Proton jets as sources of high-energy neutrinos and variable radio emission based on the RATAN-600 and CATS data at 0.01–1000 GHz

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Abstract. Monitoring observations and model analysis of instantaneous 1–22 GHz radio spectra of various samples of blazars with strong VLBI (very-long-baseline interferometry) components obtained at RATAN-600 since 1979 and supplemented outside this range with data from the CATS database are continued. The Hedgehog model of a relativistic jet in a strong quasi-radial magnetic field proposed in 1969 by N.S. Kardashev and successfully applied to interpret variable emission spectra of active galactic nuclei is used. The objective of this work is to study the structure and physical parameters of the SMBH neighborhood, as well as a possible proton source of high-energy neutrinos, using spectral methods. We have estimated the magnetic fields, brightness temperatures, angle sizes and other physical parameters for proton jets from spectra fitting.

Keywords: active galaxies: quasars; general radio continuum

1. Introduction

Oleg Verkhodanov was the main initiator and first author of the CATS Database of the SAO RAS (Verkhodanov et al. 2005). He was very proud of the demand for this database throughout the world. Now, we also start using it widely because it gives new important possibilities to study the spectra and structure in 0.01–1000 GHz range (in addition to Mingaliev et al. 1978; Kovalev & Pustilnik 1979; Berlin et al. 1983; Kovalev 1997; Kovalev et al. 1999; Kovalev & Mikhailutsa 1980; Kovalev et al. 2000, 2020; Sotnikova et al. 2022; Kovalev et al. 2022; Vlasyuk et al. 2024): 1) to improve modeling of the spectra and estimate the main physical parameters of galaxies and quasars, 2) to use the new "neutrino channel" better. Some new results can be found here (see Fig. 1–5 and the figure captions).

2. The Hedgehog model and Observations — a short history

The first RATAN-600 observations of the several extragalactic variable sources were conducted in 1977–1978 by M. Mingaliev, L. Pustilnik, S. Trushkin and two colleagues from the Armenia (Mingaliev et al. 1978). The presented regular monitoring at the radio telescope RATAN-600 was started in 1979 by the astrophysical department (headed by I.S. Shklovsky) of the Space Research Institute of the USSR Academy of Sciences (IKI AN USSR) together with the Special Astrophysical Observatory in order to study the variability of the radio spectra of quasars and galaxies. The department was transformed into the Astro Space Center of the Lebedev Physical Institute in 1990 (ASC FIAN, headed by N.S. Kardashev up to 2020).

In 1978, N.S. Kardashev has suggested to one of the authors to submit an observational Proposal to the Program Committee of the RATAN-600 to perform this task (at that time it was believed that the "Hedgehog" model (Kovalev & Mikhailutsa 1980; Kovalev et al. 2000, 2020) of variable sources could be relatively quickly tested with the help of these observations; the model was popular within certain circles of IKI (I.S. Shklovsky, N.S. Kardashev, G.B. Sholomitsky et al. — at Shklovsky's department), FIAN (LPI, L.M. Ozernoy), GAISH (the Sternberg Astronomical Institute, V.N. Kurilchik) and of some students). The first set of spectra measurements was carried out on May 1–22, 1979 for 5 calibrators and **6** well-known variable sources (BL Lac, OJ 287, 3C 279, 3C 345, 3C 454.3 and PKS 1510-089). In September of that year, the first results of 20-day observations — results for BL Lac at 4 wavelengths from 2.1 to 13 cm — were reported at the USSR radio astronomy conference and published by Kovalev and Pustilnik (Kovalev & Pustilnik 1979). The data were sufficient to disprove the belief of sceptics (V.I. Slysh) that it is impossible to obtain reliable results on variability by using an antenna with variable surface like the RATAN-600. The observations were continued due to the constant support of Yu.N. Parijskij. 11 studied objects and 6 calibrators were monitored in 11 sets of the first 3 years (Kovalev & Pustilnik 1979; Berlin et al. 1983). In the middle of the period under discussion, the number of monitored sources increased up to 115, to 1996 — up to 200, in 1997 — up to 600 (Berlin et al. 1983; Kovalev 1997).

3. Summary

1. The structure of average variable spectra for 11 objects in the range of 0.01–1000 GHz remains the same (as at 1–22 GHz) — it consists of two components: quasi-stationary low-frequency component (LFC) and variable high-frequency component (HFC). In some cases, a new HFC may appear (at frequencies above 100 GHz), which would be worth checking in the future.
2. The strong variability can be generated by the jets with relativistic protons in the strong magnetic fields by synchrotron mechanism, and the high energy part of these proton distribution may take part in the generation of high-energy neutrinos.

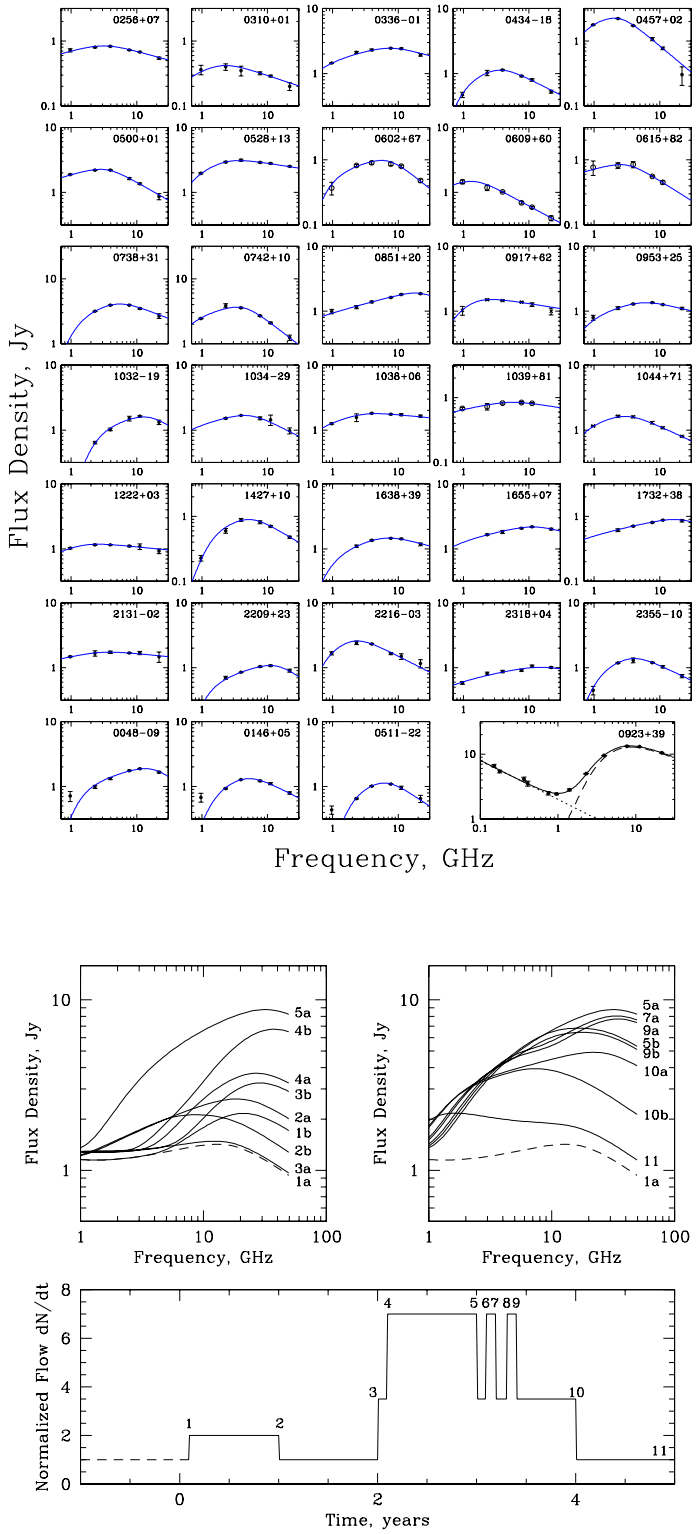

Figure 1. Top (Kovalev et al. 2000): The Hedgehog jet model spectra fitting of the RATAN-600 instantaneous 1–22 GHz spectra. The additional low-frequency data for 0923+39 are from the CATS data base. Bottom (Kovalev et al. 2000): the Hedgehog model variability of the flux density as a result of changing the jet particle flux dN/dt in the time near the jet input.

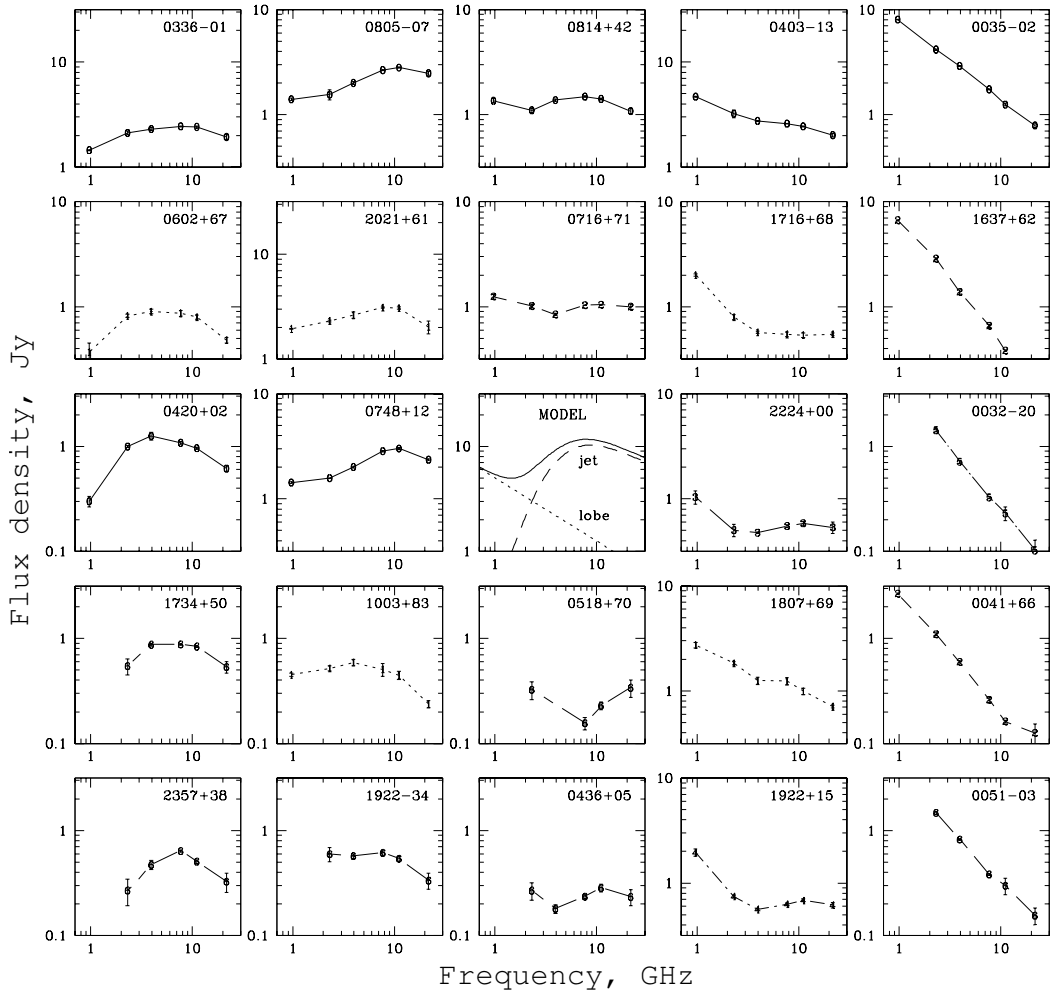

Figure 2. Two-Component spectra (a Low Frequency, LFC, plus a High Frequency, HFC, components): the contribution of the LFC to the spectra of the sources increases from the left to the right columns. The figure in the center: LFC (lobe) plus HFC (jet) give a sum spectrum observed (Kovalev & Pustilnik 1979; Berlin et al. 1983; Kovalev 1997; Kovalev et al. 1999; Kovalev & Mikhailutsa 1980; Kovalev et al. 2000). The HFC is generated by the jet. The LFC is generated by other parts of the source.

Acknowledgements The observations were carried out with the RATAN-600 scientific facility. This research has made use of the CATS database, available on the SAO website. Many of our colleagues from Kovalev (1997), including Oleg, participated in these observations and worked at SAO and RATAN-600 in previous years to ensure that the results we discussed were obtained. We are also grateful to an anonymous reviewer for the valuable comments.

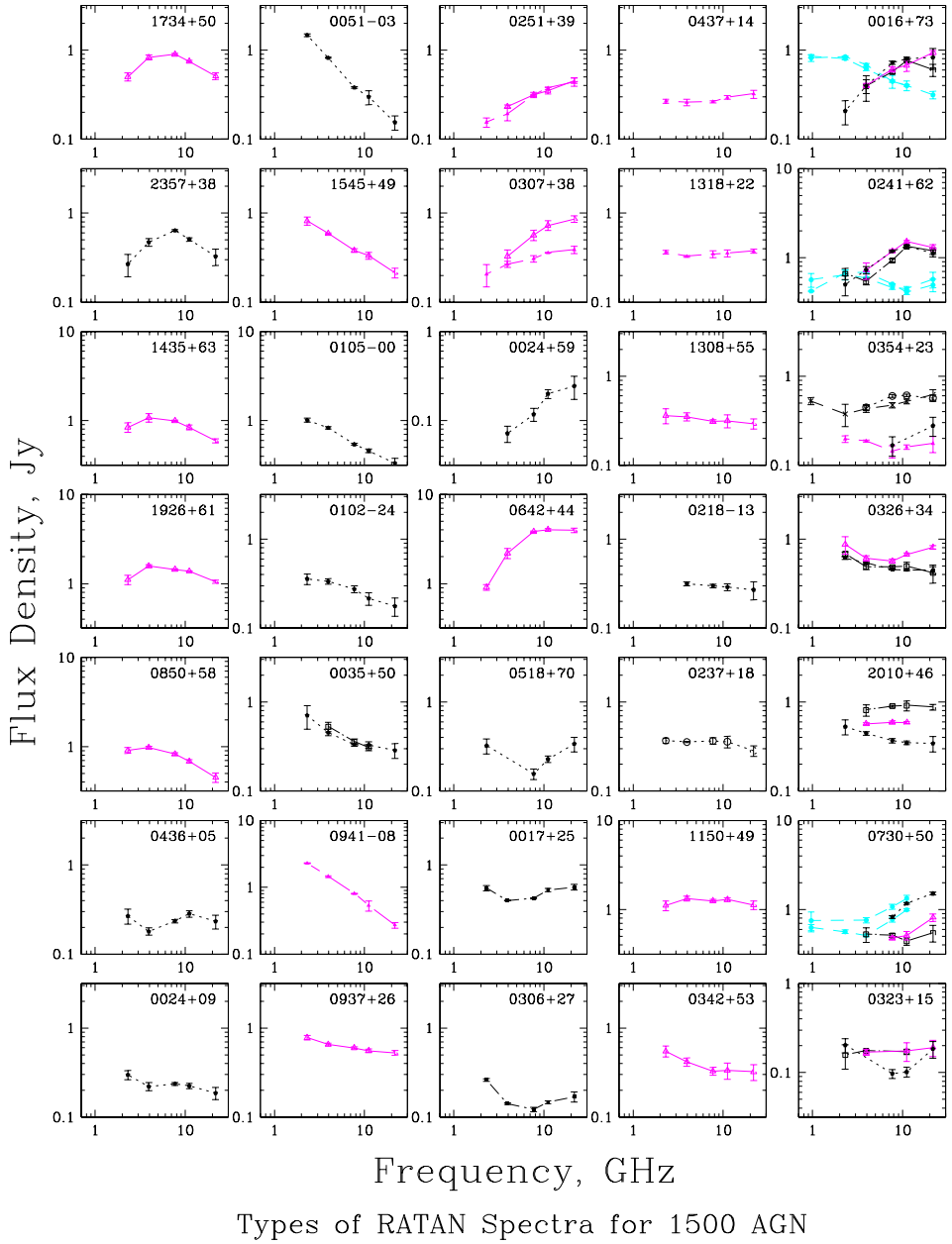

Figure 3. 5 main types of the RATAN-600 instantaneous 1–22 GHz spectra (the columns from left to right): 1) with a maximum, 2) falling and 3) rising towards higher frequencies, 4) super-flat (if the spectral index is changed by less than 0.1 for 3 or more frequencies), 5) variable (between 2, 3 or 4 previous types). Other spectral types may occur in less than 5% of observed spectra (Kovalev et al. 2020).

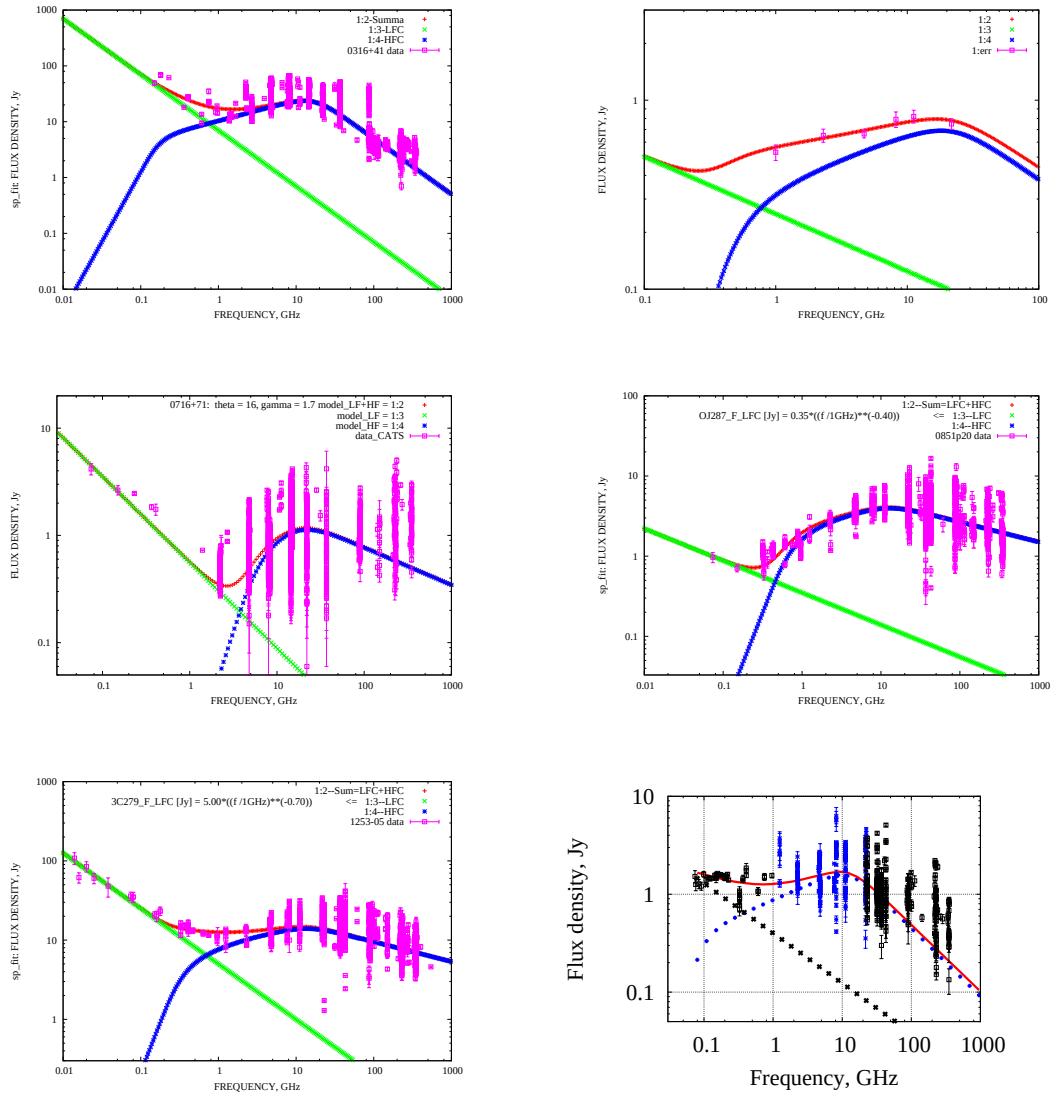

Figure 4. The flux density (in Jy) versus the frequency, (0.01–1000) GHz. Two-component variability of spectra for 11 following blasars: 1st column on the left — 3C84, B0716+71, 3C279; 2nd column – B0506+056, OJ287, B1510−08. Average high-frequency components are the proton jets spectra in the Hedgehog model (see details in Kovalev et al. 1999; Kovalev & Mikhailutsa 1980; Kovalev et al. 2000, 2020; Sotnikova et al. 2022; Kovalev et al. 2022; Vlasyuk et al. 2024). The estimated physical parameters of proton jets for these 6 objects and B1616+045, 3C454.3, B0954+65, B0235+16, B1159+29 are as follows: magnetic field $B \sim (10^3$–$10^4)$ G, brightness temperatures $T_b \sim 10^{13}$–10^{14} K, angular sizes $\Theta \sim$ (0.03–0.003) mas. Several objects may have an additional component at frequencies above 100 GHz. If we neglect losses, the Faraday acceleration mechanism allows protons to accelerate in the vicinity of a supermassive black hole to energies of $Ep \sim \Delta B * R * e/2 => 10^{21}$ eV (at $\Delta B \sim 10^4$ G, $R \sim 10^{15}$ cm). Then the neutrino energy is $E_\nu \sim E_p/20$ (see Kovalev et al. 2022; Troitsky 2024). The observational data from RATAN-600 in the frequency range 1–22 GHz for the period from 1997 to 2025 were used. The CATS data (Verkhodanov et al. 2005) contain all data outside this frequency range. The label "sp-fit" to some windows is the name of the program for fitting model spectra.

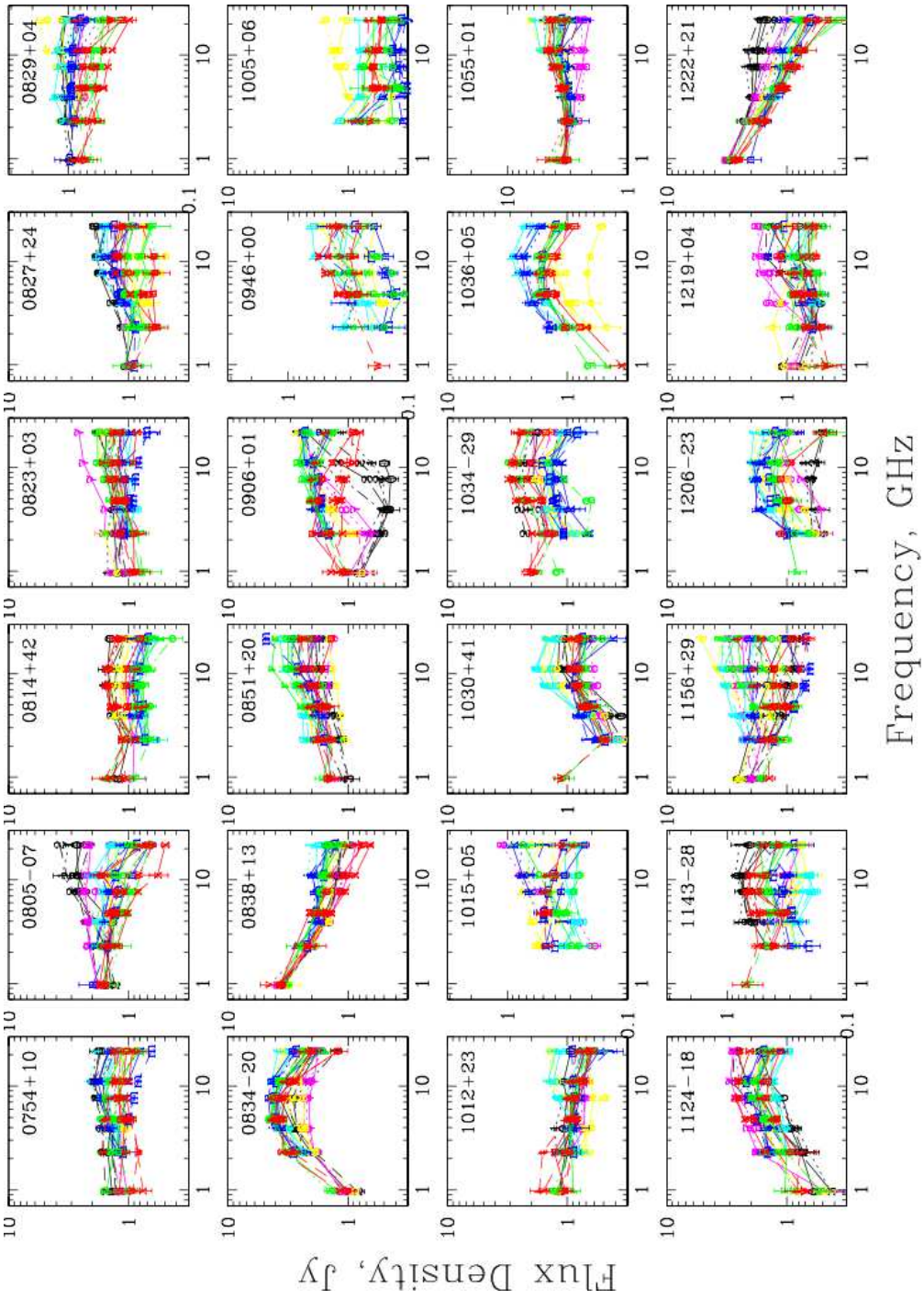

Figure 5. An example of 24 out of 144 AGNs with the strong variability of RATAN-600 1–22 GHz spectra in 1997–2008. It can be expected that such variability is generated also by proton jets. We plan to test this hypothesis similarly to Fig. 4.

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