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Problems of observational radio cosmology. Review

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Abstract. This review considers the problems of observational radio cosmology which can be solved by radio astronomy techniques. Main historical facts of development of radio cosmology all over the world associated with the discovery and investigation of the relic radiation and radio galaxies are presented. Examples of estimates of cosmological parameters from the data of radio-astronomical observations are given. The role of RATAN-600 in these fields is outlined.

Key words: cosmology: observations – cosmological parameters: cosmic microvawe background – radio galaxies – quasars

1. Introduction

The term "radio cosmology" was introduced in the early 90s of the previous century (for instance, the name of the project in the Federal Program "Astronomy"), which characterized a set of means and methods of investigation of the Universe. Observational radio cosmology as a field of astrophysics comprises the problems of measuring cosmological parameters by radio-astronomical methods. As a rule, these parameters are not measured directly, as, for instance, the Hubble constant, from observations of galaxies, they are derived by means of relationships obtained from observational data. These are characteristics of the relic radiation, counts of radio sources or the relation between the ages of formation of galaxies and the redshift.

Improvement of the quality of the observational experiment being made and numerical simulation of theoretical parameters makes it possible to speak at present about precision cosmology ("precision cosmology" is the expression of M. Longair, Manchester, 1999). Both approaches demand high quality reduction of observational data, including cleaning from noises, estimation of parameters of the signal and its modeling. The data reduction has been upgraded together with the experiment quality improvement and with new understanding of what should be observed. This is an important part of development of observational radio cosmology.

Modern observational cosmology (Peebles 1993) is based on the radio astronomical methods and constrains cosmological parameters in the most important approach which is realized in the cosmic microwave background (CMB) physics. The term "radio cosmology" can be criticized. However, radio astronomy determines a set of methods to investigate the Universe in this wavelength range, which are not necessarily connected with the CMB. In the 70s of the previous century Longair (1978) underlined three separate ways in which radio observations contributed to cosmology. These constituted the background radiation at meter and microwave ranges, radio evidence on the properties of intergalactic gas, and the space distribution and cosmological evolution of extragalactic radio sources and quasars.

Details of these ways were based on the study of the microwave background radiation, intergalactic gas, the radio source population, types of radio sources, models for extragalactic radio sources, radio-source counts, the V/V_{max} or "luminosity—volume" test, "redshift—magnitude" relation for quasars and radio sources, "the angular diameter—redshift" and "angular diameter—flux density" relations, the cosmological evolution of radio galaxies and quasars, and the relation between the cosmological evolution of quasars at optical and radio wavelengths.

A method for estimating the value of the Hubble constant and deriving the density parameter from observations of superluminous radio sources is described.

We shall consider below the cosmological tests allowing us to determine cosmological parameters by the radio astronomical methods mostly with CMB and radio galaxies and start from the history.

Let us note that some hypotheses and test results were not confirmed later, however, they called for a new study of problems and directions of cosmology and we review them here too.

2. Historical information

The given short review does not aspire to being a complete one, but still we will try to present the main stages of the development of investigations in the field of radio cosmology and modern cosmological tests in the problems connected with the nature of active galactic nuclei (AGN). AGN unification schemes and radio galaxy type dichotomy, jets, accretion disks and origin of black holes are not described here because they need a special review and are presented in details in (Robson 1996; Kembhavi, Narlikar 1999). A detailed description of physics of the magnetic fields, mechanisms of the synchrotron emission and hydrodynamics processes in radio galaxies is also given in the two books of Pacholczyk (1970, 1977).

2.1. Radio galaxies

The beginning of observational radio cosmology can be dated back to the moment of investigations of the first radio sources carried out by the groups headed by Bolton and Pawsey in Australia and Martin Ryle in England at the end of the 40s and the early 50s of the XX century (Shu 1982). At that time, after the introduction of a two-element interferometer (Smith 1952) it was managed to make comparatively accurate measurements of coordinates of radio sources and identify the powerful radio source Cygnus A (Baade & Minkowski 1954) with a peculiar galaxy (Fig. 1).

The measurement of its redshift showed that the source is at a cosmological distance from us. This discovery was a distinguishing one not only for young radio astronomy, but for astrophysics as a whole, because, on the one hand, activity of extragalactic objects was found, and, on the other hand, it was shown that objects observed in the radio range may be much farther away than the visible ones. Apart from the radio galaxy Cygnus A, the coordinates were measure for the radio sources Virgo A and Centaurus A and they were identified with galaxies (Stanley & Slee 1950).

2.2. Interferometers

On the whole, the advance in radio astronomy is associated, first of all, with placing in service interferometers, when it became possible with the aid of several antennae to determine exact coordinates of a radio source, and with upgrading radio interferometric synthesis to define the structure of a radio source (Ryle & Hewish 1960). When the optical identification and the measured redshifts were available, this provided the key to the understanding of the problems of evolution of radio objects. Radio galaxies were found to have an extended structure and refer to the hugest structures in the Universe. At the same time the group of Ryle (Elsmore et al. 1959; Edge et al. 1959) carried out the first radio surveys, which, along with the astrophysical problems of understanding the energy release inside objects, raised purely methodological problems associated with the procedures of object selection and confusion (Ryle 1959), which were also discussed by Soviet radio astronomers (Khaikin & Parijskij 1964).

In the last 20 years, several radio interferometers started to operate and made it possible to solve many astrophysical problems, including detailed study of radio structure of extragalactic objects, their physical properties, radio source statistics and evolution. Among these radio telescopes is the Very Large Array (VLA, USA), one of the world's premier astronomical radio instruments, consisted of 27 radio antennae in a Y–shaped configuration and situated on the Plains of San Agustin 80 km west of Socorro, New Mexico. Each antenna is 25 meters in diameter. The data from the antennae are combined electronically to give the resulting resolution of an antenna 36 km across, and the sensitivity of a dish 130 meters in diameter.

The two largest radio surveys, most important for cosmology, were carried out at VLA. These are NVSS (Condon et al. 1998) with a resolution of $45''$ and sensitivity up to 2.5 mJy and FIRST (White et al. 1997) with a resolution of $5''$ and sensitivity up to 1 mJy.

A very long baseline interferometer (VLBI) operates using antennae all over the world and having a baseline equal to the Earth diameter. Two most famous VLBI interferometers but of smaller size study the milliarcsecond structure of radio galaxies in US and UK. A Very Long Baseline Array (VLBA, US) is a system of 10 radio telescopes controlled remotely from the Array Operations Center in Socorro, New Mexico. The antennae are spread across the United States from St. Croix in the Virgin Islands to Mauna Kea on the island of Hawaii, making it the world's largest dedicated, full-time astronomical instrument.

MERLIN (UK), operated by Jodrell Bank Observatory, is a Multi-Element Radio Linked Interferometer Network, an array of radio telescopes distributed around Great Britain with separations of up to 217 km. It operates at frequencies ranging from 151 MHz to 24 GHz. At 5 GHz, the resolution of MERLIN is better than 50 milliarcseconds, somewhat greater than that of the Hubble Space Telescope.

2.3. Surveys

The first Cambridge surveys: 3C (3CRR) that contains a little fewer than 500 sources (Edge et al. 1959), and 4C comprising the number of objects 10 times as large (Scott & Ryle 1961; Pilkington & Scott 1965; Gower et al. 1967) came to be examples of classical radio astronomical sky surveys. To be historically correct, the first surveys had been made a few years earlier. So, after the publication of the first Cam-

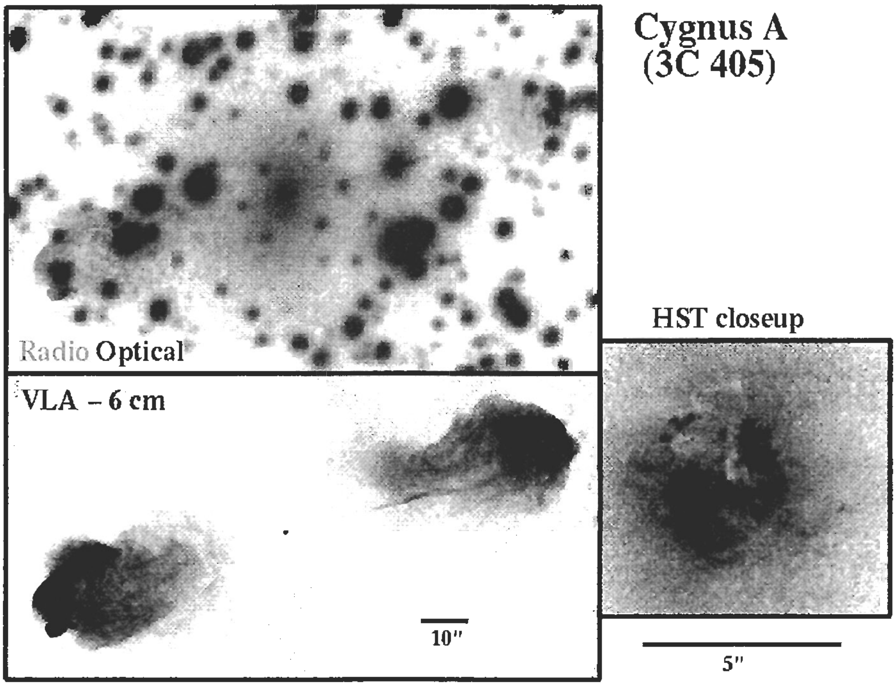

Figure 1: *Classical double radio galaxy Cygnus A. In the radio+optic image (top, left), radio emission is shown by the grey background. The figure is reproduced from Keel (2002).*

bridge Catalog (Mills 1952), which contained only 50 radio sources, the English radio astronomers made an attempt to compile a new more extensive catalog. New observations were performed at a frequency of 81.5 MHz with the aid of the radio telescope designed for this purpose, which consisted of four antennae shaped as a parabolic cylinder. Based on these observations, the Second Cambridge Catalog of radio sources (2C) was compiled (Shakeshaft et al. 1955; Shakeshaft 1957), in which about 2000 northern sky radio sources were registered. However, it was found afterwards that many of the radio sources of this Catalog were false. This was due to the confusion effect mentioned above, when the radio telescope angular resolution was not sufficient for isolation of individual faint radio sources recorded at high sensitivity of the radio telescope (see the monograph by Tovmassian (1986) for a more detailed description of the surveys).

The surveys 3C and 4C made it possible to apply a powerful statistical tool when studying the evolution of extragalactic sources of radio emission (Longair & McDonald 1969). On the one hand, the study of 3C survey radio sources enabled the quasars, the most distant objects for that time, 3C273 (Schmidt 1963) and 3C48 (Greenstein & Matthews 1963) to be discovered, and the first physical hypotheses of origin of their activity to be formed (Shklovskij 1964, 1965). On the other hand, the completeness of the surveys permitted the luminosity function of radio sources to be derived (Longair 1966; Ryle 1968) and some cosmological parameters of the Universe to be determined (Novikov & Zeldovich 1967; Doroshkevich et al. 1970).

Another important survey resulted in the Parkes radio source catalog (Otrupcek & Wright 1990) consisting of radio and optical data for 8263 radio sources. It covered almost all the sky south of declination +27° but excluded the Galactic Plane and the Magellanic Cloud regions. The latter zones are the subject of special surveys. The original Parkes radio catalog was compiled from major radio surveys with the Parkes radio telescope at frequencies of 408 MHz and 2700 MHz. The detailed study of PKS radio source significantly increased the number of optically identified radio objects and allowed one to improve the luminosity function of radio AGNs.

Among other later surveys, one can mention GB6 (Green Bank 6: Gregory et al. 1996) at 4.85 GHz up to 20 mJy, used for spectral analysis, statistics and study of radio source clustering (Rengelink 1999), selection of objects being candidates to gravitationally lensed ones (Myers et al. 2003), PMN (Parkes–MIT–NRAO: Griffith & Wright 1993, Wright et al. 1994, Griffith et al. 1994) at 4.85 GHz up to 20 mJy, which was the only one in the southern hemisphere for a long time used for spectral analysis and widely for the gravitational lens (GL) search (Winn et al. 2001), NVSS (VLA: Condon et al. 1998) covered the northern sky at 1.4 GHz and used in radio astronomy as a Palomar Sky Survey in optics, and FIRST (VLA: White et al. 1997) at 1.4 GHz. These two surveys, being the most sensitive and complete on the large sky areas, are the most important in all the modern researches connected with the radio source identification, preparation of continuous radio spectra, analysis of structure, source statistics and clustering. Another important radio survey is WENSS (Westerbork Northern Sky Survey: Rengelink et al. 1997) at 325 MHz up to 18 mJy carried out in the Netherlands and actively used in search for distant radio galaxies and galaxy clusters (De Breuck et al. 1999). All these surveys are very important in radio spectrum preparation because they have high sensitivity and cover wide bands of radio spectrum. This permits one to analyze the statistics of radio spectra and prepare samples by various spectral index criteria.

2.4. Quasars

Besides the finished optical identification and classification of radio sources in the 3-rd Cambridge Catalog, one of the most important points of the 3C catalog is the discovery of the first quasars 3C 273 and 3C 48, the most powerful sources in the Universe known at that time.

The identification of the 3C 273 and 3C 48 radio sources and the measurement of their redshift (Schmidt 1963; Greenstein & Matthews 1963) showed that these are the most visible objects in the Universe. The idea that the quasi-stellar objects emit energy up to 10^{47} ergs/s turned out to be true, despite the discrepancy of the cosmological interpretation of the quasars for the moment of their discovery.

The activity of a quasar is connected with the supermassive black hole and accretion disk (see reviews by Robson 1996 and Kembhavi, Narlikar 1999). Collimated particles form a jet visible at radio and sometimes at optical wavelengths as for 3C 273 (Fig. 2)[1].

Such a hyperactivity of quasars and radio galaxies allowed one to use them for study of young galaxies and their evolution and intergalactic medium (IGM). The IGM and objects looking like young galaxies or their ancestors were already in place at expansion factor $z + 1 \sim 6$ (Peebles 1993). This tells us that the structure formation processes in operation at smaller expansion factors had to have worked with material that already was strongly distributed by what happened earlier. Studying such a phenomena observed as narrow absorption lines, Lynds (1971) and Arons (1972) suggested that most are caused by Lα scattering in low density clouds along the line of sight between us and quasar. Observations showed (Peebles 1993) that the structure formation was well advanced when the Universe was just one–sixth of its present size, at the highest presently observed quasar redshifts.

Another possibility for using quasars for cosmological tests is a search for instability or cosmological variation of the basic physical constants, e.g. fine–structure constant α. Comparison of absorption lines of both the atomic hydrogen and molecular gas carried out by Varshalovich et al. (1996), Drinkwater et al. (1998) showed that $|\dot{\alpha}/\alpha| < 5 \cdot 10^{-16} yr^{-1}$.

The number of quasars increased significantly (tens of thousands of such type objects are known now) after identification and investigation of PKS, GB6, PMN, NVSS and FIRST sources, especially in connection with the new data of Sloan Digital Sky Survey (Stoughton et al. 2002).

2.5. Counts of sources

The results of the first radio surveys and counts of sources (plotting of the curve $\log N - \log S$ — the relationship between the number of sources and the flux density) caused a great deal of discussion concerning the interpretation of the obtained data, namely, whether the Universe is time-evolving or not (Hoyle & Narlikar 1961; Davidson 1962a,b; Sciama 1963). The properties of the curve and the presence of the cut-off in the distribution of the identified radio sources even at $z = 4$ allowed estimates to be made of the moment of formation of the first galaxies and radio sources in an expanding evolving Universe (Longair 1966). Using the source counts demonstrated conclusively (Longair 1966, Doroshkevich et al. 1970) the dependence of the radio–AGN evolution on radio luminosity: at redshifts > 1 the most powerful radio sources showed space–density enhancements by factors of $> 10^3$ over present–day densities, whereas the less powerful sources showed little or no enhancement.

Study of density distribution of quasars even suggested an idea on possible existence of a non-zero Λ-term (Kardashev 1967). Despite the fact that this work did not take into account selection effects it aroused new interest in the Λ–term ideology (see e.g. Fliche & Souriau 1979) which became later standard and confirmed by different type observations (Type–Ia Supernovae: Garnavich et al. 2002, CMB: Spergel et al. 2003).

2.6. Cosmic Microwave Background radiation

However, it is very likely that the most impressive discovery in the history of radio astronomy was the detection by Penzias and Wilson (1965) of the cosmic microwave background (CMB) radiation with a

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[1] Herman-Josef Roeser provided copies of his HST images of the jet and the ground-based image from the ESO New Technology Telescope (NTT) at La Silla, Chile. The jet image used WFPC2 and a near-IR I band filter, while the NTT image is a red-light exposure. See also Roeser et al. (1997).

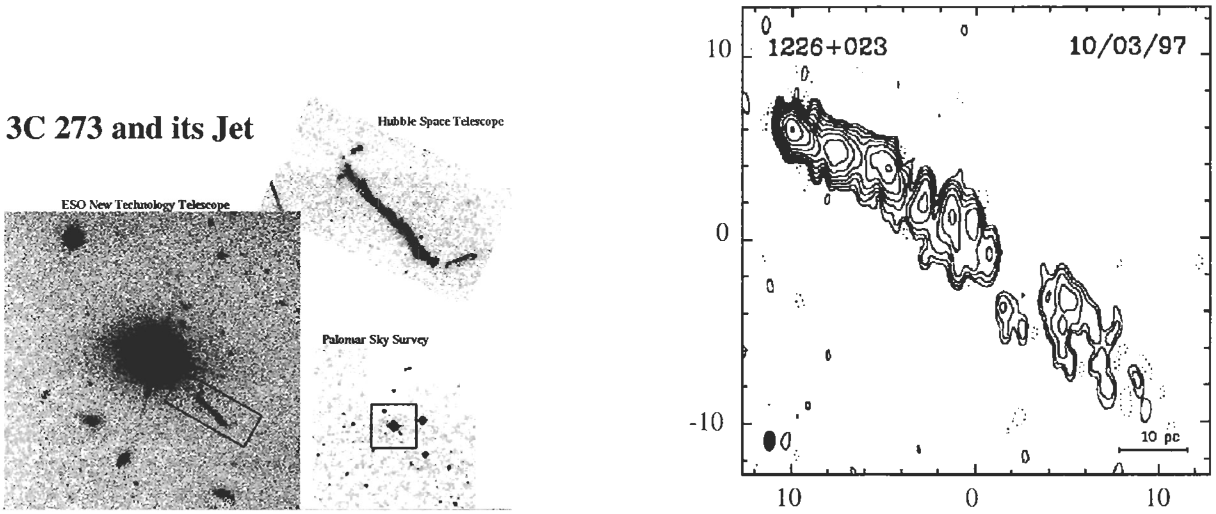

Figure 2: *Optical (left) and VLBA milliarcsec radio (right) images (Keel 2002 and Kellerman et al. 1998, repectively) of the 3C 273 object, being the first quasar identified.*

temperature of 2.7 K which had been predicted by Gamov (1946) in the 40s. The term "relic emission" (RE) widely used in Russian was suggested by I.S. Shklovskij. The history of studying the CMB has already become a classical example of formation of the present-day observational cosmology as a whole (Naselskij et al. 2003). Despite Gamov's prediction, the possibility of observing the CMB radiation was almost not discussed since its separation from the general set of emissions was thought to be impossible at that time. The reality of observing this emission in the short-wave region of the radio spectrum, where the contribution of radio sources is less, was reported by Doroshkevich and Novikov (1964) who had made a prediction on a black-body spectrum of the CMB radiation a year before it was detected, preceding from the assumption of a "hot" early Universe. The detection of this emission was one of the most significant events of the XX century not only in astrophysics but also in natural sciences on the whole. It became clear that the theory of the hot Universe was corroborated, and this opened up a new way in modern cosmology. It is interesting to emphasize that the actual advance of cosmology at the early stage of its development took place when experimental radio astronomy was consistent to advantage with theoretical astrophysics as it happened with the CMB radiation, when B. Berk recommended Penzias and Wilson (see Shu 1982), after they reported on the uniform unremovable high-frequency radio emission, to address theorists Dicke and Peebles who were preparing an experiment on observation of this emission(Dicke et al. 1965). In the former Soviet Union this emission was observed by Shmaonov from the group of S.Eh. Khaikin in Pulkovo as early as the 1950s, but his discovery was not attached great importance to at that time (Shmaonov 1957).

At the present time, the data on the CMB radiation is likely to be the most important in the procedure of obtaining cosmological parameters.

3. Determination of cosmological parameters

Which cosmological parameters can possibly be determined by radio astronomical techniques?

Beginning this section with the relic emission, it will be recalled that the Universe became transparent for radiation after the hydrogen recombination, about 380000 years after the beginning of expansion. It is exactly that time that angular temperature variations of the CMB radiation described in the literature by the power spectrum refer to. Several processes could make a contribution to formation of these fluctuations. So, Sachs and Wolfe (1967) predicted that the fluctuations of primeval curvature must exist on the scales of the horizon (of order 1000 Mpc) giving rise to fluctuations on larger angular scales with an amplitude of about one per cent. The development of cosmological notions, in particular the inflation theory, predicted the presence of adiabatic, Gaussian fluctuations which changed from quantum fluctuations to macroscopic scales at the early de Setter phase (Guth 1981; Starobinsky 1982). A simple supposition based on adiabatic fluctuations provided the possibility for galaxies and clusters to form at the current epoch at $\delta T/T$ of a few ten-thousandth on scales of a few angular minutes (Silk 1967). If the recombination occurred instantaneously, then the value of fluctuations ought to be $\delta T/T \sim \frac{1}{3}\delta\rho/\rho$. The modern predictions yield the level of fluctuations an order of magnitude lower, in particular, because they provide for the non-instantaneous character of the recombination and the presence of "cold" dark matter. The present-day theories predict also the existence of coherent peaks of emission caused by compression and rarefaction of sound waves in the primeval plasma and manifesting themselves in the power spectrum of the RE (Doroshkevich et al. 1978) and also by recombination of the primeval photon-barion plasma (Peebles & Yu 1970). The idea of acoustic peak generation belonged to A.D. Sakharov (1965) and the process of formation of density peaks is called sometimes in the current literature "Sakharov oscillations". Thus, the conditions of formation of the CMB and, therefore the cosmological parameters defining them were "inprinted" in the power spectrum of this emission (see Figs. 3 and 4), and actually defined the current state of the Universe, which made it possible to compare them with the genetic code (Parijskij et al. 2000a).

A great number of experiments were carried out for CMB measurements. The latest ones CBI (Padin et al. 2002), ACBAR (Kuo et al. 2002) and WMAP (Spergel et al. 2003) allowed estimation of the power spectrum up to $l = 2500$.

The power spectrum of the CMB radiation variations $C(\ell)$ (Fig. 4), where l, multipole, is the value inversely proportional to the angular scale, can be described as a functional depending on cosmological parameters (Naselskij et al. 2003),

$$C_\ell \equiv C_\ell(h, \Omega_b h^2, \Omega_{CDM} h^2, \Omega_\Lambda, \Omega_\nu, n, ...),$$

where

$$C_\ell = \frac{1}{2\ell+1}\left[|a_0|^2 + 2\sum_{m=1}^{\ell} |a_{\ell,m}|^2\right]$$

and the complex $a_{\ell,m}$-s are defined as coefficients in expansion of sky temperature fluctuations $\Delta T(\theta, \phi)$ on spherical functions $Y_{\ell,m}$:

$$\Delta T(\theta,\phi) = \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{m=\ell} a_{\ell,m} Y_{\ell,m}(\theta,\phi).$$

Among the parameters of the functional are shown the Hubble constant, $h = H_0/100\,\mathrm{km/s/Mpc}$, the barion matter density Ω_b, the hidden mass density Ω_{CDM}, the "dark energy" density Ω_Λ, the density of massive neutrino Ω_ν, the index of the power spectrum of adiabatic perturbations n and other parameters. The up-to-date derived values of the main parameters (the data of the WMAP experiment (Spergel et al. 2003) in conjunction with the CBI (Padin et al. 2002), ACBAR (Kuo et al. 2002) and 2dF (Percival et al. 2002)) are as follows: the Hubble constant $h = 0.71^{-0.03}_{+0.04}$, the matter density $\Omega_m = 0.27 \pm 0.04$, the barion density $\Omega_b = 0.044 \pm 0.004$, the total energy density $\Omega_0 = 1.02 \pm 0.02$, equation of state of the dark matter $w < -0.78$ (95% confidence level), age of the Universe $t_0 = 13.7 \pm 0.2 Gyr$, the spectral index at $k = 0.05\,\mathrm{Mpc}^{-1}$ $n_s = 0.93 \pm 0.03$ $\Omega_\nu h^2 < 0.0076$ (95% confidence level), which yields a neutrino mass limit of 0.23 eV. The minimization of this functional is practically automated now and can be realized by the software program *CMBFast* (Seljak & Zaldarriaga 1996), calculating smoothed power spectrum of CMB radiation by the given cosmological parameters.

Speaking about the fluctuations of the relic emission, one cannot but mention the Sunyaev–Zeldovich effect (SZ) (1972, 1980) caused by the inverse Compton scattering of the RE photons on the hot gas electrons inside galaxy clusters. The effect manifests itself in lowering of the temperature of the RE ($\sim 0.5\mu$K) in the Rayleigh–Jeans spectrum region towards the cluster. The SZ effect can be used (see review of Lasenby (2001)) to determine the Hubble constant ($H_0 = 60 \pm 10\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, Birkinshaw, 1999) and the barion matter density Ω_m ($\Omega_m \sim 0.23^{+0.06}_{-0.04}$, Grego et al. 2000).

Another set of cosmological tests can be based on investigations of **radio galaxies**. The first identifications of radio galaxies showed that they are identified with giant elliptical galaxies which are the brightest ones in the clusters of galaxies (see, for instance, Minkowski 1965 or the review on elliptical galaxies of Rogstad and Ekers (1969). The so-called diagram "K-value—redshift" (see Fig. 5) is also evidence in support of this. The infrared data (in the K-band) show that up to the redshifts $z \sim 1$, when changing to the system of counts of galaxies and using the comparison with stellar photometry, there exists an approximately constant fraction of red giants in the stellar population. This gives occasion to state that these galaxies, being already rather old at $z \sim 1$, formed more or less at one epoch and evolved in a passive manner. The data of identifications and statistics are consistent with the evolution of standard elliptical galaxies formed at the early epoch, with which radio sources are identified.

This fact and also the presence of the steep spectrum and the morphological class FR II permit selection of such radio sources as objects for cosmological studies and widely used in such investigations (Miley et al. 1992, Parijskij et al. 1994). Selection of the distant objects by the steep spectrum is one of the simpliest but strongest factors in the search for candidates for distant radio sources. This factor was detected independently in several papers devoted to radio source identification and radio spectra statistics. Tielens et al. (1979) detected that the fraction of sources with a very steep (spectral index $\alpha_{178}^{5000} < -1$) spectrum, which could be identified optically, decreased with decreasing α. Blumenthal and Miley (1979), following this work of Tielens et al. (1979) showed that the spectral index has a depen-

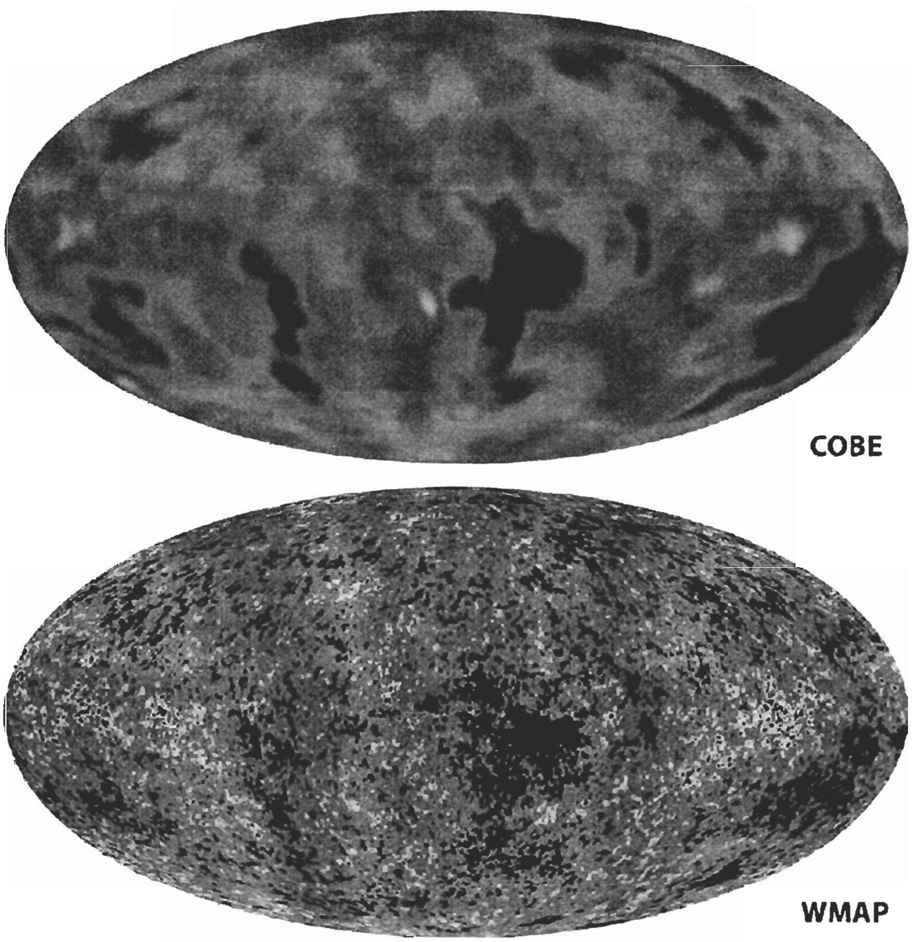

Figure 3: *A map of fluctuations (fair and dark spots) of the microwave emission from the data of COBE (top) and WMAP (bottom) satellites. Scale (angular size) of fluctuations determines corresponding spherical harmonics (multipoles), intensity corresponds to amplitude. The figure is reproduced from the paper by Spergel et al. (2003), http://lambda.gsfc.nasa.gov/product/map/map_bibliography.html).*

dence of the properties of steep spectrum 3C and 4C radio sources on the apparent magnitude, redshifts, radio luminosity, and angular size for specified object samples. The detected correlation suggested that the steep spectrum sources were on average farther away and more luminous, and the origins of the redshifts of radiogalaxies and quasars were the same. Laing and Peacock (1980) investigated the relation between radio spectrum and radio luminosity for samples of extragalactic radio sources selected at 178 and 2700 MHz. Spectra were derived for the extended regions of emission in these sources which were classified by morphological types. At low frequencies the degree of spectral curvature was found to be correlated with luminosity for sources with hot-spots. At high frequencies, the correlation between spectral index and luminosity was confirmed. They also confirmed existence of "the spectral index — redshift" relation which was constructed at 178 and 2700 MHz for FR II radio sources. The FR II radio sources, according to the classification of Fanaroff & Riley (1974), have the separation between the points of peak intensity in the two lobes greater than half the largest size of the source (see classical FR II radio galaxy in Fig 1), and the FR I sources (Fig. 6) have this separation smaller than half the largest size of the source. Slee (1981) studied spectra of approximately 2000 sources in the Culgoora–3 list of radio sources also independently detected a "radio power—spectral index relationship", and a linear dimension/spectral index correlation.

In connection with this problem, a study of steep spectrum sources at the near–infrared wavelengths was carried out by Lebofsky et al. (1983) and Walsh et al. (1985). Using ifrared measurements of 18 empty–field radio sources, they had shown that the steep spectrum empty–field sample includes a large fraction of high redshift galaxies judging by their near–ifrared colours.

The selection by the spectral index $\alpha < -1.0$ ($S \sim \alpha^{\nu}$), namely, the selection of radio galaxies as the most distant by the spectrum steepness (the far-

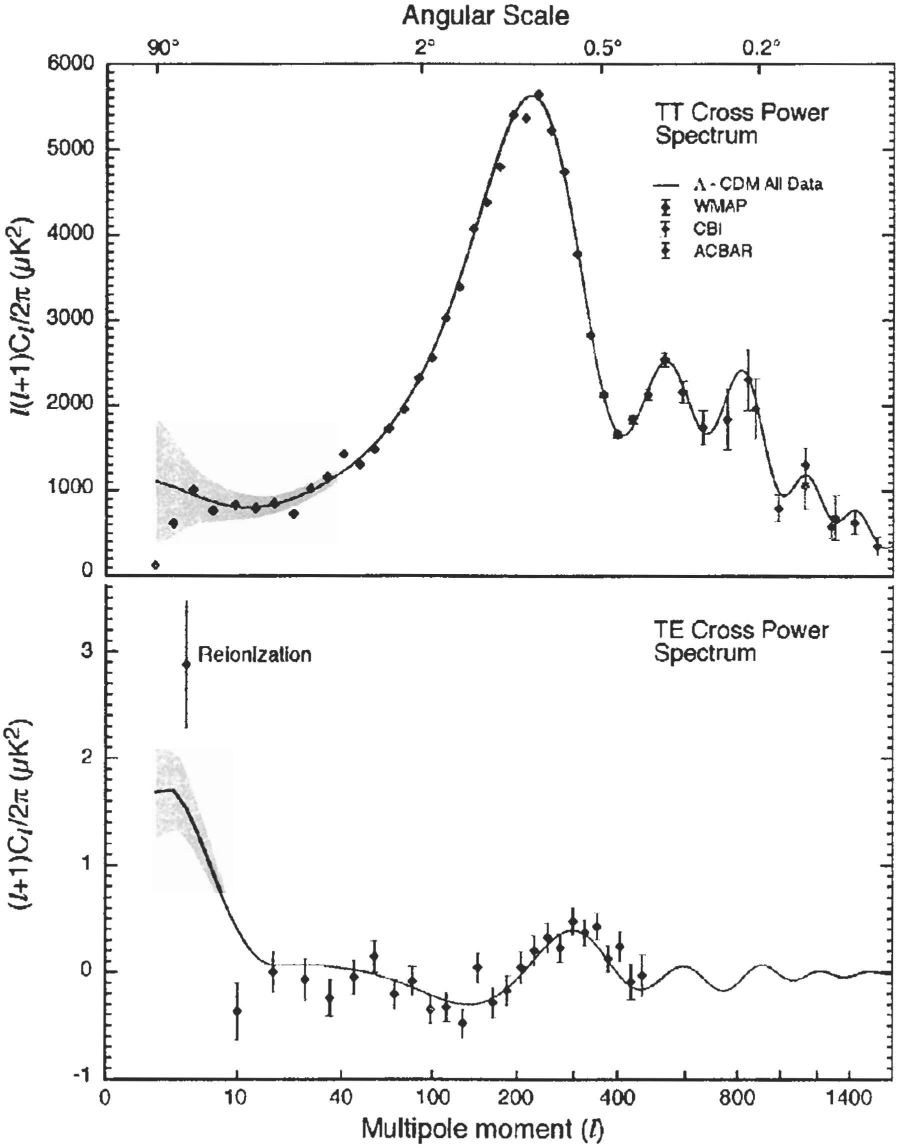

Figure 4: *The power spectrum of the CMB radiation produced from the data of the surveys WMAP, ACBAR, CBI, 2dF (top), and of the polarization emission from the data of WMAP (bottom). The figure is reproduced from Spergel et al. (2003). Peaks corresponds to maxima in the spectrum variations and formed by acoustic generation (Sakharov 1965). Positions, sizes and amplitudes of peaks are produced by the physical conditions of the Universe at the moment they were formed and can give the values of cosmological parameters. http://lambda.gsfc.nasa.gov/product/map/map_bibliography.html).*

ther the object the more likely it has a steep spectrum) is one of the first found and the strongest factors of search. In spite of the fact that this criterion works very successfully, the explanation of it is not conclusively clear even at the present time (De Young 2002). One can isolate 3 main extensively used ideas of explaining this relationship (De Young 2002): (1) a shift takes place in "cutoff" spectrum frequency towards low observed values with a factor $(1 + z)$, so the steep spectra are preferably observed at large redshifts; (2) a rise of losses is due to the Compton scattering of photons of the microwave background by relativistic electrons, since the radiation density grows as $(1+z)^4$; these rising losses lead to the aging of the population of electrons, which causes cutting or increasing the steepness of the high-energy part of the spectrum, where the losses are the greatest; (3) merely the selection effect: only bright sources are visible at large redshifts, and then one can suggest that it is exactly these sources that show the highest "exhaustion" in the high-energy part of the spectrum.

An example of a thus selected radio galaxy is a redshift record-holder radio galaxy having $z = 5.19$ and a spectral index $\alpha = -1.63$ (van Breugel et al.

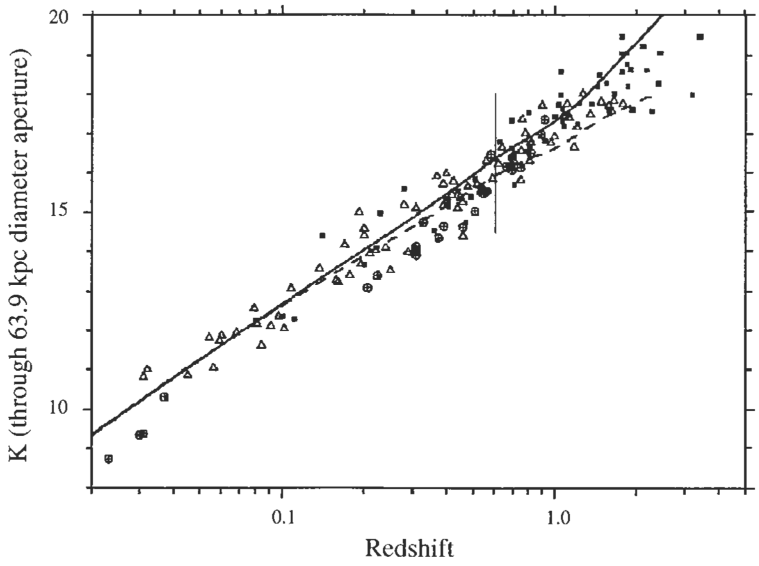

Figure 5: *Hubble diagram for the K-band for the radio sources from the 3CR catalog. The solid and dashed lines show evolution tracks for the non-evolved and passive evolved stellar population, respectively. Here are shown the 3CR radio galaxies by open triangles, 6C radio galaxies by filled squares and brightest cluster galaxies by crossed circles. The figure is taken from Best et al. (1999).*

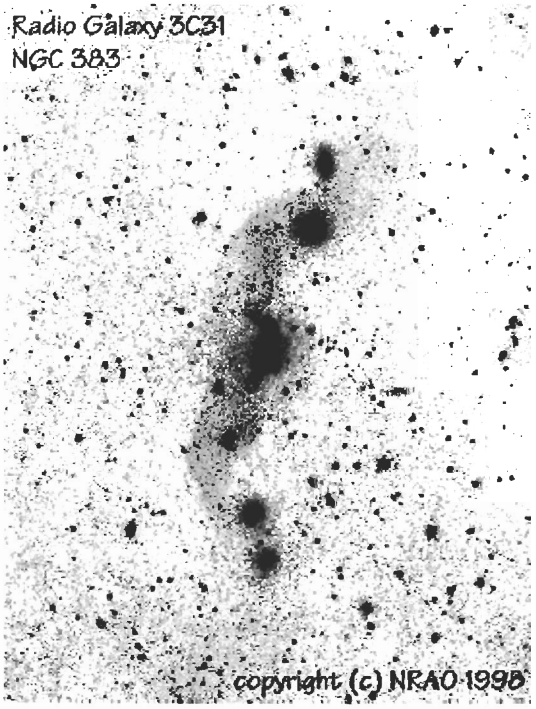

Figure 6: *FR I-type radio galaxy 3C 31. In the radio+optic image, radio emission is shown by the gray background. Two radio emitting jets are visible in the center of the figure near the optical counterpart. Figure is reproduced from Bridle (2000) (see also Leahy 2000).*

1999).

An additional factor of selection of distant radio galaxies is their membership in a population of sources with moderate fluxes (from 5 to 100 mJy on the curve $\log N - \log S$) in the cm–dm wavelength range (Soboleva 1992).

The selection of a radio source by the morphological type uses the observational fact that at large redshifts $z > 0.5$, it is most likely that galaxies of the type FR II (Fanaroff & Riley 1974) are detected, that is, with extended components whose brightness increases towards the edges with the appearance of "hot spots", than those of FR I (the brightness increases towards the object centre) (Lacy et al. 1992). This suggests that the FR I-type objects are older and, therefore, closer. There is, however, a great percentage of FR II-type galaxies which are comparatively close to us.

The remarkable thing about this simple criterion is that it correlates very closely with radio power: there is a break power of about $1025\ \mathrm{W\,Hz^{-1}sr^{-1}}$ below which nearly all double radio AGNs are FR Is, and above which nearly all are FR IIs. Owen and White (1991) found that the break power actually increases with the optical luminosity of the host galaxy; taking this into account, the FR transition is extremely sharp.

In the study of radio galaxies it is significant that parent galaxies for them are giant elliptical galaxies which could be used (Soboleva 1992) at the initial stage of selection as standard candles/rulers in cosmological investigations. Identification with elliptical galaxies is also important in tracing the evolution of stellar systems at large redshifts and in searching for distant groups of galaxies or protoclusters in the centre of which they are located, and in studying the processes of merging and interaction which may be indicated by the activity of their nuclei.

Another possibility of studying cosmological properties is construction of relations connected with the observable **size of radio galaxies**. For instance, by using the standard ratio for the relation "angular size θ — redshift z of a radio source" with the cosmological constant $\Lambda = 0$, Gurvits et al. (1999) estimated the deceleration parameter $q_0 = -R\ddot{R}/\dot{R}$ (the scale factor $R(t)$ is determined as $r(t) = R(t)r(t_0)$, t_0 is the present moment of time and $R(t_0) = 1$) from the data of a sample of 330 objects with a redshift $0.011 \leq z \leq 4.72$:

$$D(z) = \frac{q_0 z + (q_0 - 1)(sqrt(1 + 2q_0 z) - 1}{q_2^2 (1_z)^2},$$

given

$$\theta \equiv l_m D^{-1}(z) \propto lhL^{\beta}(1 + z)^n D^{-1}(z),$$

with four free parameters: the linear scale factor lh, deceleration parameter q_0 and two parameters bearing a relation to physics of compact regions radiating in the radio range β and n (n, in its turn, unites the dependences in the linear size on the cosmological evolution and on the radiating frequency, and also the expansion of the size due to the factors of propagation in the medium). Here are also introduced the metric size l_m, the angular size D, the source luminosity L. q_0, estimated in this cycle of the work, is equal to 0.21 ± 0.30. With allowance made for the Λ-term (Chen & Ratra 2003) for the same points, a limitation on the scalar field of dark energy $V(\phi) \propto \phi^{\alpha}, \alpha > 0$ is obtained, and (in the same paper) "these data are consistent (but not limited) with the data "redshift of supernovae of type Ia — stellar magnitude" (Podariu & Ratra 2000)".

Another more refined method of estimating cosmological parameters from the **dimensions of radio galaxies** uses the jet propagation velocity and, correspondingly, the velocity of growth of the radio source dimensions (Guerra et al. 2000) for 70 objects. The main idea is that the size may be estimated as the medium size $<D>$ of the full population of powerful extended radio galaxies at a given redshift or as the medium size D_* of a given source at a given redshift. If the total time during which the source ejects jets with a power L_j is t_*, the medium size of this source will be $D_* = v_L t_*$ under the assumption that the velocity of growth of the source v_L is approximately constant during its whole lifetime. The velocity v_L is estimated from the synchronous and inverse Compton mechanism of aging increasing with redshift. It is supposed that t_* decreases with increasing redshift, while the ratio $<D>/D_*$ depends on the cosmologic parameters Ω_m and Ω_Λ (see for details therein and in Daly, Guerra (2002)). With a 90% authenticity they show that $\Omega_m < 0.5$ and quintessence $-2.6 < w < -0.25$.

One of the most wonderful discoveries associated with the investigation of radio galaxies was the detection of gravitation lenses. Perhaps the most remarkable was the discovery of the first Einstein ring (Fig. 7) when studying the radio galaxies of the MIT survey (Hewitt et al. 1988) at the radio telescope VLA.

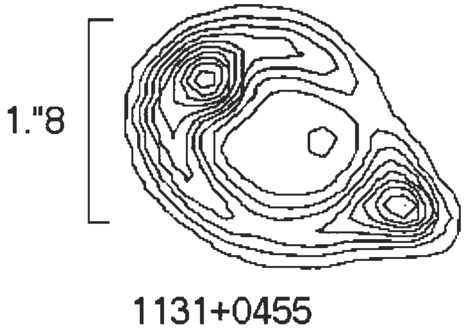

Figure 7: *The radio source MG 1131+0456 — gravitation lense of "Einstein ring" type. The figure is plotted from the data of the MIT–VLA survey (Hewitt et al. 1988) given kindly at our disposal by A. Fletcher and B. Berk. The figure is taken from Parijskij et al. (1996).*

The radio morphology of such a source shows a symmetric case of gravitation lensing in which the lensed source is extended into the ring. Obvious easiness in performing morphological selection is a comparatively high statistical probability of detection (if one considers, for instance, radio galaxies as the centres of clusters), which made it possible to work out the procedure of searching for these objects (the MIT survey (Hewitt et al. 1987, 1988) or the completed survey CLASS — "Cosmic Lens All Sky Survey" (Chae et al. 2002)). Search surveys of gravitation lenses are interesting, first of all, by cosmological application (for instance, Kochanek 1996). In this case, where a great array of statistical data is available, the estimation of cosmological parameters can be performed (Cooray 1999) by calculation of the probability $p(z, \Omega_m, \Omega_\Lambda)$ that a source of a redshift z is strongly lensed, and one can compute the number of lensed objects

$$N = \sum_i p(z_i, \Omega_m, \Omega_\Lambda) B(L_i, z_i) g(\Delta\theta, \Delta f) \equiv \sum_i \tau(z_i),$$

where $B(L_i, z_i)$ is the so called "magnification bias" (Kochanek 1996) for a radio source at a redshift z with a luminosity L, $g(\Delta\theta, \Delta f)$ is a function of selection connected with a possibility of division of images $\Delta\theta$ and the flux ratio Δf of the components of strongly lensed sources, i is the index of the source in the sample. Plotting and minimizing the function of plausibility on the basis of the statistics of lensed radio sources, one can manage to estimate the difference of the parameters $\Omega_m - \Omega_\Lambda$, or, under the assumption of the scalar field, to estimate $\Omega_x - w$, where in the equation of state $w = P_x/\rho_x$, P_x and ρ_x are the pressure and the density of the scalar field, repectively. The estimates made in the CLASS survey showed (Chae et al. 2002) that for a flat Universe with a classical cosmological constant the proportion of matter in relations to the critical density $\Omega_m = 0.31^{+0.27}_{-0.14}$ $(68\%^{+0.12}_{-0.10})$, while for a flat Universe with the equation of state for dark matter $w < -0.55^{+0.18}_{-0.11}$ (68%).

One more important parameter that can be determined in observations is the galaxy age which, in turn, is associated with the age of the Universe t_0, simply it cannot be greater than the latter. Defining the age of the Universe as $t_0 = \int dt/H(t)$ and $H(z) = H(z)/H_0$ and bearing in mind that

$$H_0 \int\limits_0^{t_0} dt = \int\limits_0^{\infty} \frac{dz}{(1+z)h(z)}$$

obtain (DeYoung 2002) that the age of the Universe is determined as

$$t_0 = H_0^{-1} \int\limits_0^{\infty} \frac{dz}{(1+z)h(z)},$$

where (therein)

$$h(z) = [\Omega_R(1+z)^4 + \Omega_m(1+z)^3 - (\Omega_0 - 1)(1+z)^2 + \Omega_\Lambda]^{1/2}$$

and Ω_R is the emission density, Ω_m is the energy density of "dark" and barion matter, Ω_Λ is the dark energy density, Ω_0 is the total energy density. The quantity τ can be found as a function of redshift, which is the difference between the age of the Universe t_0 and its age t_e for the moment of emission of the light that we see now:

$$\tau = t_0 - t_e = H_0^{-1} \int\limits_0^{\infty} \frac{dz}{(1+z)h(z)} - H_0^{-1} \int\limits_z^{\infty} \frac{dz'}{(1+z')h(z')}.$$

The galaxy age permits the age of the Universe to be derived, since some time is needed for the formation of the galaxy itself after the Universe came into existence:

$$\mathrm{age}_{gal} = t(z_{obs}) - t(z_c) + \alpha t(z_c),$$

where the parameter α characterizes the typical age of stars in fractions of the age of the Universe, i.e. the so-called epoch of collapse (Peacock et al. 1998; Peacock 1999). For elliptical galaxies at the present epoch, even only the relationship "color–magnitude" permits the mass to be approximately doubled through the merging of galaxies since the moment of star formation termination, which the coefficient $\alpha \simeq 0.3$ corresponds to.

The age of galaxies also characterizes the evolution of matter in the Universe as a whole, activity of galaxy nuclei, and supermassive black holes associated with them. So, the detection of the radio galaxy TN J0924-2201 with the redshift $z = 5.19$ (van Breugel et al. 1999) showed that the presence of a massive black hole, that ensures the activity of the galaxy, at an age of the Universe of about 1 billion years can be explained only by the presence of a primeval black hole. Another iteresting problem is the existence of a very old stellar population at high redshifts (Dunlop et al. 1996) which can be solved in cosmology with the Λ–term.

4. Counts of radio sources

The counts of sources described by the so-called curve "log N – log S", " logarithm of the number of sources — logarithm of the flux density", in the sky radio surveys became another method of evaluating parameters and evolution of matter in the Universe, which has come to be classical. Longair (1966) detected a cutoff in the distribution of the identified radio sources at $z = 4$, which provided a foundation for the development of evolution models of the Universe. In the same paper, the isotropic distribution of the radio sources of the catalog 4C up to the same redshift was noted.

To describe the counts of sources nowadays, a differential curve log N – log S in the form $n(S)dS$ is used, where $n(S)dS$ is the number of the radio sources within the flux densities from S to $S + dS$ at a given wavelength. It is usually normalized by the factor $S^{5/2}$ associated with the number of sources in the Euclidean model (Condon 1984):

$$S^{5/2} n(S) = \frac{1}{4\pi} \int\limits_0^{\infty} S^{5/2} \eta(S, z) dz,$$

where (therein) $\eta(S, z)dSdz$ is the total number of the sources with flux densities from S to $S + dS$ within the redshifts from z to $z + dz$:

$$\eta(S, z) = \frac{cA^2(1+z)^\alpha \rho(L, z)}{H_0(1+\Omega z)^1/2},$$

where $\rho(L, z)$ is the luminosity function of the radio sources, $A = 4\pi D^2$ is the area of the sphere with a source in the centre, and the observer being inside this sphere, $\Omega = 2q_0$ is the density parameter. An example of the normalized differential curve of the counts of sources with flux densities S within $30\mu\mathrm{Jy} \leq S < 56$ Jy at a frequency of 1.4 GHz is displayed in Fig. 8.

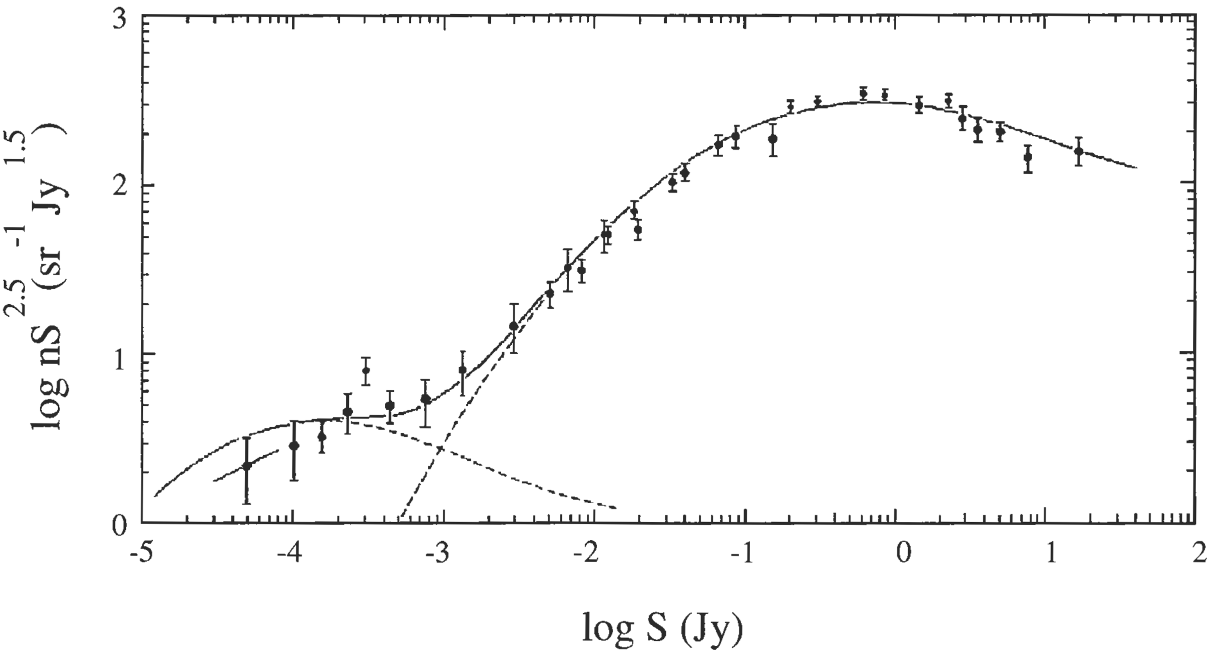

Figure 8: *The normalized curve of counts of radio sources at a frequency of 1.4 GHz. The solid curve shows the best model dependence on the four parameters with* $\Omega = 1$ *from Condon (1984). The dashed curve shows the contribution of the radio sources evolved in the components of the luminosity function of the spiral and elliptical galaxies. The abscissa gives the flux density in Jy, the ordinate shows the logarithm of the differential counts of sources multiplied by* $S^{2.5}$, *(*$sr^{-1} Jy^{1.5}$*). The figure is taken from Condon (1984).*

The curve log N – log S demonstrates the evolution features of radio sources (e.g. dual-population unification scheme (Jackson & Wall 1999)) and also allows making use of the additional selection factor associated with the choice of a population of radio sources for cosmological studies (Kapahi & Kulkarni 1990, Soboleva 1992). It can be seen from Fig. 8 that the optimum regions of search for distant radio galaxies lie in the zone of moderate flux densities, from 5 to 100 mJy, which elliptical galaxies correspond to. Fainter radio galaxies are related to nearby spiral galaxies. It should also be noted that the source size, as an additional selection factor, can also be used in selecting elliptical galaxies. As it was shown in the paper by Fielden et al. (1983), the median angular dimension of the sources identified with elliptical galaxies approaches asymptotically to $5'' - 10''$ at flux densities of about 10 mJy, while all known radio sources in spiral galaxies are limited by the size of their disks. The median redshift of the radio sources of this cosmological part of the curve log N – log S, which contains the greatest number of detected radio sources in the modern sky radio surveys is approximately equal to 1 (Condon 1989). Using the galaxy luminosity functions determined, in particular, by counts of radio sources, it is also possible to construct the mass density function of black holes related to radio sources (Sadler et al. 2002).

The cosmological applications of statistical studies of radio sources find reflections in searching for angular clustering of sources in sensitive radio surveys and studying of the Hubble diagram in the K range. In the first case, in the distribution of radio galaxies situated at cosmological distances, it is possible to detect the dipole of anisotropy caused by increasing surface density of distant objects in the direction of movement of our system (Blake & Wall 2002b,c) correlated with the dipole in the distribution of the relic emission. It is also possible to construct (Blake & Wall 2002b,c) the angular correlation function from the data of the most sensitive sky surveys at 21 cm, NVSS (Condon et al. 1998) and FIRST (White et al. 1997) which has the shape $w(\theta) \propto \theta^{-0.8}$. The amplitude of clustering corresponds to the spatial clustering length $l_0 \sim 6h^{-1}$ Mpc.

Another method of statistical investigations is related to the analysis of the relation $K - z$. Willot et al. (2003) approximated the data of magnitude measurements of galaxies from the catalog 7C in the K filter by a second order polynomial and derived the relationship

$$K = 17.37 + 4.53 \log_{10} z - 0.31 (\log_{10} z)^2,$$

which supports the model of a passively evolving galaxy with instantaneous star formation at $z_f \approx 10$ and having a luminosity of about $3L_*$ at the present epoch.

5. Soviet/Russian observational radio cosmology

As has already been mentioned, the Soviet investigations in the field of observational radio cosmology, besides observations, were associated with theoretical calculations, on the one hand, and with development of engineering facilities ensuring the observations, on the other hand.

I.S. Shklovskij and V.L. Ginzburg showed independently the possibility of existence of high-relativistic electrons in the powerful non-thermal radio sources and generation of the synchrotron radiation. In spite of the fact that this was obtained for solar physics, Shklovskij proposed to apply this mechanism for the Crab nebula. In fact, this was the first mention that generation of the synchrotron radiation is possible at great distances (several or even several thousand light years) from us (Robinson et al. 1965), which was subsequently employed in extragalactic radio astronomy.

After identification of the first radio galaxies in the early 1950s, V.A. Ambartsumian made an assumption of galactic nuclei activity and ejection from their centers of massive objects. This was announced at the physical conference in Brussel in 1958 (see also Ambartsumian 1961, 1968). At the same time there appeared the first models of extragalactic radio sources (Shklovskij 1960, 1962, 1963; Ginzburg 1961; Kardashev et al. 1962, Kardashev 1963) with the help of which mechanisms of generation of radio emission were studied, and in the paper by Kardashev et al. (1962) the first evaluation of the age of a radio source (of order 0.5 mln years) was performed on the basis of explanation of a high-frequency cutoff of the spectrum by synchrotron energy losses of relativistic electrons. In the same period, a study of radio emission from clusters of galaxies was started (Tovmassian & Shakhbazian 1961; Tovmassian & Moiseev 1967). It was established that most of the high-latitude radio sources were identified with galaxies being members of clusters. Attention was also paid to the fact that galaxies associated with radio sources turned out to be peculiar in both their morphology and optical emission spectrum. At the same time, it was a failure to establish correlation between the parameters of radio emission of clusters and richness or morphological class of clusters.

The first papers on interpretation of observational data in 1955 on the basis of investigations of Ryle (Vitkevich 1959) showed the presence of cosmological evolution of radio sources. These conclusions were at variance with the stationary model of the World and demanded more accurate and deeper counts of radio sources, which became the main argument in the proposals put forward by V.V. Vitkevich and B.M. Chikhachev to build a big cross-like radio telescope in Pushchino, which were formulated in 1956 (Dagkesamanskij 1996; see also Gindilis et al. 1988). This group also dealt with studying of radio sources, plotting of their continuous radio spectra and estimations of distances (see Dagkesamanskij & Korchak 1963; Artyukh et al. 1967, 1968; Dagkesamanskij 1969). So, a relationship between the spectral index α and the flux density S was detected for extragalactic radio sources (Dagkesamanskij 1969, 1998) and a conclusion was drawn that distant quasars ($z > 1.0$) of the 3C catalog have deeper spectra, while among less distant ones one can also find objects with a less steep spectrum. Later the relationship dependence was obtained for other samples in radio wavelength range for median values of α and S (Steppe & Gopal-Krishna 1984, Kapahi & Kulkarni 1986).

In the field of radio source physics it was shown that one could estimate the limiting angular sizes θ_a for synchrotron radio emission sources from the synchrotron reabsorption (Slysh 1963):

$$\theta_a = const \cdot \nu_m^{-5/4} F(\nu_m)^{1/2} H^{1/4},$$

where ν_m is the frequency of maximum flux denisty $F(\nu_m)$ in the spectrum, H is the magnetic field.

The radio emission from normal galaxies and quasars ivestigated at the cm–dm wavelength and thier radio spectra were classified and interpreted by Kurilchik (1965, 1966, 1970a,b).

Under the leadership of S.Eh. Khaikin the **Big Pulkovo Radiotelescope** (BPR) was put into operation in 1956 with a variable profile antenna designed in cooperation with N.L. Kaidanovskij. The telescope insured high angular resolution in the cm wavelength range.

Owing to the high resolution and cm wavelength range, BPR made it possible to solve many problems of extragalactic radioastronomy, that is to study the structure of radio sources from direct observations (Zakharenkov et al. 1963; Parijskij & Timofeeva 1964; Parijskij & Prozorov 1964; Golnev & Parijskij 1965). Using the obtained accurate coordinates, optical identification of radio sources was started (Iskudarian & Parijskij 1967). From the observational data of double radio sources and continuous spectra, upper limits of velocities of separation of components were evaluated (Parijskij & Soboleva 1980; Soboleva & Parijskij 1982). One of the main directions of cosmological investigations in radio astronomy was the exploration of the relic emission (Parijskij 1968), the discovery of which by Penzias and Willson in 1965 caused a squall of papers both abroad and in the Soviet Union. It should be noted that actually immediately after the creation of BPR, T. Shmaonov, a member of Khaikin's group, discovered (though with a horn antenna) homogeneous background emission, measured its temperature, but did not pay much attention to it because of some contingency.

Note that the radio astronomers from Gorkij (now Nizhnij Novgorod) also began to study the microwave background. They carried out measurements of temperature of relic emission from millimeter to decimeter wavelength range (Puzanov et al. 1967; Pelyushenko, Stankevich 1969; Stankevich 1974).

Returning to the theoretical papers, note that the manifestation of the CMB radiation was discovered as early as the 1940s from observations of rotational levels of cyanogen molecules (McKellar 1941), but a correct interpretation was given in the paper by I.S. Shklovskij in 1966 (see Novikov 1990) (as well as by Field and Hitchcock 1966, and Thaddeus & Clauser 1966) in which he explained the anomalous population of energy levels of cyanogen molecule in the interstellar medium by the action of the CMB radiation in the millimeter range and proposed a method for temperature determination of the relic radiation from the intensity of optical molecular lines of the interstellar gas.

The techniques of focusing, observations, data reduction have been tested and developed on the telescope BPR and the experience acquired was used in designing and mounting of the world's biggest reflector radio telescope RATAN-600. From the observational data obtained with BPR at the 4 cm wavelength in 1968 (Parijskij 1968) with a sensitivity of a few mK, it was proved that 3 K background could not be explained by the unresolved GHz-peaked radio sources (this study was initiated by the detection of the first GPS objects in Australia). Using BPR with new generation radiometers, it was managed (Parijskij 1972, 1973a,b,c) to set a new limit on isotropy of the relic radiation at a level of 0.8×10^{-4} on scales of $3' - 1^\circ$ at a wavelength of 2.8 cm, to plot the relationship $\log N - \log S$ in the centimeter wavelength range, to detect hot gas in the cluster of galaxies. After the paper by Rees (1968) had appeared, an attempt was made in the same year to detect the predicted effect of polarization of the relic radiation with repeated scattering both in the period of recombination and in the zone of "secondary heating" (Parijskij, Pyatunina 1968; Pyatunina 1971).

The first flux density measurements of many famous radio sources were made also in the centimeter wavelength range (Golnev, Parijskij 1965), their continuous spectra were constructed, and steepening of their spectra with frequency growth was found, which is one of the explanations of the selection effectiveness of distant radio sources from the spectral indices. In identification of radio galaxies a non-linear relationship between radio luminosity and optical luminosity of radio galaxies $L_{rad} = k * L_{opt}^{2.5}$ was detected (Iskudarian, Parijskij 1967), where k is a certain coefficient. This relationship was rediscovered 30 years later (Franceschini et al. 1998). It is the non-linearity that enables photometric redshifts to be estimated simply from the flux density ratio in the radio and optical range. This effect was subsequently employed for evaluation of limiting stellar magnitudes $m - m_{lim}$ in the optical range in the program "Big Trio" (Kopylov et al. 1995a,b).

With the placing in service of RATAN-600 (Korolkov & Pariiskij 1979) in 1977 (the first observations had been conducted as early as 1974), a new epoch of extensive observational radio cosmology actually began in the Soviet Union. To realize the capabilities of the telescope RATAN-600, the experiment "Cold" was suggested (Parijskij & Korolkov 1986, hereafter PK86). In fact, the inspection of the data of this survey led to the formation of radio cosmology in Russia as a separate direction of radio astronomy.

By that time a lot of theoretical problems of cosmology and evolution of the Universe at large redshifts, associated with the manifestation in the radio range had been solved, fluctuations of the CMB radiation and their spectrum had been predicted (Zeldovich & Novikov 1967, 1975; Doroshkevich et al. 1978; Zabotin & Naselskij 1982; Naselskij 1983), and a model of rapidly expanding Universe at the initial stage (known now as inflation theory) had also been suggested and upgraded (Starobinsky 1978, 1980, 1982, 1983a,b; Linde 1983, 1984).

6. Experiment "Cold"

Let us return to the survey "Cold". The principal goal of this survey (PK86) was a considerable advance in the search for protogalaxies predicted in the theory of formation of galaxies from primeval inhomogeneities (Silk 1967). The limit of the inhomogeneity of the relic radiation was at a level of 3.6 mK (Conklin, Bracewell 1967). Before the experiment "Cold" was started, in 1980, the level had been lowered to 1 mK from the BPR and RATAN-600 data, when the new generation of radiometers (Parijskij, Pyatunina 1968, 1970; Parijskij 1972, 1981; Parijskij et al. 1977; Parijskij, Syunyaev 1978; Berlin et al. 1982a, 1983).

With the development of the theory it became clear that the nature of small-scale anisotropy of the three-degree background is associated not only with the structure of the Universe at $z = 1000$, but also with the fundamental problems on singularity, the theory of Great Unification of interactions, the theory of formation of radiation and matter, the processes that took place after hydrogen recombination, gravitation waves, neutrino mass etc. (PK86, see also the first section). Thus, the search for anisotropy on small scales would help throw light on many questions of astrophysics, cosmology and physics of elementary particles.

Within the available facilities (antenna shape, radiometer sensitivity, noises, geographical location of the radio telescope) an optimum strategy of carrying out the survey was selected. From the preliminary estimates it was expected that the search for the low-scale anisotropy (comparable with the beam pattern of the telescope) could be limited only by thermal variations in individual scans and that the sensitivity, resulting from the averaging of 10-30 scans, will be limited only by the level of "confusion" (PK86). The search for extended structures was limited by the level of the atmospheric noise. A new low-noise cooled radiometer (cryoradiometer) (Berlin et al. 1982b) was employed in the survey at the wavelength 7.6 cm. Special screening was used on the antenna for limiting the temperature noise. As a result of updating and upgrading performed, the noise temperature of the system was reduced to a level of $T_{sys} = 37.3\,\mathrm{K}$, and the laboratory measured radiometer sensitivity at an integration time of $\tau = 1\,s$ was $dT = 2.5\,mK$. The North sector of RATAN-600 was used for the observations. The computed shape of the beam pattern of the telescope in this configuration was taken from the paper by Korzhavin (1977). The North sector was set in the stationary mode for the constant elevation corresponding to the passage of the source SS 433 — the most interesting object of this epoch. The Earth rotation ensured formation of a 24 hour scan with a resolution of $1'$ at the central wavelength 7.6 cm. Besides, the radiometers at 1.35, 2.08, 3.9, 8.2 and 31 cm were employed, but they were less sensitive. They helped perform the tasks of cleaning (PK86) of noises at the central frequency (with the aid of a duplicating radiometer at 8.2 cm), atmospheric noises (2.08 and 3.9 cm), low-frequency local noises (for instance, caused by cars) and galactic radiation (31 cm). The total accumulation time was 4 months.

In the field of extragalactic and cosmological investigations the survey data were supposed (PK86) to be used for

- plotting the curve $\log N - \log S$ in the region of 1–14 mJy;
- study of the detected sources, including optical identification;
- definition of spectra, structure and search for variability;
- check of isotropy of the distribution of sources over the sky;
- search for fluctuations of the relic emission;
- search for the Sunyaev–Zeldovich effect;
- search for peculiar galaxies (using the Byurakan Observatory lists).

The preliminary data reduction included (PK86) re-pixelization with a decrease in the resolution to $30''$, removal of low-frequency and pulse interference, smoothing by the function $\sin(x)/x$ to suppress frequencies higher than the limiting, averaging signal records over several days. After the averaging of records, for searching out systematic and random radiation, the sums and differences of the same groups of averaged records were used, and for separation of spatial frequencies the Fourier analysis was applied.

Among the first basic results of the survey "Cold" were, in particular, the data presented in (PK86):

- a new upper limit of anisotropy of CMB radiation $dT_b/T = 10^{-5}$ on scales of searching for protoclusters $5' - 10'$;
- a catalog of sources (about 1.5 thousand up to 5 mJy) at several wavelengths of the centimeter–decimeter range, and also detection of new bright radio sources with a flux density $S > 0.2$ Jy;
- plot of a curve "number of sources – flux density" ($\log N - \log S$) to a level of 0.86–10 mJy in the centimeter wavelength range.

Even the first anisotropy measurements on scales of $1'$ at the mK level set a new upper level on the CMB anisotropy and required the theory of formation of fluctuations on scales of protoclusters predicted by Silk (1967) to be corrected.

The accuracy 0.3 mK reached in the experiment "Cold" at the 3.9 cm wavelength on a scale of about $22'$ (PK86) placed rigorous constraints on the Hubble expansion variations both for the moment of recombination and in the period of the secondary heating. The small-scale polarization was shown to be absent, which limited the energy density of low frequency gravitation waves (Dautcourt 1969; Doroshkevich et al. 1967) and showed a minor role of the secondary scatter (i.e. the period of the secondary ionization in the Universe). From the observations of the Syunyaev–Zeldovich effect, the variant of formation of the background near our Galaxy by decaying particles has been checked. The background is shown (Parijskij 1972) to originate behind the clusters of galaxies in Coma.

The experiment rejected a number of models of the World (scalar, vector, tensor) predicting a high noise level on scales of protoclusters. Among the rejected hypotheses was also the hypothesis of "neutrino proto-pancakes". Later on, the data of the experiment re-processed by a different procedure (by the use of three-point dispersion) showed (Parijskij et al. 1992) that after the removal of the non-thermal radiation of the Galaxy (with the spectral index 2.55) and of the noise associated with the atmospheric water vapor, a correlated signal remains. This gives an agreement with the inflation model on scales above 0.5° (therein). Besides, the RE fluctuations on the sub-degree scales were shown to be black-body by means of comparison of the 7.6 cm data of the 80s with the new data of the millimeter range. Using the integrated data and the results of the latest RATAN-600 observations, a transparency window of the Galaxy and Metagalaxy is shown (Parijskij et al. 2002) to exist on the "scale–frequency" plane, where

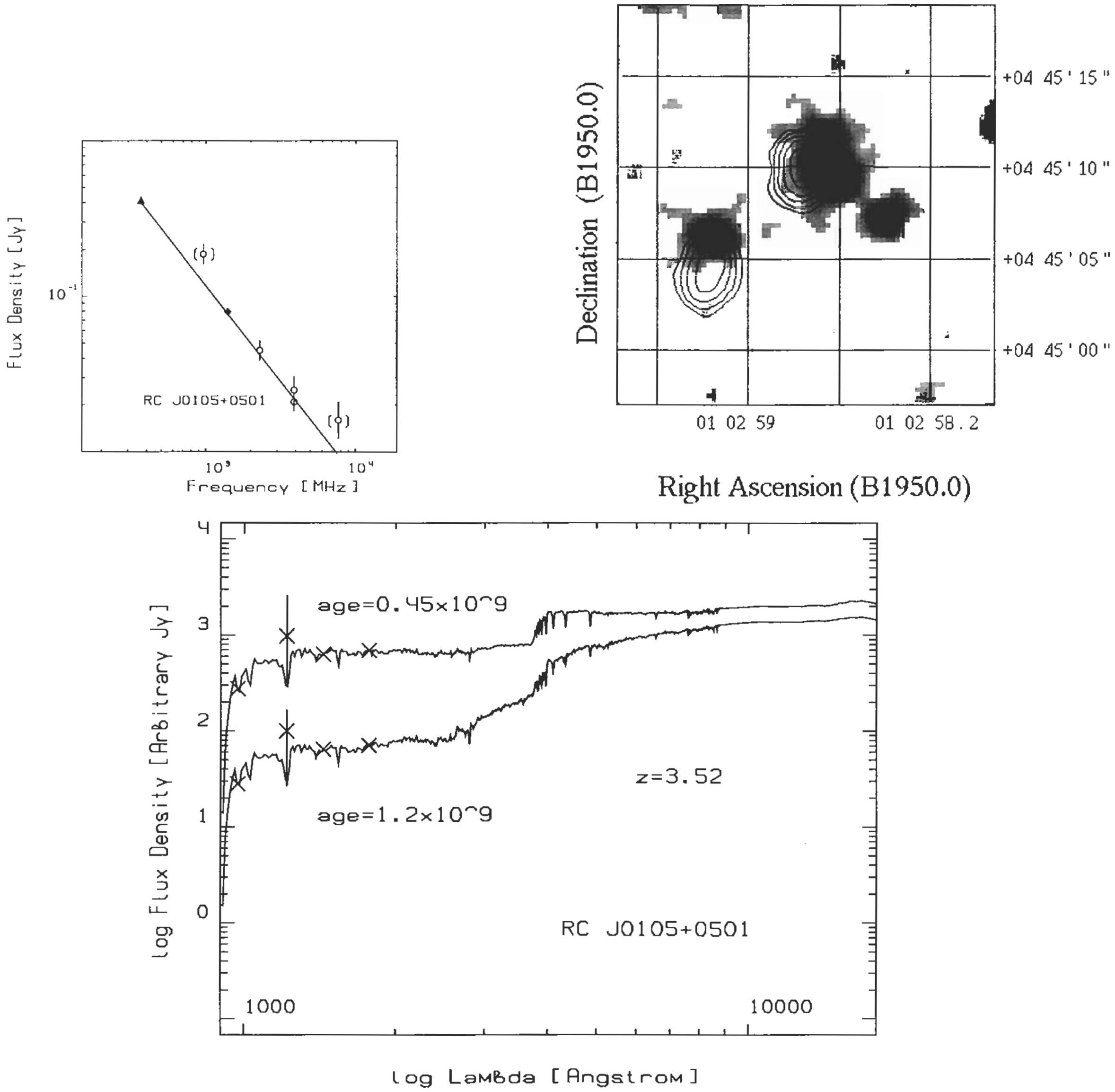

Figure 9: *Example of investigation of the radio galaxy RC J0105+0501 according to the "Big Trio" program. The upper left panel shows the continuous radio spectrum of the object. The spectral index* $\alpha = -1.22$ *(*$S \sim \nu^{\alpha}$*) from the data of RATAN-600 and other radio telescopes. The upper right panel displays optical identification of the radio galaxy RC J0105+0501. Isophotes of the image taken with VLA at a frequency of 1.4 GHz are superposed on the R-band image obtained at the 6 m telescope of SAO. The bottom panel: the estimate of the photometric redshift and age of the stellar system from photometry data of the 6 m telescope and data of synthetic evolution spectra of elliptical galaxies.*

the depth of investigations depends only on the sensitivity of the detectors, and measurements are possible with a submicrodegree precision of the processes at the "dark age" epoch.

The examination of the objects from the subsample of steep spectrum radio sources identified with elliptical galaxies opened a new project, "Big Trio", which includes several stages (Soboleva 1992; Goss et al. 1992; Kopylov et al. 1995a,b; Parijskij et al. 1994, 1996), namely,

- selection of radio sources by the spectral index (i.e. selection of objects with the spectral index $\alpha < -0.9$, $S \propto \nu^{\alpha}$) using the data of the catalog "Cold", additional RATAN-600 observations and the Texas survey data (Douglas et al., 1980, 1996);
- revealing the structure of radio sources from

the results of VLA observations and selection of FR II type sources;

- optical identification by the Palomar Atlas and selection of objects for BTA investigations;
- optical identification and multicolor (BVRI) photometry at BTA;
- spectroscopy of identified sources;
- study of the stellar population age.

Fig. 9 demonstrates investigation of one of the objects of the project — the radio galaxy RC J0105+0501 with a photometric redshift of $z \approx 3.5$ (Soboleva et al. 2000).

Using the "Big Trio" project data, an independent confirmation was derived of the existence of the border in redshifts for the population of powerful radio galaxies. The first independent estimate of the Λ-term was made from the evaluation of the age of host galaxies (Parijskij, 2001), and the first attempts were undertaken to reconstruct the equation of state of the Universe by a model-independent procedure from the distribution "age–redshift". Recent results of cosmological parameters estimated with the integral function fitting (Verkhodanov et al. 2002b, 2003) are demonstrated in Fig. 10. The smoothed curve is the function of age $t(z)$ calculated as

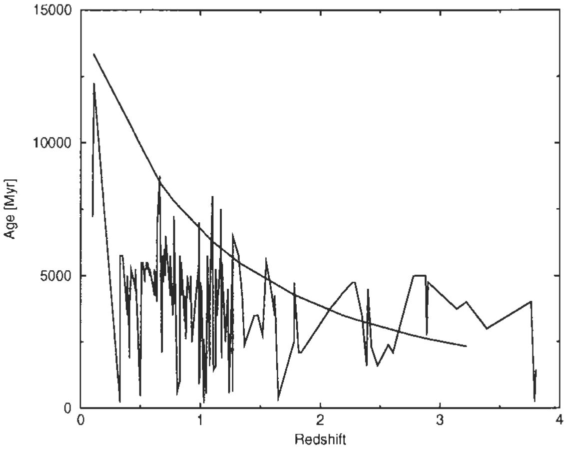

Figure 10: *Elliptical galaxy age versus redshift z and function $t(z)$ (smoothed curve) constructed by the maximum values of age in $\Delta z = 0.3$ discrete intervals in the GISSEL model.*

$$t(z) = \int_z^\infty \frac{d\tilde{z}}{(1+\tilde{z})H(\tilde{z})}$$

using the data of radio galaxy ages vs redshift z. The function $H(z)$ is expressed as a 4-parameter function

$$H^2 = H_0^2[\Omega_m(1+z)^3 + A + B(1+z) + C(1+z)^2],$$

where $A+B+C = 1-\Omega_m$. The function $t(z)$ is fitted by varying of 4 parameters (H_0, Ω_m, A, B). Separating data in discrete intervals of $\Delta z = 0.3$ and considering the maximum values of age in each interval, one could find a stable solution of the $t(z)$-function minimum deviation with $H_0 = 71.5\pm10$ and $\Omega_\Lambda = 0.8\pm0.1$ (where $\Omega_\Lambda = 1-\Omega_m$, $A = B = 0$) (Verkhodanov et al. 2002b, 2003) using the GISSEL'98 model (Bruzual & Charlot 1993) of the stellar population evolution.

The "Big Trio" project is also in progress at the present time (Parijskij et al. 1998, 1999, 2000a,b,c; Pursimo et al. 1999; Soboleva et al. 2000; Dodonov et al. 1999; Verkhodanov et al. 1999, 2000, 2001, 2002a,b).

7. Some other work

Note that other experiments were carried out at RATAN-600, for instance, the Zelenchuk survey by Sternberg Astronomical Institute of Moscow University (Amirkhanian et al. 1980a,b) in a wider declination band than it was in "Cold", but with a lower sensitivity. The results of the survey were used to search for inhomogeneities in the distribution of sources in the sky (Gorshkov et al. 1975), counts of sources (Gorshkov, Konnikova, 1981), to construct distributions of spectral indices. Later on, Gorshkov (1991) derived an analytical relation between the distribution of counts and spectral indices and the frequency, allowing reproduction of log N – log S at different wavelengths.

The cycle of surveys carried out at the Ukrainian telescope UTR (Braude et al., 1978, 1979, 1981, 1985, 1994, 2002) made it possible to obtain for the first time complete catalogs of radio sources in the decameter wavelength range. From these data Sokolov (1986) plotted a differential curve of counts of sources at a frequency of 25 MHz and indicated the existence in this range of classes of objects "responsible" for the strong cosmological evolution of extended extragalactic sources.

In 1989 Dagkesamanskij and Zheleznykh (1989) suggested a method of detection of neutrino and other superhigh energy elementary particles by radio astronomical techniques from results of their interaction with the surface of the Moon and other celestial bodies. Though this method is indirectly related to radio cosmology, it shows a possibility of measuring a density of super-high energy particles in the surrounding space, therefore, we mention it here.

Komissarov (PRAO) and Gubanov (AI SPbU) (1994) used radio sources with ultra-steep spectra ($\alpha \leq -2.0$) to measure magnetic fields of relic radio galaxies in which the activity of the nuclei had already stopped. Explaining the steepness of the spectrum by synchrotron losses of relativistic electrons after the process of injections of new particles into extended radio components had terminated, they employed the models of spectrum aging and, in particular, showed that the location of the high-frequency cut-off of the spectrum caused by the losses depends on the time passed since the moment of attenuation of activity and the redshift and permits the magnetic field intensity to be estimated. The typical magnetic field intensity is assessed at 10^{-5} G and the typical attenuation time at $\tau \approx 100$ Myrs.

It cannot but be mentioned also the domestic satellite studies of the relic emission with the aid of the radiometric system at the wavelength of 8 mm — the experiment "Relikt" (Strukov, Skulachev 1984). The satellite "Prognoz-9" was launched in 1983 June for making a map of large-scale anisotropy of the CMB radiation. The first data showed that at the 0.2 mK level the quadrupolar component was not detected. The data re-processing (Klypin et al., 1992) showed that the new results following from the "Relikt" satellite data are in good agreement with the data of the satellite COBE in measuring the dipole. New upper limits on the quadrupole have been set. The synchrotron thermal radiation and dust make a contribution to the Galaxy radiation, and this contribution can be taken into account when seaking for the RE fluctuations. The search for relic recombination lines in the microwave background radiation at RATAN-600 by spectroscopic methods (Gosachinsky et al. 2002) can also be referred to the additional work in the field of radio cosmology. From the results of this work, upper limits were established on the possibility of observing spatially-spectral details in the 3K background which were predicted at SAO (Dubrovich 1977) and associated with the scatter by primary molecules such as LiH. In particular, it is shown (Gosachinsky et al. 2002) that in the frequency band $\approx$1 MHz at the wavelength of 6.2 cm in the range of spatial periods from $0'.1$ to $16'$, the spectrum of spatial fluctuations is flat and has no features exceeding $\delta T/T = 10^{-3}$. If this estimate is assumed to be an upper limit of the first rotational transition of LiH molecules at $z = 90.7$, then at a mass of protoclusters at the stage of beginning of their gravitation compression of about $10^{13} M_{\odot}$, this restrict the relative abundance of LiH molecules by a value of about 3×10^{-14}.

8. Conclusions

When examining the above examples of the procedures employed and estimates of parameters, a question may arise of "whether cosmology is solved", as Peebles expressed himself (Peebles 1999), since nearly all cosmological parameters are known, the Universe is shown to be expanding, the Hubble constant and the contribution of different components to the total energy density are measured confidently. Indeed, the class of admissible models of the Universe is narrowed, but ample opportunities of choosing inside acceptable boundaries still remain. The estimates of parameters made by different techniques must not be conflicting, and their difference should be explained within the frames of physical models.

The measurement of parameters with smaller errors, on the one hand, and new test applied to manifestation of parameters in the evolution of objects, on the other hand, are important points here.

Refinement of cosmological parameters from the power spectrum of the relic radiation and, as a consequence, constraints on evolution models of the Universe, as well as elucidation of the nature of the main energy component of the Universe associated with the Λ-term, in particular, from results of investigation of radio galaxies, remain important matters among the problems of observational radio cosmology. Many problems related to measuring fluctuations of the relic radiation at 10 wavelengths of the millimeter and submillimeter range by the analysis of CMB charts and evaluation of cosmological parameters will be solved by the project "Planck" of the European Space Agency in the realization of which a community of about 300 astronomers is engaged. It is contemplated to launch into orbit the satellite "Planck" in 2007 and in the period of 2 years to obtain the most sensitive chart of the RE from observations from point L2. The radio telescope RATAN-600 (see the description of the project "Cosmological gene of the Universe", Parijskij 1999). has been called upon to play an important part in this direction connected with the accompanying ground-based observations.

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