards from a central supermassive black hole (e.g. Begelman, Blandford, & Rees 1984).

As can be seen from Figure 1, the most powerful radio galaxies are always AGN, but there is a wide range in radio luminosity for which AGN and star–forming galaxies have similar space densities. It can be difficult to separate the two classes using radio data alone, particularly at moderate to low radio luminosities, but optical spectra usually allow us to distinguish AGN and star–forming galaxies unambiguously (e.g. Sadler et al. 1999). Star–forming galaxies show strong, narrow Balmer lines (Figure 2), whereas AGN have either an absorption–line spectrum like that of a giant elliptical galaxy (Figure 3), with

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or without weak LINER–like emission lines, or a stellar continuum dominated by nebular emission lines such as [OII] or [OIII] (Figure 4).

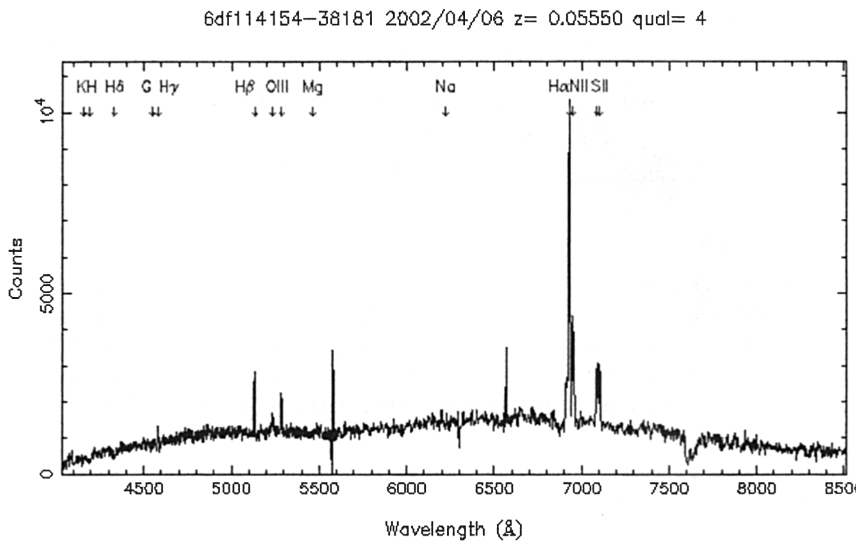

Figure 2. 6dF Galaxy Survey (6dFGS; Colless, this meeting) spectrum of a star–forming galaxy at $z = 0.05$ identified with a SUMSS radio source. The star–formation rate estimated from the radio continuum luminosity is around $80\,M_{\odot}\ yr^{-1}$.

Here we describe a new sensitive radio imaging survey of the far southern sky and discuss some of the ways in which radio continuum surveys can be used to 'map the cosmos', especially in combination with the new generation of large–area optical redshift surveys.

2. The Sydney University Molonglo Sky Survey (SUMSS)

The Molonglo Observatory Synthesis Telescope (MOST), located near Canberra in south–eastern Australia, is a 1.6 km imaging radio telescope operating at 843 MHz with a 43 arcsec synthesized beam. The MOST was upgraded in 1993–6 to give it a field of view of 5 square degrees, making it possible to carry out a sensitive radio imaging survey of the whole southern sky, the Sydney University Molonglo Sky Survey (SUMSS; Bock, Large, & Sadler 1999).

Table 1 compares SUMSS with the three sensitive radio imaging surveys recently carried out in the Northern Hemisphere, the NRAO VLA Sky Survey (NVSS: Condon et al. 1998), the FIRST survey (Becker, White, & Helfand 1995) and Westerbork Northern Sky Survey (WENSS: Rengelink et al. 1997). SUMSS has similar sensitivity and resolution to NVSS, and covers the region of the sky at $\delta < -40°$ which is inaccessible to northern telescopes. SUMSS is now almost complete, and a source catalogue is available (Mauch et al. 2003; online at www.astrop.physics.usyd.edu.au/sumsscat).

Table 1. Comparison of SUMSS with northern radio imaging 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

These surveys probe extremely large volumes of space, since they cover the whole sky and select objects with a median redshift of $z \sim 0.8$ (Condon 1989). Radio surveys also pinpoint the most massive galaxies (and the most massive black holes) at any given redshift (e.g. De Breuck et al. 2002) and have been used to identify massive galaxies at $z > 5$ (van Breugel et al. 1999).

3. Mapping Radio Sources in the Local Universe

About 5% of SUMSS and NVSS radio sources are associated with galaxies in the local ($z < 0.3$) universe, and $\sim 1.5\%$ of galaxies in the 2dF Galaxy Redshift Survey (2dFGRS) are detected as radio sources by NVSS and/or SUMSS. About half of these are 'normal' star–forming galaxies, and half are radio galaxies and AGN (Sadler et al. 2002). The radio detection rate for galaxies in the 6dF Galaxy Survey (see Colless 2004) is much higher (around 10%), because the 6dF galaxies are on average closer, and so galaxies of lower radio luminosity are detectable.

3.1. Star–forming Galaxies

Star–forming galaxies in the local universe follow the well–known correlation between far–infrared and radio luminosity (Helou et al. 1985), and their radio luminosity can be used to estimate their star–formation rate in a way which is unaffected by dust (e.g. Sullivan et al. 2001). Combining data from radio and optical surveys therefore allows us to measure the total amount of star formation per unit volume in the local universe, and to determine how this changes with cosmic epoch. The local star–formation density measured from radio data (Sadler et al. 2002) agrees well with the value measured by Gallego et al. (1995) from Hα emission; and Condon, Cotton, & Broderick (2002) have recently shown that there appears to be evolution in the global star–formation rate even at moderately low redshifts ($z \sim 0.1$).

3.2. Active Galaxies

The 2dFGRS and 6dFGS will together yield spectra and redshifts for up to 10,000 radio–selected active galaxies out to $z \sim 0.3$. Only about 10% of local radio galaxies have strong optical emission lines. The remainder, like the object shown in Figure 3, would be hard to recognize as active galaxies based on their

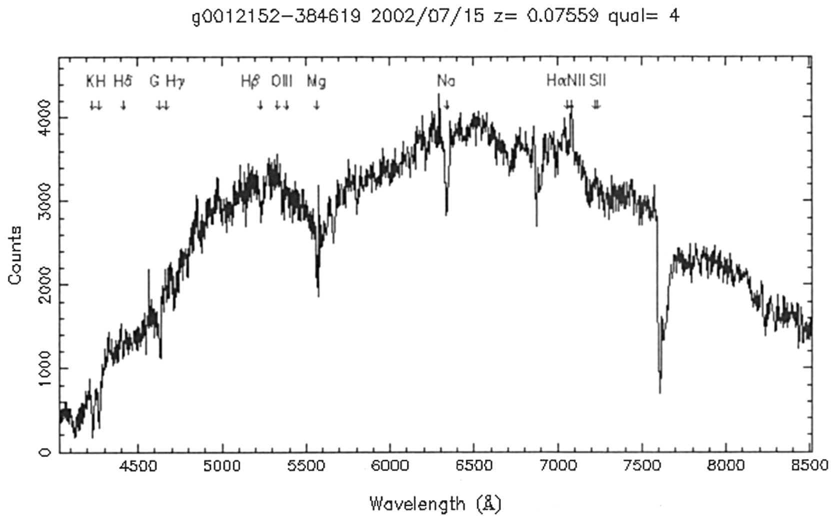

Figure 3. 6dFGS spectrum of a radio-emitting AGN in an elliptical galaxy at $z = 0.08$. The radio continuum luminosity of this galaxy is similar to that of the galaxy in Figure 4.

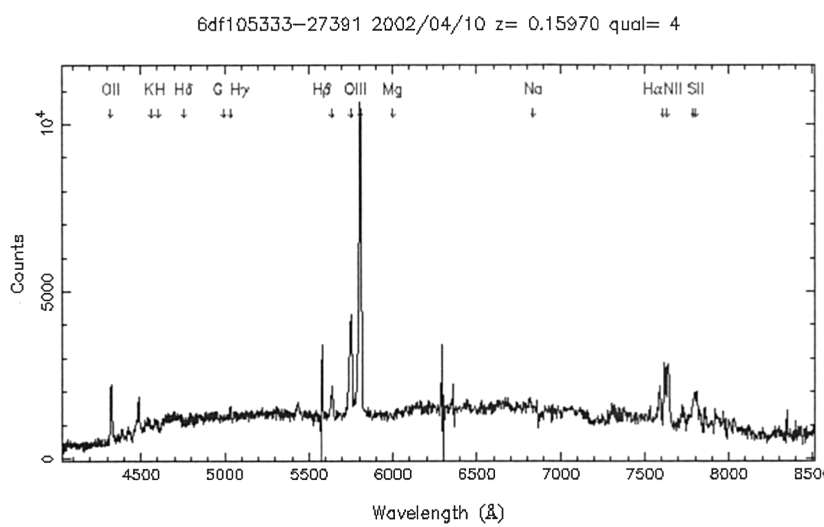

Figure 4. 6dFGS spectrum of a radio–emitting AGN with strong optical emission lines. In the local universe such objects are largely outnumbered by those with weak or no emission lines like the one in Figure 3. Both classes probably contain equally–massive central black holes.

https://doi.org/10.1017/S0074180900196652 Published online by Cambridge University Press

optical spectra alone. Radio surveys therefore play an important role in mapping the local space density of supermassive black holes by providing a more complete census of AGN activity.

4. Radio Sources as Probes of Galaxy Clustering at $z \sim 1$

The current generation of large–area radio surveys contain sufficiently large numbers of sources ($n > 10^5$) to allow the detection of large–scale structure in both two and three dimensions. Angular clustering in the WENSS, FIRST and NVSS surveys has now been studied by several groups (Cress et al. 1996; Magliocchetti et al. 1998; Blake & Wall 2002a,b; Overzier et al. 2003).

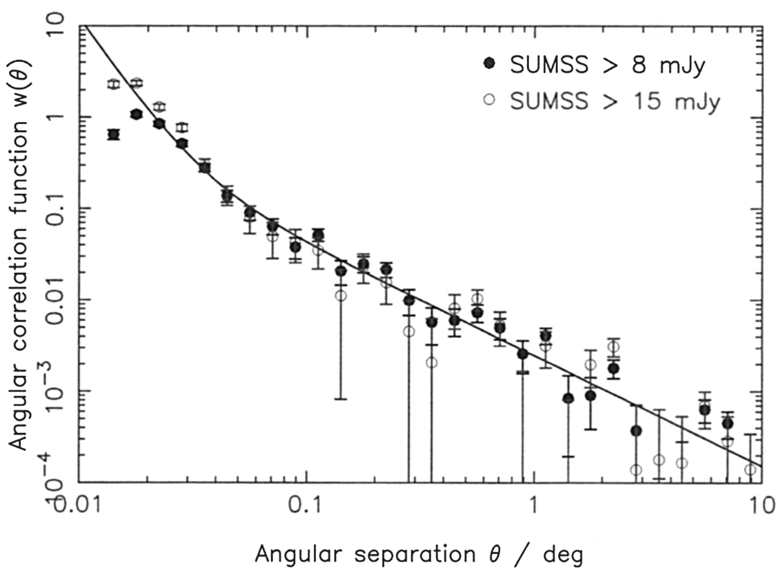

Figure 5. Measurement of the SUMSS angular correlation function at flux-density thresholds $S_{843\,\mathrm{MHz}} = 8\,\mathrm{mJy}$ (filled circles) and 15 mJy (open circles), from Blake et al. (2004). The solid line shows the best–fitting sum of two power laws.

The characteristic imprint of large–scale structure is also clearly detectable in the SUMSS catalogue (Blake, Mauch, & Sadler 2004, see Figure 5), and the clustering scale appears to be independent of radio frequency. Once the characteristic redshift distribution for mJy–level radio sources has been determined, the projected clustering measurements will allow a robust description of large–scale structure at $z \sim 0.8$, the expected median redshift of these sources.

5. A Search for Distant Radio Galaxies from SUMSS and NVSS

High–redshift radio galaxies (HzRGs) provide an ideal opportunity to study the early universe and gain insights into the formation and evolution of massive galaxies. The technique of selecting the highest–redshift radio galaxies through their ultra–steep radio spectra (USS) has been successfully applied for more than a decade (e.g. Röttgering et al. 1994; Chambers et al. 1996), but the search for HzRGs has until recently been confined to the northern hemisphere. We have now (De Breuck et al. 2004) begun using multi–frequency radio data in the NVSS–SUMSS overlap region at declination $-30°$ to $-40°$ (Figure 6) to search for the highest–redshift radio galaxies in the south, where they are accessible to the increasing number of large southern optical/IR telescopes.

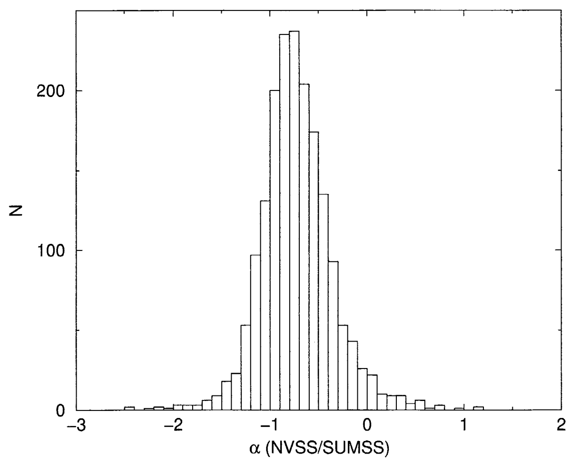

Figure 6. Distribution of radio spectral index α (defined by S $\propto \nu^{\alpha}$ for flux density S at frequency ν, and analogous to an optical colour) for radio sources detected by both NVSS and SUMSS. Galaxies with ultra–steep radio spectra ($\alpha < -1.3$) are candidates for the highest–redshift galaxies.

SUMSS and NVSS are particularly well matched for such a study, since they have near–identical sensitivity and resolution. Preliminary results from this study show that selection of HzRGs based on their 843–1400 MHz radio spectral index produces at least as high a yield of very distant ($z > 3$) galaxies as previous northern studies. Follow–up studies of a sample of 76 HzRG candidates are in progress, and the goal for the next 4–5 years is to identify at least 50 southern radio galaxies above $z = 3$.

Acknowledgments. We acknowledge financial support from both the Australian Research Council and the University of Sydney for the operation of the Molonglo Observatory. EMS is supported by an ARC Professorial Fellowship. We thank the Molonglo site staff for their hard work in keeping the telescope running at close to 100% efficiency over the past six years. The SUMSS survey is dedicated to Dr Michael Large, whose expertise and vision made the project possible.

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