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Long-Term and Rapid Variability of the Radio Source J1603+1105

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Abstract—We present the long-term light curve of the radio source J1603+1105 and results of the study of its variability on timescales from several days to several weeks. From 2007, a flare with the maximum in 2010 was observed for the object that earlier showed no significant variations of flux density. Three flares with a successively decreasing amplitude were detected at an active phase in the long-term light curve. The characteristic time of the first one was 2.5 yrs. In five sets of daily observations of 95 to 120 days, the flux density variability on scales from 9 to 32 days in 2011, 2012, 2015, and 2016 was detected; in 2015 it was detected at three frequencies simultaneously. In 2011, the variability was found at a single frequency of 4.8 GHz; in 2012—at two frequencies, 4.8 and 7.7 GHz; in 2015—at 4.6, 8.2, and 11.2 GHz. We present instant spectra of the source at different flare phases showing that the dynamics of the flare development is consistent with the model, in which the variability is the result of the shock wave evolution in the radio source jet.

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1. INTRODUCTION

The radio source J1603+1105 was detected in the MGB survey [1]. Its galactic latitude is $|b| = 42°$. From the 13th edition of the catalog of quasars and active nuclei, the source is classified as BL Lac object with a magnitude of $V = 18\overset{\mathrm{m}}{.}3$ and a redshift of $z = 0.143$ [2]. However, the redshift is $z = 0.3855$ from the SDSS[1] catalog with no significant lines in the spectrum. Additional studies are needed to reliably determine the redshift of an object identified with J1603+1105.

In 2005, the source was observed with the VLA in the range of 1.4–22 GHz, where its spectrum was flat [3]. From observations of J1603+1105 at the 40-m Owens Valley telescope 08.2008–04.2009, the flux density was 250–280 mJy at 15 GHz [4]. In 2006–2008, the source was observed at RATAN-600 in the range of 1–21.7 GHz [5]; flux densities from these data are close to those we obtained in corresponding epochs.

We monitored the source at the RATAN-600 radio telescope within the sample of objects with the flux densities $S > 200$ mJy from the GB6 catalog in the declination range of $10°$–$12°30'$ (J2000) at the right-ascension interval of 0^{h}–24^{h} from November 2001. Observations were carried out at five frequencies in the range of 2.3–21.7 GHz. We presented the results of studying this sample up to 2010 in papers [6–8].

During seven years, the source J1603+1105 showed no significant variability, its flux density at all frequencies did not exceed 0.25 Jy, and the spectrum was almost flat. From 2008, the flux density began to increase at all frequencies; the maximum of the flare was observed in October 2010, the maximum flux density was 0.6 Jy at 21.7 GHz. A series of flares with successively decreasing amplitude were detected up to 2016.

Variability from several days to a month was studied in daily observing runs up to 105 days. The results obtained are presented in this paper.

2. OBSERVATIONS AND DATA REDUCTION

Observations of the source J1603+1105 were carried out in 2001–2002 and from 2006 at the Northern sector of RATAN-600 simultaneously at frequencies of 2.3, 4.8 GHz (from 2014— 4.6 GHz), 7.7 GHz (from 2013—8.2 GHz), 11.2 and 21.7 GHz. In 2003–2005, we did not observe the source because of technical works at the telescope; furthermore, the matter of priority at that time was the study of the

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source J1608+1029 close by coordinates and having considerable long-term and rapid variability. From 2011 to 2015, there were no observations at 2.3 GHz due to industrial interferences. They were continued from 2015 at a frequency of 2.27 GHz.

For data reduction, we used the a program package allowing us to obtain both the flux density during a single observation of the source and the average flux density during any interval within the period of observations. The reduction technique was based on the optimum filtration of initial data, it is described in more detail in [6]. Section 3.2 describes the method of studying the rapid variability.

With the purpose of studying the source variability on scales from several days to a month, we conducted daily observations: in 2011—from July 01 to October 03, in 2012—May 01—August 15, in 2013—May 18—September 15, in 2015—June 15—September 05, and in 2016—June 13—September 15. We have used J1347+1217 as a calibration source, the spectrum of which is approximated with a straight line with flux densities of 1.46, 1.99, 2.3, 2.36, 2.99, 4.12, and 4.15 Jy at frequencies of 21.7, 11.2, 8.2, 7.7, 4.6, 2.3, and 2.27 GHz respectively. We controlled the changes of the antenna effective area using other sources with constant flux density.

3. RESULTS

3.1. Long-Term Light Curve

In 2001—2002 and 2006, we did not detected any significant variability of the source. From 2007, the flux density began to increase and attained its maximum in October 2010. The first flare was followed with two more flares with smaller amplitudes each of which developed at the decay of the previous one. Figure 1 gives the light curves of J1603+1105 at frequencies of 21.7, 11.2, 8.2, 4.6, and 2.3 GHz from our observations from June 2001 to September 2016. For long sets in 2011, 2012, and 2013, the flux densities are given for the beginning and the end of observations. Flux densities at 7.7 GHz up to 2013 are recalculated to a frequency of 8.2 GHz. Due to significant variability of the source during the observing run of 2015, average flux densities are given in the long-term light curve.

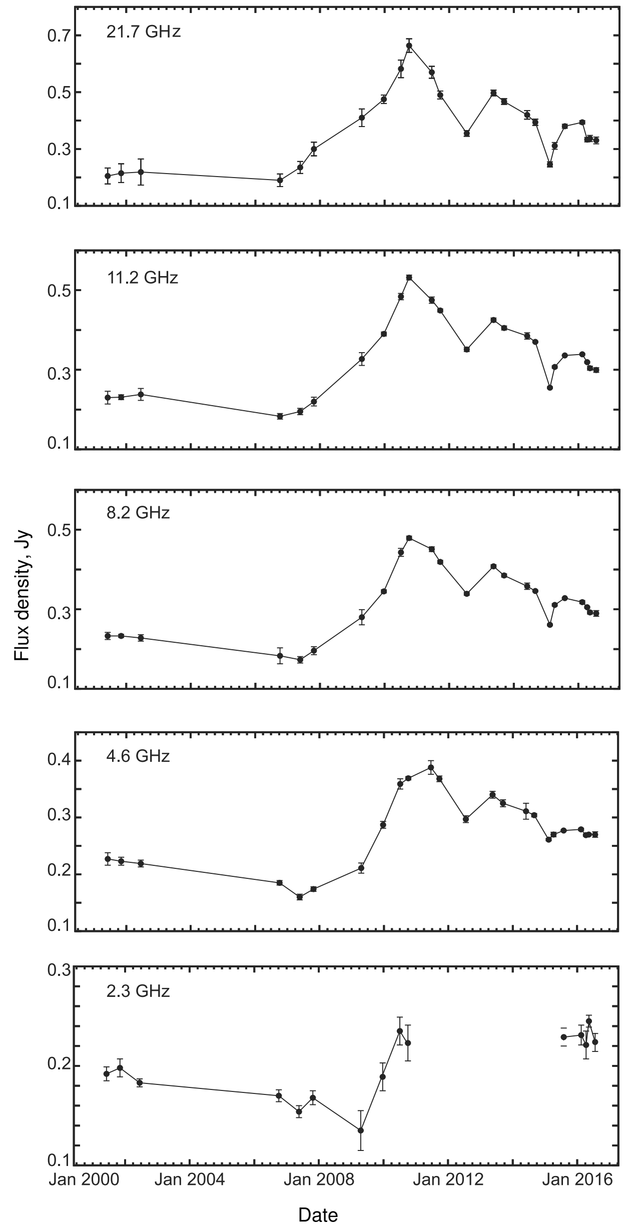

Fig. 1. Light curve of J1603+1105 obtained at RATAN-600 in 2001—2016.

Light curves at all frequencies are almost identical. From the ascendant part of the first flare, we estimated its time scale, $\tau_{\rm var}$. We used the method suggested in [9] in order to derive it. This value remains constant in case when the flux density variation during the flare is exponential.

In practice, the characteristic time is determined in the following way. The half of the flux density detected immediately before the beginning (or directly after the end) of the flare is subtracted from the data. If there are several data points in the light curve between the beginning (or the end) and the maximum of the flare, then dt_i is calculated for each one as a time interval between the beginning (or the end) of the flare and the moment of observation S_i, and the value $d\ln S_i$—as the difference between the flux density logarithms at the corresponding moments. The $\tau_{\rm var}$ value is derived as an average of all the measurements. Subtraction of the half of the flux density before the beginning of the flare allows us to take into account at least some part of the quasi-polar component which is determined by

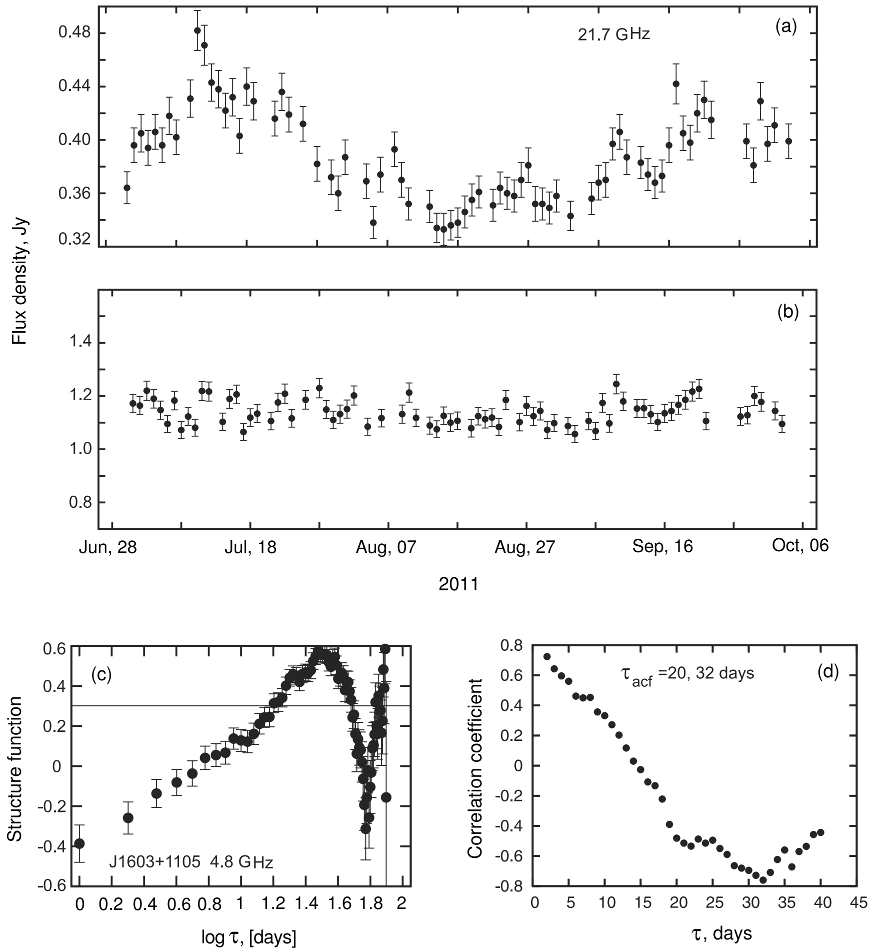

Fig. 2. Light curves of J1603+1105 (a) and of the constant source J1640+1220 (b), structure (c) and autocorrelation (d) functions obtained in the observational set in 2011 at a frequency of 4.8 GHz.

the superposition of some average density of the jet flux and old far evolved flares.

We estimated that the ascendent part of the first flare of the source J1603+1105 is close to exponential. The characteristic time of the process along its ascendent branch is $\tau_{\rm var} = 2.5$ yrs.

3.2. Rapid Variability of the Source

To search for variability on timescales of a day at least in the objects from two samples in the declination range of 4°−6° (B1950.0) and 10°−12°30′ (J2000.0) [8, 10], we used the method described in detail in [10].

Here we list the main steps in brief.

First, we filtered the measured flux densities distorted by interference of various kinds (due to weather conditions or industrial factors) using the Fisher criterion.

Then we removed the long-term variability (approximated by a parabolic or linear trend) with characteristic times greater than the duration of observations.

We determined the average flux density at all frequencies over the observing set.

Variability characteristic times were roughly estimated by the shape of first-order structure functions (SF)

$$D^1(\tau) = \langle [f(\tau) - f(t+\tau)]^2 \rangle,$$

where τ is a time shift.

If there is a non-noise component, then above the instrument noise level the SF increases according to a power law until it approaches the saturation level characterizing the total dispersion of the process. The intersection of the power-law segment and the saturation level gives the time scale $\tau_{\rm sf}$.

We also uses structure functions to derive the dispersion of the variable component:

$$\sigma^2_{\rm var} = \sigma^2_{pr} - \sigma^2_n,$$

where $\sigma^2_{pr} = \sum_{i=1}^{n} (S_i - \langle S \rangle)^2/(n-1)$ is the process dispersion; $\langle S \rangle$ is the mean flux density averaged over

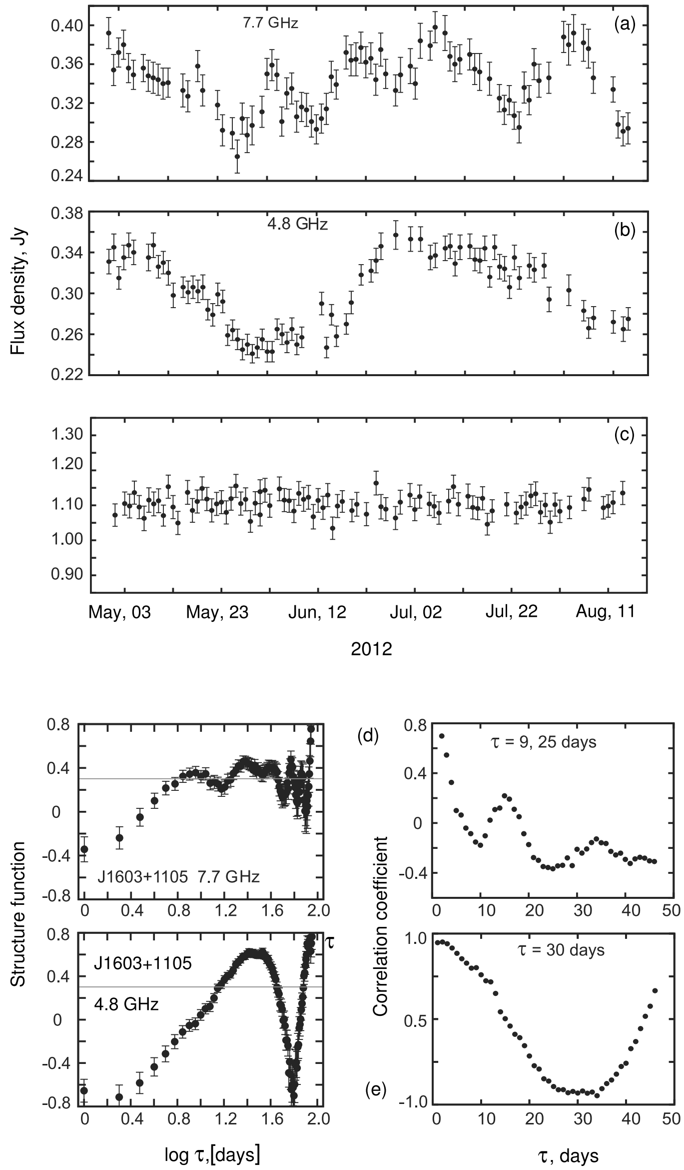

Fig. 3. Light curves of J1603+1105 at frequencies of 7.7 (a) and 4.8 GHz (b), of the constant source J1640+1220 at 4.8 GHz (c), structure and autocorrelation functions of J1603+1105 at frequencies of 7.7 (d) and 4.8 GHz (e), in the observational set in 2012.

the entire observing run; $\sigma_n^2 = D^1(1)/2\ 2$ is the dispersion of the noise component; $D^1(1)$ is the value of the SF for a one-day time shift.

We characterize the variable component by the modulation index defined as $m = 100\sigma_{\rm var}/\langle S\rangle$.

We also calculated the autocorrelation functions (ACF) and used them to accurately estimate the variability time scale $\tau_{\rm acf}$ from the correlation minima.

We assumed that the significance level of the main process should not exceed 1%. The significance level of other processes can be higher in this case.

Judging from the form of the ACF, one can determine not only the time scale but also characteristics of the variability, particularly, whether the process is periodic, represents one or more random flares, or combines both of these processes.

We also determined time lags of maxima at the frequencies under study using the cross-correlation functions.

Let us consider the results of the rapid variability study by years.

During a long run of daily observations in 2011 at 4.8 GHz, we detected variability with the modulation index $m = 0.08$. In the light curve (Fig. 2a), we can see one main period, the timescale $\tau_{\rm acf} = 32$ days. Moreover, an additional process with $\tau_{\rm acf} = 20$ days and considerably smaller amplitude can be seen in the diagrams of structure and autocorrelation functions

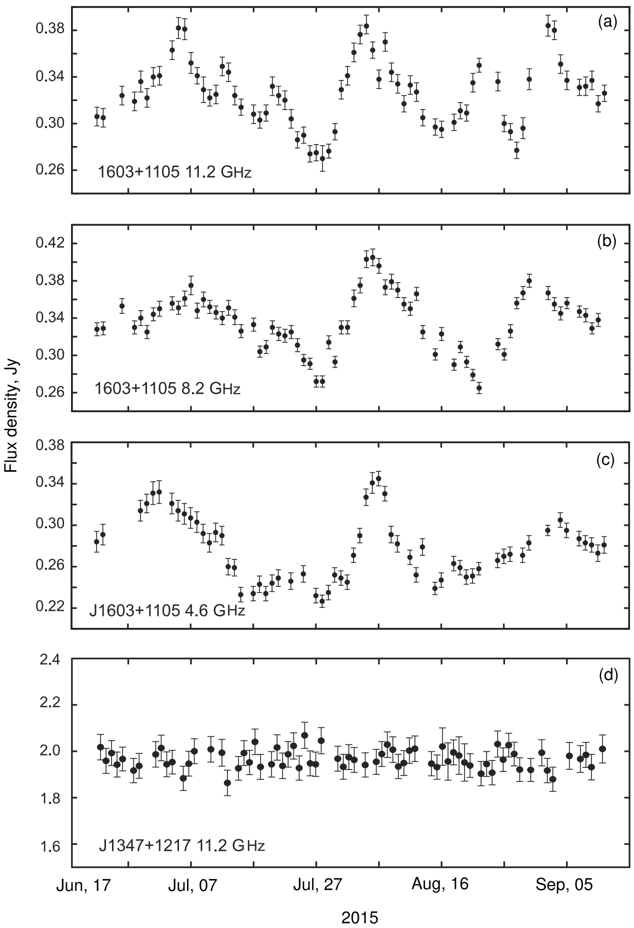

Fig. 4. Light curves of J1603+1105 at frequencies of 11.2 (a), 8.2 (b), and 4.6 GHz (c) and of the reference source J1347+1217 at 11.2 GHz (d) during the observing set of 2015.

(Fig. 2c, d). Figure 2b presents the light curve of the constant source J1640+1220 close by the right ascension for comparison.

Figures 3a and 3b show the light curves in the set of 2012 at 7.7 and 4.8 GHz respectively. Completely different characters of variability are obvious. At 7.7 GHz during one observing run, we detected five maxima of the light curve with the characteristic time 10 days and one process with the characteristic time 25 days. The modulation index at this frequency is $m = 0.075$. At 4.8 GHz, a single wave is observed with $\tau_{\rm acf} = 30$ days and the modulation index $m = 0.105$. Figure 3c shows the light curve of the permanent source J1640+1220 by comparison. Figures 3d and e present the structure and autocorrelation functions of J1603+1105 at frequencies of 7.7 and 4.8 GHz.

In 2003, the flux density variability at the accepted significance level was not found.

In the observing run of 2015, we detected considerable variability of the source at frequencies of 11.2, 8.2, and 4.6 GHz. Figure 4a–d presents the light curves built. As a comparison, we give the light curve of the reference source J1347+1217. It can be seen that the variability at all frequencies is quasi-periodic, the light curves are correlated to a large extent. The structure and autocorrelation functions (Fig. 5a–d) yield similar characteristic time at frequencies of 11.2 and 8.2 GHz. At a frequency of 11.2 GHz, a process can be detected having small amplitude and a time scale of seven days apparently caused by a local flare with the maximum on July 20. At a frequency of 4.6 GHz, the process shows two characteristic times, 10 and 16 days with similar amplitudes. Two plateaux are also seen at 4.6 GHz in the structure-function diagram.

Figure 6a shows cross-correlation functions between frequencies 11.2–8.2 and 8.2–4.6 GHz. A small time lag can be seen between these frequencies which does not exceed two days.

The cause of variability on short scales can be both internal—processes inside the source, and external—scattering on inhomogeneities of the interstellar medium. It can be possible to distinguish between these kinds of variability when observing at several frequencies. The spectrum of the variable component growing towards high frequencies and time lags of maxima at various frequencies are indicative of the internal factor—processes inside the source, while the spectrum of the variable component decreasing towards high frequencies and the absence of time lags at various frequencies are indicative of the external factor of variability—scattering on inhomogeneities of the interstellar and intergalactic medium.

From the data at three frequencies, we obtained almost flat spectrum of the variable component. Such a spectrum does not make it possible to unambiguously determine the cause of the detected variability: whether it is internal or external, conditional on the interstellar medium.

Unfortunately, very bad weather conditions and partially instrumental disorders during the run in 2016 did not allow us to study and analyze the flux density variability of the source to the full extent. Surely, there is variability at frequencies of 8.2 and 4.6 GHz, but its detection significance is smaller than the accepted. Although, time scale can be determined from structure and autocorrelation functions [2]. Figures 6b, c show the diagrams of these functions. There are components with time scale of 5 and 15 days at both frequencies.

[2]Characteristic times of the variability of a process can be determined both from structure and autocorrelation functions, although, the latter gives a more accurate result and allows the character of variability to be determined.

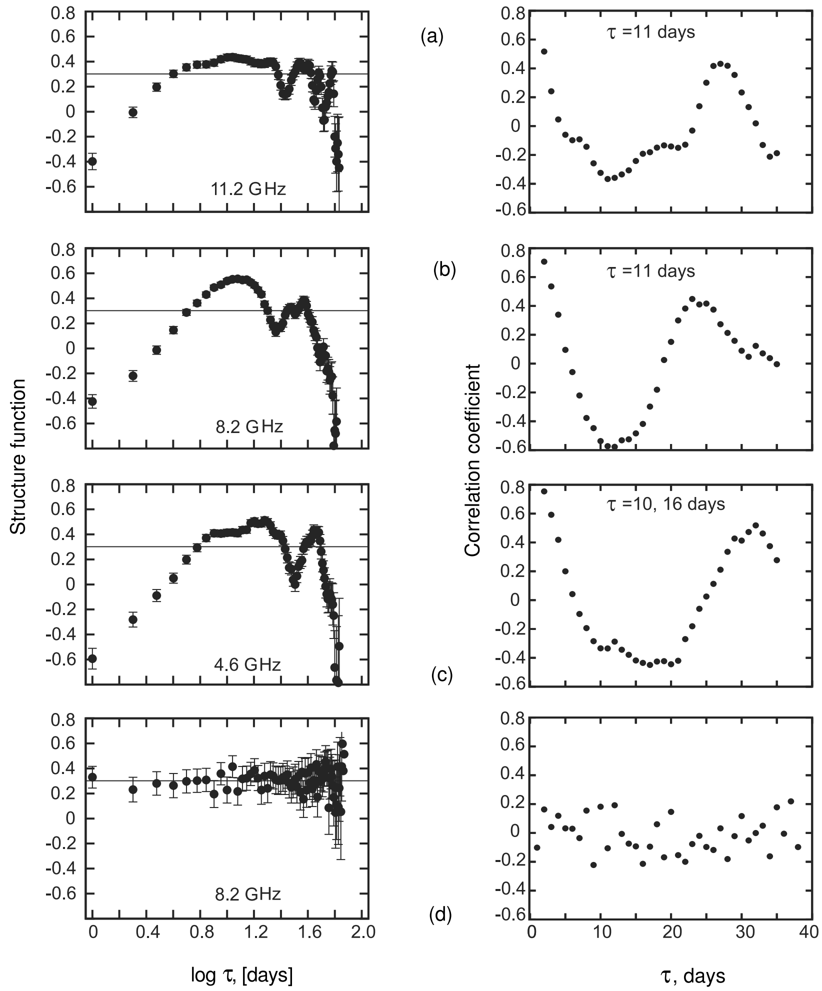

Fig. 5. Structure and autocorrelation functions of J1603+1105 at frequencies of 11.2, 8.2, and 4.6 GHz (a–c) and the same for the reference source at a frequency of 8.2 GHz (d).

3.3. Spectra of the Source

We obtained the spectra of the source in different phases of flares and also in the minimum, maximum, and intermediate section of the ascendent curve of the flare during the long run in 2015 (see Fig. 7).

Observations in 2001 and 2006 showed that the variability is weak, the spectra are almost flat (Fig. 7a).

Figure 7b presents the spectra at the beginning (May 2007) and in the middle of the ascending branch (April 2009) of the first maximum. One can notice the consistent growing of the spectral index from $\alpha_{4.8-11.2} \approx +0.16$ to $\alpha_{4.8-11.2} \approx 0.55$.

Figure 7c shows the spectrum of the source in the maximum of the first flare (on October 5, 2010) and from two measurements before and after it. The frequencies of the maximum of the spectrum have been determined by approximating the observed data obtained on the given dates and are equal to 33, 50, and 15 GHz respectively. There is obvious evolution of the spectrum with time, i.e., radiating the flare off at high frequencies.

Figure 7d gives the spectra of J1603+1105 at the beginning, in the middle, and at the end of the second flare. In the maximum of the second flare, the spectrum is rising with an index of $\alpha_{4.8-11.2} \approx 0.17$, at its end—decreasing: $\alpha_{4.8-11.2} \approx -0.06$.

Figure 7e shows the spectra of J1603+1105 in the minimum and maximum of the phase of rapid variability in 2015, on July 27 and August 03 respectively. The power-law spectrum was obtained in the middle of the ascending branch of the flare on July 30, 2015 ($\alpha = 0.22$).

Figure 7g presents the spectra of the third flare. One can see the power-law ascending branch, gradual decline in the flux density, and gradual shifting of the maximum in the spectrum towards the operating range.

The study of the light curves an spectra of J1603+1105 in different phases of activity showed

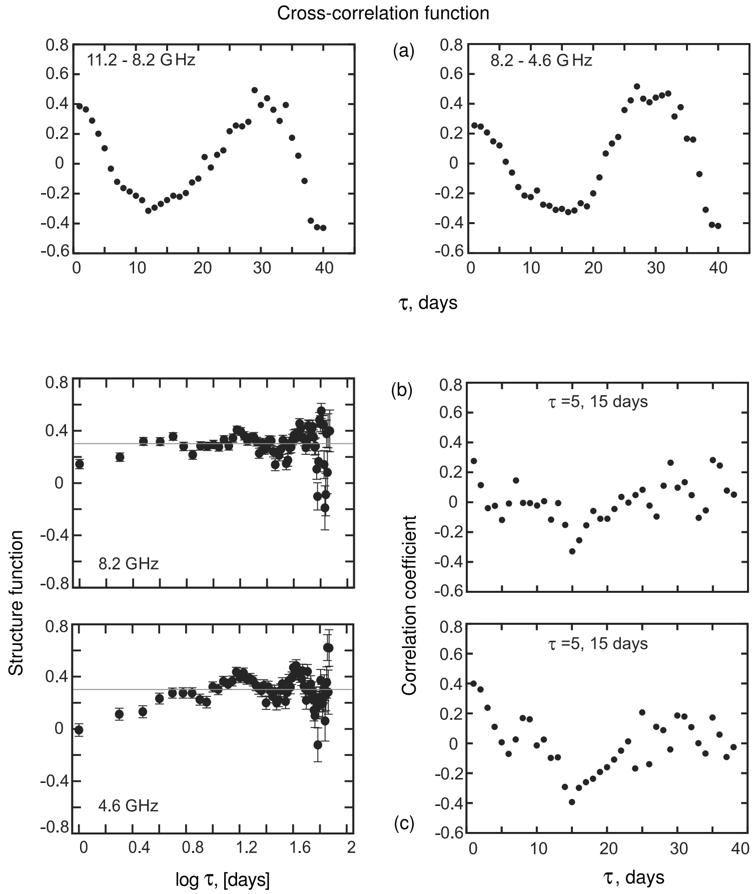

Fig. 6. Cross-correlation functions between frequencies 11.2–8.2 and 8.2–4.6 GHz (a); structure and autocorrelation functions of J1603+1105 at frequencies of 8.2 (b) and 4.6 GHz (c) during the set of 2016.

that in most cases the dynamics of the flare development complies with the model, in which the variability is the result of the shock wave evolution in the radio source jet.

4. CONCLUSION

In the long-term light curve of the J1603+1105 source, we detected the flash of flux density which almost did not change for 7–8 years. The period associated with the active phase represents three flares, every subsequent one of which was of smaller amplitude and developed at the decay of the previous one. The variability characteristic time along the ascending branch of the first flare is $\tau_{\rm var} = 2.5$ yrs.

During long runs of daily observations of the source, we have detected the rapid variability in 2011 at 4.8 GHz only; the process has two characteristic times, $\tau_{\rm acf} = 20$ and 32 days, the modulation index $m = 100\sigma_{\rm var}/\langle S\rangle = 0.08$.

In 2012, significant rapid variability was found at frequencies of 7.7 and 4.8 GHz. The modulation indices at 7.7 and 4.8 GHz are $m = 100\sigma_{\rm var}/\langle S\rangle = 0.08$ and 0.105 respectively. At 4.8 GHz, the process represents a single wave with the time scale of $\tau_{\rm acf} = 30 \pm 2$ days; at 7.7 GHz, the flux density variations are chaotic, five maxima can be observed, average time scales of variability are 9 ± 0.5 and 25 ± 1 days.

In 2013, the variability matching the accepted criteria was not found.

In 2015, we detected the variability of the source at frequencies of 11.2, 8.2, and 4.6 GHz; all the processes are quasi-periodic with $\tau_{\rm acf} = 10$–11 days. One can notice one more process at a frequency of 4.6 GHz with $\tau_{\rm acf} = 17 \pm 2$ days, most likely caused by the long third flare. The time lag between frequencies of 11.2–8.2 GHz and 8.2–4.6 GHz does not exceed two days. From three frequencies, the reference spectrum of the variable component is close to flat within error. The data obtained do not allow one to unambiguously determine if the detected variability is caused by an internal factor or an external one, conditional to the interstellar medium.

In 2016, we detected the variability with a characteristic time of about 15 days at frequencies of 8.2 and 4.6 GHz, but the significance of the result is lower

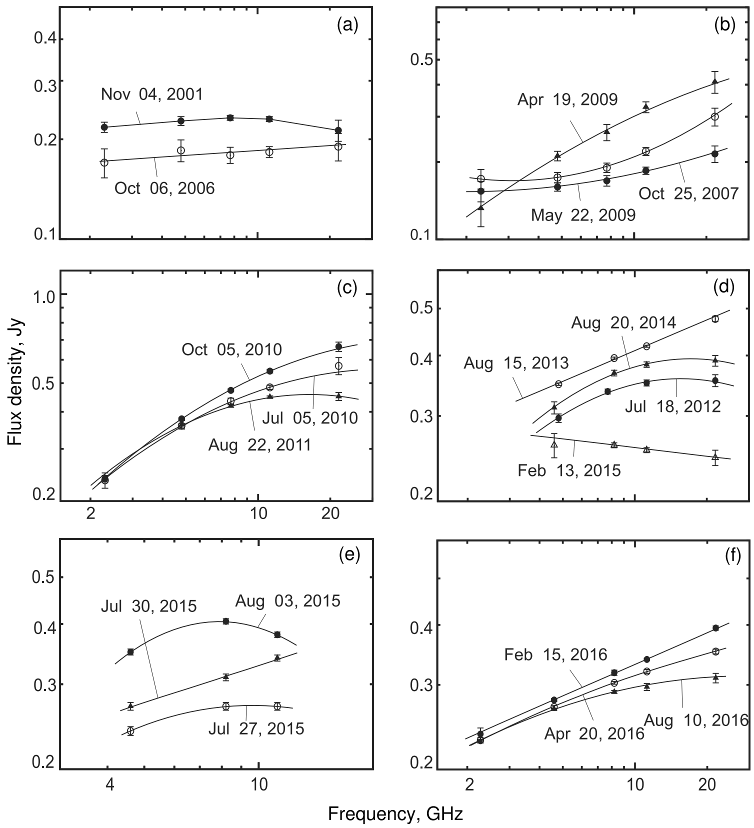

Fig. 7. Spectra of J1603+1105 in different phases of the activity of the source. See the text for further details.

than the stated mainly due to weather conditions and instrumental problems.

The spectra obtained in different phases of the flares yield a typical pattern showing that the flare development dynamics is consistent with the model, in which the variability is the result of the evolution of a shock wave in the radio source jet.

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