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The keys by Nikolai Kardashev and Yuri Parijskij to the Nature of Active Galactic Nuclei

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Yu.A. Kovalev,[a,*] **N.A. Nizhelsky,**[b] **Y.Y. Kovalev,**[a,c] **S.V. Troitsky,**[d] **G.V. Zhekanis,**[b] **P.G. Tsibulev,**[b] **S.A. Pustilnik,**[b] **M.G. Mingaliev,**[b] **Yu.V. Sotnikova,**[b] **A.K. Erkenov,**[b] **V.A. Soglasnov,**[a] **A.V. Popkov**[c,a] **and A.V. Plavin**[a]

[a] *Astro Space Center of P.N. Lebedev Physical Institute, Profsoyuznaya St. 84/32, Moscow, Russia*
[b] *Special Astrophysical Observatory of RAS, Nizhny Arkhyz, Russia*
[c] *Moscow Institute of Physics and Technology, Institutsky per. 9, Dolgoprudny, Russia*
[d] *Institute for Nuclear Research of RAS, 60th October Anniversary Prospect 7a, 117312, Moscow, Russia*

E-mail: ykovalev@asc.rssi.ru

The Joint AGN Research Observing Program of IKI RAS/ASC FIAN and SAO RAS has been carried out at RATAN-600 since April 1979 thanks to the initiative of Nikolai Kardashev and the constant support of Yuri Parijskij ("Key-1"). The main task is to study active galactic nuclei (AGNs) based on RATAN-600 surveys and monitoring of instantaneous 1–22 GHz spectra of AGNs. The "Hedgehog" model of AGNs was proposed in 1969 by N. S. Kardashev and developed in the works of a number of authors ("Key-2"). The report summarizes the main observed properties of AGNs obtained in the Program based on the RATAN-600 instantaneous spectra for a large sample of extragalactic objects with VLBI compact components. It is shown that the 6-frequency RATAN-600 1-22 GHz spectra and their long-term variability are consistent with the Hedgehog model for a relativistic jet of electrons and protons in the strong longitudinal magnetic field from an AGN nucleus. The RATAN-600 spectral support of ground-space VLBI has been performed for the projects *VSOP* (1997–2003) and *RadioAstron* (2011–2019) including a study of many AGNs with the RadioAstron detections of super-high brightness temperatures up to 10^{14} K, "Key-3"). Since 2020, the work has been supplemented by a new topic of multichannel astronomy, "radio-neutrino" ("Key-4"), the current results of which show that the earlier role of the synchrotron radio emitting protons in the strong magnetic field of the jet could be underestimated in AGN astrophysics. New data of this topic will test this hypothesis.

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[*] Speaker

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1. Introduction

The history of discovering the radio emission variability in extragalactic objects is full of drama. After the discovery of the variability by G. B.Sholomitsky in 1965 and its first successful theoretical description by I. S. Shklovsky in 1965 (according to his own model of 1960), the interest to this phenomenon has not been weakening for more than 50 years. Particularly important are detailed regular studies of a many number of variable sources at many frequencies in the widest possible range and with extreme high angular resolution using ground and ground-space VLBI (VSOP and RadioAstron projects). Today such work has been transforming into a new field of multichannel astronomy in connection with the recent detection of possible extragalactic high-energy neutrinos with IceCube and other neutrino telescopes. Thanks to the efforts of N. S. Kardashev and Yu. N. Parijskij, on their initiative and with their support, a long-term joint research program at RATAN-600 has been carried out from 1979 to the present [1–3]. The key contribution of NSK's and YuNP's work to the main obtained results are briefly summarized in the report.

2. Key-1: RATAN-600 instantaneous 1–22 GHz spectra

The rare ability of the radio telescope RATAN-600 to measure practically instantaneous spectra at many frequencies in a wide wavelength range [1] turned out to be fundamentally important in mass studies of the long-term variability of extragalactic objects (active galactic nuclei, AGNs).

Figure 1 shows 35 examples of the strong variability in the RATAN-600 1–22 GHz AGN emission spectra [4]. The regularity in the evolution of the emission spectrum on scales of several months or more is clearly visible: each perturbation of the spectrum (radiation burst) begins at higher frequencies; expanding, the perturbation gradually propagates towards lower frequencies until it stops (if it "has time" to do this before the next burst). For the sources 0007+10 and 0235+16 as well as for 0906+01 and 2121+05, the pattern of spectrum variability is clearly visible during the development of a burst at the stage of increasing outflow (the second two objects) and during the increase and decrease of the burst (the first two objects). The "stepped" perturbation from high frequencies (HF) moves sequentially along the spectrum: positive (negative) with increasing (decreasing) outflow, gradually capturing lower and lower frequencies until it stops. Then this process can be repeated: not regularly, with different amplitudes, signs, and burst durations.

3. Key-2: The Hedgehog model

As is known, the first most successful model of a variable extragalactic radio source was proposed by I. S. Shklovsky in 1960 and 1965. Van der Laan in 1966 gave it an elegant mathematical form, the elements of which are still used by many authors today. The physics of radiation variability in this model is based on the evolution of the synchrotron radio emission spectrum of a cloud in the internal chaotic magnetic field during the expansion of the cloud ejected from the AGN. This model had been very popular during about 20 first years because it made possible to explain many observed properties of variable objects, but, as a rule, only at close frequencies. The agreement between the model and observations worsened with the expansion of the analyzed wavelength range.

Kardashev in 1969 proposed the another, "Hedgehog," model [5]. Its main difference from Shklovsky's model was that the internal chaotic magnetic field of the cloud was "replaced" by an

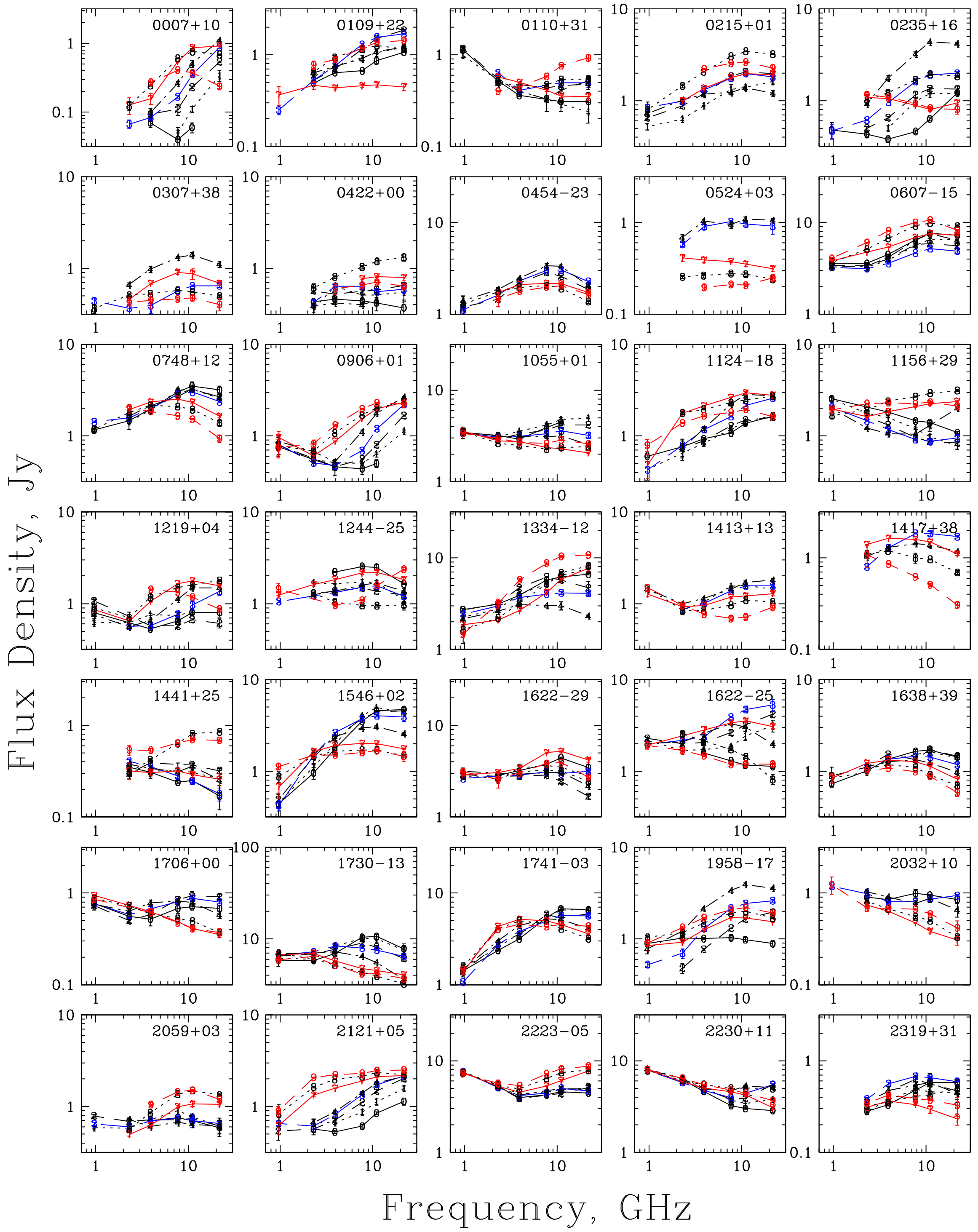

Figure 1: Three-year typical behavior of spectra with strong long-term variability. The RATAN-600 instantaneous spectra in March 1997 – April 2000 at wavelengths of 1.4, 2.7, 3.9, 7.7, 13, and 31 cm [4]. Ten spectra (with numbers from 0 to 9) for each of 35 selected AGNs are shown. Each spectrum is separated from the neighboring spectra by about 4 months in time. Most of the AGNs have two-component spectra: the variable high-frequency and non-variable low-frequency components. The sources B0906+01 and B2121+05 show the best examples of the regular evolution of spectra with a monotonous slow increase during the burst. The objects B0007+10 and B0235+16 are the same, but with slowly increasing and rapidly decreasing bursts.

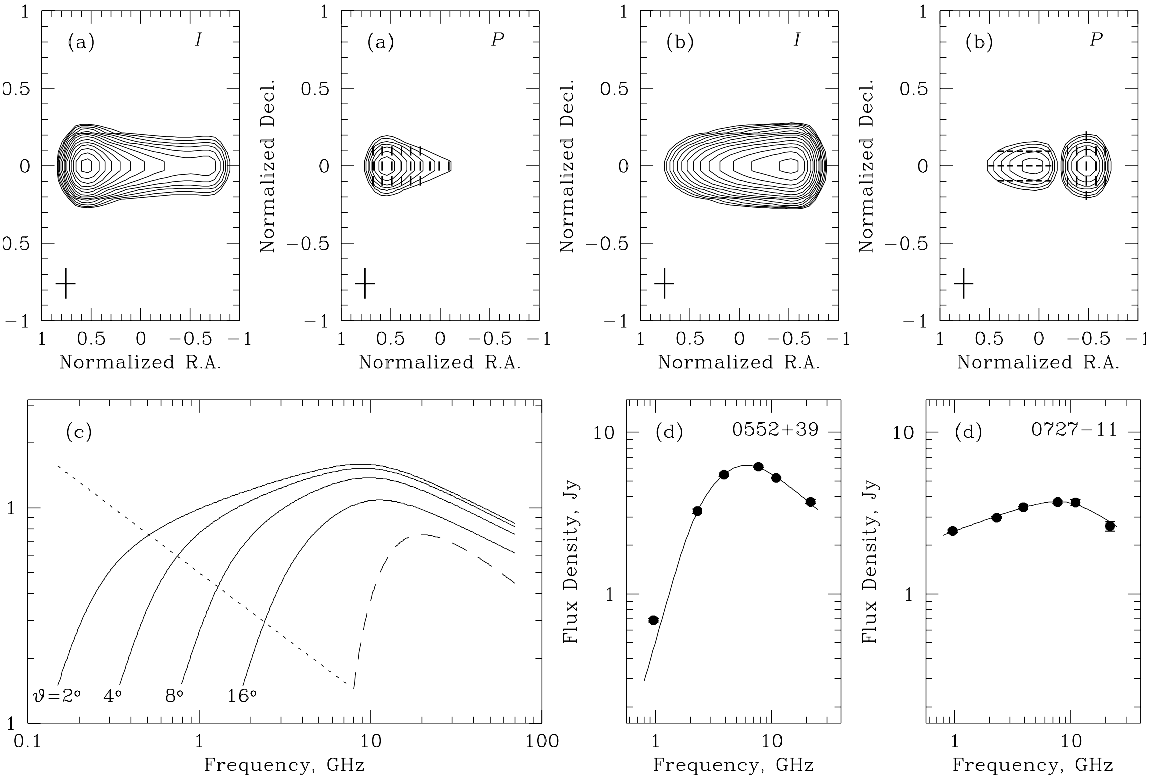

Figure 2: The Hedgehog model spectra, images, and polarization of a continuous relativistic jet, the case of stationary particle outflow $dN(t)/dt$ = const at the core of the jet [7]. Top: total (I) and polarized (P) intensity maps (the width of the radiation pattern is shown by the cross). Bottom: the calculated spectra (c) and the spectra fitted by the model to the instantaneous observed spectra for two variable AGNs (d); ϑ = 2°–16° are the angles between the line of sight and the jet, the dotted line is the spectrum of the LF background component, the spectrum on the right is typical of a point synchrotron source (for a comparison). Images (a) and (b) are given for the frequencies above and below of the jet spectrum maximum (c) respectively.

external relatively strong longitudinal magnetic field of the jet, which thus "controlled the motion of the cloud of radiating particles." This model has been successfully "working" so far and explains the main observed properties of the instantaneous RATAN-600 spectra, the spectra of some bright objects in the range from 0.01 to 1000 GHz (see below), and the observed movements of the VLBI components with apparent superluminal velocities (more details with references see in [6–7, 15]).

In the general case, the model spectrum consists of two main components (see Figures 2–5): the high-frequency (HF) variable spectrum of the jet with three sections: optically thin, thick, and intermediate), and the low-frequency (LF) almost non-variable optically thin radiation spectrum of the source magnetosphere, including a distant extended cloud "accepting the plasma stream of the jet." The combination of these two components, by varying the frequency and flux density of the HF component spectrum maximum as well as the relative contribution of the HF and LF components to the total spectrum, can explain more than 95% of all the studied spectra for several thousand AGNs [3, 4, 7, 10].

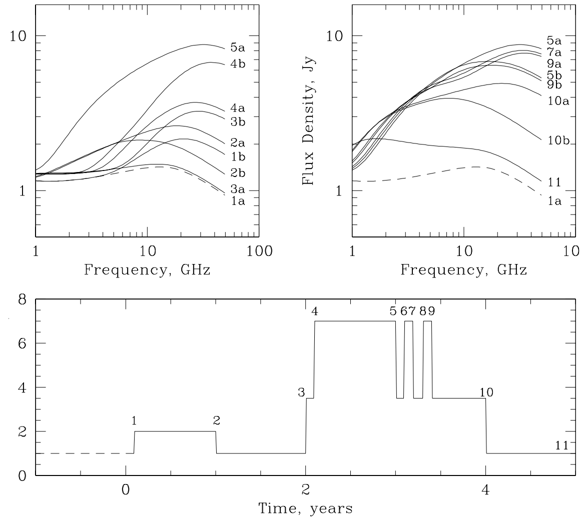

Figure 3: Spectra variability in the Hedgehog jet model [8, 7]. The typical behaviour of the spectra (top) in dependence on the time variability of the particle outflow dN/dt in the jet core (bottom). The labels Na and Nb near the spectra point out the spectra at the time moments $N = 1, 2, ...$ in the bottom picture when the particle outflow at the jet core varies in time: before the "step" (Na) and after it (Nb). Spectra 1a, 1b, 2a, and 2b are strongly different because dN/dt between steps 1 and 2 is two times greater then before them.

4. Key-3: *RadioAstron* high brightness temperatures

In 1967, N. Kardashev together with L. Matveenko and G. Sholomitsky proposed the principle of constructing the VLBI. Under his leadership, the RadioAstron ground-space VLBI [13] successfully operated in flight from July 2011 to January 2019. One of the important results of the RadioAstron project was the detection of very high brightness temperatures of many AGNs: up to $T_\mathrm{b} \sim 10^{14}$ K, see [18] and references therein. This exceeds the well-known Compton brightness temperature limit for electron radiation $10^{11.5}$ K by a factor of 100–1000. The ground-based RATAN-600 spectral support for the space VLBI RadioAstron showed that the spectra behavior of these objects in 2011-–2019 had been typical since 1997. This testifies in favor of the typicality of such high brightness temperatures in these objects, including the objects that are possible emitters of extragalactic neutrinos [9, 10]. Such high brightness temperatures could be achieved by the synchrotron radiation of protons [10-12, 15], but the inverse Compton effect can decrease them.

Using the method of [16], we can obtain the following Compton limitation on the brightness temperature T_b of proton/electron synchrotron radiation (via the energy densities of the emission U_{rad} and of the magnetic field U_B, the frequency of the spectra maximum ν_{max}, and a function $C_g(\gamma) \sim 1$): $U_{rad}/U_B \sim 4 \cdot 10^{-68}\, T_b^5\, \nu_{max}\, M_{2e}^{-6}\, C_g(\gamma) < 1$. Assuming $\nu_{max} \sim 10^{11}$ GHz, $M_{2e} = 1$ for electrons, and $M_{2e} = 1836$ for protons, we get $T_b < 10^{11.3}$ K for electrons and $T_b < 10^{15}$ K for protons. Kardashev [11,12] obtained an order of magnitude higher maximum brightness temperature of the proton source, since he additionally took into account the possible enhancement of the observed radiation due to the Doppler effect. The "replacement" of synchrotron electrons by protons would effectively solve this and other problems. But the "price" of such a "replacement" is the significant increase in the total radio source energy.

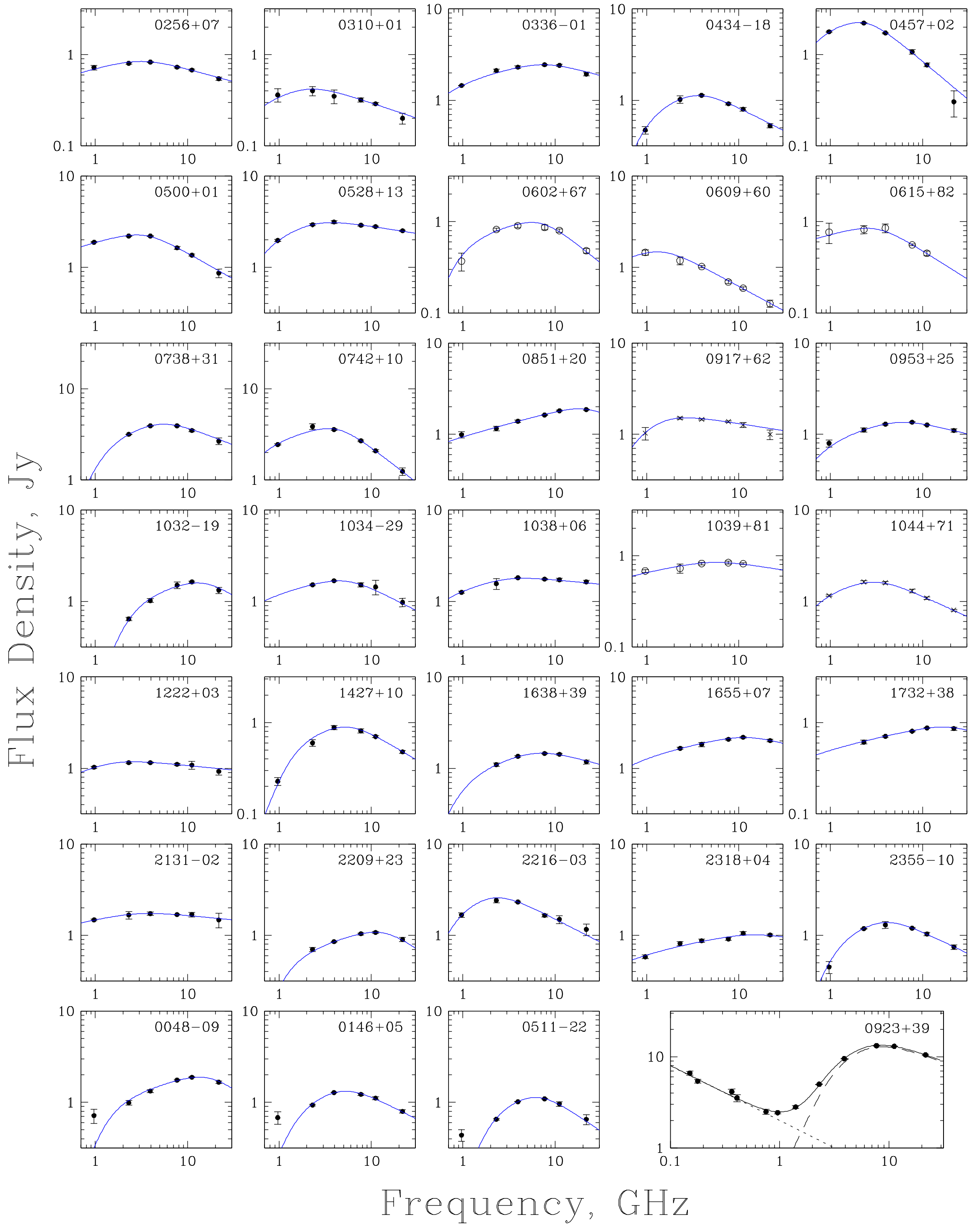

Figure 4: An example of fitting the spectra for 34 of 80 VSOP/RadioAstron AGNs to the Hedgehog jet model on the data of RATAN-600 instantaneous 1-22 GHz spectra measured in 1996–1998 [7]. The spectra fitting to observations are shown by the lines. The χ^2-test with a confidence level of 0.95 have been used succesfully. Allmost all the objects have the one – HF – component of the spectra. Possibly, three the sources in the down windows on the left have the LF-component also. The quasar B0923+39 only has the two components here. Additional low-frequency data for B0923+39 are from the CATS data base.

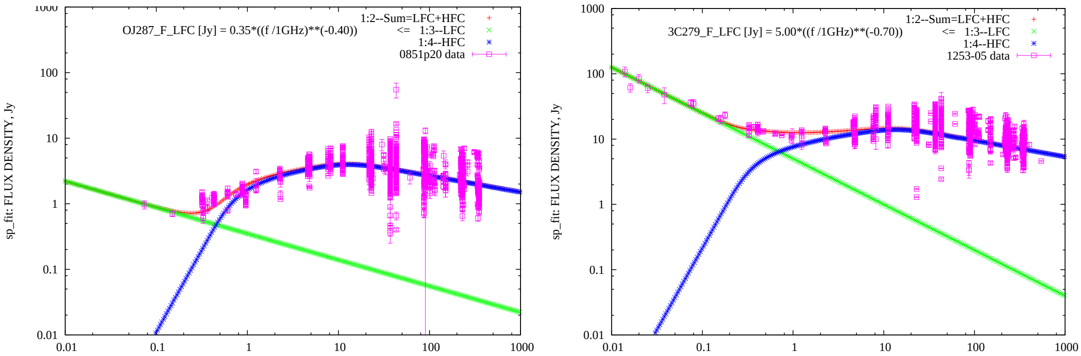

Figure 5: Broadband two-component 0.01–1000 GHz radio spectra of OJ 287 and 3C 279 (in addition to TXS 0506+056 and PKS 1502+106 in [3, 15]). The RATAN-600 1–22 GHz spectra and the CATS data at other bands are shown. The RATAN-600 spectra at 0.96 (1.2), 2.3, 4.7, 7.7 (8.2), 11.2, and 22.3 GHz were measured in 1997–2017. The CATS data [14] combine ~7600 radio measurements from 74 literature sources, covering a time period of about 40 years. The green line represents the Low-Frequency linear model fit for the synchrotron radiation in optically thin extended structures up to kpc scales. The blue line represents the High-Frequency Hedgehog jet model component with the constant outflow $dN(t)/dt = const$. Time variations of this outflow give time variations of the spectra. The red line is the sum of the two components.

5. Key-4: Relativistic protons as possible “radio-neutrino” emitters in AGNs

Let us list the main results and problems which require the “replacement” of electrons by protons in the synchrotron radio emission of relativistic jets [3, 9, 10, 15]: 1) the energy density of the magnetic field has to be much greater than the kinetic energy density of the radiating particles for many cases; 2) the time of electron emission due to radiation losses is usually on the verge of acceptable, in contrast to this time for protons, 3) ultra-high brightness temperatures, up to 10^{14} K, exceed the permissible temperatures $10^{11.5}$ K for electron synchrotron radiation because of the losses due to the inverse Compton effect, even taking into account the Doppler amplification of radio emission, 4) extragalactic neutrinos with energies of tens and hundreds of TeV require for their birth the presence of protons with energies tens of times higher than the neutrino energies (while for synchrotron radio emission it is sufficient to have protons with the same gamma factors γ_E as for electrons, in the interval $\gamma_E \sim$ (1–1000), i.e., with proton energies of $\sim(10^9 - 10^{12})$ eV).

Possible “radio–neutrino” connections for AGNs have been detected based on the RATAN-600 and IceCube data [9] . The spectra fits in Figure 5 and in [3, 15] give the estimates of the physical parameters for the proton jets in 0506+056, 1502+106, OJ 287, and 3C 279 similar to the way in [15]: $\nu_{max} \sim (10 - 20)$ GHz, $\gamma_E \sim (100 - 300)$, $\vartheta \sim (1 - 3)^\circ$, $T_b \sim (0.3 - 1) \cdot 10^{14}$ K, $B \sim (0.3 - 1) \cdot 10^4$ Gauss.

Therefore, radio-emitting protons can simply be a low-energy part of the total energy distribution $N(E)$ of relativistic protons, which is formed in the region of accretion from the disk onto the black hole. In this region, a particle with a charge e can be accelerated by the known induction mechanism up to the energies of $E \sim \Delta B \cdot R \cdot e/2$ [17]. Here ΔB is the variation of the magnetic field in the region limited by the contour of the radius R. From here, for $\Delta B \sim 10^4$ Gauss and $R \sim 10^{15}$ cm we get $E \sim 10^{21}$ eV if any losses are neglected (or protons can be accelerated at least up to PeV energies if the energy losses due to the synchrotron or curvature emission are significant).

6. Conclusions

1. The Joint AGN Research Program uses the following key ideas, tools, and results of Nikolai S. Kardashev and Yuri N. Parijskij: 1) the creation of RATAN-600, its ability to measure instantaneous 1–22 GHz radio spectra, and the results of these measurements; 2) the VLBI method and the creation of the ground-space VLBI of the RadioAstron project, its ability and the unique results of brightness temperature measurements; 3) the Hedgehog model as an effective physical model for AGNs, 4) the fruitful results of the year 2000 on the importance of relativistic protons.

2. Ultra-high brightness temperatures of AGNs (up to 10^{14} K!), detected in the RadioAstron project, cannot be explained by the synchrotron radiation of electrons, but are successfully explained by the synchrotron emission of relativistic protons. Relativistic protons can be the main emitter of both radio emission and neutrinos in AGNs, at least in VLBI-bright AGNs. Then the low-energy part of the energy distribution of protons gives the main part of the observed radio emission, and the high-energy part participates in the production of high-energy neutrinos.

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