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SPECTRAL FEATURES OF A SINGLE TYPE III BURST OBSERVED BY PSP ON 04.06.2020

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ABSTRACT. Spectral features of single Type III burst observed by PSP on 4 June 2020 in the frequency range 1.4–19 MHz are studied. This burst was also observed by radio telescopes URAN-2 and GURT in the frequency band 10–70 MHz (Melnik et al., 2024). At the first time the velocity spectrum of electrons, which responsible for the radio emission of different bursts levels, was found in the wide frequency band because this Type III burst was fairly powerful. The duration dependence as well as the flux dependence on frequency was analyzed in the frequency band of 10–70 MHz. This paper is the extension of the previous paper with the aim to expand essentially the frequency band using PSP observations. The discussed burst is also fairly powerful one at the frequencies 1.4–19 MHz so the analyzing procedure can be repeated for these frequencies as well. Comparing the obtained results with previous ones shows that the velocity spectrum is practically unchanged. The duration-frequency dependence is almost the same too. At the same time behavior of the burst flux at the frequencies of 1.4–19 MHz is essentially differed of it in the common band of 10–19 MHz even. According to PSP data the burst flux is decreased with decreasing frequency in this band, but not increased as follow to URAN-2 – GURT data. We associate it with the fact that PSP and URAN-2 – GURT observed this burst from different directions.

Keywords: PSP, URAN-2, GURT, Type III burst, drift rate, duration, flux, electron velocity, beam-plasma struc-ture.

АНОТАЦІЯ. В роботі вивчаються спектральні характеристики поодинокого сплеску III типу, що спостерігався космічною місією PSP 4 червня 2020 року в частотному діапазоні 1,4–19 МГц. Цей сплеск також спостерігався, але в діапазоні 10–70 МГц, українськими радіотелескопами УРАН-2 та ГУРТ (Melnik et al., 2024). З тієї причини, що він достатньо потужний, вдалось вперше знайти швидкісний спектр електронів, які відповідають за радіовипромінювання на передньому та задньому фронтах, а також в максимумі сплеску в широкому діапазоні частот. Також була досліджена залежність тривалості сплеску та його інтенсивність від частоти в полосі частот 10–70 МГц. Дана робота є продовженням попередньої роботи з метою суттєво розширити частотний діапазон аналізу, використовуючи дані отримані PSP. В діапазоні частот 1,4–19 МГц сплеск також досить потужний, тому вдається практично повністю повторити процедуру і для цього діапазону. Порівняння отриманих результатів з попередніми показує, що швидкісний спектр електронів практично не змінюється. Це ж стосується залежності тривалості від частоти. В той самий час потік сплеску на частотах 1,4–19 МГц значно відрізняється від поведінки навіть в загальній полосі 10–19 МГц. За даними PSP потік не тільки не збільшується із зменшенням частоти як було за даними УРАН-2 та ГУРТ, а повільно зменшується. Ми пов’язуємо це з тим, що цей сплеск спостерігався PSP та радіотелескопами УРАН-2 та ГУРТ з різних напрямків.

Ключові слова: PSP, УРАН-2, ГУРТ, сплеск III типу, швидкість дрейфу, тривалість сплеску, потік сплеску, швидкістьрухуелектронів,пучково-плазмове утворення.

1. Introduction

Solar Type III bursts are the important part of sporadic radio emission of the Sun (Suzuki & Dulk, 1985). They have be studied for decades since 1950 (Wild, 1950) both experimentally and theoretically. It is generally agreed that fast electron beams propagating through coronal plasma with velocities from 0.2c to 0.6c are responsible for their radio emission (Suzuki & Dulk, 1985). Fast electrons generate Langmuir waves at every point and these waves are transformed into fundamental and harmonic of electromagnetic waves (Ginzburg & Zheleznyakov, 1958). Propagation of fast electrons through coronal plasma and generation of Langmuir waves are multi-level and essentially nonlinear processes because these Langmuir waves absorbed by fast electrons too, that affects the motion of these electrons in the plasma (Ryutov & Sagdeev, 1970). It was shown analytically (Melnik, 1995) and numerically (Kontar et al.,1998; Mel'Nik et al.,1999) that such nonlinear process leads to formation of a nonlinear object, beam-plasma structure, which consists of fast electrons and Langmuir waves, and moves with a constant velocity as a soliton. Because this object consists of Langmuir waves it can generate electromagnetic waves, which manifest themselves in the solar corona as Type III bursts (Melnik & Kontar, 2003). Therefore, Type III bursts have properties of beam-plasma structures: every level propagates with very own velocity, where greater velocities correspond to the burst front and smaller velocities correspond to the burst tail (Reid & Kontar, 2018;

Zhang et al., 2019). At the same time velocity of the burst maximum is constant and equals average velocity between maximum and minimum velocities of beam-plasma structure (Kontar et al., 1998). So the learning of Type III burst velocity spectrum is very important for the confirmation of the theory of beam-plasma structure. Radio telescopes of new generation, LOFAR, NenuFAR, GURT and modernized with new registered facilities, UTR-2 and URAN-2, with high sensitivity and with high frequency-time resolutions allow to register and analyze fine spectral features of Type III bursts in a wide frequency band. New cosmic mission, PSP, gives an opportunity to expand frequency range in the low frequency band: from 20 kHz to 19 MHz.

First such observations and data analysis (Melnik et al., 2024) show that, really, electrons with different velocities are responsible for the different burst phases: fast and slow electrons are responsible for the front and the back of burst, accordingly. Also for the first time the spectrum of velocities corresponding different levels of Type III burst, 0.1, 1/e, 0.5, 0.7 at the front and back of the burst as well as for maximum flux, was found (Melnik et al., 2024). It was shown that Type III burst observed on 4 June 2020 was generated at the second harmonic in Newkirk corona (Newkirk, 1961). It was turned out that velocity associated with the maximum was equal to 0.6 of the velocity, which was associated with 0.1 level on the front. This is precisely the value obtained in the theory of beam-plasma structure (Kontar et al.,1998). It was shown also that the Type III burst duration τ dependence on frequency was close to Elgaroy-Lingstad law (Elgaroy & Lingstad, 1972) $\tau = 6.21(f/30)^{-2/3}$. The Type III flux was increased with decreasing frequency as $I \sim f^{-1.63}$ and $I \sim f^{-1.74}$ in frequency bands of 30-70 MHz and 10-30 MHz respectively. This result confirmed earlier obtained results (Suzuki & Dulk,1985).

In this paper available PSP data of observations of single Type III burst in the frequency band of 1.4-19 MHz registered on 4 June 2020 by radio telescopes URAN-2 and GURT are used. It allowed studying spectral features of a single burst in unprecedentedly wide frequency band from 1.4 up to 70 MHz. We found the velocity spectrum of this Type III burst and the dependence of the latter's duration on frequency. We also obtained the changeability of burst flux with frequency in the frequency band of 1.4-19 MHz and discussed the divergence with results got with radio telescopes URAN-2 and GURT earlier.

2. Observations

Observations of solar radio emissions with radio mission PSP are conducted with the help of two receivers, Low Frequency Receiver (LFR) and High Frequency Receiver (HFR). In this paper we shall use data obtained with HFR. This Receiver module onboard the Parker Solar Probe mission (Bale at al., 2016) receives radio emission in the frequency band of 1.275 – 19.17 MHz. This band is unprecedentedly wide in terms of overlap ratio (the ratio of the highest frequency of the range to the lowest one), which equals 15. For this reason, frequency resolution of the equipment is frequency dependent maintaining constant relative frequency resolution (df/f) of about 0.04

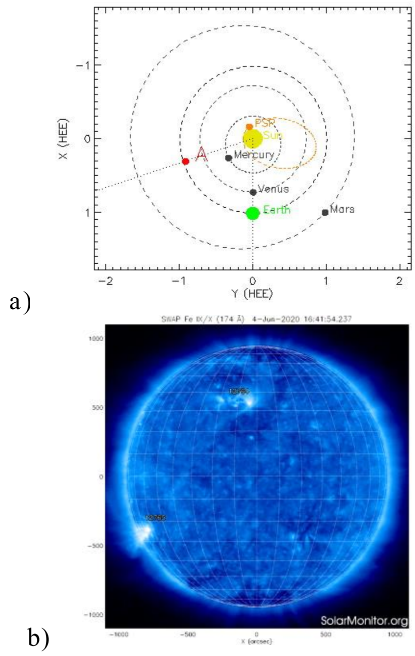

Figure 1: a) Location of cosmic mission PSP relatively to the Sun and the Earth. b) Active region NOAA 2765 on the solar disk on 4 June 2020.

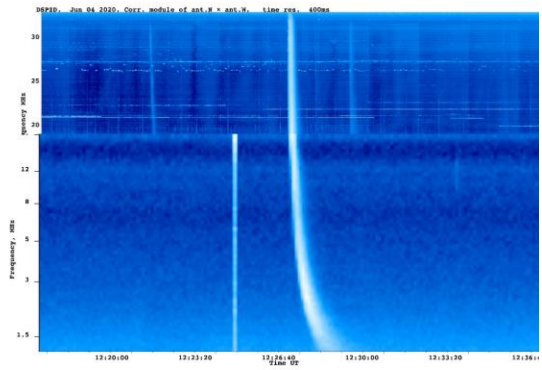

Figure 2: United dynamic spectrum of the Type III burst observed by URAN-2 (19-32 MHz) and PSP (1.4-19 MHz) on 4 June 2020.

throughout the whole frequency band. This provides absolute frequency resolutions from 0.8 MHz at 19MHz up to 47kHz at 1.3 MHz. Time resolution is also variable depending on the spacecraft orbital position. It changes from 3-7s during 12 days around the perihelion down to 56 s during the rest of the orbit. Observations on 4 June 2020 were conducted during 5 perihelion (Figure 1a) and time resolution that time was 7 s. This time PSP was situated practically beyond the Sun of the east side. Discussed Type III burst was initiated with active region NOAA 2765 (Figure 1b) which was at the east side of the solar limb practically in picture plane and this burst was observed with URAN-2 and GURT under the angle of 90°.

The dynamic spectrum of Type III burst according to PSP and URAN-2 data it the frequency range 1.4 – 32 MHz is shown in Figure 2. The time synchronization of observations on the Earth and cosmic mission PSP takes

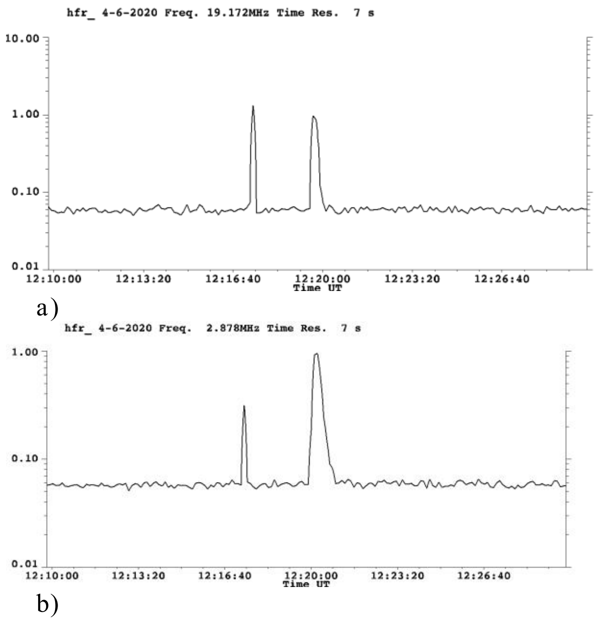

Figure 3: Profiles of Type III burst at frequencies 19.17 MHz (a) and 2.87 MHz (b) at 12.20 UT according to PSP data.

into account the different time of arrival. This burst disappears at frequencies lower than 1.4 MHz.

Profiles of the Type III burst are shown in Figure 3. We see that this burst is enough strong (its maximum flux is more than 10 times larger than the background flux) so it is possible to measure drift rates of different levels of the burst practically in the whole frequency band of 1.4 – 19 MHz.

This burst was not registered by LFR of PSP because the solar corona could not let its radio emission through at such low frequencies in the direction "back".

We measured drift rates with the method used in (Melnik et al., 2024). We found arrival time of corresponding burst level in the dependence of frequency $t = t(f) = A \cdot f^{-\alpha}$ and then found drift rate $df/dt = -B(f/30)^{\beta}$ from this equation, where $B = 30^{\beta}/A\alpha$ and $\beta = 1+\alpha$. Values for B and β for the whole frequency range 1.4-70 MHz are presented in the Table in the second and the third columns. In the fourth column corresponding velocities are presented. They were obtained in the assumption of harmonic generation in the Newkirk coronal plasma ($n(r) = 4.2 \cdot 10^4 \cdot 10^{4.32/r}$, $r = R/R_S$) (Newkirk, 1961). B, β and v from (Melnik et al., 2024) are shown in the fifth, sixth and seventh columns for comparison. We see that all values differed slightly, and the velocities obtained in wider band are some larger only for the front part.

The examples of approximations for the observed drift rates for levels 0.5± and maximum (1) for Newkirk coronal plasma are presented in the Figure 4. Here "+" and "-"denote the burst front and tail respectively. For other levels the situation is approximately the same. The velocity spectra obtained for the frequency bands of 1.4-70 MHz and 10-70 MHz (Melnik et al., 2024) are shown in Figure 5. These spectra are very close and similar. It is

Table

levels of flux	B	β	v, c	B	β	v, c
0.1+	6.3	1.75	0.55	5.6	1.89	0.5
1/e+	5.8	1.74	0.47	4.5	1.94	0.42
0.5+	5.2	1.76	0.43	4.2	1.97	0.39
0.7+	5.1	1.74	0.42	4	1.95	0.37
1	4.4	1.69	0.34	3.5	1.85	0.31
0.7-	3.7	1.64	0.29	3.2	1.74	0.27
0.5-	3.2	1.67	0.25	3	1.71	0.25
1/e-	3.2	1.62	0.24	2.9	1.67	0.24
0.1-	2.3	1.68	0.18	2.8	1.56	0.23

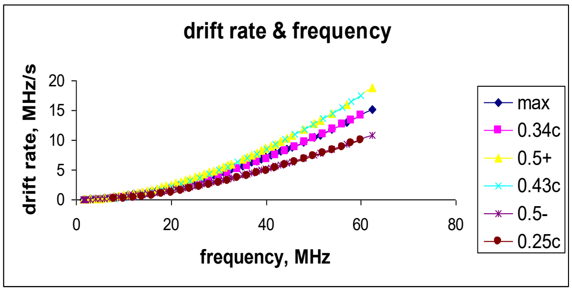

Figure 4: Drift rates dependence on frequency for levels 0.5± and maximum (1) and approximations for the harmonic radio emission in the Newkirk model.

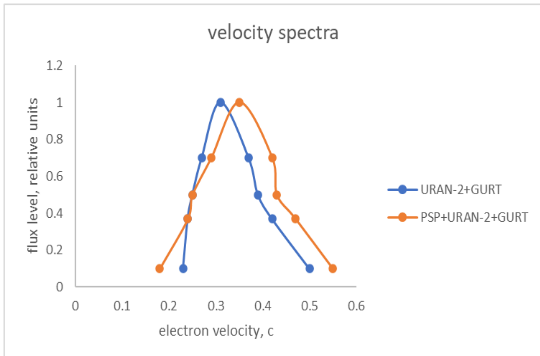

Figure 5: Velocity spectra of Type III burst for the cases for the frequency bands of 10-70 MHz and of 1.4-70 MHz.

important that despite the difference in the velocity values the maximum to minimum velocities ratio is the same and equal 0.62.

The duration of discussed Type III burst increased with decreasing of frequency according to PSP data. This dependence including data obtained with URAN-2 and GURT is shown in Figure 6. The corresponding equation for this dependence is $\tau = 6.22(f/30)^{-0.59}$ and it agrees with

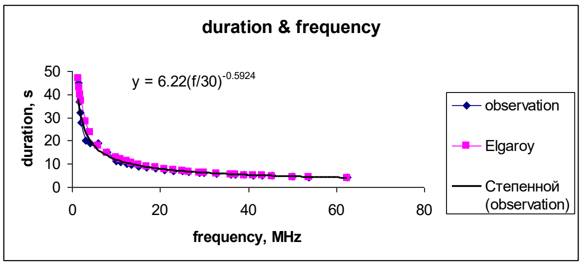

Figure 6: The duration dependence on frequency for Type III burst in the frequency band 1.4-70 MHz and Elgaroy-Lingstad dependence.

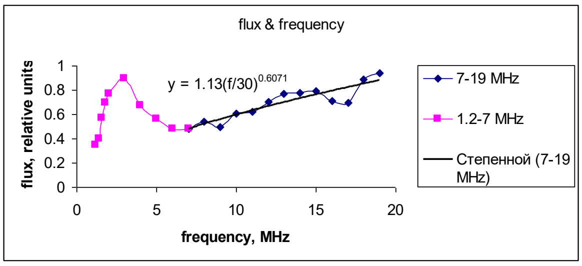

Figure 7: Radio emission flux of Type III burst in the frequency band of 1.4-19 MHz according PSP observations.

that for the URAN-2 – GURT data $\tau = 6.17(f/30)^{-0.53}$. The well-known dependence of Elgaroy-Lingstad (Elgaroy & Lingstad, 1972) is shown also. We see that our dependence is very close to it but is a little below. According to PSP observations the flux of discussed Type III burst behaves significantly differently than that according to URAN-2 – GURT data. The last one was and followed the laws, $I \sim f^{-1.63}$ in the frequency band 30-70 MHz and $I \sim f^{-1.74}$ at frequencies 10-30 MHz. For PSP data the flux frequency dependence is shown in Figure 7 and demonstrates a twofold decrease when frequency decreases from 19 MHz to 6 MHz with the equation of $I = 1.13(f/30)^{0.61}$. Starting from 5 MHz the flux increased two times to frequency 3 MHz. Below this frequency the flux decreased again very quickly and at frequency 1.2 MHz it equals the background flux.

3. Discussion

Observations of Type III burst with PSP on 4 June 2020 gave an opportunity to expand frequency band of analysis to 1.4 – 70 MHz. For this particular burst PSP data obtained in frequency band of 1.4-19MHz supplement data obtained with URAN-2 and GURT in frequencies 8-32MHz and 8-70 MHz respectively (Melnik et al., 2024). Frequency bands overlap allows combining these data in the wide frequency band of 1.4 – 70 MHz in a correct way. Concerning drift rates of the burst different levels we have very nice correspondence of the results obtained with different radio telescopes. The drift rate dependences on frequency in the expanded frequency band of 1.4-70 MHz are very close to those in the frequency band of 10-70 MHz. The assumption that fast electrons propagate in the Newkirk solar corona and that they generate radio emission at the second harmonic allows finding their velocities. The corresponding spectra for both frequency bands, 1.4 -70 MHz and 10-70 MHz, are practically identical (Fig. 5). The only difference is the spectrum in the first case shifted toward a little higher velocity. In our opinion there is a very important point, that the velocity for burst maximum equals about 0.62 of maximum velocity, $v_1 = 0.62 \cdot v_{0.1+}$. This value is close to that in the theory of beam-plasma structure, which propagates through coronal plasma. In this theory beam-plasma structure consists of fast electrons and Langmuir waves, generated by these electrons and absorbed by them. This structure moves through plasma with constant velocity and it can be a source of electromagnetic waves, t, by means of transformation of Langmuir waves, l, in the processes of scattering on ions, i, $l + i = t + i$, and coalescence of Langmuir waves, $l + l = t$ (Ginzburg & Zheleznyakov, 1958). The velocity of beam-plasma structure equals the mean velocity of electrons $(v_{max} + v_{min})/2 = 0.36c$, where $v_{max} = v_{0.1+} = 0.55c$ and $v_{min} = v_{0.1-} = 0.18c$ in our case. Different parts of beam-plasma structure move with different velocity as different levels of Type III burst. The density of fast electrons can be found from the equation (Vedenov & Ryutov, 1975)

$$v_{max}/v_{min} + \ln(v_{min}/v_0) = 1 + \frac{\pi}{\Lambda}\omega_{pe}\frac{n'}{n}\tau$$

which connects the minimal and the maximum electron velocity and the duration of the burst. It equals about $n'/n \approx 10^{-7}$. It gives the energy density of Langmuir waves $W/nkT = \frac{n'}{n}(\frac{v_0}{v_{Te}})^2 < 10^{-4}$ ($v_{Te} = 5 \cdot 10^8 cm/s$) in beam-plasma structure. This value is the necessary condition for the regime of weak turbulence ($W/nkT \approx n' \cdot mv_0^2/nkT \approx (n'/n)(v_{max}/v_{Te})^2 \approx 10^{-4}$) (Tsytovich, 1970) and namely in this regime beam-plasma structure can only exist. Thus we can conclude that existence of beam-plasma structure is confirmed by observations.

The duration of Type III burst can be connected with the passage of fast electrons across the given plasma level in the solar corona (Melnik et al., 2017; Melnik et al., 2024) and be defined with the velocity dispersion of different levels of beam-plasma structure (Melnik et al., 2024). In this case the duration can be found from the equation

$$\Delta t = (\frac{4.32}{\lg\frac{\pi m f^2}{1.6 \cdot 10^5 e^2}} - 1) \cdot R_S \cdot \frac{v_{0.5+} - v_{0.5-}}{v_{0.5+} v_{0.5-}}$$

assuming generation at generation at the second harmonic. This dependence for this burst is shown in Figure 8 as well as observational dependence for the comparison. It is seen that for frequencies > 10 MHz they are practically coincided but at frequencies <10 MHz the settlement curve is higher. It connected with the fact that radio emission at the frequency 10 MHz is generated at the distance of about R=5Rs, where the local plasma frequency is 5 MHz and approximately at these distances the Newkirk law for coronal plasma ceases to be correct (Newkirk, 1961; Suzuki & Dulk, 1985). So we conclude that for this burst at frequencies >10 MHz the burst duration is defined by longitudinal size of beam-plasma structure.

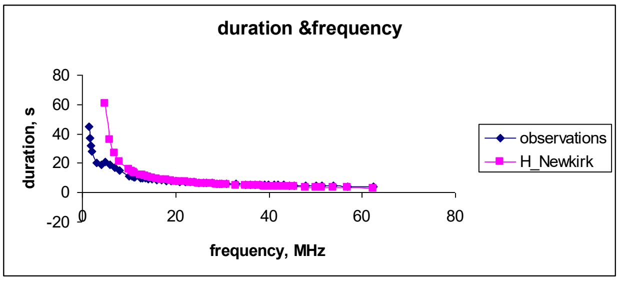

Figure 8: Duration dependencies on frequency, observational and calculated in assumptions that duration is determined by electron velocity dispersion in Newkirk plasma.

Flux dependence on frequency is also an interesting result. In spite of a similarity and closeness of the results on drift rates of different burst levels and burst duration obtained by URAN-2 – GURT and PSP in different frequency ranges, the flux dependencies in common frequency band of 10-19 MHz are essentially different. We explain this by different angles at which the source of the burst was visible from the URAN-2 and PSP (Figure 1). It is well-known (Zheleznyakov, 1977) that directivity pattern of the harmonic radio emission has 4 lobes, two lobes in the direction of electron propagation and two other different in the opposite direction moreover their values and directions depend on the phase velocity of electromagnetic waves. Besides the radio emission registered by PSP was under influence of solar corona because of scattering and even partial absorption. The latter is the possible cause of abrupt stop of radio emission lower than 1.4 MHz.

4. Conclusion

Frequency band broadening (up to 1.4-70 MHz) of spectral properties analyzes of Type III burst observed on 4 June 2020 by radio telescopes URAN-2, GURT and PSP confirmed the main results obtained in the tighter frequency band of 10-70 MHz.

The first, each level of the burst has its own velocity at that this velocity for the front is higher than for the back. The velocity for the burst maximum equals 0.6 of maximum velocity (level 0.1+). This result is weighty argument in favor of the theory of beam-plasma structure, specific composite soliton, which appears at nonlinear propagation of fast electrons in plasma.

The second, the duration-frequency dependence for this burst is very close to the Elgaroy-Lingstad law in the whole frequency band of 1.4-70 MHz. We show that the duration of this Type III burst is defined by the velocity dispersion in the beam-plasma structure in the Newkirk coronal plasma. This is correct for the distances not exceeding approximately $5R_S$, where the Newkirk law can be used.

The third, the difference of flux-frequency dependences for the band of 10-19 MHz according to URAN-2 and PSP data is connected with different sight angles of observations.

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