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# ENERGY FLUX OF SOLAR PLASMA IN A SECTORIAL STRUCTURE OF THE INTERPLANETARY MAGNETIC FIELD

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## SUMMARY

Computed in this paper are the three-hour values of the density of kinetic energy flux of the directed motion of the plasma $q_1$, and the flux density ofbthermal ($q_2$) and electromagnetic ($q_3$) energies for the positive and negative sectors of the interplanetary magnetic field, observed from December 1963 to February 1964 with the aid of AES IMP-1. The character is discussed of $q_1, q_2, q_3$ distribution in sectors and their relationship with solar plasma velocity. It is shown that $q_1 \gg q_2 \approx q_3$ and that there is no particular difference between the sectors. Estimates are made of energy fluxes through sectors' cross-sections.

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The detection at the distance of Earth's orbit of sectorial structure of the interplanetary magnetic field on AES IMP-1 (December 1963 to February 1964) [1] and the subsequent corroboration of this discovery on the basis of data of MARINER-4 (December 1964 to February 1965) and Mariner-2 (August through December 1962) [2] have shown that the sectorial structure is apparently a constant property of the interplanetary medium.

The investigation of the sectorial structure for a quiet interplanetary magnetic field (in a period of low solar and geomagnetic activities) allowed to establish in [3] the character of the distribution in it of magnetic field H intensity, of the velocity V, of the concentration n of the flux nV of solar plasma, the presence of approximately linear relationship between the daily sum of $K_p$-index and V and H, and the absence of any link between $\Sigma K_p$ with n and nV. Moreover, an opposite relationship has been established between $\bar{H}$ and the intensity of galactic cosmic rays observed on the Earth's surface.

* POTOK ENERGII SOLNECHNOY PLAZMY V SEKTORNOY STRUKTURE MEZHPLANETNOGO MAGNITNOGO POLYA.

A further investigation of field and plasma characteristics for the sectorial structure has been conducted in [4, 5].

According to data on V, n and H from [3] and plasma temperature T in the form assumed in [4] ($T_B$ is the upper limit, $T_H$ is the lower limit; analogous indices have values corresponding to the latter), three-hour values values are computed in the current work of the density of kinetic energy flux of the directed plasma motion $q_1$, the flux density of thermal ($q_2$) and electromagnetic ($q_3$) energies for the positive and negative secotrs observed on AES IMP-1. All the values referring to the positive or negative sectors will be denoted below by symbols "plus" or "minus".

If the sectorial structure prepresents an ideal magnetohydrodynamic medium, the total density of energy flux [6] is

$$\mathbf{q} = \frac{\rho V^2}{2}\mathbf{V} + \rho w \mathbf{V} + \frac{1}{4\pi}[\mathbf{H}[\mathbf{VH}]], \qquad (1)$$

where the first term from the right is $q_1$, the second $q_2$ and the third $q_3$; $\rho = mn$, where m is the mass of the proton; the thermal function of the unit of mass is $w = \gamma nkT / (\gamma - 1)\rho$; k is the Boltzmann constant; $\gamma$ is the adiabate indicator, further assumed to be 1.5. Inasmuch as in the first approximation V is radial [7], the flux density moduli have the following form

$$q_1 = \frac{\rho V^3}{2}, \quad q_2 = 3nkTV, \quad q_3 = \frac{H\sqrt{H^2 - H_R^2}}{4\pi}V,$$

where $H_R$ is the radial component of the field.

The computed values of $q_1^+$, $q_2^+$, $q_3^+$ and $q_1^-$, $q_2^-$, $q_3^-$ are plotted in Figure 1 where the origin of the sector is taken for the zero day.

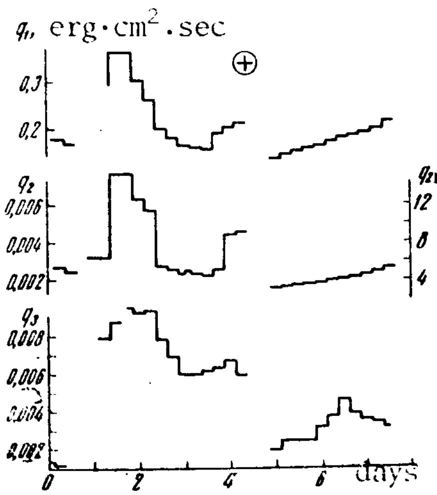


Fig.1a

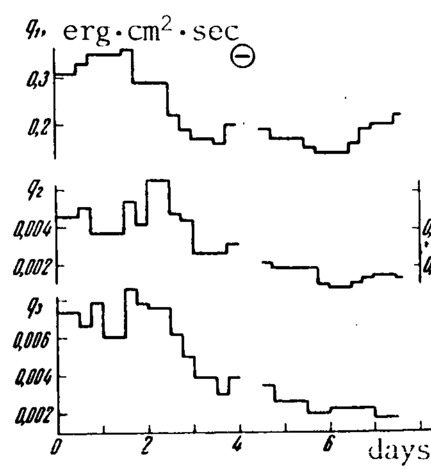


Fig.1b

the state of the interplanetary medium for 2.5 revolutions of the Sun (Dec.1963 to February 1964). Note that during this period $K_p \leq 5_-$ .

Analysis of the character of flux density distribution for the positive sector shows that at the beginning of the first day of Earth's presence in the sector, wevy low values of flux densities are observed :

$$q_1^+ \approx 1{,}7 \cdot 10^{-1}, \quad q_2^+ \approx 2{,}6 \cdot 10^{-3}, \quad q_3^+ \approx 1{,}2 \cdot 10^{-3} \ \mathrm{erg \cdot cm^{-2} \cdot sec^{-1}}$$

which increase rapidly and reach a rather sharp maximum at the end of the second day:

$$q_1^+ \approx 3{,}6 \cdot 10^{-1}, \quad q_2^+ \approx 7{,}7 \cdot 10^{-3}, \quad q_3^+ \approx 9{,}5 \cdot 10^{-3} \ \mathrm{erg \cdot cm^{-2} \cdot sec^{-1}}$$

at the end of the second and at the beginning of the third day. Then follows a decrease of $q^+$ to

$$q_1^+ \approx 1{,}6 \cdot 10^{-1}, \quad q_2^+ \approx 2{,}3 \cdot 10^{-3}, \quad q_3^+ \approx 6{,}0 \cdot 10^{-3} \ \mathrm{erg \cdot cm^{-2} \cdot sec^{-1}}$$

at the middle of the fourth day. At the beginning of the fifth day a small increase of $q^+$ is noted till

$$q_1^+ \approx 2{,}0 \cdot 10^{-1}, \quad q_2^+ \approx 4{,}5 \cdot 10^{-3} \ \text{and} \quad q_3^+ \approx 6{,}7 \cdot 10^{-3} \ \mathrm{erg \cdot cm^{-2} \cdot sec^{-1}}$$

After that there is a lowering to the minimum:

$$q_1^+ \approx 1{,}3 \cdot 10^{-1}, \quad q_2^+ \approx 1{,}6 \cdot 10^{-3} \ \text{and} \quad q_3^+ \approx 1{,}9 \cdot 10^{-3} \ \mathrm{erg \cdot cm^{-2} \cdot sec^{-1}}$$

at the end of the fifth day. Then a feeble rise is seen through the end of the sector for $q_1^+$ and $q_2^+$, whereas for $q_3^+$ an additional maximum seems to emerge with amplitude $\sim 4.6 \cdot 10^{-3}$ erg·cm$^{-2}$·sec$^{-1}$.

Roughly speaking, the distibution of $q^+$ may be represented in the form of a wave, of which the first half is contracted to a greater extent with a greater amplitude by comparison with the second half. Additional variations are superimposed to that wave. Let us point out that that the character of $q^-$ distribution is almost similar to that of $q^+$. The most substantial difference consists in that at the beginning of the first day very high values of $q_1^-$, $q_2^-$, $q_3^-$, are observed, which reach almost maximum values, while the basic maximum of $q^-$ is wider by comparison with that of $q^+$. At the end of the sector the weaker additional maximum for $q_3^-$ is not visible.

Roughly speaking, the distribution of $q^+$ may be represented in torm of a wave, of which the first half is more contracted and its amplitude is greater by comparison with the second half-wave. Additional variations are superimposed on this wave. We shall point out that the character of $q^-$ distribution is almost similar to that of $q^+$. The most substantial difference consists in that at the beginning of the first day there are observed very high values $q_1^-$, $q_2^-$, $q_3^-$, reaching almost maximum values, while the basic maximum of $q^-$ is broader (wider) by comparison with the maximum of $q^+$. For $q^-$ a weaker maximum at the end of the sector is not visible.

Note that the behavior of q coincides in the greater part of the sector with the behavior of V, i. e. a satisfactory direct connection is observed between q and V. It is true, however, that there is noted at the end of the positive sector (beggnning from the sixth day) a feedback between $q_1^+$, $q_2^+$ and V. The conclusion obtained agrees satisfactorily with the results of work [8].

The mean values of flux densities q and limits of q variation (numbers in parentheses) are presented in Table 1 for the period under consideration, for both the positive and negative sectors. Moreover, for the sake of comparison compiled in the table are also the corresponding values of energy fluxes for the data of MARINER-2 (partially brought out in [8].

TABLE 1

| PARAMETER | | IMP-1 | | MARINER-2 |
|---|---|---|---|---|
| | | positive sector | negative sector | |
| $\bar{q}_1$, | erg cm$^{-2}$ sec$^{-1}$ | $2,1\cdot10^{-1}$<br>$(1,3\div3,6)\cdot10^{-1}$ | $2,3\cdot10^{-1}$<br>$(1,4\div3,6)\cdot10^{-1}$ | $6,0\cdot10^{-1}$<br>$(0,1\div30)\cdot10^{-1}$ |
| $\bar{q}_{2B}$, | '' | $6,0\cdot10^{-3}$<br>$(3,2\div15,4)\cdot10^{-3}$ | $6,0\cdot10^{-3}$<br>$(1,6\div13)\cdot10^{-3}$ | $20\cdot10^{-3}$<br>$(1\div100)\cdot10^{-3}$ |
| $\bar{q}_{2H}$, | '' | $3,1\cdot10^{-3}$<br>$1,6\div7,7)\cdot10^{-3}$ | $3,1\cdot10^{-3}$<br>$(0,8\div6,5)\cdot10^{-3}$ | |
| $\bar{q}_3$, | '' | $5,2\cdot10^{-3}$<br>$(1,2\div9,5)\cdot10^{-3}$ | $4,5\cdot10^{-3}$<br>$(1,7\div8,5)\cdot10^{-3}$ | $7,2\cdot10^{-3}$<br>$(0,1\div40)\cdot10^{-3}$ |
| $\bar{q}_1 S$ | | $1,2\cdot10^{26}$<br>$(0,70\div2,4)\cdot10^{26}$ | $1,3\cdot10^{26}$<br>$(0,8\div2,4)\cdot10^{26}$ | $1,5\cdot10^{26}$; $1,5\cdot10^{26}$<br>$(0,02\div6,0)\cdot10^{26}$ |
| $\bar{q}_{2B} S$ | | $3,4\cdot10^{24}$<br>$(1,8\div8,5)\cdot10^{24}$ | $3,4\cdot10^{24}$<br>$(0,9\div7,4)\cdot10^{24}$ | $3.4\cdot10^{24}$; $4,8\cdot10^{24}$<br>$(0,2\div20)\cdot10^{24}$ |
| $\bar{q}_{2H} S$ | erg sec$^{-1}$ | $1,8\cdot10^{24}$<br>$(0,9\div4,4)\cdot10^{24}$ | $1,8\cdot10^{24}$<br>$(0,5\div3,7)\cdot10^{24}$ | |
| $\bar{q}_3 S$ | | $2,9\cdot10^{24}$<br>$(0,7\div5,4)\cdot10^{24}$ | $2,5\cdot10^{24}$<br>$(1,0\div4,8)\cdot10^{24}$ | $1,4\cdot10^{24}$; $2,0\cdot10^{24}$<br>$(0,02\div8,0)\cdot10^{24}$ |
| $\bar{q}_1 St$ | | $1,0\cdot10^{31}$<br>$(0,6\div2,1)\cdot10^{31}$ | $1,1\cdot10^{31}$<br>$(0,7\div2,1)\cdot10^{31}$ | |
| $\bar{q}_{2B} St$ | | $2,9\cdot10^{29}$<br>$(1,6\div7,1)\cdot10^{29}$ | $2,9\cdot10^{29}$<br>$(0,8\div6,4)\cdot10^{29}$ | |
| $q_{2H} St$ | erg | $1,5\cdot10^{29}$<br>$(0,8\div3,8)\cdot10^{29}$ | $1,5\cdot10^{29}$<br>$(0,4\div3,2)\cdot10^{29}$ | |
| $q_3 St$ | | $2,5\cdot10^{29}$<br>$(0,6\div4,7)\cdot10^{29}$ | $2,2\cdot10^{29}$<br>$(0,8\div4,2)\cdot10^{29}$ | |

Such a comparison offers interest, for measurements on MARINER-2 were conducted in a period of somewhat higher solar and geomagnetic activity. In this period the limits of velocity $V - 306 - 842$ km/sec$^{-1}$ variation for an average value $V \approx 504$ km sec$^{-1}$ of proton concentration $n \approx 0.44 - 54$ cm$^{-3}$ for $n \approx 5.4$ cm$^{-3}$, the mean plasma temperature is $T \approx 1.7 \cdot 10^{5\circ}$ K [9].

Consequently, the state of the interplanetary medium at a heliocentrical distance of 0.8 – 1 a.u. during observations on MARINER-2 differed from the state of the medium during measurements on IMP=1, when the variation limits were $V \approx 270 - 346$ km sec$^{-1}$ as $\bar{V} \approx 315$ km sec$^{-1}$ and $n \approx 6 - 14.5$ cm$^{-3}$ as $\bar{n} \approx 9$ cm$^{-3}$, and $T_{11} \approx 2.5 \cdot 10^{4}$ °K and $\bar{T}_{5} \approx 5 \cdot 10^{4}$ °K [3, 4].

It may be seen from the table that the energy density of the directed motion considerably exceeds (by 1 – 2 orders) the flux densities of thermal and electromagnetic energy, while $q_2 \approx q_3$. The last deduction ageees well with the result obtained in [8]. Note incidently that the contribution of variations with period < 3 hours is not taken into account in $q_3$ , which leads to its certain underrating [8]. It is also obvious that a significant difference between the flux densities for the positive and negative sectors is absent, and that $\bar{q}_1 < \bar{q}_1^M$, $\bar{q}_2 < \bar{q}_2^M$, $\bar{q}_3 \lesssim \bar{q}_3^M$, where $q_i^M$ are the densities of the respective fluxes measured on MARINER-2. Note that the values of $q_1$ obtained in the present work coincide with those obtained in [10].

We shall estimae the fluxes of energy through the cross-sections of the positive and negative sectors (their cross-sections are identical and at the Earth's orbit level are approximately $S_c \approx 5{,}7 \cdot 10^{26}$ $см^2$) per second ($qS_c$) and per day ($qS_c t$). They are brought out in Table 1, the limit values being shown in parentheses. For comparison we brought out in Table 1 the corresponding values from MARINER-2 data according to [8] for the September and October (1962) plasma jets, whose cross=section $S_{ст} \approx 2{,}2 \cdot 10^{26}$ $см^2$ (for the values $\bar{q}^M S_{ст}$ the left-hand number refers to the September jet and the right-hand one to that of October). It is obvious that $\bar{q}_1^+ S_c \approx \bar{q}_1^- S_c \leqslant \bar{q}_1^M S_{ст}$, $\bar{q}_{2n}^+ S_c \approx \bar{q}_{2n}^- S_c \lesssim S_{ст} \bar{q}_2^M$, $\bar{q}_3^+ S_c \gtrsim \bar{q}_3^- S_c \gtrsim \bar{q}_3^M S_{ст}$. It is interesting that the energy flux of directed and thermal flows through the cross-section of the sectorial structure (in the period Dec.1963 to February 1964) is less or coincides by order of magnitude with the corresponding fluxes through the cross-sections of the September and October 1962 jets, though $S_c / S_{ст} \approx 2{,}5$.

The above estimates of energy fluxes may constitute a certain interest in connection with questions bearing on the generation and emergence of plasma fluxes from the surface of the Sun, on their possible acceleration in interplanetary space, and also on the question of recurrent magnetic disturbances. Inasmuch as the boundaries of the considered sectorial structures represent the region of polarity shift of the interplanetary magnetic field, the plasma acceleration mechanism at the expense of field annihilation in the neutral layer deserves attention [11]. However, the qualitative examination of the available data on q in the current work, and also of data on energy density of the directed and thermal motions and of the magnetic field in [4], failed to yield convincing deductions in favor of action of that mechanism.

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***** THE END *****

I Z M I R A N

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## REFERENCES

[1]. N. F. NESS, J. M. WILCOX., Science, 148, 1592, 1965.
[2]. P. J. COLEMAN, L. DAVIS, E. J. SMITH, D. F. JONES. J.Geophys. Res. 71, 2831, 1966.
[3]. J. M. WILCOX, N. F. NESS. J. Geophys. Res. 70, 5793, 1965.
[4]. I. V. KOVALEVSKIY. Geom. i Aeronomiya, 7, No.5, 878, 1967.
[5]. I. V. KOVALEVSKIY. Ibid. p.784, 1967.
[6]. L. D. LANDAU, E. M. LIFSHITS. Elektrodinamika sploshnykh sred. Electrodynamics of Continua) Fizmatgiz, 1959.
[7]. E. F. LYON. The Solar Wind (Ed. Mackin & Neugebauer) .Perg.Pr.295, 1966.
[8]. K. G. IVANOV, I. V. KOVALEVSKIY. Geom. i Aeronomiya, 7, 5, 880, 1967.
[9]. M. NEUGEBAUER, C. W. SNYDER. J. Geophys. Res/ 71, 4469, 1966.
[10]. J. M. WILCOX, K. H. SCHATTEN, N. F. NESS. Ibid. 72, 19, 1967.
[11]. H. E. PETSCHEK.- AAS - NASA Symposium on the Physics of Solar Flares. NASA SP-50 (Ed. Wilmot N.HESS) 1964.