STUDY OF SATURN ELECTROSTATIC DISCHARGES IN A WIDE RANGE OF TIME SCALES

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ABSTRACT. Saturn Electrostatic discharges (SED) are sporadic broadband impulsive radio bursts associated with lightning in Saturnian atmosphere. After 25 years of space investigations in 2006 the first successful observations of SED on the UTR-2 radio telescope were carried out [1]. Since 2007 a long-term program of ED search and study in the Solar system has started. As a part of this program the unique observations with high time resolution were taken in 2010.

New possibilities of UTR-2 radio telescope allowed to provide a long-period observations and study with high temporal resolution. This article presents the results of SED study in a wide range of time scales: from seconds to microseconds. For the first time there were obtained a low frequency spectrum of SED. We calculated flux densities of individual bursts at the maximum achievable time resolution. Flux densities of most intensive bursts reach 4200 Jy.

Key words: electrostatic discharges, microstructure, flux density, dispersion delay

Introduction

The study of thunderstorm activity in planet atmospheres in the solar system is the new direction in the planetary astrophysics. For the last seven years both of ground-based and space observations made a great progress in ED study. Cassini space craft (SC) monitoring and new UTR-2 results provided gives new findings storm activity seasonality, episode variations of frequency characteristics, microsecond time structure.

Due to the modernization of the receiving equipment on the UTR-2 radio telescope it became possible to study the SED with high temporal resolution, as well as long-time observations give the opportunity to study hourly variations of lightning activity.

The interest to high time resolution SED study is caused by several reasons. The main one is that it can provide more deep investigation of SED nature. Only in 2009 there were finally established that SED is a radio emission from lightning. There were first detected optical flashes simultaneously with SEDs in Saturn atmosphere in the time of spring equinox [2]. But we still don't know what kind of lightning they are. The most common suggestion is intra-cloud lightning. Moreover, SED study with high time resolution gives us opportunity to investigate energy characteristics of SEDs.

This paper present the results of observation of Saturnian storm called J conducted in 2010. The storm J was a fascinating and incredible phenomenon [3], the largest and one of the longest storms in SED investigations history. CS Cassini registered the peak number of bursts and the most powerful bursts. The last one is very important for ground-based high time resolution studies.

Observations and data processing

Search of wide-band cosmic signals in presents of earth lightning and different nature interference, is a very difficult task. Therefore, we use a number of methods [4,5] to confirm the origin of cosmic signals.

UTR-2 can provide simultaneous observations with 5 spatially separated beams. To select the signal from direction toward the source (i. e. Saturn) we use ON-OFF mode of observation when the third (central) beam of UTR-2 telescope is pointed at the source, and the fifth-no.

We used correlation recording mode for observation with time resolution of 20 milliseconds. We use such time resolution for data volume compressing and increasing of sensitivity of the radio telescope in comparison to waveform mode. The ability of back-end facility of UTR-2 to record large amounts of data allows carrying out several hours lasting observations. The average length of a single recording was 6-6.5 hours (except waveform mode). That gives us the possibility to keep track of the full period from the rising and setting of the planet without any a priori information about phase of storm (longitude of storm source on the Saturn's surface).

We used 3 receivers for observations in December 2010 session. Two receivers were in correlation mode to provide ON-OFF regime respectively. This data were used for SED identification and search of extremely high intensity bursts. Such regions were found in the record for 23 December [7]. The third digital receiver was in the waveform mode with data time resolution of 15 ns. The third receiver was used to record only signals from the third beam.

Automatic search was provided by the multichannel algorithm described in details in [4]: signal is detected only in case of its presence in 2 or more sub-bands (bandwidth of sub-band is equal 1 MHz) with limit 4σ. According to the Voyager and Cassini data the maximum duration of the signal was determined as 500 ms. In our algorithm the duration of detectable signals should not exceed this value.

After identification of SED signals with time resolution 20 ms there were conducted high time resolution study. Below there are some estimations of expected flux densities of registered signals.

As a minimum detectable flux density value we use the 4σ - level:

$$4\sigma = \frac{4 \cdot 2kT}{A_e\sqrt{\Delta f \Delta t}} , \qquad (1)$$

where k – is the Boltzmann constant, T is the galactic background temperature (30000K at 20 MHz considering the Saturn position for 23 December 2010), A_e is the effective area of the UTR-2 in Saturn direction on 23 December 2010 (declination -4° 11′ 09″) (90000 m^2), Δf and Δt, are bandwidth and time resolution, respectively. For frequency band 1 MHz and time resolution 20 ms (in correlation mode) we have 4σ flux density level equal to 26 Jy. For waveform mode: in case of accumulation by a factor of 16 (time resolution 484 ns) and for 14 MHz frequency band the 4σ - level equals to 2000 Jy. From this calculation, it follows that parts of records (selected according to results of detection in low time resolution data), where the signal-to-noise ratio (S/N) varies from a few dozen to hundreds are perspective for studying with microsecond time resolution.

To resolve SED fine structure we had to modernize multichannel algorithm. We used only the strongest SEDs choosing by criterion discussed above. For data analysis we used different time scales: subsecond, submillisecon and microsecond time resolution.

Results and discussion

Figure 1 shows the spectrograms of lightning at different time scales. The top panel shows the sequence of several bursts with a typical duration of tens of milliseconds. This coincides with a time measured for SED according to Cassini and ground-based measurements [4,8,9].

In the paper [10] there are considered two possible variants of Saturnian lighting nature: a superbolt variant when the fine time structure of SED consists of several tens of microseconds peaks with the energy 1013 J of one burst. And second one - if those tiniest peaks have one-microsecond duration, when the total energy decrease to 107 J. In figure 1 on the middle and lower panels it shown the internal structure of lightning with millisecond and microsecond time resolution. An important result is that the SED consists of short (about one hundred microseconds) discharges of varying intensity. When passing to microsecond resolution (lower panel), a fine structure is almost indistinguishable or absent.

On the spectrograms in figures 1, 2 it can be clearly seen a time delay between high (fmax) and low (fmin) frequencies. It is a propagation delay t (due to dispersion phenomenon) in ionized medium (ionospheres of the Saturn and Earth, and interplanetary medium), that is equal [11]

$$t = 10^{16} \cdot \frac{DM}{2.410331} \left(f_{\min}^{-2} - f_{\max}^{-2}\right) , \qquad (2)$$

where DM is "dispersion measure" in pc cm^{-3}. For DM = 4 10^{-5} pc cm^{-3}, $f_{\max}$ = 33.0 MHz and $f_{\min}$ =16.5 MHz the value of this propagation delay is several hundred microseconds.

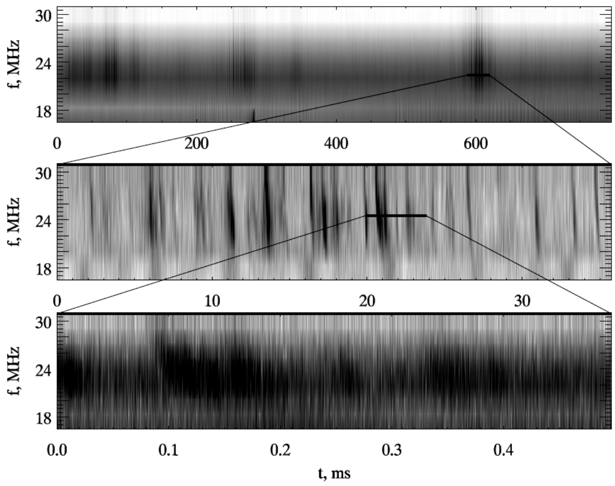

Figure 1. Different time scales of SEDs

The dispersion observed in fine time structures is both the SED criteria and the confusing factor for SED characteristics investigations.

At higher frequencies earth lightning signals are reflected from higher layers of earth ionosphere and pass longer trace than at lower ones. Terrestrial lightnings fully light up and are not detectible for ground-based equipment at frequencies where the Earth's ionosphere becomes transparent. As a result they have cut-off at some frequency and also the delay at high frequency in contrast of dispersive delay (2) of SED spectra [12].

Time delay of the signals at different frequencies leads to "smearing" of the lightning fine structure. Therefore, we applied a coherent method of removing the dispersion delay [12]. After this step, we can improve the S/N ratio with the aid of the signal accumulation by time or frequency.

For the first time, we obtain the lightning low-frequency spectrum. In figure 2 the time sequence (the bottom panel) and the result of its FFT (the top panel) are shown. This result is valid if SED spectrum is plain and has no peculiarities in radio band and we can estimate some features of that spectrum.

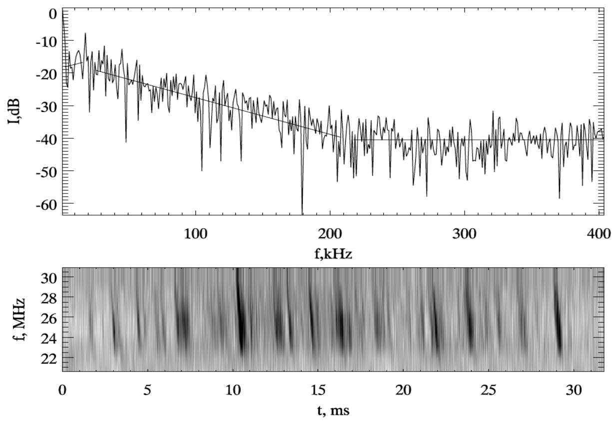

Figure 2. Low frequency spectrum of 32 milliseconds record

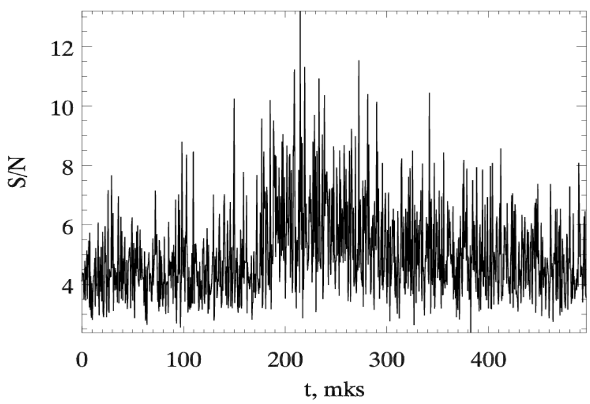

Figure 3. The example of fine time structure of SED. Burst profile in frequency band 14-28 MHz.

As we can see Saturnian lightning have similar frequency characteristics as earth ones [13]. Terrestrial lightning have the maximum power at frequencies near 7 kHz. Above that frequency the spectrum drops as f^{-1} up to 40 kHz, and f^{-2} above 100 kHz [13].

Characteristics of the SED, defined from Fig. 2 are next. Spectral index defined in the frequency range 20 ... 200 kHz is approximately equal to –2. The maximum intensity is close to 17 kHz. Above 200 kHz the power of SEDs is masked by external noise. To increase the sensitivity the accumulation of a large number of lightning in a high-frequency part (200 kHz and above) is required. The obtained results also show that the elements of the temporal structure of lightning (with typical durations of the order of a microsecond) are a small contributor to the total power. The main part of power has the components of a typical duration of hundreds of microseconds. It also speaks in favor of the fact that the total energy of lightning is about 10^{12}... 10^{13} J [10].

Signal accumulation by frequency results in a higher sensitivity (1). It is necessary to find a compromise between increasing the time resolution and maintaining sensitivity. To search for a microsecond elements in the time structure, we have chosen Δt = 484 ns. Only SC Voyager-1 could record data with Δt = 0.1 ms. Although the microstructure was not identified, but it has been concluded that it probably exist.

Figure 3 shows the structure of the individual bursts. The burst consists of a great number of short peaks. Attempts to find unresolved counts (intensity of the nearest points falling down in e times) in the most intense lightning did not lead to positive results. Thus, we can assume that, for time resolution of 484 ns, the fine structure of SED was resolved.

As mentioned in [4], increasing of the time resolution will reveal the most intensive bursts. In our data their intensity reaches approximately to 4200 Jy.

Conclusion

The ground-based observations of storm J in 2010 extended our knowledge of the possibility of ground-based studies of extraterrestrial planetary lightning.

The results accumulated to date have several points. For the first time there were resolved SED signals with submicrosecond time resolution. There have been found a multilevel structure of SED signals. The submillisecond structure (signals with a typical duration of the order of 0.1 ms) first was identified together with the well-known millisecond structure. The presence of the microsecond structure, which gives a significant contribution to the total radiation power of the lightning, is questionable. The achieved signal-to-noise ratio shows that the number of unresolved microsecond bursts in the records is very low or even zero.

For the first time there were obtained a low frequency spectrum, and its character is in good agreement with the existing theory (for terrestrial lightning) and observations.

Thus, the ground-based observations with the UTR-2 radio telescope give us the unique opportunity to explore the lightning on Saturn over a wide range of time scales: from long-term SED variations investigations to fine time structure study.

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