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Radio properties of young SNe/SNRs in Arp220

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Radio observations of young radio supernovae (SNe) and supernova remnants (SNRs) can provide a unique window on the stellar/ISM properties of starburst galaxies. Such observations can potentially constrain issues of cosmological importance such as whether stellar IMFs are radically different in extreme star-forming environments. Recently published observations of the nearest ultra-luminous infra-red galaxy Arp 220 have revealed the radio spectra of a group of SNe/SNR. About half of the sources detected at high frequency have spectral and variability properties consistent with young Type IIn supernovae interacting with their pre-explosion stellar winds. However the high rate of appearance of these sources implies that an unusually large fraction of core-collapse supernovae are highly luminous, which might be at least partly explained by a top heavy IMF. The other half of the compact sources found in Arp 220 were interpreted as SNRs interacting with a dense (10^4 to 10^5 cm^{-3}) ISM. In this paper we report on new more sensitive VLBI observations at wavelengths of 2 cm and 3.6 cm. We find that the spectral evolution of most of the suspected SNe sources is consistent with them being of Type IIn. However two rapidly dimming objects may instead be of Type Ib/c or IIb. Most of the long-lived candidate SNR sources show small or undetectable flux density variations, however one almost doubled its 3.6 cm intensity in 11 months. Another source also shows some variability and a complex spectrum. These two objects plus another with a flat spectrum up to 2 cm are the best candidates for an AGN core, though the data does not yet require this interpretation. At least three sources show signs of resolution with diameters in the range 0.1 to 0.2 pc. These sizes put them sightly above, but still consistent with, the size-luminosity correlation for SNRs. The SKA will have sufficient sensitivity to detect the emission from Arp220-like compact sources out to cosmological distances (i.e. up to z$\approx$ 0.5). However the SKA needs global baselines both to separate out the discrete sources from more extended radio emission and to resolve them apart.

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1. Introduction

Star-formation properties may be quite different in dense nuclear starbursts compared to galactic disks. Theoretically it is expected that in the dense hot conditions within such nuclei the stellar initial mass function (IMF) may be very top heavy [1]. IMF variations in dense environments are a significant uncertainty in deriving the star formation history of the universe. These variations may affect the redshift at which total star-formation rate peaks because an increasing fraction of stars form in dense systems as z increases [2]. For this and other reasons it is important to obtain as detailed an understanding as possible of the IMFs, star-formation rates and stellar evolution in local LIRGs and ULIRGs. Unfortunately optical and IR observations are limited by the large dust obscuration columns toward the centres of these objects. Radio observations can however penetrate this foreground material to observe Radio Super-Novae (RSNe) and Super-Nova Remnants (SNRs) both of which can then be used to constrain nuclear properties.

Specifically, observations of the evolution of young RSNe (age $<$ few years) interacting with their pre-explosion circumstellar medium (CSM) can constrain the stellar-wind properties of the progenitor stars [3] and hence progenitor type and stellar evolution in ULIRGs. At later times, when the ejecta reaches beyond the stellar-wind and interacts with the dense ISM (SNR phase) the radio source can be used as an in-situ probe of ISM density and pressure. Furthermore from the rate of newly observed RSNe/SNRs the formation rate of massive (> 8 $M_\odot$) stars can be found and compared to other estimates of total star formation rate in order to constrain the stellar IMF.

2. Previous Radio Observations of Arp 220 Compact Objects

For over a decade, the nearest ULIRG Arp 220 has been the subject of a high sensitivity VLBI campaign to observe the evolution of a cluster of compact SNe/SNR sources [4]. A total of 49 such sources have been detected at 18 cm with 4 ± 2 new sources appearing every year [5]. However until recently they had not been detected at wavelengths shorter than 18 cm [6]. Progress was made by Parra et al [7] who detected Arp 220 first at 6 cm in a Effelsberg–Arecibo VLBI snapshot observation and then in three wavelength (3.6, 6 and 13 cm) VLBA[1] observations (see Figure 1). Previous failures to detect the sources at wavelengths shorter than 18 cm is due to no nearby catalogued calibrators being available in the past.

Parra et al. [7] showed that amongst the 10/18 sources found at high frequency which were detected since the discovery paper by Smith et al. [4] most had peaked spectra and 18 cm variability properties consistent with being type IIn SNe. By contrast amongst the long-lived sources (8/18) all but one had stable 18 cm flux densities. These latter sources showed a wide range of spectral shapes from flat to steep to peaked. It was argued that they were predominantly SNRs in which the supernova ejecta was interacting directly with an ISM of density $\sim 10^4$ to $\sim 10^5$ cm^{-3}. Source W33 did not however fit this picture, showing variability at 18 cm and a complex spectrum. This object and possibly the three flat spectrum sources were noted as possible AGN candidates (see recent arguments from Downes & Eckart [9] arguing for a buried AGN in Arp 220). In [7] the rate of appearance of new compact radio sources was compared with the star formation rate inferred

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

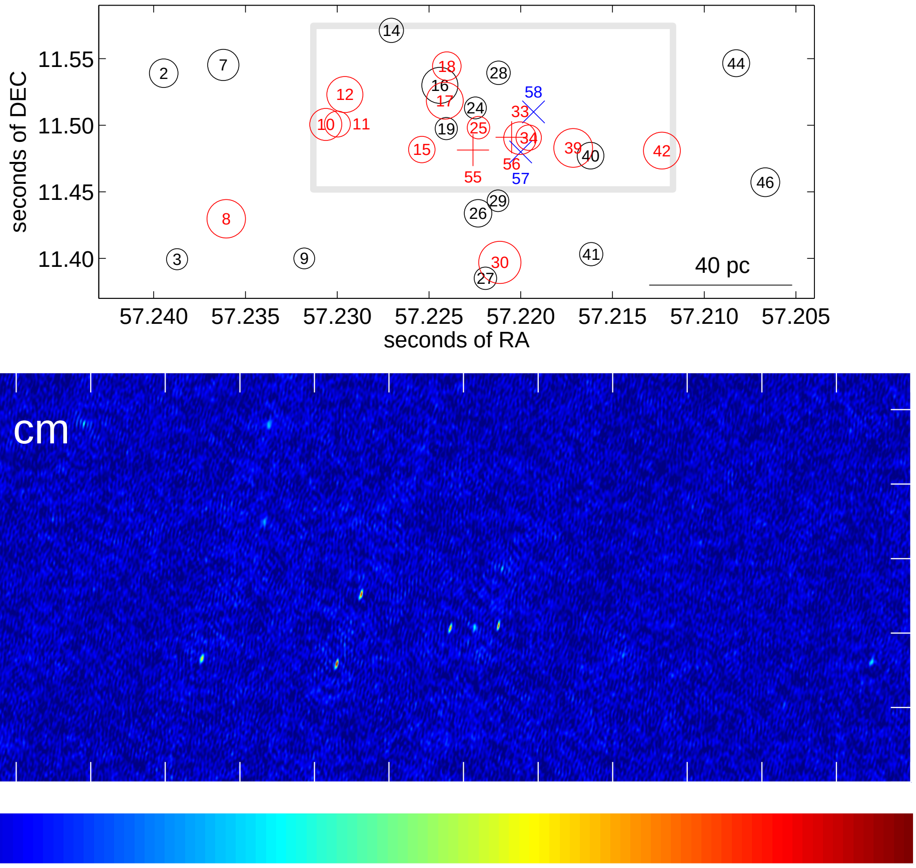

Figure 1: Compact radio sources in the central region of the western nucleus of Arp 220. **Top Panel:** Circles show the 18 cm detections from [5], with area proportional to 18 cm flux density. Circles drawn in red indicate sources also detected at shorter wavelengths. Red crosses (+) indicate the sources W55 and W56 first detected in the VLBA observations of January 2006 [7]. Blue crosses (×) show the positions of two sources (W57 and W58) first detected in our new observations of late 2006. **Bottom Panel:** Expanded view of the gray rectangle in the top panel showing the new uniformly weighted 3.6 cm image from data taken on November 2006. Tick marks are every 20 mas and the colour-scale is proportional to brightness.

from the FIR luminosity and it was found that they could only be consistent in the unlikely event that virtually every core-collapse SNe produced an extremely luminous Type IIn RSNe. Various possible explanations for this apparent discrepancy were offered including a very top heavy IMF or an extremely short intense burst of star formation.

3. New Results

3.1 Observations and new source detections

In late 2006 we obtained new and more sensitive observations at 3.6 cm with a global array (observed November 28, 2006) and for the first time 2 cm observations, made with the High Sensitivity Array (on December 28, 2006). Each run used 256 Mbit s^{-1} recording and observed for a full track. Both data sets achieved sensitivities 2.5 times better than the multi-wavelength VLBA-only

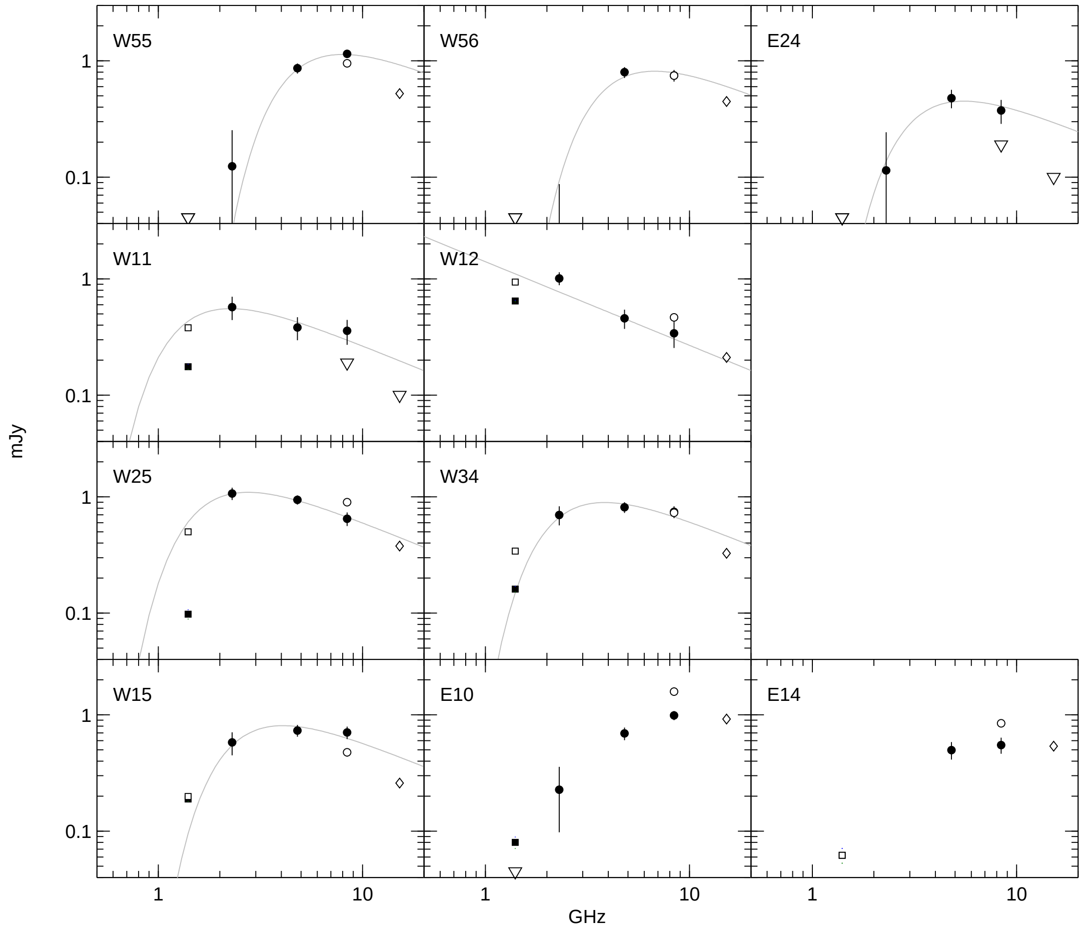

Figure 2: Spectra of all the compact radio sources that have been newly detected since the Smith et al. [4] discovery paper. The majority of these sources were interpreted as young SNe by Parra et al. [7]. The first three rows order spectra roughly according to estimated SNe age, the last row shows sources with an ambiguous SNe/SNR classification. Filled circles at 3.6, 6 and 13 cm show data from the VLBA observations of January 2006. The open squares at 18 cm data represent data from March 2005 and the filled squares from November 2003. New 3.6 cm (November 2006) measurements are shown as open circles and new 2 cm data (December 2006) as open diamonds. Upper limits (3 sigma) at all frequencies/epochs are shown as triangles. Note at the two wavelengths where we have two epochs of data (3.6 cm and 18 cm) in sources where there is little or no variability often only one symbol is visible. The solid lines represent power law plus free-free absorption models as fitted to the original January 2006 data in Parra et al. [7].

observations published by [7]. The bottom panel of Figure 1 shows the 3.6 cm wavelength image of the Western nucleus in which 13 sources are clearly detected. At 2 cm wavelength 12 sources were detected in this nucleus. Taking both wavelengths together two sources were found which were not detected before (at the positions indicated by blue crosses in the top panel of Figure 1). In the Eastern nucleus (not shown) three sources were found (including one newly detected source). All of the new detections are relatively weak and would not have been detected in the previous 3.6 cm epoch 10 months earlier even if they had the same flux density. Given this we cannot be sure if these are new rapidly evolving SNe sources or instead weak but stable SNR sources.

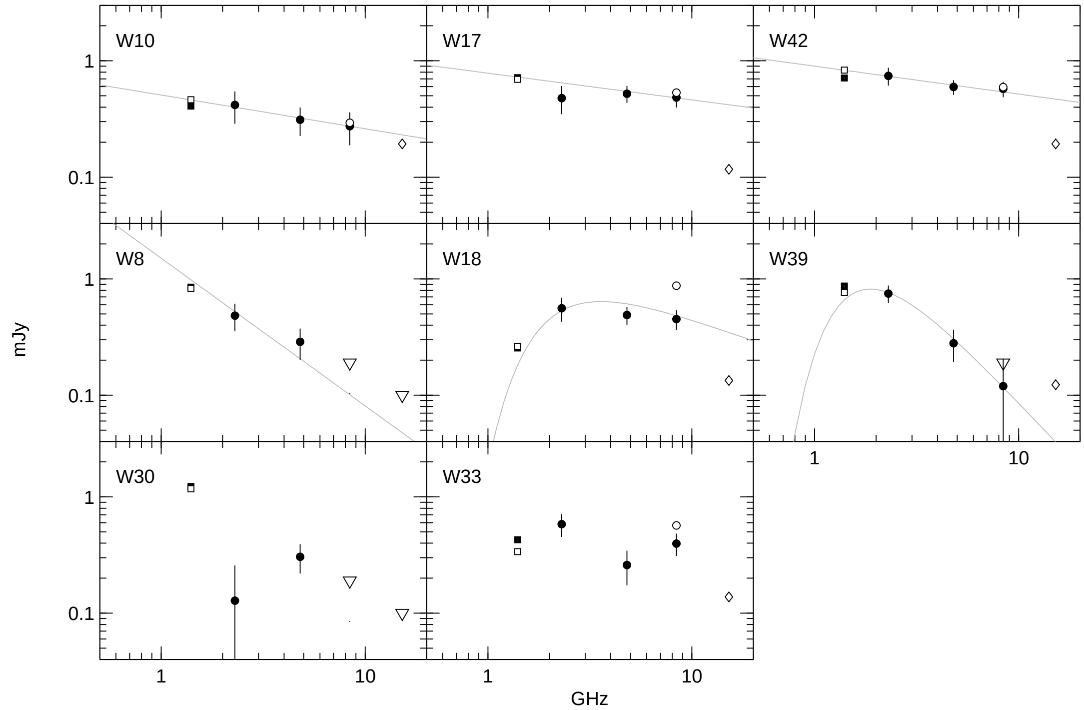

Figure 3: Spectra of the long lived sources known since Smith et al. [4]. The rows attempt to group sources with similar spectral properties. Most of the sources in this figure were interpreted by Parra et al. [7] as likely SNR candidates. Filled circles at 3.6, 6 and 13 cm show data from the VLBA observations of January 2006. The open squares at 18 cm represent data from March 2005 and the filled squares from Nov 2003. New 3.6 cm (November 2006) measurements are shown as open circles and new 2 cm data (December 2006) as open diamonds. Upper limits (3 sigma) at all frequencies/epochs are shown as triangles. Note at the two wavelengths where we have two epochs of data (3.6 cm and 18 cm) in cases where there is little or no variability often only one symbol is visible. The solid lines represent power law plus free-free absorption models as fitted to the original January 2006 data in Parra et al. [7].

3.2 High frequency spectra and variability

Based on these new observations, updated source spectra are shown for all the sources detected by [7] in Figures 2 and 3. The former figure shows sources interpreted as type IIn SNe by [7]. Unexpectedly amongst this group two sources previously detected at 3.6 cm wavelength (E24 and W11) were not detected in the new 3.6 cm data despite its much higher sensitivity. This implies that the 3.6 cm flux densities of these two sources have decreased by factors $\gtrsim 3$. This behavior is consistent with radio supernovae of classes Type Ib/c or Type IIb - some of which have peak luminosities comparable to SNe of Type IIn [8]. For the remaining sources more modelling is required but they seem to show behavior consistent with being type IIn SNe. For such sources roughly speaking it is expected that if the spectral peak in early 2006 was at a wavelength shorter than 3.6 cm the flux density at this wavelength should increase; conversely if the peak was at a longer wavelength then the flux density should decrease. Sources E10 and E14 show the expected increases and W55 and W15 the expected decreases. Other sources however show stable flux densities (W56 and W34) or an increasing flux density when a decrease is expected (W12 and

W25). Despite these apparent inconsistencies a type IIn SNe interpretation is still tenable because observed radio light-curves often show small timescale variations [3]. Longer term high frequency monitoring is required to determine if these sources really behave in ways inconsistent with type IIn SNe.

Turning to the long-lived candidate SNR sources shown in Figures 3 we again see a wide variety of spectral and variability properties. Those sources which were undetected in the original 3.6 cm observations (W8, W30 and W39) remain undetected to lower limits - implying steep spectra. The three sources identified by [7] as showing relatively flat spectra (W10, W17 and W42, see top row Figure 3) all appear to have stable flux densities at 3.6 cm wavelength. Of these, two show a spectral turn-down at 2 cm. Possibly these are SNRs with inhomogeneous shell structures. Source W10 remains fairly flat with a 18 cm–2 cm spectral index of 0.39.

In terms of its variability properties source W18 stands out, almost doubling its 3.6 cm flux density in 11 months. Notably this source also showed [7] a strong *decrease* in its 6 cm flux density between a small amount (2 hrs) of reanalysed archive data from 2003 and the VLBA data from 2006. In our new data we also see a large difference between its 3.6 and 2 cm flux densities implying either a very steep high frequency spectral index ($\alpha = 3.2 \pm 0.3$) or variability on timescales of less than a month. It is unclear what this object could be. Such spectral/temporal behavior is inconsistent with a SNR origin and if it is a SNe the rise at 3.6 cm would suggest that the light-curve peak at this wavelength has not yet been reached even though the minimum source age is 12 yrs. An SNe origin also appears inconsistent with its 6 or 18 cm variability (see [6] where it is called SN7). In [7] it was speculated that there should exist SNe/SNR transition objects, but it is thought these should simultaneously brighten at all wavelengths. An increase only at high frequency might however be consistent with plerion powered sources such as SN1986J (see Bientenholz et al. these proceedings).

Another source showing 3.6 cm variability in our data is W33. This source apparently varies at 6 cm also [7]. The spectrum of this source is hard to characterise and like W18 it shows a large difference in flux density between 3.6 and 2 cm. This again implies either a very steep spectral index of $\alpha = 2.4 \pm 0.3$, or a very large variability in the 30 days between the 2 and 3.6 cm observations. This source was identified by [7] as a possible AGN candidate, as for W18 a plerion powered object is another possibility.

3.3 Source Resolution

A first look at the individual source images indicates that several sources are resolved. The top left panel of Figure 4 shows as a control the young SN source W55 which is bright and almost identical to the beam and hence unresolved. The other three panels show the resolved sources. One of these is W42 which was identified as being resolved by [7]. This source has a flat spectrum to 3.6 cm and then a turn-down at 2 cm (see Figure 3). The other two confirmed resolved sources W15 and E14 have peaked spectra and modest 3.6 cm variability (see Figure 2). Both were classified by [7] as having 'ambiguous' classification since it was not clear whether they were newly created SNe or long lived SNRs. Further work needs to be done to decide between their origin as SNR with large foreground ISM free-free absorption or a class of rapidly expanding SNe. Plotting data for all three resolved sources we find that they lie above the size-luminosity correlation for SNRs established from M82 and SNRs in the Magellanic clouds and our galaxy (see Figure 8 in [7]).

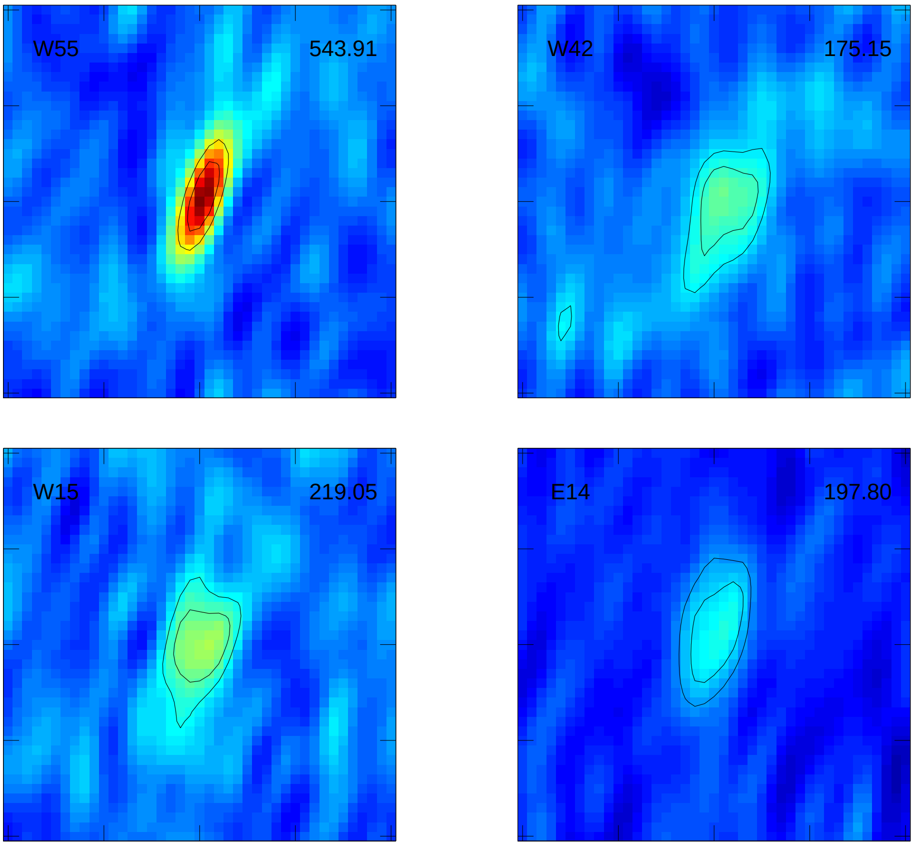

Figure 4: Individual source images at 2 cm wavelength in the uniformly weighted image with noise rms of 29 μJy beam^{-1}. The top left panel shows a source (W55) whose contours are almost identical to that of the restoring beam and hence is unresolved. The remaining panels show the three sources (W42, W15 and E14) which show the clearest evidence for being resolved. These three sources are also marginally resolved at 3.6 cm wavelength. For each panel contours are plotted at 50% and 75% of the peak panel brightness (given in the top right corners in μJy beam^{-1}). Colours indicate absolute brightness levels. Tick marks are 1 mas apart.

However, given the large scatter in that correlation and that we preferentially plot only the large luminosity/size objects we can detect/resolve they still seem to be consistent with this correlation.

4. Future Prospects for Arp 220 and for the SKA

Given the evidence in Arp 220 of compact sources with rapid flux density variability over only 11 months it is clear that more frequent multi-wavelength observations are warranted. Such observations will be able to check whether previous annual monitoring have missed a significant rate of Type Ib/c or the faster evolving Type II SNe. In addition detailed modelling work is ongoing on relating the rate of occurrence of different classes of SNe with the shape of the stellar IMF to see whether the theoretical expectation of a top heavy IMF in starburst nuclei is confirmed. A number of the compact sources have odd properties, perhaps indicative of new classes of objects.

Future intensive monitoring observations should help characterise and understand these discrepant objects. It is possible that one or more compact sources marks the position of a buried AGN, such a source might be revealed if we find long lived sources showing random flux density variations.

The SKA when completed will be able to detect compact sources of the same luminosity as those in Arp 220 at the same signal to noise in one hour of integration out to cosmological distance (i.e. $z \approx 0.5$). At these distances however angular sizes the will be 25 times smaller and the main problem will be to separate out the compact sources from the diffuse radio emission (which gives 95% of the radio emission at 18 cm [5]) and then to separate apart the individual compact sources. Such source separation at z=0.1 to 0.5 will require global baselines. Many other kinds of science (e.g. stellar radio observations) would benefit from high sensitivity long baselines. Alternatively it may be useful to have a complementary northern hemisphere array, perhaps based on SKA technology but with the highest possible bandwidth. This complementary array would be optimised toward the higher frequencies ($\nu > 1$ GHz) and could perhaps have 10% of the SKA collecting area. Such an array would have a widely distributed element distribution so that most of the sensitivity was concentrated in the longest global baselines.

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