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The radio source population at high frequency: deductions from 9C follow-up observations

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A sample of sources selected from the 15-GHz 9th Cambridge survey has been followed up with simultaneous multi-frequency observations in the range 1.4 to 43 GHz, enabling classification of each source by spectral type. In addition we have conducted VLBI imaging of a sample of the compact sources and flux monitoring at 15 GHz over a three-year period. We find that 43% of the sample, mostly lobe-dominated, extended radio sources, have spectra falling steeply with frequency and have stable flux densities at 15 GHz. 13% of the sample have a prominent spectral peak in the range 0.5 to 5 GHz; these have stable flux densities at 15 GHz and are very compact on the sky (all <5 mas). 12% of the sample have a prominent spectral peak at a frequency greater than 5 GHz; we find that these are almost all variable at 15 GHz and are also all <5 mas. The remaining 32% of the sample are classed as "Flat Spectrum"; these sources exhibit a large range of angular sizes and one half of them are variable at 15 GHz.

Taking the spectral index distributions and the known 15 GHz source count, we have made empirical estimates of the counts at 30, 43, 70 GHz (corresponding to the *Planck* lower frequency bands) and at 90 GHz (an ALMA frequency). Given the difficulties inherent in making wide-field blind surveys at these frequencies, such estimates are important for assessing the foreground point-source population in cosmic microwave background (CMB) observations. We have compared our source counts with other predictions and find, in particular, that, although our 90 GHz count is significantly lower than previous estimates, it is in good agreement with recent results from the Australian telescope, ATCA.

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1. The 9C survey

9C [1] is a survey of extra-galactic radio sources at a frequency of 15 GHz, made with the Cambridge Ryle telescope over the years 1999–2006. Although designed specifically to identify the foreground sources in the CMB observations of the Very Small Array (VSA), it has also proved valuable in a wider investigation of the radio source population at high frequency. The survey is in 7 fields centred on: 0023+30, 0303+26, 0729+54, 0938+31, 1232+53, 1540+45, 1732+42 (RA,Dec J2000), covering a total area of ~ 640 deg^2 to a completeness limit of 25 mJy. It comprises some 2000 sources, 320 of which form a deeper sample complete to 5 mJy.

2. The Radio Source Population at 15 GHz: Multi-frequency, High-resolution and Multi-epoch data.

Figure 1: Population of spectral classes from the 25mJy, 15 GHz sample

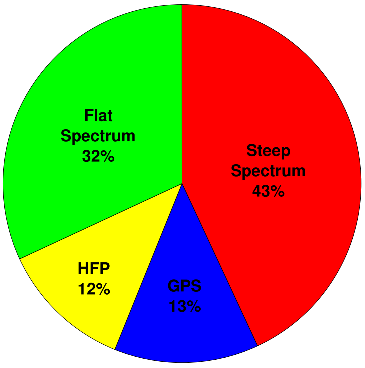
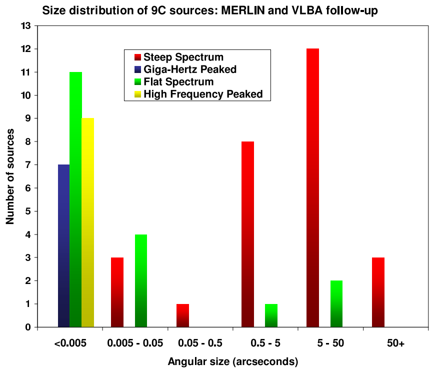


Figure 2: Angular size distribution for different spectral types



Simultaneous multi-frequency follow-up of a sample of 124 sources taken to be complete to 25 mJy in 9C was conducted between 2001-2002 using the VLA, the Cambridge Ryle Telescope and the OVRO 40m dish (at 31 GHz). Using the spectra thus obtained the sources have been classified by spectral type, based on a quadratic fit in log(Flux), log(Frequency) space.

Figure 1 shows the proportions of sources falling into the four spectral classes: Steep Spectrum (SS), with no spectral peak and a spectral index at 10 GHz $\alpha_{10\mathrm{GHz}} > 0.5$ ($S \propto \nu^{-\alpha}$), Giga-hertz Peaked Spectrum (GPS) sources, with a well-defined peak at a frequency between 0.5 GHz and 5 GHz, High-Frequency-Peaked (HFP) sources, with a well-defined peak at a frequency above 5 GHz, and Flat Spectrum (FS) sources, with no well-defined peak and $\alpha_{10\mathrm{GHz}} < 0.5$. We find that selecting at 15 GHz increases the proportion of sources with peaked spectra, compared to defining samples at lower frequency (see [2] and references therein).

In addition to the multi-frequency follow-up we also made high resolution images of a sample of sources that remained unresolved in the VLA maps; we took 5 GHz data with the MERLIN array and with the VLBA, ultimately reaching a resolution of better than 5 mas. Whilst all the SS objects were resolved either with the VLA or with the VLBI work, 60% of the FS sources remained unresolved at 5 mas. None of the GPS or HFP sources was resolved with the VLBA. See Figure 2 and [3].

Figure 3: 15 GHz Variability for different spectral classes

15 GHz Variability	**Variable**		**Not Variable**	
Steep Spectrum	0	**0%**	16	**100%**
GPS	0	**0%**	8	**100%**
HFP	8	**89%**	1	**11%**
Flat Spectrum	9	**50%**	9	**50%**

Alongside the high resolution work we also conducted a 3-year study into the 15 GHz variability of a randomly selected sub-sample of 51 sources from the 9C sample using the Ryle Telescope. The flux calibration of the Ryle Telescope limits the sensitivity to variability to fractional variations of around 6%. The data revealed a strong dependence of variability on spectral type, with **none** of the SS ot GPS sources seen to vary. 50% of the FS sources were found to vary and 90% (eight out of nine studied) of the HFP sources varied: see table in Figure 3. Further analysis is given in [4].

3. Empirical estimation of the source counts at 30, 43, 70 and 90 GHz

Figure 4: Spectral index distributions:
α_{15}^{22} (red) median 0.54
α_{15}^{43} (blue) median 0.89 $(S \propto \nu^{-\alpha})$

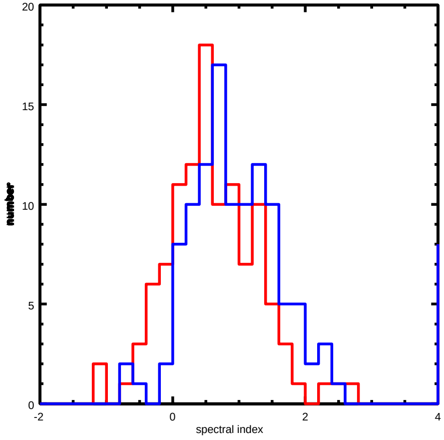
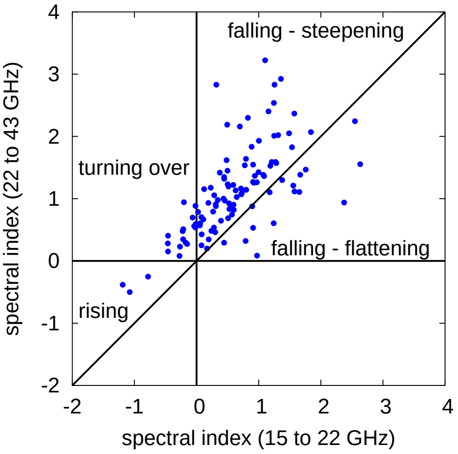


Figure 5: α_{22}^{43} versus α_{15}^{22} $(S \propto \nu^{-\alpha})$



In order to estimate the source counts at the higher frequencies we selected a complete sample of 110 sources with flux densities in the range 25–665 mJy at 15 GHz and with simultaneous follow-up observations at both 22 and 43 GHz [5]. Taking $S \propto \nu^{-\alpha}$, we find that the median value of the spectral index increases from 0.54 for α_{15}^{22} to 0.89 for α_{15}^{43} (figure 4) and that, in fact, only three sources continue to have rising spectra from 22 to 43 GHz, whereas 91 (83%) have falling spectra with both α_{15}^{22} and $\alpha_{22}^{43} > 0$ (figure 5). To calculate the counts we have first interpolated and extrapolated the spectra of the sources to estimate their flux densities at the required frequencies. We then make the assumption that the spectral indices are independent of the flux densities and indeed we have detected no correlation within our sample. This means that, given the known source count at 15 GHz,
$n_{15}(S) \approx 51(S/\mathrm{Jy})^{-2.15}\mathrm{Jy}^{-1}\mathrm{sr}^{-1}$,
the count at another frequency will have the same exponent (-2.15) but a different pre-factor, A_ν, or
$n_\nu(S) \approx A_\nu(S/\mathrm{Jy})^{-2.15}\mathrm{Jy}^{-1}\mathrm{sr}^{-1}$.
For a sample of m sources,

$$A_\nu = \left(\frac{1}{m}\sum_{i=1}^{m} r_i^{-1.15}\right) \times 51\mathrm{Jy}^{-1}\mathrm{sr}^{-1}$$

where, for the ith source, $r_i = (15/(\nu/\mathrm{GHz}))^{-\alpha_i}$. This gives values of A_ν at 30, 43, 70 and 90 GHz of 31 ± 2, 22 ± 2, 15 ± 2 and 13 ± 3 $\mathrm{Jy}^{-1}\mathrm{sr}^{-1}$, respectively.

Figure 6: Our 30-GHz count compared with counts from the VSA, DASI and CBI

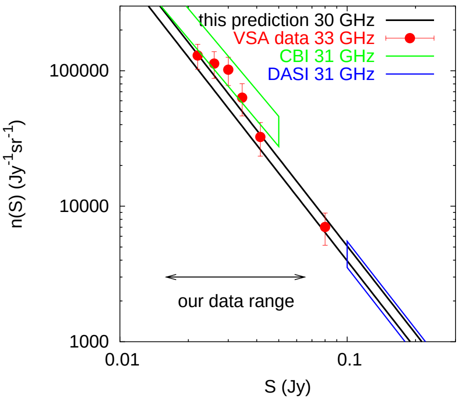
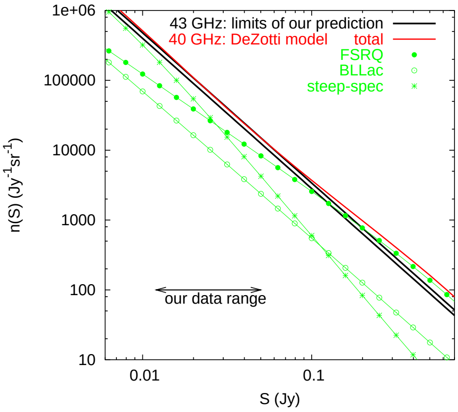


Figure 7: Our 43-GHz count compared with the de Zotti model at 40 GHz



The only directly measured counts with which we can compare our predictions are those from the VSA at 33 GHz, DASI (Degree Angular Scale Interferometer) at 31 GHz and CBI (Cosmic Background Imager) also at 31 GHz. (See figure 6 and references within [5]). We find that our 30 GHz count is consistent with counts from both the VSA and DASI and close to, though somewhat below, that from CBI.

We have also compared our results with the models of de Zotti et al. [6]. We find they agree well at 30 GHz but at 43 GHz and above, although there is good agreement at the lower flux densities, at the higher values our counts diverge progressively from those of de Zotti, in that ours imply significantly fewer flat spectrum sources (see figure 7). We are aware that our data are sparse at values above ∼ 100 mJy at 15 GHz, but we have not detected in our sample any significant shift in the spectral index distributions with increasing flux density, which might account for this discrepancy.

At 90 GHz our count is also markedly below the estimate made by Holdaway & Owen [7] for ALMA, by a factor of approximately two. However, it agrees well with the recent 95 GHz count from the Australian telescope, ATCA [8], in the region of common flux density, 80–200 mJy. This agreement is significant since our estimates are derived from completely independent high-frequency data sets.

Our source count results have important implications for CMB observations such as those of *Planck*, in characterising the foreground point-source confusion. They are also relevant to ALMA, in estimating the density of sources available as phase calibrators for that intrument.

References

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[2] R. C. Bolton et al., *MNRAS* **354** (485) 2004

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[7] M. A. Holdaway & F. Owen, *ALMA Memo* **520** 2005

[8] E. M. Sadler et al., [`arXiv:0709.3563`] 2007