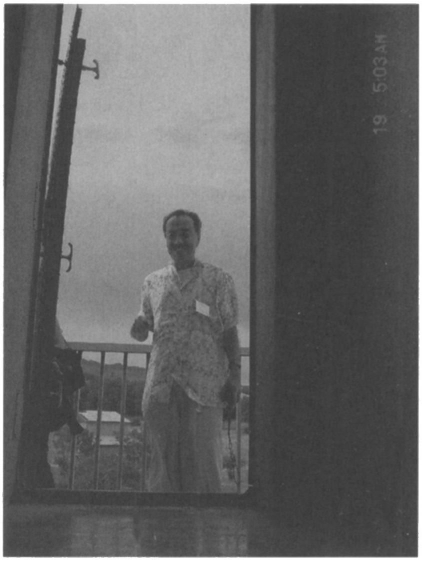
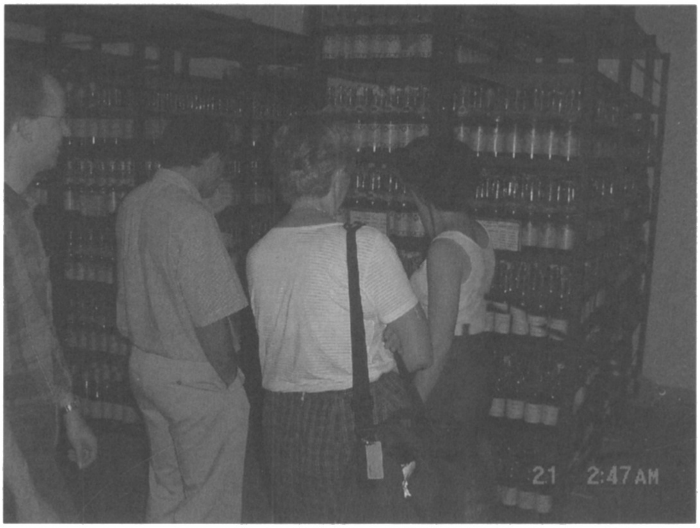
Part 4

Radio Surveys for AGN



Yoshi Taniguchi outside the 2.2m dome



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R.F. Green, E.Ye. Khachikian, D.B. Sanders

Surveys of Parsec-scale Radio Structures in AGN

L.I. Gurvits

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

Abstract. Several recent global and Space VLBI surveys of quasars and other types of AGN provide a wealth of material on milli- and sub-milliarcsecond radio structures in hundreds of sources. Results of these projects are presented with an emphasis on the statistics of redshift- and angular-scale-dependent properties of the milli- and sub-milliarcsecond radio structures. These studies make possible disentanglement of intrinsic (possibly, evolutionary) phenomena of parsec-scale radio structures and the imprints of the cosmological model.

1. Introduction

Over the last decades it has become commonplace to call AGN the most luminous powerhouses of the Universe. Indeed, their radiation, with as high an intensity as 10^{48} erg/s, originates in regions on the scale of parsecs and smaller. Not surprisingly, AGN are the most popular targets of high angular resolution studies in all domains of the electromagnetic spectrum. Of the presently available astronomical techniques, Very Long Baseline Interferometry (VLBI) offers an unrivaled angular resolution reaching milliarcsecond (mas) and sub-mas scales (see review by Kellermann & Moran 2001). As any other astronomical technique, VLBI began by observing just a few "famous" sources. However, its rapid progress since the first observations in the late 1960s has resulted in VLBI surveys of thousands of extragalactic sources, mostly AGN. Table 1 presents the major imaging VLBI surveys published to date.

Present-day VLBI systems operate at meter to millimeter wavelengths (frequencies from $\sim$ 0.3 to $\sim$ 100 GHz, respectively) at baselines comparable to the diameter of the Earth. The resolution of a VLBI system is defined by the difraction limit, λ/B, where λ is the wavelength and B is the projection of the baseline on the picture plane. For a typycal wavelength of $\lambda = 6$ cm and a practical maximum baseline length between two Earth-based radio telescopes of $B \approx 10000$ km, the achievable angular resolution is $\theta \approx 1.5$ mas. Since 1997, the first dedicated Space VLBI mission VSOP (Hirabayashi et al. 1998) makes it possible to observe with baselines up to 30000 km, which gives about a three times "sharper" image than the longest global Earth-based interferometers.

There is good reason for radio-loud AGN to be primary targets of VLBI studies: in order to be detected on baselines of $\sim 10^4$ km with "modest" 25-m class radio telescopes operating with a bandwidth of tens of MHz, a radio

Table 1. On-line VLBI survey data bases

Survey	Freq [GHz]	URL
PR and CJ[1]	5 & 1.6	www.astro.caltech.edu/ tjp/cj/
USNO RRFID[2]	2.3, 8.4 & 15	rorf.usno.navy.mil/rrfid.html
VLBA Calibrators[3]	2.3 & 8.4	magnolia.nrao.edu/vlba_calib/index.html
VLBApls[4]	5	www.jive.nl/jive/jive/svlbi/vlbapls/
VSOP Survey[5]	5	oj287.vsop.isas.ac.jp/survey/
VLBA 2 cm Survey[6]	15	www.cv.nrao.edu/2cmsurvey/

[1] Pearson–Readhead (Pearson & Readhead 1988) and Caltech–Jodrell Bank (Taylor et al. 1996 and references therein) surveys;
[2] USNO Radio Reference Image Database (Fey & Charlot, 2000, and references therein)
[3] VLBA Calibrator Survey, Peck & Beasley (1998)
[4] VSOP/VLBA Prelaunch Survey of Extragalactic Radio Sources, Fomalont et al. 2000
[5] VSOP Survey Program, Hirabayashi et al. 2000a
[6] 2 cm Survey of Extragalactic Radio Sources, Kellermann et al. 1998; Gurvits et al. 2001

source must have a brightness temperature[1] $T_B \geq 10^7$ K (see Thompson, Moran & Swenson 2001 for deep insight into the technique of radio interferometry in general and VLBI in particular). Kellermann and Pauliny-Toth (1969) have shown that, for a stationary source, there is an inverse Compton cooling limit on brightness temperature at $T_B \sim 10^{12}$ K. As became clear in early VLBI observations, some bright sources associated with AGN (mostly quasars) indeed have components as bright as 10^{12} K. As an example of a strange cosmic coincidence, the size of our planet permits intereferometers which can just barely resolve sources of that brightness. I leave out of this short review the question of whether or not this mysterious coincidence indicates a very special place occupied by our civilization in the Universe...

As pointed out by Zensus (1997), the de-facto paradigm of the AGN phenomenon, the relativistic jet model (Blandford and Königl, 1979), is based on three pillars: (*i*) accretion onto the massive central object, (*ii*) relativistic ejection from nuclei, and (*iii*) relativistic beaming. Accretion theory descends from the work done in the 1950s-1970s and has received its present form in direct application for AGN by Begelman et al. (1984; also references therein). Relativistic ejection from galactic nuclei has been suggested by Rees (1966) as a mechanism of powering extended (kpc-scale) radio structures in extragalactic sources. Earlier, the idea of relativistic ejection from the core of M87 (Vir A) was mentioned by Ambartsumian (1958) as a possible mechanism for fueling its synchrotron emission (similar to the Crab Nebula). Finally, relativistic beam-

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[1] It is a historical tradition in radio astronomy to present the source's brightness in terms of its brightness temperature, which is equal to the physical temperature of a black body of the same brightness at the particular wavelength. This "thermal" flavor of the definition is in sharp discord with the non-thermal synchrotron mechansm which dominates the radio emission of AGN.

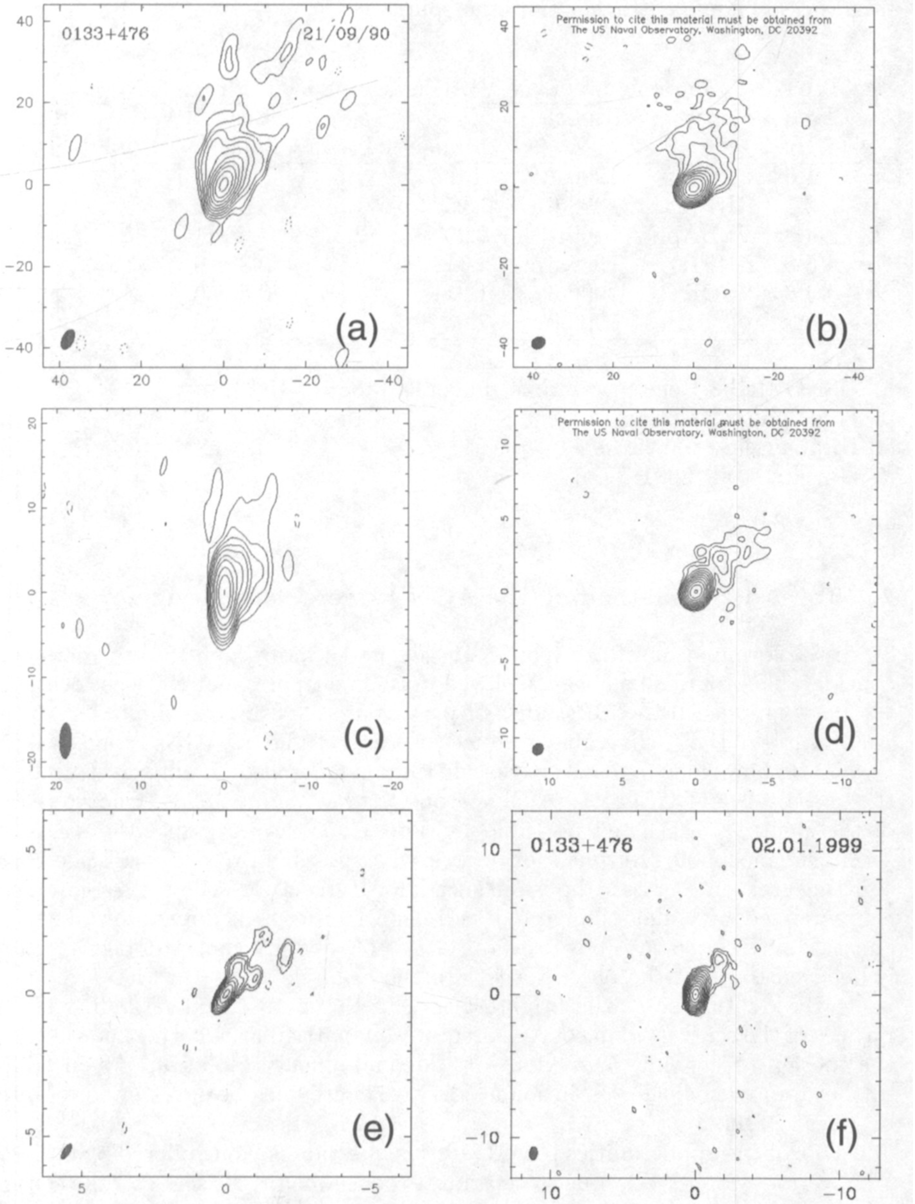

Figure 1. Images of the quasar J0136+4751 (0133+476) from VLBI surveys. See Table 2 for details.

ing was proposed by Shklovskii (1963) as an explanation of the apparent high brightness of some extragalactic radio sources.

Table 2. Parameters of the VLBI images shown in Fig. 1

	Freq GHz	Survey	Epoch	B_S Jy/bm	b_{LC} mJy/bm	Beam FWHM [mas] P.A.	Ref.
a	1.6	CJ1	1990.72	1.0	1.5	5.2 × 2.7, −24°	[1]
b	2.3	RRFID	1998.61	1.25	1.8	3.5 × 2.8, −59°	[2]
c	4.9	VLBApls	1996.43	2.29	2.3	4.2 × 1.4, −2°	[3]
d	8.6	RRFID	1998.61	2.11	2.0	0.8 × 0.7, −35°	[2]
e	4.8	VSOP	1999.62	1.21	7.8	0.5 × 0.2, −31°	[4]
f	15.3		1999.01	2.65	1.6	0.9 × 0.5, −7°	[5]

[1] Polatidis et al. 1995
[2] USNO Radio Reference Frame Image Database (RRFID)
[3] Fomalont et al. 2000
[4] Hirabayashi et al. 2000a
[5] Gurvits et al. 2001

2. Toward Understanding the AGN Power Plant Design

Since the formulation of the relativistic jet model more than twenty years ago, considerable progress has been achieved in its fine tuning, not the least owing to the data supplied by VLBI studies of particular AGN or their limited samples. An example of the "deliverable product" of VLBI studies of AGNs is presented in Fig. 1. It shows mas- and sub-mas-scale radio images at different wavelengths of the quasar J0136+4751 ($z = 0.859$, Véron-Cetty & Véron, 1998). Charcteristics of these images are listed in Table 1. This example represents the so called "core-jet" morphology typical for an overwhelming majority of mas-scale radio emitting areas in AGN. In almost all such known structures, there is a component characterized by a flat or inverted radio spectrum which dominates the radio emission at frequencies above several GHz. This component, dubbed a "core" is believed to lie at the base of a jet. In the example shown in Fig. 1 the core is clearly identifiable as the brightest spot in the maps. Understanding of the physics of the central engine of AGN requires, in particular, a better knowledge of the "design" of its emitting region with adequate linear resolution. The need for further improvement in resolution at all wavelengths has been reviewed recently by Rees (2001).

One of the opportunities to address this question is being offered by imaging VLBI surveys. They allow us to determine the characteristic scales of the central engine, or at least of its appearance in radio waves. Fig. 2 represents the mean value of the correlated flux density versus projected baseline for a subsample of about 100 radio-loud AGN. The value of correlated flux density can be considered a measure of radio emission coming from an area defined by the synthesized beam of the interferometer. The longer the baseline, the smaller the beam, and for a resolved source, the smaller the correlated flux density. An unresolved source has a constant flux density at all baselines.

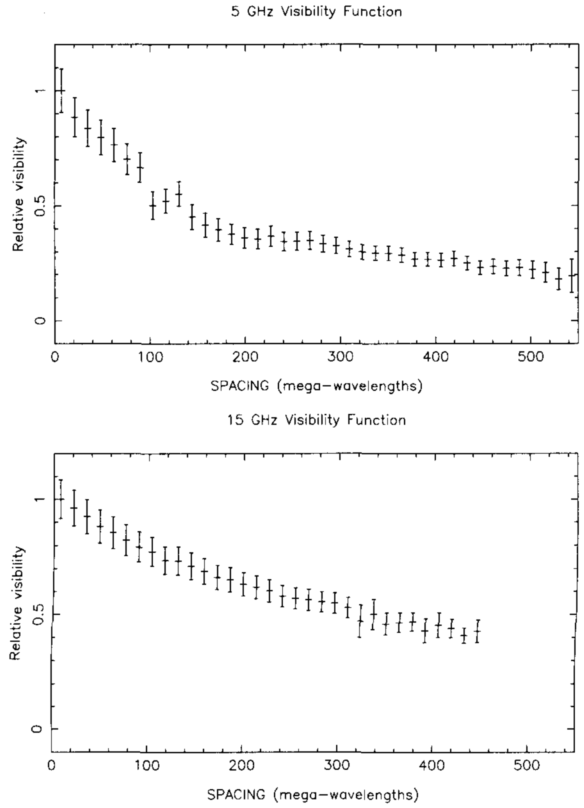

Figure 2. The mean value of correlated flux density versus projected baseline for a combined sample of VLBApls and VSOP Survey sources observed at (*top*) 5 GHz and (*bottom*) 15 GHz. The 5 GHz data used are from Hirabayashi et al. (2000) and Fomalont et al. (2000), 15 GHz data are from Kellermann et al. (1998) and Gurvits et al. (2001). Courtesy E.B.Fomalont.

Both plots in Fig. 2 indicate that on average the sources are resolved significantly on baselines up to $\sim$ 500 Mλ at both frequencies. A small "kink" visible at about $\sim$ 120 Mλ at 5 GHz and $\sim$ 340 Mλ at 15 GHz most likely is caused by a sampling effect of the Very Long Baseline Array used in both cases: the array seems to have a peculiar geometrical configuration on the scale of about 6600 km corresponding to $\sim$ 120 Mλ and $\sim$ 340 Mλ at 5 and 15 GHz, respectively.

More significant for the physics of the sources is a clear flattening (change of the slope) of the dependence at around $\sim$ 200 Mλ at 5 GHz (Fig. 2, top) which corresponds to an angular scale of about 1 mas. Indeed, as known from hundreds of available VLBI images at 5 GHz, AGN radio structures on the scale of several milliarcseconds (baselines shorter than $\sim$ 200 Mλ) typically represent a combination of core and extended jet (e.g. Gurvits, Kellermann & Frey 1999, Fomalont et al. 2000). Not surprisingly, at these baselines the slope is steep. The flatter slope at baselines ≥ 200 Mλ seems to indicate that on sub-mas scale the core starts to be resolved, and its inner structure is not self-similar to the large-scale "core-jet" morphology.

The change of slope described above is almost absent at 15 GHz (Fig. 2, bottom). This comes as no surprise if the change of morphology from "core-jet" to "core only" indeed takes place around the angular scale of ~ 1 mas. As the extended mas-scale jets have significantly steeper radio spectra than the cores, the contribution of jets to the correlated flux density at 15 GHz is smaller than that at 5 GHz. Thus, the "disappearance" of jets on sub-mas scales at 15 GHz is less prominent than at 5 GHz.

I note that the result at 5 GHz shown in Fig. 2 (top) is a combination of ground-based VLBA observations (up to a baseline length of ~ 150 Mλ, Fomalont et al. 2000) and the VSOP Survey (from ~ 50 Mλ to ~ 550 Mλ, Hirabayashi et al. 2000). The significance of the VSOP results is obvious, because the change in structural regime takes place at baselines exceeding those available for ground-based VLBI systems at 5 GHz.

It has to be noted also that the change of structural regime described here is purely qualitative and is based on a sample of sources at different redshifts (thus, observed at different rest frame frequecies). Further detailed investigation must account for redshift-dependent effects.

3. AGN Pc-Scale Radio Structures and Cosmology

VLBI data on radio-loud AGN provide measurable parameters which could be looked at in a cosmological perspective. These parameters are the source's characteristic angular size, apparent proper motion of its structural components and the source count statistics.

The radio emission from the AGN cores on the milliarcsecond scale ought to be controlled by a limited number of parameters (such as, e.g., the mass of the central black hole, the ambient and intrinsic magnetic fields in the base of jet, the accretion rate and the angular momentum of the black hole). Kellermann (1993b) argued that the milliarcsecond-scale radio structures in AGN are much less dependent on source evolution and properties of the interstellar/intergalactic medium compared to the arcsecond (kiloparsec) scale structures. Thus, mas-scale radio "cores" could be considered as non-ideal cosmological standard rods. The dependence of their apparent angular sizes on redshift (the so- called "$\theta - z$" test, Fig. 3) contains an imprint of the cosmological model. Attempts by Gurvits (1993, 1994) and Kellermann (1993a, 1993b) to extract the cosmological information from independent ad hoc VLBI samples favored a value of the cosmological deceleration parameter $q_0 \leq 0.5$ (under assumption that the cosmological term $\Lambda = 0$). Further work on the milliarcsecond scale "$\theta - z$" test by several authors (reviewed by Gurvits, Kellermann & Frey 1999) addressed various "pros" and "cons" of the approach. In particular, Dabrowski et al. (1995) pointed out the difficulty in obtaining a meaningful constraint on the average density Ω due to the effects of relativistic beaming in limited (let alone ad hoc) source samples. They estimated that cosmologically conclusive results could be obtained with VLBI samples containing several thousand sources. Recently Lima & Alcaniz

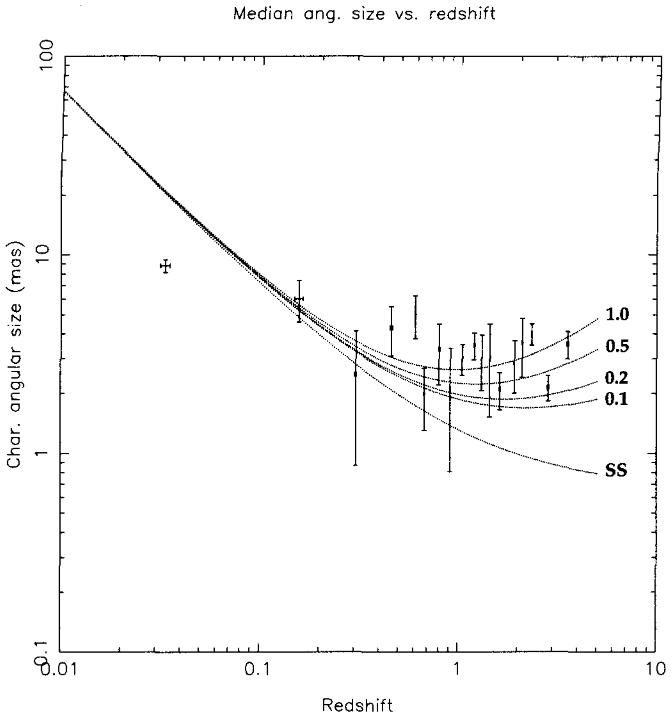

Figure 3. An example of the "$\theta - z$" test: median angular size of the sample of 330 AGN versus redshift (Gurvits, Kellermann & Frey 1999). The full length of the error bars corresponds to 1σ. The solid lines correspond to the assumed linear size of 9.6 pc, the Steady-state model (SS) and models of a homogeneous, isotropic Universe with $\Lambda = 0$ and values of $q_o = 1.0, 0.5, 0.2, 0.1$ (as marked on the plot). Data are binned into 18 bins nearly equally populated (18–19 sources per bin). The curves are shown as examples only. none of them represents the best fit.

(2000, 2001) applied the "$\theta - z$" data from Gurvits, Kellermann & Frey (1999) to constrain the parameters of the cosmic equation of state. Their result favors the conventional flat ΛCDM model ($\omega = -1$) with $\Omega_m = 0.2$. Wiik & Valtaoja (2001) modified the "$\theta - z$" test by assuming shocks in AGN jets as standard objects. Applying this approach to 14 AGNs with both total flux density monitoring and VLBI data available, they were able to demonstrate the potential of the method for estimating the dynamical parameters of the cosmological model.

The statistics of apparent velocity of VLBI components in AGN jets as a function of redshift (the "$\mu - z$" test) has been analysed by Vermeulen & Cohen (1994) and refined later by Vermeulen (1995) as a promising tool for studying the beaming model under various unification scenarios as well as a means of measurement of the Hubble constant H_0 and the deceleration parameter q_0. This method is based on the assumption of a "standard velocity" of moving features in milliarcsecond scale jets translated into observed apparent, sometimes superluminal, velocities (Pelletier & Roland 1989). An effort to exploit the "$\mu - z$" test with multi-epoch VLBI data for the CJF sample of AGN (several hundred sources) is underway (S.Britzen, 2001, private communication).

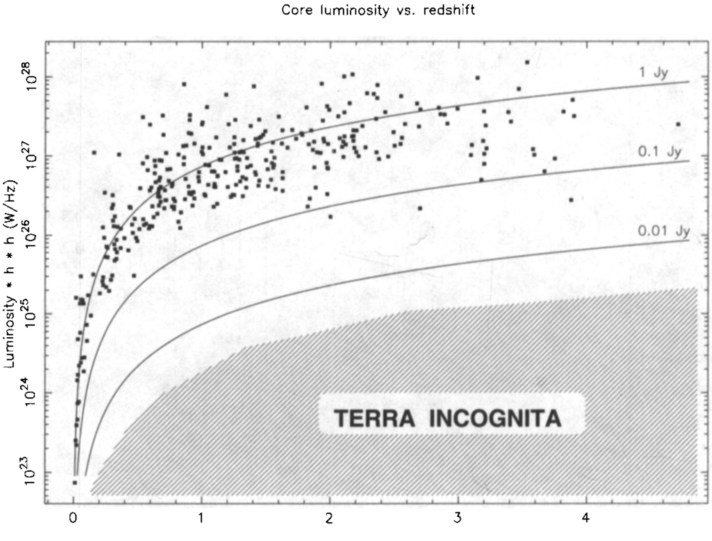

Figure 4. Luminosity (Lh^2) as a function of redshift for a sample of 330 sources (almost exclusively AGN of various types) at 5 GHz, adopted from Gurvits, Kellermann & Frey (1999). The solid lines show luminosities of sources with flux densities of 1, 0.1 and 0.01 Jy, calculated assuming spectral index $\alpha = 0$. The plot indicates a strong luminosity selection effect in VLBI samples presently available. In spite of the ad hoc nature of the sample based on various publications, the sources' luminosity distribution closely follows the lines which correspond to flux densities within the range from 300 mJy to several Jy.

Finally, direct number counts of correlated flux densities of radio loud AGNs detected at various VLBI spacings (i.e. projected baseline lengths) analysed in much the same way as "traditional" source counts offer a cosmological hint which might become significant if conducted on a large enough sample of sources (Gurvits 2001).

4. Future Outlook

The experience of VLBI AGN surveys reviewed above has shown convincingly that their astrophysical and cosmological applications are far from being exhausted. Further progress will require improvement of angular resolution and sensitivity. The former is needed to confirm and exploit in full the trend hinted by the dependences shown in Fig. 2. The significance of the latter is illustrated by Fig. 4. The data points in this plot show the dependence of luminosity on redshift for a typical flux density limited sample (the data taken from Gurvits, Kellermann & Frey 1999). It is clear that a large volume of the "luminosity – redshift" space (dashed in Fig. 4) requires inclusion in all-sky VLBI imaging surveys objects with flux densities in the range of 100 – 1 mJy (and perhaps less in specially selected deep fields), which correspond to luminosities $\leq 10^{25}$ W/Hz. This will increase the size of VLBI imaging samples by 2–3 orders of magnitude. Several ongoing instrumental developments will bring about higher angular resolution and higher sensitivity of VLBI imaging.

Higher resolution will become possible with the next generation Space VLBI missions, such as VSOP-2 (Hirabayashi et al. 2000b) or ARISE (Ulvestad 2000). Compared to the VSOP mission, their higher angular resolution will be achieved owing to a slightly higher orbit (by a factor of ~ 2) and higher observing frequencies (by a factor of $\sim 8 - 16$). Millimeter VLBI is also promising to achieve higher sensitivity thus allowing en masse imaging of AGN with sub-mas angular resolution. The improvement of sensitivity will materialize with the advent of the Square Kilometer Array – a new radio telescope with collecting area of ~ 1 km^2 distributed over baselines up to thousands of kilometers (Taylor 1999). Both these developmets will bring new excitement in surveying compact radio structures in the powerhouses of the Universe.

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