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Distant star forming galaxies, next generation radio telescopes and the radio universe before re-ionisation

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Abstract. I present the various capabilities of upgraded and next generation radio telescopes, in particular their ability to detect and image distant star forming galaxies. I demonstrate that e-MERLIN, EVLA and LOFAR can detect systems similar to Arp 220 out to cosmological distances. The SKA can detect such systems out to any reasonable redshift that they might be expected to exist. Employing very long integration times on the multiple-beam SKA will require the array to be extended beyond the current specification - simply to avoid confusion noise limitations at 1.4 GHz. Other arguments for extending the SKA baseline length are also presented. As well as going "deeper" all these instruments (especially LOFAR and the SKA) will also go "wider" - detecting many tens of thousands of galaxies in a single day's observing. I briefly comment on the prospects of detecting radio emission at much earlier epochs, just before the epoch of re-ionisation.

1. Introduction

The continuum sensitivity of radio astronomy instruments is set to improve by at least an order of magnitude over the next 10 years. Developments include the broad-banding of existing facilities (e.g. e-MERLIN and the EVLA) or the design and construction of entirely new, next generation instruments, such as the Low Frequency Array (LOFAR) and the Square Km Array (SKA). VLBI arrays are also expected to take advantage of the increasing capacity of disk-based recording systems, and the real-time connection of antennas and correlators via commercial optical fibre networks. These upgraded and next generation telescopes will routinely reach noise levels which are at the very limit of what is now feasible with existing facilities. Deep surveys of the micro-Jy radio sky (e.g. Fomalont et al. 2002) suggest that the radio emission will be associated with a dominant population of moderate and high redshift galaxies that are subject to on-going, massive star formation.

In this paper I consider and contrast the capabilities of next generation and upgraded radio telescopes, in particular their ability to detect and image these faint and distant systems out to redshift 6. I also briefly comment on the prospects of detecting radio sources with the SKA before the epoch of re-ionisation.

2. Technical and Scientific Assumptions

In this paper I use the following sources of information regarding telescope parameters:

– VLA Expansion Project (see `www.nrao.edu/evla`),
– e-MERLIN Science Case & Technical Specification (see `www.merlin.ac.uk/e-merlin/`),
– LOFAR Basic Specifications (`www.lofar.org`),
– SKA Technical Specification (`www.skatelescope.org`),
– *e*EVN (`www.evlbi.org/eEVN/sens_uvcov/eEVN.htm`).

I make use of two spectral energy distributions (SED) that I have constructed from publicly available data of two well known, nearby star forming galaxies - Arp 220 and M82. While the radio SEDs of these two galaxies are similar, they differ in detail *e.g.* the low-frequency radio spectrum of Arp 220 is much flatter than M82. It is not yet clear which (if either) is more representative of the population of high-z star forming galaxies. It is certainly worth remembering that the most distant systems have star formation rates (SFR) one or two orders of magnitude greater than Arp 220 and M82 respectively.

I assume and extrapolate the 1.4 GHz source counts of Richards (2000), imposing a simple frequency dependence on the counts in order to investigate LOFAR source counts at 200 MHz. Throughout this paper I assume the currently "preferred" cosmological model ($\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km/sec/Mpc).

3. Detection of star forming galaxies at cm wavelengths

3.1. Continuum sensitivity and Star Formation Rates

Fig. 1 shows the 12 hour (5σ) sensitivity of e-MERLIN, the EVLA, the *e*EVN and SKA at cm wavelengths as a function of observing frequency. Superimposed on top of this is the SED of Arp 220, projected to redshifts 1, 4 and 20. The plot shows that the upgraded instruments can in principle detect Arp 220 (SFR ~ 250 M$_\odot$/yr) out to $z \sim 1$ or beyond in only 12 hours. The performance of the *e*EVN is particularly encouraging; with the current high sensitivity array augmented by the 64-m Sardinia Radio Telescope, the upgraded Lovell 76-m telescope and the 45-m Yebes telescope, the *e*EVN out-performs the EVLA. Naturally

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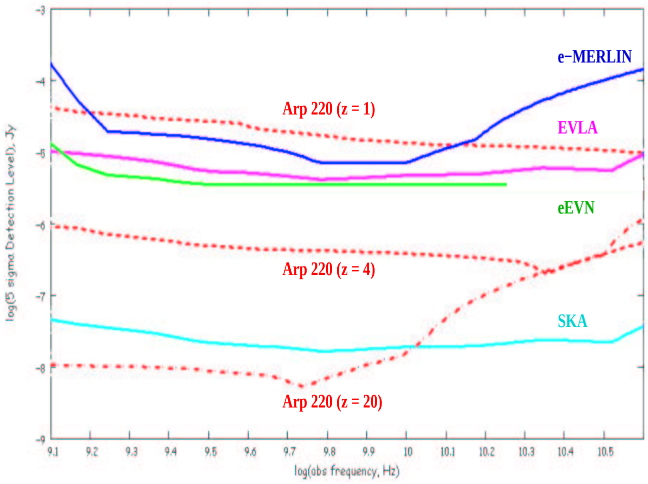

Fig. 1. The 5σ detection limit (solid lines) plotted for e-MERLIN, the EVLA, *e*EVN and SKA as a function of observing frequency. Superimposed the SED of Arp 220 (dotted/dashed lines) projected to $z \sim 1$, $z \sim 4$ and $z \sim 20$.

some of these faint radio sources will be resolved-out by the higher resolution *e*EVN (but see section 3.5). The SKA goes about 2 orders of magnitude deeper than any of the other arrays, easily detecting Arp 220 at $z \sim 6$ in 12 hours. Note also that at high-z the peak in the FIR (rest-frame) begins (in principle) to redshift into the radio part of the spectrum (but see section 4 for some caveats). Fig. 1 also suggests that deep radio surveys will be conducted over a broad range of frequency space, lower frequencies may take advantage of the possible steep spectrum nature of the sources (especially at high-z, see section 4) but higher frequencies benefit from the availability of large continuum bandwidths.

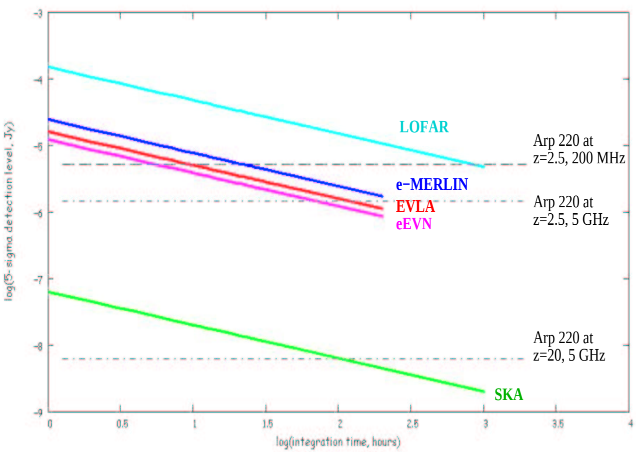

Fig. 2. The (5σ) sensitivity (solid lines) of various instruments as a function of integration time. The flux density of Arp 220 (dotted/dashed lines) is indicated for three redshift/frequency combinations.

3.2. Multiple beams and long integration times

So far we have assumed *typical* integration times of $\sim$ 12 hours. However, this is really a lower limit for deep field surveys, especially for next generation telescopes such as LOFAR and SKA. These instruments will possess a multiple beam capability, permitting simultaneous, full-sensitivity observations to be made over widely separated regions of the sky. It is expected that some beams will be dedicated to particular areas of research, permitting very long integration times to be employed for particular deep field surveys.

Fig. 2 shows the (5σ) sensitivity of various instruments as a function of integration time. Without a multiple beam capability, I have limited the longest EVLA and e-MERLIN observations to 100 hours. Fig. 2 demonstrates that the sensitivity of LOFAR is comparable to e-MERLIN and the EVLA, provided very long integration times (up to 1000 hours) can be successfully employed. LOFAR deep field surveys are optimised (in terms of survey depth) at the high-end of the LOFAR band, $\sim$ 200 MHz. In principle, the SKA appears to be capable of detecting star forming galaxies such as Arp 220 out to any reasonable redshift that they might be expected to exist (but again see section 4).

Fig. 3 presents the SFR that can be probed by various instruments assuming the Condon (1992) relation between SFR and radio luminosity. In this plot we present the current sensitivity of the VLA and WSRT at 1.4 GHz (assuming typical integration times of a few days). Only SFR in excess of 1000 $M_{\odot}$/yr are currently detectable beyond redshift $\sim$ 1.6. The SFR probed by the deepest LOFAR and e-MERLIN/EVLA observations (the latter being con-

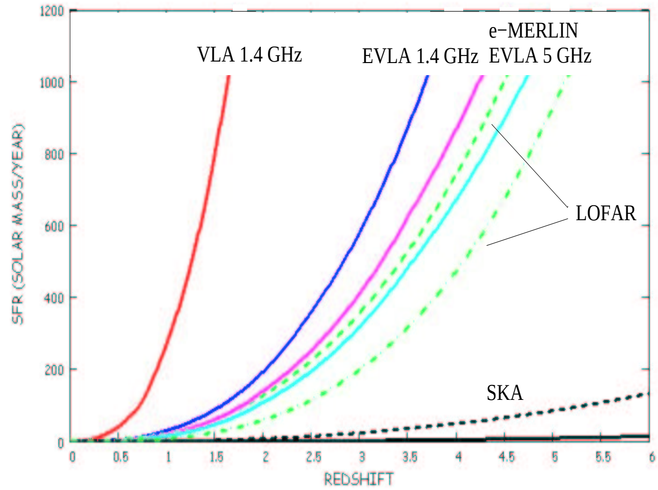

Fig. 3. A plot of SFR versus redshift assuming in all but one case an Arp 220 SED. Various instruments are included - the integration times, observing frequencies are listed within the brackets (from left to right): VLA (1.4 GHz, 2 days), the EVLA at (1.4 GHz, 2 days), EVLA (5 GHz, 2 days), LOFAR (200 MHz, 1000 hours), e-MERLIN (5 GHz, 18 days, Arp 220), LOFAR (200 MHz, 1000 hours, $\alpha \sim 0.8$ spectral index), SKA (5 GHz, 12 hours), SKA (5 GHz, 1000 hours).

ducted at 5 GHz) are similar, the exact details depending on the radio SED of the sources. Plots are presented for LOFAR assuming the (flattish) SED of Arp 220, and a steeper ($\alpha \sim -0.8$) spectral index. The SKA is able to detect normal star forming galaxies with SFR ~ 1 M$_\odot$/yr (comparable to the Milky Way) out to redshift 2 (assuming integration times of 1000 hours).

3.3. The number of detectable sources in the FoV

Operating at the lowest radio frequencies, the LOFAR field-of-view (FoV) is naturally much larger than either the EVLA or e-MERLIN. The effect of this, together with multiple beams is shown in Fig. 4. Assuming an effective dimension of 65 meters for each LOFAR station, somewhere between 10^4 and 10^5 star forming galaxies can be detected using all 8 beams. Again the numbers are dependent on the assumed radio SED at cm wavelengths (see Fig. 4). For the EVLA and e-MERLIN, the number of star forming galaxies detected in the field of view is set to increase from a few tens of sources per day to several hundred sources per day. The SKA (with significantly more independently steerable beams) is likely to have a similar capability to LOFAR, even at much higher frequencies.

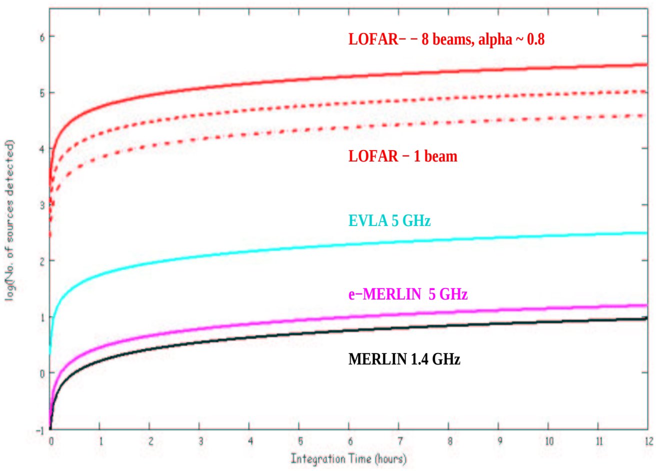

Fig. 4. A plot of the number of sources in the field-of-view versus observing time (hours). LOFAR will detect in 1 hour as many star forming galaxies as current instruments (e.g. MERLIN) detect only after many days of integration. Three curves are drawn for LOFAR (the top curve assumes a spectral index of -0.8 and includes contributions from 8 beams, the middle curves assumes a spectral index of -0.4, and the bottom curve represents the performances of a single beam.

3.4. Confused ? You might very well be!

Source confusion usually provides a fundamental limit beyond which the image noise level no longer improves - irrespective of the integration times employed (Condon 1974). Confusion usually kicks in when the surface density of sources (number of sources per beam area) exceeds some limit, the exact figure depending on the slope of the source counts. The steeper the count, the earlier confusion noise begins to dominate the image (see Hogg 2001 and references therein).

It is important to realise that at these micro-Jy levels of sensitivity the radio sky literally lights-up. For example, in an observing run with the *e*EVN of only 1 hour, there are potentially more than 1000 (5σ) radio sources within the primary beam of the Effelsberg 100-m telescope. Fig. 5 plots the confusion noise at 200 MHz, 1.4 and 5 GHz as a function of angular resolution. Again the SED assumed for LOFAR is an important factor in determining how quickly the confusion limit is reached. Here we have taken possibly the worst case: - $\alpha \sim -0.8$. Observing at 200 MHz and with a resolution of ~ 0.7 arcsecs, LOFAR reaches the confusion noise (~ 1 microJy) in 1000 hours (see also Rottgering 2002 for a discussion about confusion and plans for a deep LOFAR continuum survey). Similarly, the current SKA configuration (see Ekers 2002) specifies a resolution of at least 0.1 arcsec at 1.4 GHz (equivalent to a baseline length of 400 km at 1.4 GHz). Such a specification suggests the SKA will hit the confusion limit rather quickly, ~ 24 hours at 1.4 GHz. It seems likely that a capable multiple-beam instrument such as the SKA will permit much longer integration times to be employed, similar to the 1000 hour long observations envisaged for LOFAR deep field surveys. The inescapable conclusion to be drawn from Fig. 5 is that the SKA will require a significant fraction of the array to be distributed over baselines of up to several thousand km in extent. Longer baselines will inevitably lead to a sparse SKA array but the (u, v)-coverage will still be good since large fractional bandwidths can be employed. Indeed, the incorporation of longer baselines might alleviate image dynamic range limitations – the brightest and most troublesome confusing sources at the edge of the beam being largely resolved on baselines longer than a few thousand km.

3.5. The need for high angular resolution

While confusion places initial lower limits on the minimum baseline length of next generation interferometers, we also need to consider what optimum resolution is required to resolve and image these distant star forming galaxies (not to mention other extra-galactic radio sources, such as AGN that make up at least 20% of the faint micro-Jy radio source population). The deep MERLIN and VLA detections of moderate redshift micro-Jy radio sources in the HDF-N (Muxlow et al. 1999), suggest that the angular size distribution of the majority of sources peaks at about 1 arcsec with some sources clearly showing compact sub-structure on sub-arcsecond scales. If more distant star forming systems present radio emission on similar scales as local nuclear starburst galaxies such as Arp 220, linear resolutions much better than 500 pc will be required just to begin to probe the resolved structures of these sources. At $z \sim 2$ the 500 pc subtends an angle of ~ 60 milliarcsecond. This is very similar to the resolution of e-MERLIN at 5GHz. Combined e-MERLIN and EVLA observations should have sufficient resolution and surface brightness sensitivity to begin to probe the radio structures of these sources in some detail. In addition, much higher resolution observations with the *e*EVN will be able to distinguish between AGN and starburst activity in the population of high-z, dust obscured, optically faint systems that only reveal themselves in the radio and sub-mm wavebands. The observations made by these upgraded instruments will be crucial in determining the optimum distribution of SKA collecting area. Simple confusion noise arguments already argue for baselines on scales of at least ~ 1000 km (see section3.4). Accurate astrometry, reliable identification and complementarity with new sub-mm, near infra-red and the next generation of extremely large (optical) telescopes (ALMA, NGST, OWL, CELT etc) also present a strong case for an extended SKA. With 2 orders of magnitude better sensitivity than any of its predecessors, it would be short-sighted indeed to limit the resolution of SKA to that currently employed by existing, connected interferometers. With a resolution of ten milliarcsecond, the SKA will be able to detect the sea of individual SNe, SNR, HII regions and GRBs that will be the dynamic radio loud signature of massive star formation in the early Universe. Resolving such structures will provide crucial clues to understanding the process of galaxy formation, perhaps distinguishing between monolithic collapse and hierarchical merging processes. But in the meantime, the challenge of the next few years will be to design a SKA that can do all this and more, without significantly compromising the high brightness sensitivity required for other programmes, such as narrow-band HI observations of both the nearby and distant Universe.

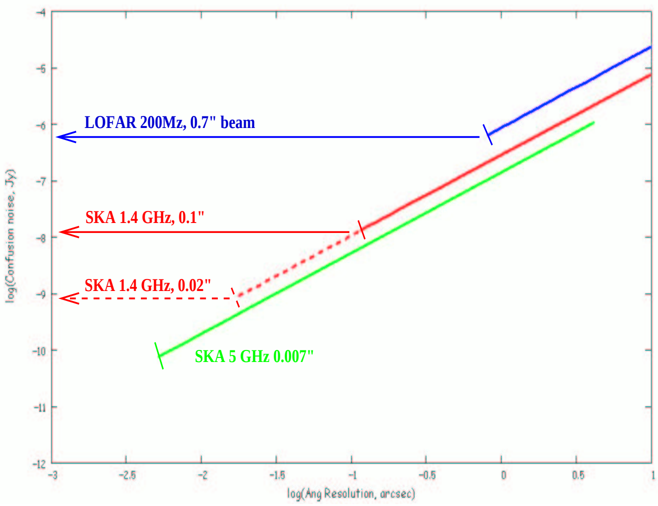

Fig. 5. A plot of the 1σ confusion noise versus angular resolution for 200 MHz, 1.4 GHz and 5 GHz. After around 1000 hours LOFAR is confusion limited (assuming a baseline length of 400km). The SKA at 1.4 GHz reaches the confusion limit with the same baseline length after ~ 1 day. Assuming much longer integration times are employed in deep field continuum surveys, an angular resolution of 0.02 arcsec is required, implying a baseline length in excess of 1000 km.

4. The radio Universe at $z > 6$ - beyond the epoch of re-ionisation

I have confined my discussion to radio emission at $z < 6$. While the the FIR-radio correlation is now known to apply to at least $z \sim 1$ (Garrett 2002), at some critical redshift the synchrotron emission from relativistic electrons is expected to be significantly reduced. In particular, as inverse Compton losses (via the CMB) scale as $(1+z)^4$, these will begin to dominate over synchrotron losses beyond $z \sim 6$ (Carilli, Gnedin & Owen 2002). The synchrotron spectrum will steepen considerably and will be quenched all together in regions where particle injection or re-acceleration has ceased. Prompt emission from SNe and GRBs should still be detected however. It is also interesting to note that at $z \sim 20$, the peak in the FIR dust emission will begin to shift through the sub-mm wave-bands into the high frequency radio part of the spectrum (see Fig.1). The thought that next generation radio instruments might bask in the favourable k-correction that sub-mm instruments such as SCUBA currently enjoy (at $z \sim 1 - 10$) is an exciting one. However, at these early epochs, star formation is in its infancy, and the dust content may therefore be quite low. If there is emission from dust, we can also expect the CMB to work against us again, setting a minimum grain temperature and shifting the peak in the dust emission towards higher frequencies at higher redshifts. But to end on a positive note, it is worth noting that radio emission from non-relativistic electrons (good old free-free emission) will not be affected by IC losses, and its relatively flat spectral index will make it "future proof" in terms of the k-correction (Blain 2002). Free-free emission will thus begin to dominate the total radio emission that might be emitted by sources at the very highest redshifts ($z > 10$). As Blain (2002) also notes, it may be one of the best sign posts to early galaxy formation at redshifts greater than 10.

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