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Exploring the MicroJy and NanoJy Sky: From the VLA to the SKA

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Deep radio surveys made with the VLA which reach sources as faint as 10 microJy at 20cm are giving new insight into the cosmic history of star formation and formation of supermassive black holes. High resolution VLA/MERLIN observations of the Hubble Deep Field North and new VLA surveys of the Hubble Ultra Deep Field, the Chandra Deep Field South and the Extended CDFS at 6 and 20 cm suggest that star formation contributes to less than half of the sub-mJy radio source population. We discuss the prospects for extending these studies with the EVLA and eMERLIN as well as the opportunities and challenges for observing the nanoJy source population with the SKA, including sensitivity, dynamic range, and resolution requirements.

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1. Introduction

Star and galaxy formation is a complex process in which mergers and interactions along with supermassive black holes (SMBHs) all appear to play important roles. Studies of cosmic evolution for radio galaxies,[1] optically selected quasars,[2] radio loud quasars,[3,4] X-ray sources,[5] and star formation[6] all indicate a similar pattern of an increase in luminosity and/or density up to epochs corresponding to redshifts of 1 to 2 followed by a rapid decline to current epochs. The near simultaneity (on cosmic time scales) in the formation of stars, galaxies, AGN, and quasars suggests a common link or interaction among these phenomena.

Does the presence of an AGN stimulate star formation, or do high rates of star formation lead to AGN? Or, is there some underlying phenomenon which is responsible for both? Deep radio observations give unique insight into the processes of star formation and the formation of SMBHs as radio waves penetrate the gas surrounding galaxies and obscured quasars and AGN. Moreover, the sub-arcsecond resolution which may help to discriminate between star formation and AGN driven radio emission is easily achievable from ground based observations even for very faint radio sources.

2. Deep Radio Surveys

The extragalactic radio source population ranges from normal galaxies with luminosities near 10^{37} ergs/sec to galaxies whose radio emission is as much as 10^7 times greater owing to regions of massive star formation and/or to an AGN. The population of radio sources with flux densities greater than 1 mJy is dominated by AGN driven emission in which virtually all of the energy is generated by a SMBH in the nucleus. For these sources, the observed radio emission includes the classical extended jet and double lobe radio sources, as well as compact radio components that are more directly associated with energy generation and collimation near the AGN central engine.

Below 1 mJy there is an increasing contribution to the radio source population which has been attributed to synchrotron emission resulting from relativistic plasma ejected from supernovae of young stars associated with massive star formation in galaxies or groups of galaxies where mergers or interactions appear to be important.[7,8] The radio emission associated with star formation is closely correlated with the FIR emission.[9] Because of the lack of absorption at radio wavelengths, the observed radio flux density gives an especially good estimate of star formation activity. However, combined VLA and MERLIN observations of the HDFN[10] with a resolution of 0.2 arcsec showed the complexity of the microjansky radio emission consistent with a mixture of AGN and star formation contributing to the sub-milliJansky radio emission.

Other deep radio observations of the µJy sky made with the VLA covering the Hubble Deep Field North,[11,12] SSA13,[13,14] as well as other fields,[15,16,17,18] with the WSRT,[19,20,21] and with the ATCA[22,23,24] have given new insight into star and galaxy formation, interaction, and evolution and their relation to AGN and the formation of

SMBHs. While the opportunities for exploring the sub-µJy sky with the EVLA, eMERLIN, ASKAP, MeerKat and later the SKA, are exciting, there are potential pitfalls that must be avoided to fully exploit the sensitivity expected from these next generation facilities.

3. The Chandra Deep Field South

One of the best studied fields is the Chandra Deep Field South (CDFS) which includes the Hubble Ultra Deep Field (UDF) and is contained within the Extended Chandra Deep Field South (E-CDFS). The extensive observational material in this area available at X-ray (Chandra), optical (HST and ground based observations) and IR (Spitzer) wavelengths, as well as at radio wavelengths allows for an especially thorough study of the relation between AGN and star formation and their cosmic history.

VLA studies include both high resolution (3.5 arcsec or better) observations at 6 and 20 cm of the CDFS[25] and the E-CDFS[26] and lower resolution (13 arcsec) observations made with better surface brightness sensitivity.[27] Observations with the ATNF cover a larger region, but with reduced sensitivity and resolution.[24]

Observations of the Hubble UDF, the CDFS and the E-CDFS in other wavebands include:

- Chandra X-ray satellite observations with an exposure of 942 ksec reaching a limiting flux of 5 x 10^{-17} ergs/sec in an area ~250 arcmin^2. [28]
- The E-CDFS with four Chandra pointings and covering an area ~10^3 arcmin^2.[29]
- The Hubble UDF[30] was observed for nearly 1 Msec with B, V, i, z ACS photometry and covers an 11 arcmin^2 region with some 10^4 galaxies brighter than magnitude i=29.
- GOODS ACS observations cover 160 arcmin^2 with B, V, i, photometry and are complete to magnitude I= 28. [31]
- Ground based imaging with the ESO VLT and 2.2m telescopes cover the CDFS at up to 4 bands (U, B, V, I) down to magnitude ~ 26.[32]
- IR data is available from both ground based[32] and Spitzer observations.

Optical or IR counterparts were found for > 95% of the radio sources in the complete CDFS radio sample above 43 µJy. However a few relatively strong radio sources have no detected optical, X-ray, or IR counterpart. Spectroscopic[33] or photometric[34] redshifts are available for more than 70% of the cataloged radio sources in the CDFS.

From analysis of these multiwavelength studies, Padovani et al.[35] have argued that the steepening of the sub-milliJansky radio source count is apparently not entirely due to a population of starforming galaxies, and that the fraction of AGN contribution to the sub-milliJansky population is greater than previously thought. Earlier studies, which were largely based on incomplete identifications, apparently missed the galaxies with very high ratios of radio to optical luminosity inconsistent with known star formation rates.

4. The SKA: Opportunities and Challenges

The EVLA will give up to an order of magnitude further improvement in sensitivity at arcsecond resolution and eMERLIN up to 2 orders of magnitude improvement in sensitivity at subarcsecond resolutions, while enhancements to the VLBA will give perhaps a factor of 5 improvement in the milliarcsecond sensitivity needed to distinguish between faint radio emission due to star formation and that due to AGN

The SKA will have sufficient sensitivity to explore the sub-μJy sky to levels more than another order of magnitude fainter. With a sensitivity of 10,000 m^2/deg (SEFD = 0.3 Jy), the SKA could reach rms noise levels of only a few tenths of a μJy in about 1 hour and a few tens of nJy in 100 hours if limited only by thermal receiver nosie. If the SKA has sufficient resolution (< 0.01 arcsec) and dynamic range ($>10^{6.5}$) to exploit the raw sensitivity, it will be able to study the formation of galaxies and SMBHs and their cosmic evolution over a wide range of cosmic time, and better understand the relation between SMBHs and star formation. But, there are a number of challenges to achieving these goals.

5. Sources of Error and Discrepancies among Current Radio Surveys

Below about 1 mJy at 20 cm, the scatter among source counts from the different survey fields is much greater than would be expected from the individual surveys.[25] While, it is tempting to interpret the large scatter as evidence for real cosmic variance, more likely it is the result of underestimating the errors in determining the flux density of radio sources which are near the detection limit as well as in calculating the effective area corresponding to different limiting flux densities. Indeed, even within the same field, measurements of individual sources made with different instruments sometimes differ by considerably more than their combined errors.[26]

In addition to the statistical uncertainty due to thermal noise, a major source of error is the differing resolutions used by different observers and the different assumptions and procedures used in converting from “peak” flux densities to “integrated” flux densities. Moreover, in deep surveys made with arrays such as the VLA, WSRT or ATNF, the observed field is usually contained within a single primary beam. Additional uncertainties are introduced in converting the observed “map image” to a true “sky image.” The corrections applied to the observed “image flux density” to get the true “sky flux density” is very dependent on accurately knowing the shape of the primary beam, and the distorting effects due to finite bandwidth and finite integration time.

Moreover, since the full array sensitivity is reached only at the center of the beam, there is an additional uncertainty in calculating the area covered as a function of flux density level, and a corresponding uncertainty in the surface density of sources. The SKA will mosaic large fields of view with nearly uniform sensitivity, but in order to meet the high dynamic range requirements, the performance within each primary beam must be understood and remain constant to a level much better than has been achieved so far.

Kellermann et al.[25] have examined the statistics of confusion noise in the 20 cm CDFS image and find an rms noise of ~2 µJy with a 3.5 arcsec resolution. This suggests that to reduce confusion noise below the thermal noise, better resolution will be needed for sub-µJy surveys. However, comparison of the CDFS 3.5 arcsec VLA image with one of comparable sensitivity but with 13 arcsec resolution, indicates that there is not only missing flux density in the 3.5 arcsec image, but that there are a significant number of sources seen in the 13 arcsec image and not in the 3.5 arcsec image.[27] So it appears that there will be no single optimum resolution to use for deep EVLA/eMERLIN/SKA surveys; rather a wide range of resolution and surface brightness will be needed to insure completeness and accuracy for these next generation radio telescopes.

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