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Modeling on "Alphabet" of Jovian S-Bursts

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It is shown that the typical elements of complex S-bursts in dynamic spectra of Jovian decametric radio emission ("alphabet") could be explained by propagation delay of radiation due to helicoidal trajectory of S-emitter.

1. Introduction

The fine structure of dynamic spectra of the S-component from Jupiter's decametric radio emission has been studied since 1956 [1]. This component, short (S-) bursts, is observed from 6 to 36 MHz [2]. In their simplest form, an S-burst is a narrow band frequency drifting radiation having drift rate and instantaneous bandwidth of the order of –20 MHz · s^{-1} and 30 kHz, respectively, and a pulse duration from ~1 ms to ~300 ms [2, 3].

Much more complex burst forms are not uncommon. Their high-resolution dynamic spectra have been summarized as an "alphabet" of S-bursts (Fig. 1, [3]) in the frequency-time (*f*-*t*) plane. Few simplest forms have been considered in current theoretical models [4-10]. Unknown short-lived density [4] and/or acceleration structures [2], and the general concept of self-organized criticality [3] have been proposed as ways of interpreting more complex S-burst patterns. According to B. P. Ryabov [11], the S-alphabet is a puzzle: "Such spectra are hardly explicable with the principle of

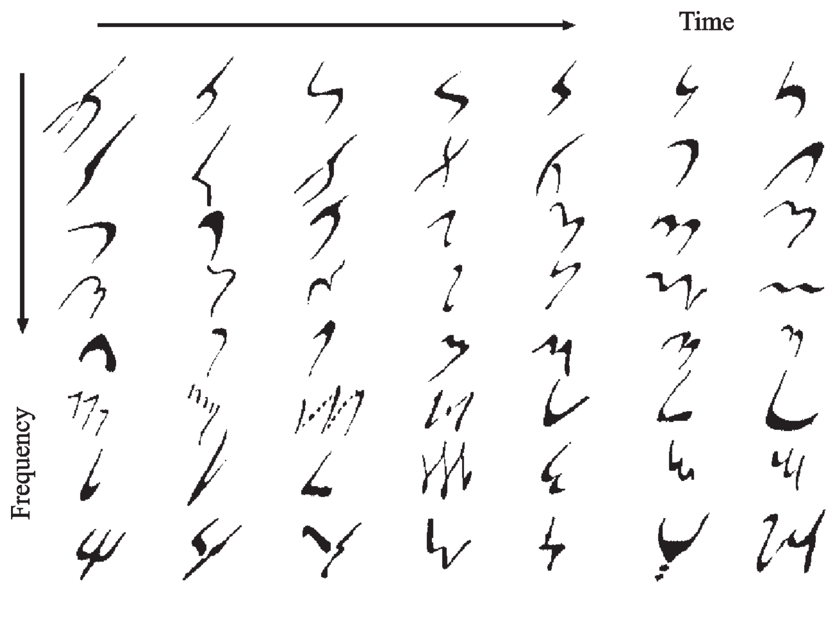

Fig. 1. *Types of S-bursts in dynamic spectrum ("alphabet") [3]*

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causality, because the emission appears independently on very different frequencies at the same time, and after that the spectrum smoothly merges in one point on *f-t* plane".

It is shown in this report that the problem of interpreting complex S-bursts has a simple solution.

2. Topological Solution of the Alphabet

The causality paradox could be explained by the small group velocity of an S-emission. The slow propagation of Jovian decametric radio emission was predicted theoretically (e. g., [10, 12, 13]). It is generally believed that the compact (< 100 km in extent) source of an S-burst moves along the Io flux tube (IFT) and generates radio emissions in a narrow frequency band slightly above the local cyclotron frequency f_c of electrons (e. g., [2, 6]). In the inhomogeneous magnetic field of Jupiter, the dynamic spectrum of an S-burst must be a reflection of the source trajectory. Various topologies of source trajectories for modeling complex S-burst spectra were evaluated. The best results have been obtained for helicoidal trajectories.

The simple geometrical model (Fig. 2) was used as the first approximation. The frequency scale of complex S-bursts is short, about 2 MHz [3]. Accordingly, the gradient of electron cyclotron frequency $\operatorname{grad} f_c$ and the group speed V_g were

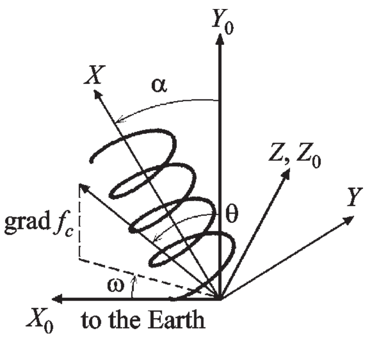

Fig. 2. *Schematic diagram of the model used to determine the spectra of S-bursts. The S-emitter moves along the helix trajectory and emits at local cyclotron frequency according to* $\operatorname{grad} f_c$

adopted as constants. The frequency dispersion of radio emission is ignored as a second order effect. For modeling most observed spectra, the simple helix trajectories are used:

$$X = V_s t,$$

$$Y = R\sin\left(2\pi V_s t/\lambda\right),$$

$$Z = R\cos\left(2\pi V_s t/\lambda\right),$$

where V_s is the source velocity along the IFT, R is the helix radius, and λ is the helix step

The motion of the emitter of the S-burst could be observed with various inclinations $(90° - \alpha)$ of the helix relative to the direction of the Earth. Hence, the source coordinates are calculated in the observer's frame X_0, Y_0, Z_0, where X_0 axis is directed toward the Earth:

$$X_0 = X\sin\alpha - Y\cos\alpha,$$

$$Y_0 = X\cos\alpha + Y\sin\alpha,$$

$$Z_0 = Z.$$

The visible direction of $\operatorname{grad} f_c$ can be characterized by the inclination angle θ and the azimuthal deviation ω. Therefore, the variations of time delay and frequency are:

$$\Delta t = -X_0/V_g,$$

$$\Delta f = \left|\operatorname{grad} f_c\right|\left(X_0\sin\theta\cos\omega + Y_0\cos\theta + Z_0\sin\theta\sin\omega\right).$$

According to the VIP4 model of the Jovian magnetic field [14], we used $\left|\operatorname{grad} f_c\right| = 10^{-3}$ MHz/km for $f_c \sim 20$ MHz. This gradient leads to the observed frequency scale of S-bursts of 1-3 MHz [3] with $\lambda \sim 2000$ km. The dimension of the IFT in the

Jovian ionosphere is about 1000-2000 km [15]. Hence, a helix radius of 200 km < R < 750 km was assumed in the model. Accordingly, 1 % of light speed c is used as V_g for the time scale of a complex S-burst of 0.1-0.3 s [3]. The average drift of a linear S-burst, ~15 MHz · s^{-1} at 20 MHz [2], is modelled with $V_s = -15000$ km · s^{-1} and $\alpha = \theta = 0$.

As a result, the theoretical S-spectra (the emitter's trajectories in frames of Δf and $t + \Delta t$) have been calculated with various sets of parameters (Table 1). The striking similarity between observed and calculated S-spectra is shown in Fig. 3. Two parts of the model curve are combined into the calculated spectrum No. 17. Forms No. 22 and No. 36 were modeled with

Fig. 3. *Comparison of the observed S-forms (middle) with the model spectra (right), which are based on the parameter values in Table 1*

Table 1. *Parameters for modeling the "S-alphabet"*

No.	R, km	α, deg.	θ, deg.	ω, deg.	A_X, km	λ_2, km	φ, deg.
1	500	20	50	0	–	–	–
2	750	–10	0	0	–	–	–
3	500	–45	0	0	–	–	–
4	500	0	35	0	–	–	–
5	500	0	60	0	–	–	–
6	500	0	60	0	–	–	–
7	150	0	50	340	–	–	–
8	500	0	40	340	–	–	–
9	500	0	60	330	–	–	–
10	500	0	60	340	–	–	–
11	500	0	60	320	–	–	–
12	600	0	60	40	–	–	–
13	500	0	60	20	–	–	–
14	500	0	50	20	–	–	–
15	500	20	80	40	–	–	–
16	500	45	70	80	–	–	–
17	300	20	20	0	–	–	–
18	700	0	40	0	–	–	–
19	500	0	140	0	–	–	–
20	500	0	40	20	–	–	–
21	500	20	40	20	–	–	–
22	500	20	50	0	50	200	90
23	500	20	40	340	–	–	–
24	500	0	40	340	–	–	–
25	500	0	120	20	–	–	–
26[a]	500	0	140	20	–	–	–
27	500	20	100	20	–	–	–
28	500	0	100	20	–	–	–
29	500	0	120	0	–	–	–
30	500	–20	20	20	–	–	–
31	500	0	140	0	–	–	–
32	500	–20	20	280	–	–	–
33	500	20	120	0	–	–	–
34	500	70	140	40	–	–	–
35	200	90	0	0	–	–	–
36[b]	700	70	160	0	100	250	0
37	500	20	110	10	–	–	–
38	500	20	100	10	–	–	–
39	500	20	110	0	–	–	–
40	500	20	120	340	–	–	–
41	500	–45	40	80	–	–	–
42	500	–45	50	80	–	–	–
43	500	0	120	340	–	–	–

$V_s = -15000$ km·s^{-1} is used for all models.
$V_g = 3000$ km·s^{-1} for all models with the exception of No.26.
$\lambda = 2000$ km for all models with the exception of No.36.
a) $V_g = 2000$ km·s^{-1}.
b) $\lambda = 500$ km.

periodic disturbances along the helix axis:

$$X = V_s t + A_X \sin\left(2\pi V_s t/\lambda_2 + \varphi\right)$$

with amplitude $A_X = 50$ km or 100 km, distribution wavelength $\lambda_2 = 200$ km or 250 km, and phase $\varphi = 90°$ or $0°$ for forms No. 22 and No. 36, respectively.

3. Interpretation of the Model

It is often accepted that an S-burst emission propagates as a fast extraordinary wave (or *x* mode) [9, 10, 13, 16]. The group velocity for the *x* mode can be small if the refractive index $n_x \ll 1$ near the cut-off frequency [10, 17]. Hence, the model requirement of $V_g/c \ll 1$ is plausible [10, 12, 13].

Electrons move along helical trajectories in a magnetic field. However, the Larmor radius of the electron orbit around the magnetic line is too short for S-source (≤12 cm with $f_c = 20$ MHz and $V_s \sim 15000$ km·s^{-1}). Nevertheless, the magnetic field is helixed around the electrical current [18, pp. 222-226]. It is known that powerful currents flow in the IFT through the source of S-bursts. That is why the S-burst emission has been attributed to the helical magnetic lines curling around the IFT [8]. However, this model cannot explain the S-burst forms with $|\theta| \gtrsim 45°$, i. e. $43/56 = 77\ \%$ of the alphabet. Indeed, the gradient of the cyclotron frequency is not fixed in such a model: grad f_c rotates around the central current in process of S-emitter moves along the helix. As a result, the calculated alphabet is inconsistent with observed S-burst forms.

To reproduce the observed S-spectra, a quasi-constant grad f_c is used in our model. It is possible in the system of many filaments of electrical currents which flow along the IFT. Their collective net magnetic fields, combined with that of Jupiter, provide a background for the motion of the S-emitter along one of IFT currents, which is in the form of a helix. This emitting helix must be sufficiently small and displaced from the main axis of the net current. Theoretically this is possible since the parameters V_g, V_s, R, and λ could be scaled by a constant factor, say $1/10$, and the identical S-spectra would result. Therefore, the adopted value of *R* must be considered as the estimation of upper limit.

Another possible explanation of helical trajectories of S-emitters is the well-known helix instability of an electrical current in external magnetic field [19, pp. 165-167]. For example, the growing helix of a falling mercury stream with an electrical current and within axial magnetic field has been photographed (Fig. 3.19 [18]). Indeed, similar increasing helixes have been observed in the dynamic spectra of S-emissions, e. g. 16 May 1995 (Fig. 4, [3]). An approximate curve is calculated with $\alpha = 20°$, $\theta = 110°$, $\omega = 15°$, $|\mathrm{grad}\, f_c| = 0.004$ MHz/km and exponential growth:

$$R = R_0 \exp(\gamma t),$$

$$\lambda = 2\pi R\,\mathrm{tg}\,\beta = \lambda_0 \exp(\gamma t),$$

where β is the angle of helix twist, $R_0 = 300$ km, $\lambda_0 = 2\pi R_0$, $\beta = 1300$ km, and $\gamma = 3$ s^{-1}. Apparently, such helix instability could lead to the chaotic entangling of currents and their dissipation. Perhaps, this process is observed as exotic S-forms – the spectra No. 3, 34-36 and unmodeled forms.

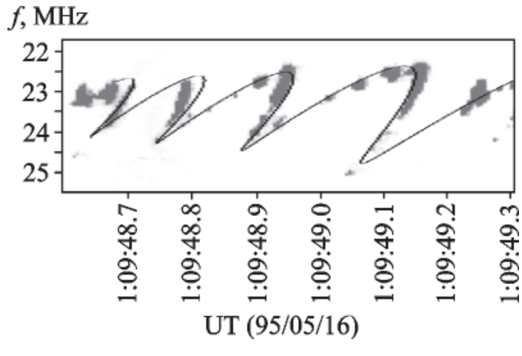

Fig. 4. *Helix instability in the S-spectrum of 16 May 1995. The solid curve is calculated with the exponentially growing helix*

The periodic disturbance of S-helix is included in the models of spectra No. 22 and 36. Probably, the axial periodic electrical field of an Alfven wave could make these modulations in V_s and X. Alfven waves in the IFT are considered as an important factor for generation of S-bursts [2, 3].

The Fig. 4 and spectra No. 22, 37, 38, 39 shows that the flux of radio emission is increased, when the S-emitter moves toward the observer (i. e. $t+\Delta t$ is decreasing). However, many types of S-alphabet with $\alpha \le 20°$ argues rather for more isotropic radiation pattern of emitter. Apparently, S-flux is controlled by other factors too. The emitter can work only on a part of helix period; or we can see the S-burst only through the “zone of visibility”, where the disturbed IFT border is perpendicular to the Earth direction [4, 5]. Hence, the restoration of radiation pattern of S-emitter seems a difficult problem for future studies.

The Io phase control is due to the sharp beaming of S-emission, because this propagates from the source with the refractive index of $n \ll 1$ to the medium with $n=1$. The beam is oriented along the density gradient which, in turn, is approximately perpendicular to the IFT [10]. It was shown numerically that the difference between such perpendicular beaming and the observed radiation pattern could be explained by the refraction in the inner Jovian magnetosphere [20].

4. Conclusions

It is shown that about 90 % of complex S-spectra can be explained in terms of the motion of S-emitters along helical trajectories with a very low ($\lesssim 0.01\,c$) group velocity of the emission. This is a simplest explanation for the old puzzle of the recurrent, scale-invariant fine structure of S-emissions.

The model used can be explained in terms of electrical currents that flow along the IFT and disturb the planetary magnetic field. Displaced helixes near the border of the IFT are needed to explain most observed S-spectra.

Apparently, there is an exponential growth of the S-helix sometimes. This effect could be explained in terms of well-known helix instability of electrical current in an axial magnetic field.

The slight disturbances in some S-helixes are needed for modeling of exotic S-types. The electrical field of Alfven waves is a possible explanation.

The fine structure of S-bursts provides the means for studying the IFT, the origin of S-emissions, and the ambient plasma. Our model provides a key to understanding this structure.

References

1. J. D. Kraus. Astron. J. 1956, **61**, No. 4, pp. 182-183.
2. P. Zarka, et al. In: Planetary Radio Emissions IV, ed. H. O. Rucker, S. J. Bauer, A. Lecacheux. Vienna, Austrian Academy of Sciences Press, 1997, pp. 51-63.
3. B. P. Ryabov, et al. In: Planetary Radio Emissions IV, ed. H. O. Rucker, S. J. Bauer, A. Lecacheux. Vienna, Austrian Academy of Sciences Press, 1997, pp. 65-89.
4. A. G. Boev, T. E. Shcherbinina. Kinematika i Fizika Nebesnykh Tel. 1997, **13**, No. 3, pp. 3-9.
5. A. G. Boev, T. E. Shcherbinina. Radiophysics and Radioastronomy. 1998, **3**, No. 2, pp. 166-172.
6. M. Y. Boudjada, et al. In: Planetary Radio Emissions IV, ed. H. O. Rucker, S. J. Bauer, A. Lecacheux. Austrian Academy of Sciences Press, Vienna, 1997, pp. 91-99.
7. M. Y. Boudjada, et al. In: Planetary Radio Emissions V, ed. H. O. Rucker, M. L. Kaiser, Y. Leblanc. Vienna, Austrian Academy of Sciences Press, 2001, pp. 187-193.
8. B. P. Ryabov. J. Geophys. Res. 1994, **99**, No. E4, pp. 8441-8449.
9. A. J. Willes. In: Planetary Radio Emissions V, ed. H. O. Rucker, M. L. Kaiser, Y. Leblanc. Vienna, Austrian Academy of Sciences Press, 2001, pp. 97-103.
10. V. V. Zaitsev, E. Y. Zlotnik, V. E. Shaposhnikov. Astron. Astrophys. 1986, **169**, No. 1-2, 345-354.
11. B. P. Ryabov. Radiophysics and Radioastronomy, 2001, **6**, No. 1, pp. 103-130.
12. D. Le Queau, R. Pellat, A. Roux. Adv. Space Res. 1983, **3**, No. 3, pp. 25-29.
13. D. B. J. Melrose. J. Geophys. Res. 1986, **91**, No. A7, pp. 7970-7980.
14. J. E. P. Connerney, et al. J. Geophys. Res. 1998, **103**, No. A6, pp. 11929-11939.
15. J. T. Clarke, et al. Science, 1996, **274**, No. 5286, pp. 404-409.
16. P. Zarka. J. Geophys. Res. 1998, **103**, No. E9, pp. 20159-20194.
17. R. G. Hewitt, D. B. Melrose. Aust. J. Phys. 1983, **36**, No. 5, pp. 725-743.
18. H. Alfven, C. G. Falthammar. Cosmical Electrodynamics. Oxford, Clarendon Press, 1963 (Перевод: Г. Альвен, К.-Г. Фельтхаммар. Космическая электродинамика. Москва, Мир, 1967, 260 с.).

19. B. B. Kadomtsev. In: Problems of Plasma Theory, ed. M. A. Leontovich. Moscow, Gosatomizdat, 1963, **2**, pp.132-176. (Б. Б. Кадомцев. В сб.: Вопросы теории плазмы. Вып. 2. Москва, Госатомиздат, 1963, с. 132-176).
20. A. V. Arkhipov. Kinematics and Physics of Celestial Bodies. 1989, **5**, No. 5, pp.68-74.

Моделирование “алфавита” S-всплесков Юпитера

А. В. Архипов

Показано, что характерные элементы сложных S-всплесков в динамических спектрах декаметрового радиоизлучения Юпитера (“алфавит”) могут быть объяснены задержкой распространения излучения при спиральной траектории излучателя.

Моделювання “алфавіту” S-сплесків Юпітера

О. В. Архипов

Показано, що характерні елементи складних S-сплесків у динамічних спектрах декаметрового радіовипромінювання Юпітера (“алфавіт”) можна пояснити за допомогою затримки поширення випромінювання при наявності спіральної траєкторії випромінювача.