Cosmology, Galaxy Formation and Astroparticle Physics
on the pathway to the SKA
Klöckner, H.-R., Rawlings, S., Jarvis, M. & Taylor, A. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

Compact extragalactic sources in the SKA sky: liabilities or assets?

L.I. Gurvits

Joint Institute for VLBI in Europe, P.O. Box 2, 7990 AA, Dwingeloo, The Netherlands

Abstract. A role of SKA in high-resolution surveys of compact extragalactic sources is revisited. The surveys will be useful tools for cosmological tests and link various SKA science programs.

1. Introduction

It is a well known fact: the sky would look very different if our eyes were tuned into radio instead of optical waves. The dominant population of the radio sky is composed of discrete extragalactic radio sources. Due to this fact these sources dominated the agenda of radio astronomy over a significant fraction of its 70-year history. The interest in these sources stimulated developments of radio interferometry and aperture synthesis. These techniques enabled radio astronomy first to match optical astronomy in terms of angular resolution, and then, owing to Very Long Baseline Interferometry (VLBI) surpass it by orders of magnitude.

Recent developments in astrophysics and cosmology shifted interest toward studies of extended low brightness sources and morphological features of the radio sky, especially in the cosmological context. These proceedings provide visible evidence for this very well-justified interest. One of the central topics of this conference, the search for the Epoch of Reionization (EoR, one of the SKA Key Science Programmes) is a strong driver for development of instrumental capabilities for studying low brightness features in very wide (tens of degrees) fields. Inhomogeneities of the CMB radiation, including cosmologically meaningful Baryon Acoustic Oscillations (BAOs) also require exceptional sensitivity for low brightness contrasts. In instrumental terms, these requirements pose something totally opposite to the drive toward high angular resolution that dominated the development of radio astronomy earlier. Moreover, from time to time, one can hear references to discrete extragalactic radio sources as "boring foreground" which interferes with cosmological experiments.

Does this mean that compact extragalactic radio sources are fading from the radio astronomy scene and will not be prominent subjects in the observing schedule of the Square Kilometre Array? Probably not. After all, AGN remain natural beacons on the cosmological scale, with luminosities exceeding 10^{40} W making them visible at any cosmological distance. Simple estimates show that today we deal with a negligible fraction of AGNs, only those with a (specific) radio luminosity above 10^{25} W/Hz. AGNs with lower radio luminosity accessible to the today's VLBI systems are confined to our immediate neighbourhood at $z \leq 0.2$. An overwhelming majority of the sources belonging to this luminosity class are too weak (total flux density below ~ 10 mJy) for massive surveys with present day VLBI systems (see Gurvits 2004 for further details). A multi-fold increase in the number of these relatively weak AGN available for detailed studies at high redshift will bring about a new quality in their understanding and "utilisation" as tracers of galaxy formation and evolution at earlier epochs.

VLBI surveys of AGN have demonstrated their potential use in cosmological tests (see Gurvits 2003 and references therein). The subject attracted considerable attention in the 1990's but was deemed to be cosmologically inconclusive until much large samples of optically identified, VLBI-imaged AGN became available (Dabrowski et al. 1995). However, as pointed out recently by Jackson and Jannetta 2006 (see also Lima and Alkaniz 2002), the cosmological "angular size – redshift" ("$\theta - z$") tests based on rather limited VLBI surveys of several hundred AGN hinted at a prevalence of dark energy in the overall balance of the cosmological density before the much-acclaimed cosmological results based on supernovae and microwave background measurements in recent years. Much more can be expected from future high-sensitivity VLBI surveys of AGN in terms of their applications for cosmological studies. However, to realise this potential, the surveys must involve at least tens of thousands of sources.

2. AGN VLBI surveys go deeper

The role of the Square Kilometre Array in future VLBI observations brings serious implications for the choice of the array configuration and the architecture of the data processing system. Various aspects of SKA involvement in high angular resolution studies were discussed in a number of papers (e.g. Garrett 2003; Krichbaum et al. 2003; Gurvits 2003) and became a focus of a special workshop held at the Max Planck Institute for Radio Astronomy in 2001[1]. Among various aspects of optimisation of the SKA array configuration and size, one has to keep in mind the

[1] www.euska.orgworkshopshr_ws_MPIfR_Bonn.html

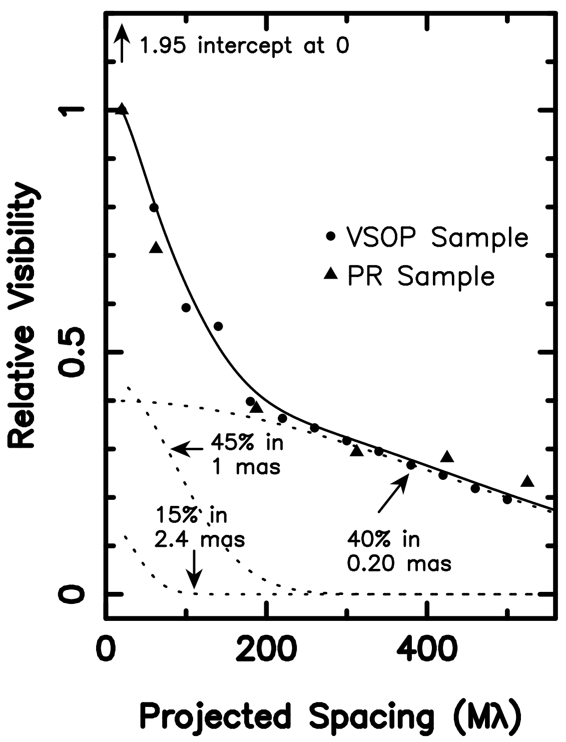

Fig. 1. The relative visibility (normalised correlated flux density) versus projected baseline length for 165 sources of the VSOP Survey at 5 GHz. The visibility normalised to 1 at 20 Mλ. The dashed line shows the expected dependence of the relative visibility for a three-component model with components sizes and fractions of total flux density as indicated. Note the change of the slope around 200 Mλ. See further details in Horiuchi et al. 2004.

imbalance of weights on baselines connecting telescopes with very different collecting areas (see Garrett 2003). Leaving details aside, I note that the percentage of the overall SKA collecting area in its compact core will be under close scrutiny during the design stage of the project; it will be addressed in various SKA design simulations.

Let us assume that the technical issues of high resolution applications of SKA are sorted out favourably for VLBI observations. How many extragalactic sources, AGN of all kinds in particular, can be detected and imaged for a given level of sensitivity? While answering this question, one should not forget that at total flux densities below $\sim$ 1 mJy, the extragalactic sky becomes dominated by star-forming galaxies, not AGN (Condon 2003). Although the latter are present in sufficient numbers, until recently their milliarcsecond-scale radio structures remained untouched – they were just to weak for VLBI observations.

Recent advances in VLBI technology have made it possible, if not to conduct en-mass imaging of mJy-level AGN with milliarcsecond angular resolution then to come close. In order to explore what kind of "yield" one can expect from mas-scale studies of mJy-level AGN, a special pilot Deep Extragalactic VLBI-Optical Survey (DEVOS) was conducted (Mosoni et al. 2006). It demonstrated that from a FIRST-based sample of sources with total flux densities above 30 mJy and SDSS identification as QSO, the overall yield of detectable mas-scale structures is about 30%. Note that this yield corresponds to today's VLBI sensitivity. Still, it would result in 10,000 mas-imaged radio AGN/QSO structures over a quarter of the sky. Majority of these sources will have radio luminosity below 10^{25} W/Hz and redshift above 0.5. This parameter-space is practically unexplored and surely will offer a lot of exciting surprises.

3. AGN VLBI surveys go sharper

There are two principal ways of sharpening images of celestial sources – decrease of observing wavelength or increase of interferometer baseline. Both are being addressed in modern studies of compact radio structures in AGN, both sources of specific interest and surveys.

The former option is pursued by steadily improving sensitivity in mm-VLBI surveys. The latest published Global mm-VLBI Array (GMVA) survey provides more than 100 images of AGN at 86 GHz (3 mm) with resolution of 50 to 100 μas, corresponding to a linear scale of $10^3 - 10^4$ Schwarzschild radii (Lee et al. 2006). It is realistic to expect further increase in sensitivity and angular resolution (the latter – owing to the eventual en-mass observations at 220 GHz) in the coming 10–20 years. Because this frequency domain is very much outside of the SKA range, I will not discuss this topic here.

The latter possibility of 'sharpening' surveys of compact extragalactic sources comes with the advent of Space VLBI. The first dedicated Space VLBI mission VSOP (Hirabayashi et al. 1998) devoted about 25% of its operational time to the survey of extragalactic sources at 5 GHz (Hirabayashi et al. 2000). It included 402 AGNs, mostly quasars, which composed a complete sample of sources with total flux density higher than 0.95 Jy at 5 GHz and spectral index flatter than -0.45. More than 240 sources from the complete sample were actually imaged with baselines about three times longer than Earth diameter (Dodson et al. 2007, in preparation). While the complete analysis of the VSOP Survey results is still in preparation, preliminary statistical results point to one potentially important property of the sub-milliarcsecond radio structures of AGN. It appears that at the angular scale of about 1 mas (corresponding to a baseline length of about 200 Mλ) there is a noticeable change in the slope of the dependence of correlated flux density to baseline length (Horiuchi et al. 2004). Figure 1 illustrates this effect. Traces of similar behaviour of sub-mas radio structures in AGN were noted earlier in 15 GHz VLBA data (Gurvits et al. 2007, in preparation). If confirmed, this effect will require thorough investigation in view of its potential implications for AGN properties. The "200 Mλ mark" in the radio structure could also help to define a linear scale useful for cosmological "$\theta - z$" tests. However, it is clear that further statistical studies of structural properties will require considerably deeper VLBI surveys, including surveys with future Space VLBI missions. According to the current plan, the next generation Space VLBI mission VSOP-2/Astro-G is scheduled for lift off in 2012 and, with its projected life-time of 5 years, is likely to coincide with the implementation phase of SKA (Hirabayashi 2005). Whether Astro-G and SKA can create the most sensitive Earth-Space baseline is a question of frequency compatibility: the lowest operational frequency of Astro-G will be 8 GHz.

4. VLBI surveys with SKA: a wishlist

As in many other SKA science themes, it is hard to predict what kind of VLBI observations will have the strongest scientific impact. However, with our current knowledge of up to a thousand of VLBI-imaged extragalactic radio sources, the following VLBI survey projects with SKA seem to be most attractive.

1). An all-sky deep VLBI survey including at least 10^4 optically identified AGN with measured redshift will bring a new quality to statistical "$\theta - z$" studies (Dabrowski et al. 1995; Gurvits 2003 and references therein; Jackson and Jannetta 2006). These studies will serve as a "sanity" check for other cosmological "standard rod" or "standard candle" tests. The most popular current "standard candle", SN Ia, will remain cosmological beacons within a relatively short range of redshift, even in the era of a 30-m-class optical telescopes. QSOs will remain a population of objects covering much larger ranges of redshift thus serving as a natural bridge in diagnostics of cosmological parameters in the range of redshift between the supernovae and the EOR.

2). One of the highlights of VLBI studies of the past decades was the discovery of a relativistic machine in the core of galaxy NGC 4258 (Miyoshi et al. 1995). A combination of precise Doppler measurements of its H_2O maser emission and VLBI-based measurements of the source geometry provided the best known confirmation of the existence of a super-massive black hole. But the source is also an ideal measuring rod at a distance of several megaparsecs. A similar source at a larger, cosmologically meaningful, distance would be a most welcome addition to the suit of cosmological standard objects. So far, attempts to find other "NGC 4258–like" sources have been unsuccessful primarily due to a lack of necessary sensitivity (Greenhill 2004; Morganti et al. 2004). The discovery and "cosmological utilisation" of NGC 4258–like objects is a challenging but very attractive task for extragalactic radio surveys. Of course, this task pushes the envelope of SKA specification toward higher frequencies, all the way to 22 GHz. However, this push is not unique, other SKA science projects, and at least one Key Science Project in particular, Cradle of Life, have a similar drive toward higher frequencies.

3). Gravitational lenses form another class of objects with great potential for astrophysical and cosmological studies. Radio morphological studies of gravitationally lensed objects provide substantial input into understanding of both lensed and lensing objects. In addition, a well-characterised physical phenomenon like grav-lensing offers the possibility to measure cosmological parameters. As demonstrated recently by Wucknitz et al. (2004), a data processing tool called LensClean applied to grav-lensed images of the source B0218+357 can help to estimate the Hubble constant with less susceptibility to systematic errors than the HST or WMAP measurements. Grav-lensed images will be present in any massive survey of extragalactic sources. For example, in the prelaunch VLBA observations of the VSOP 5 GHz Continuum Survey, Fomalont et al. (2000) "re-discovered" several known grav-lensed images in the total list of 374 compact extragalactic sources. With the same rate of gravitational lens appearance, a VLBI survey of 10,000 targets is likely to produce on order of 100 grav-lensed images of extragalactic objects. Even if a few of these hundred sources would serve as measuring tools for cosmological parameters as demonstrated with B0218+357, the scientific impact of such survey will be non-negligible.

5. Conclusions

Three possible future survey projects of compact extragalactic sources with SKA do not exhaust the list of tasks in which detailed knowledge of the SKA "extragalactic" sky will be of great value. One can think to use the compact sources in various SKA calibration procedures – an important topic that awaits detailed insight and input from the LOFAR experience. Another synergy that deserves a separate investigation is between deep SKA-based VLBI astrometric surveys of extragalactic sources and the GAIA optical astrometry. But even this incomplete list of tasks for SKA allows us to answer the question in the title of this contribution: compact extragalactic sources in the SKA sky are assets beyond doubt. This understanding should be kept in mind at all stages of the SKA design and implementation.

Acknowledgements. The author is grateful to E. Fomalont, S. Horiuchi, S. Frey, K. Kellermann, Yu.Yu. Kovalev, L. Mosoni, Z. Paragi and other colleagues involved in large VLBI surveys for endless discussions of the results mentioned here in brief. The author is also grateful to I. Avruch and O. Wucknitz for assistance in preparation of this paper. The author acknowledges the EC FP6 SKADS project for facilitating the workshop.

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