ANGULAR STRUCTURE OF EXTRAGALACTIC RADIO SOURCES AT LOW FREQUENCIES

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The low frequency VLBI of URAN network operated in the decameter range has been designed in Ukraine to study cosmic radio sources. The network consists of five radio telescopes making up of four interferometers with baselines range from 42 to 913 km with UTR-2 radio telescope operated as the main antenna of the interferometers. The angular resolution of the network amount to 1 arcsec at the highest frequency of the range, and its sensitivity is about 20 Jy. Regular observations of galactic and extragalactic radio sources are performed with the network. Some results of studies are presented here.

INTRODUCTION

Studies of angular structure of radio sources are very important for progress of modern astronomy and they are carried out in a wide frequency range. Investigations at very low frequencies were restrained for a long time because of specific peculiarities of the range. At the same time various mechanisms of radio wave emission, absorption and scattering prove themselves particularly brightly at longer wavelengths. Being “linear” at high frequencies, the synchrotron spectra of radio sources often reach maximum at lower frequencies and then their radiation decreases smoothly. Such distortion of “linear” frequency characteristics can result from various physical processes in a space plasma, such as a reabsorption in the source, a radiation absorption in the space plasma both in the source and along the path of radio wave propagation, and also the effect of Razin–Tsytovich. In some cases when the spectral characteristics of the source or its component are well determined at high as well as at low frequencies, it is possible to evaluate such important characteristics of the space radio sources as magnetic field power, electron temperature, emission measure, electron concentration and other.

Therefore, the determination of the angular structure at decameter wavelengths is very important to clarify the mechanisms of generation and propagation of energy in the space. The low frequency VLBI of URAN network with resolution up to 1 arcsec operated at decameter wavelengths has been used to study of the space radio sources and influence the mechanisms of generation and propagation of radio waves at their angular structure.

APPARATUS AND METHODS

The decameter wavelength VLBI of URAN network consists of five antenna arrays: the world biggest decameter radio telescope UTR-2 and four smaller instruments, *i.e.*, URAN, making up four interferometers with baselines range from 42 to 913 km. The central instrument of the interferometers is the North–South arm of the UTR-2 radio telescope. Multiplying the signals received by the UTR-2 with the signals of the URAN antenna arrays forms the interference fringes. The UTR-2 antenna receives only single linearly polarized signals, while the URAN antennas receives simultaneously two orthogonal linear polarizations. This enables us to correct for the Faraday rotation effect in the Earth’s ionosphere and the cosmic plasma, which is very substantial at decameter wavelengths. As a rule, the measurements are performed simultaneously at 25 and 20 MHz during nighttime. The measurements produce the amplitude of the visibility functions in an interval up to ±3 hr on either side of the source culmination. Its values are obtained at various hour angles in 20 min steps. When processing the recordings, we determine the mean visibility function amplitudes for each 20-minute interval. The data obtained for each hour angle are averaged over all days of the observations, and the mean-weighted

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observational values are determined with their errors. We use a method described in [2] to calibrate the interferometer data, using special digital noise generators to imitate the response of the interferometer to a point source. The calibration generators and local time scales are synchronized at all interferometer points using GPS receivers.

As the URAN interferometers did not provide good coverage of the UV plane, and also due to an absence of phase measurements, the most suitable method for deriving the angular structure of the source is the model fitting. The image of a source is presented as a number of elliptical components with Gaussian brightness distribution, position, intensity, position angle, magnitude and axis ratio of which are adjusted when the model is fitted. The χ^2-criterion is used to test a consistency of the models and the observational data.

It is well known that the determination of models using only the visibility function amplitudes can lead to ambiguities in solutions and requires the large amounts of computing time, especially if the structure of the object is complex and the UV plane coverage is not very complete. In addition, comparison of the resulting models with higher frequency maps of the radio source in order to determine variations in the structure with a frequency can be only qualitative. We use the following algorithm to simplify the model fitting procedure and to determine quantitative properties of the frequency dependent variations in the source structure. At the first stage we analyze a high frequency map of a studied source with an angular resolution comparable with the URAN network resolution by calculation of hour angle dependencies adequate to tracks of the source at the UV-plane, as it would be observed with URAN interferometers. Then, we match a simple model consisted of the elliptical details with the same hour angle dependencies at the URAN's baselines which adequately describes the real source image. This model is used as the first approximation in the fitting procedure to determine low frequency models of the source. The number of the solutions obtained are then analyzed by cluster analysis. The low frequency image and high frequency one represented its models can be compared quantitatively and frequency dependences of its parameters can be defined.

So, the analysis of the experimental hour angle dependences of the visibility function modulus for different baselines and frequencies combined with the high frequency data allowed us to determine the models of brightness distribution of investigated sources at the decameter wavelengths and their quantitative and qualitative variations depending on frequency.

STRUCTURE OF THE SOURCES

The objects studied with VLBI of URAN network were galactic and extragalactic radio sources. At the decimeter and centimeter wavelengths extragalactic radio sources usually possess compact component and a total size of the source is of the order or less than resolving power at the shortest baseline of the URAN network. At the decameter waves quasars and radio galaxies structures are shown to change essentially as compared with their images obtained at higher frequencies. The most compact details disappear due to reabsorption, other are enlarged in dimensions. The most interesting feature of some studied sources is extended components, which are not observed at higher frequencies due to their steep spectrum and low surface brightness, and their diameters noticeably exceed the full size of the source measured at higher frequencies. Often these extended components contribute most of the decameter emission of the studied sources. Total spectra of the sources and their components are measured at the decameter wavelengths too. The obtained dependencies allow us to estimate physical conditions in the radio sources plasma and in the intergalactic medium.

Let us illustrate that by the example of the quasar 3C 196. At centimeter and decimeter wavelengths the angular structure of the source is well known owing to maps and interferometer data available at longer wavelengths. The angular structure of the radio source is constant in the wide frequency range. At the frequencies above 500 MHz the simplest model consisting of two details (the angular diameter of each is about 2.5 arcsec, separation is about 5.5 arcsec and the spectral indices are equal to 0.83) describes the source brightness distribution with a satisfactory accuracy. Observations with the URAN interferometers have shown that the source low frequency structure differs from known one at higher frequencies. Only one compact detail remains and an extended steep spectrum component with angular diameter of about 25 arcsec at 50% level of Gaussian brightness distribution has been detected. The latter has not been observed earlier in the source. Further analysis of flux measurements and interferometer data in the wide frequency range allows us to determine the angular dimensions and spectra of all the components in the source brightness distribution model at the frequencies range from 20 to 5000 MHz. In the general case, the source model contains three components: two compact features and the extended one. Their spectra (S_{s-w}, S_{n-e}, S_e) and source total spectrum (S_0) are shown in Fig. 1.

One can see that the model has two components at the frequencies above 500 MHz, because the extended feature has steep spectrum. At the frequencies lower than 150 MHz radio emission of the compact detail (S_{n-e}) decreases dramatically with a spectral index of 2.5 because of reabsorption in the component and at the frequencies less than 45 MHz the model possess the single compact detail (S_{s-w}) and the extended region of the emission (S_e). Calculations based on this model were compared with the results of interferometer

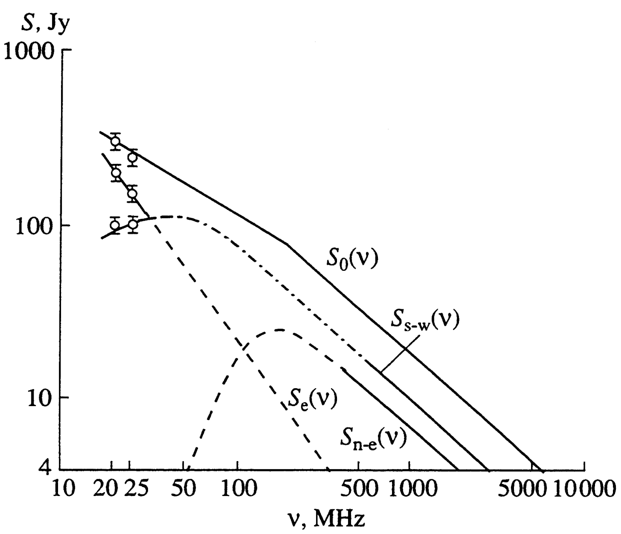

Figure 1. Spectral properties of 3C 196; S_0 (v) is the frequency dependence of the spectral flux density of the quasar total emission; $S_{s\cdot w}(v)$ and $S_{n-e}(v)$ are the spectra of the southwestern and northeastern components of the quasar; and $S_e(v)$ is the frequency dependence of the spectral flux density of the emission of the quasar extended component

measurements and 3C 196 maps obtained at higher frequencies. Part of the total source flux density, which could not be explained by the integrated radiation of the compact components, generally coincides with the model estimation of the extended component flux density up to 5000 MHz. Hence, the reasons of the angular structure changes in the 3C 196 are: a) reabsorption in the compact detail; b) existence of the extended component with steep spectrum (spectral index is equal to 1.4); c) absorption in the interstellar medium which distorts the spectrum of the component S_{s-w} at the frequencies less than 40 MHz. In the component with reabsorption the magnetic field can be evaluated when spectrum and angular size are measured [1]. In this case, it is equal to 170 μG. The determination of the magnetic field gives the possibility to estimate such valuable physical parameters as energy of magnetic field and relativistic electrons, their density.

The studied 3C 216 and 3C 254 quasars have the same core-halo structure at the decameters with halo dimensions about 20 arcsec and spectral index equal to 1.0. In the case of the 3C 154 and 3C 380 quasars the more extended ~40 arcsec halos have been detected with the spectral indexes of 1.5 and 1.0, respectively. Physical sizes of such extended components in studied quasars are range from 150 to 280 kpc. For those compact components, which are visible at higher frequencies and disappear at lower ones the physical parameters of space plasma have been evaluated if the physical mechanisms responsible for falling of their flux density were determined.

In contrary to the previous radio sources two details with angular distance between them about 54 arcsec have been found at decameter wavelengths in the quasar 3C 47. The location of the details are close to the position of known high frequency extended components of the source but their angular sizes at the decameter wavelengths are about 20 arcsec at 50% level of Gaussian brightness distribution versus 10–15 arcsec at zero level at decimeter wavelengths maps.

Another class of studied extragalactic radio sources is represented by radio galaxies. At decimeter and centimeter wavelengths these ones often are the FRII radio sources with two well separated radio lobes. The same structure they have at decameters, however their components are enlarged essentially as in the case of the 3C 47 quasar. Such structural changes have been detected in the 3C 111, 3C 338, and 3C 234 radio galaxies. Unlike them the 3C 295 radio galaxy has the angular brightness distribution at low frequencies similar to the quasars with halo-like structure.

3C 295 is a compact steep spectrum radio source associated with a giant elliptical galaxy. At centimeter wavelengths it consists of two radio lobes about 2 arcsec in size separated by 4 arcsec. The low frequency model of the source consists of a single component with Gaussian brightness distribution which has dimensions 7.4×8.7 arcsec at 25 MHz and 9.1×10.6 arcsec at 20 MHz. They are shown in Fig. 2 with the correspondent VLA maps at 8.7 GHz (the diameters of the decameter components are shown at the 50% intensity level). An interesting feature of the source total spectrum is a sharp turnover at low frequencies that can be explained by absorption of radiation in the source plasma. This feature allows us to determine such important characteristics of the source plasma as electron temperature $T_e = 160$ K, emission measure $ME = 16.1$ cm^{-6}pc, and, when the dimension of the radio galaxy at the decameter waves is about 70 kpc, electron concentration $N_e \approx 0.015$ cm^{-3}.

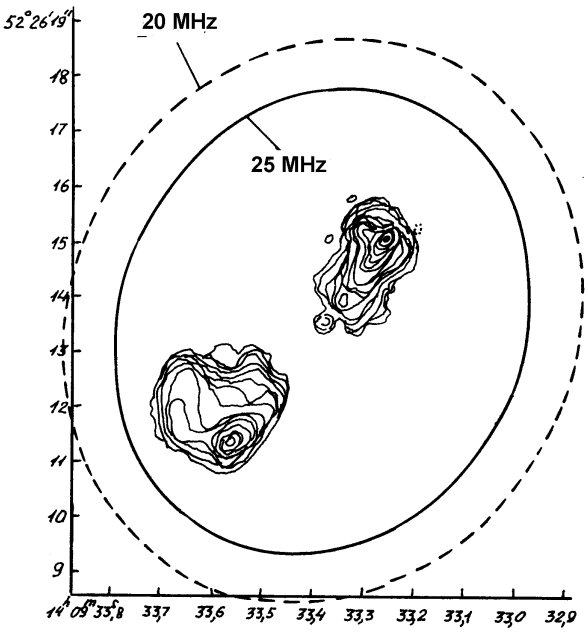

Figure 2. The most probable one-component model of the brightness distribution of the 3C 295 radio galaxy in the decameter wavelengths range (solid line is 25 MHz, dashed line is 20 MHz) using the VLA map obtained at the frequency of 8711 MHz

From the galactic radio sources the supernova remnants Crab Nebula (3C 144) and Cassiopeia A (3C 461) have been studied in detail using URAN network. The flux density and the angular size of the Crab shell and its well-known low frequency compact component coinciding with the pulsar were measured separately. The shell parameters do not differ essentially from those at shorter wavelengths, but the angular diameter of the compact detail is determined by scattering of the radio waves on the inhomogeneities of the interstellar medium.

We have shown that the structure of the Cassiopeia A does not differ from the high frequency image of the source up to 25 MHz. The experimental hour angle dependency of source visibility function modulus obtained in the ranges of ±240 min the source culmination was in a good agreement with calculated curve of the VLA map of the source. However, distortion of the total spectrum is accompanied by a change of the radio image at lower frequencies. The possible reason of both modifications is the influence of the interstellar medium along the line of sight.

CONCLUSION

The results obtained allow us to affirm that the structure of the studied extragalactic radio sources changes at the decameter wavelengths. The reason of the changes is as a rule a combination of various effects of radio wave generation and propagation. The peculiarities of the brightness distribution in the range are:

1. The compact details (hot spots) in the radio galaxies and quasars are usually less prominent at the decameter wavelengths due to self-absorption in the source and absorption in the interstellar medium. Their angular diameters are equal to those at higher frequencies or slightly enlarged by scattering.
2. The lobes dimensions are enlarged.
3. The characteristic feature of a quasars structure at low frequencies is the extended components with steep spectra producing the main part of the source fluxes at the decameter wavelengths. Their angular diameters exceed the total size of the source as measured at higher frequencies. Such halos can be revealed in some radio galaxies too.

The galactic supernova remnants studied using URAN network mainly possess the same features of their structure as at higher frequencies. The most prominent changes in their low frequency structure are weak increasing of their compact details size due to scattering. The form of the shells can be evaluated from the high frequency maps of the source with respect to spectral indexes of source parts.

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[2] *Megn A. V., Rashkovskiy S. L., Shepelev V. A., et al.* URAN system of decametric interferometers (II). Equipment and observation methods // Radio Phys. and Radio Astron.–1998.–**3**, N 3.–P. 284–293.