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Process of flow-around the Moon from solar wind as a source of magnetospheric disturbances

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1. Introduction

The problem of the magnetohydrodynamical lunar wake being due to the interaction of the solar wind with a super Alfvenic velocity (Alfvenic Mach number $M_A = 4 \div 20$) with the lunar pseudo-magnetosphere has not been clarified yet. Only when the spacecraft Explorer-35 (IMP-E) was launched on 19 July 1967 and placed into lunar orbit on 22 July 1967, the first precise measurements of the nature of the interaction of the solar wind with the Moon were made [1-3]. These measurements showed that during the interaction of the solar wind with the Moon there was no formation of a bow shock wave on the noon side of the Moon, but a plasma wake was indicated on its night side. So the Moon has been regarded as a nonmagnetic sphere with relatively low conductivity, which absorbs (or neutralizes) the solar plasma occurred on it.

Thus the presence of the Moon does not disturb the interplanetary field lines except for in the free plasma region on the night side [1, 2, 4]. As a result an umbra is formed behind the Moon that could not exist, if the Moon had possessed a high conductivity. The principal phenomena in the solar wake are [5, 6]:

a) A downwind plasma umbral cavity or void containing an enhanced intensity of the interplanetary magnetic field (IMF) (<+30%) only slightly perturbed in direction;

b) A downwind penumbral region aft of a rarefaction wave or Mach cone, elliptical in cross sectional geometry, contains a reduced plasma flux and magnetic field (>–30%);

c) A very limited penumbral region, upwind of the lunar Mach cone, sometimes contains an enhanced (<+30%) magnetic fields and plasma fluxes.

Although the data from the Explorer-35 and their interpretation increase our understanding of the interaction between the solar wind and the Moon, there are unresolved problems as for example:

1) What sort of source mechanism is producing the positive penumbral anomalies sometimes observed in the IMF?

2) How far behind the Moon is its wake detectable and by what means?

3) Whether the lunar wake effect exists on the Earth magnetosphere and on which of its processes and parameters?

Indeed each geomagnetic phenomenon with period equal to the lunar synodic period of 29,53 days can be related to the magnetic field of the Moon, or to the lunar pseudo-magnetosphere wake, as it is known that the solar wind disturbs the Moon magnetic field strongly, regardless of its origin.

The object of this work is to discuss some of these problems. The effect of the lunar wake on the magnetosphere disturbances has been studied by using: a) comparative analysis; b) correlative analysis; c) spectral analysis and d) theoretical analysis of the small irregularities due to the lunar wake on the magnetosheath and on the magnetopause during the new Moon.

2. Comparative analysis

The catalogues [7] and the Solar-Earth data [8] have been used as an initial base for the interplanetary medium parameters (the velocity V of the solar wind, the direction and the IMF polarity). It is evident that the long tail of the night side of the Moon appears to be a peculiar magneto-corpuscular eclipse, limited by the irregular magnetic fields. The region of this eclipse is much larger than the optical one and does not coincide with it at all. The effect of the magneto-corpuscular eclipse (if it exists) could be observed more often than the optical one as it would influence the Earth when the optical umbra did not reach it.

The preliminary analysis of the so selected periods for all new Moons from 1970 to 1980 showed that in a number of cases at comparatively quiet values of the solar wind on the zero day or on the ±1st, 2nd ... day, moderate increases of geomagnetic $\sum K_p$ - index are obtained during one day, which is in no case a magnetic storm, but eventually can be a weak influence of a lunar wake on the magnetosphere. Several cases of this kind are shown on Fig. 1 with effects on the zero day — the day of the new Moon (on Febru-

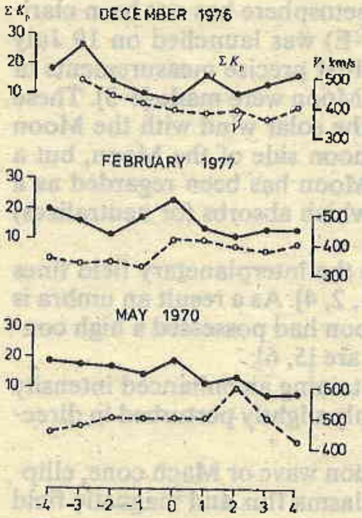

Fig. 1. Examples demonstrating the geomagnetic index increase by new Moon at quiet values of the velocity of the solar wind. There can be observed 102 such increases out of a total of 114 investigated periods, i. e. in 89 per cent from the cases

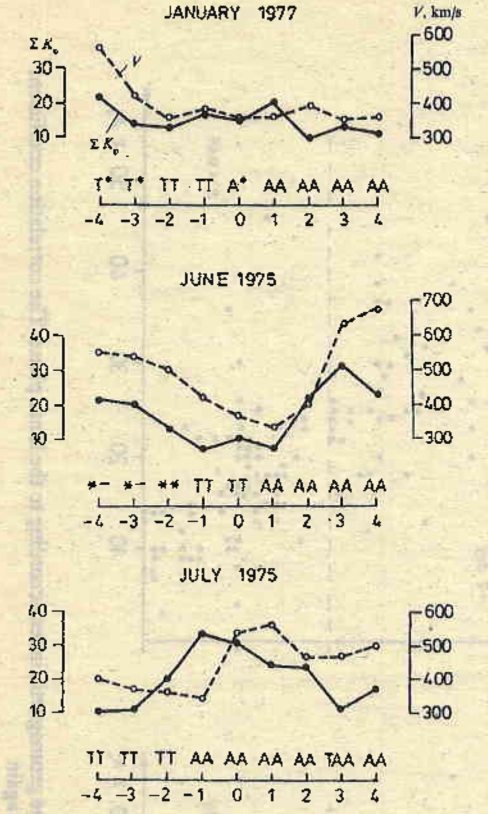

Fig. 2. Similar as on Fig. 1. The change of the polarity of the IMF is shown besides

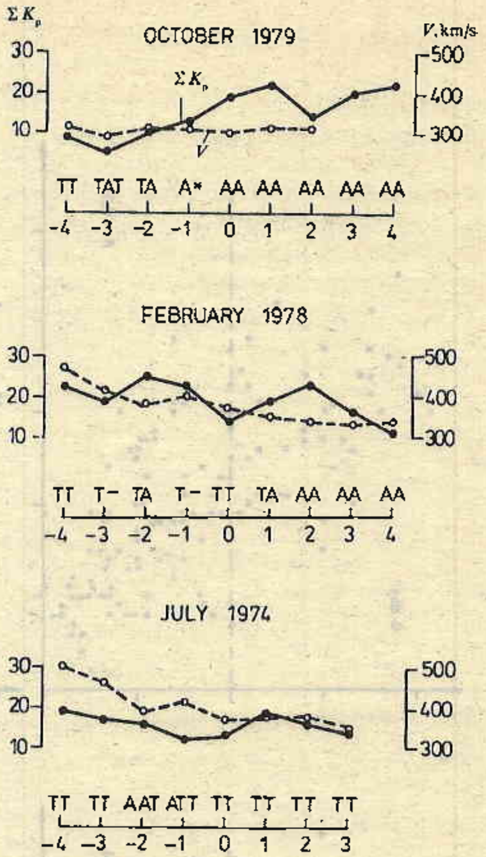

Fig. 3. The same as on Fig. 1. A perturbation in the polarity of the IMF by the new Moon is shown in addition. There are 112 perturbations out of a total of 145 investigated periods, i. e. in 77 per cent from the cases

ary 1977 and on May 1970) and on the first day after the new Moon (on December 1976). However, these cases are not isolated and have comparatively high frequency. The analysis of 114 new Moon periods (–4, +4 days) during the period 1970-1980 showed that there are 102 such days of the $\sum K_p$ - index increase. These weak increases of $\Delta\sum K_p \approx 5 \div 10$ on the background of the comparatively quiet (even abating in time) course of the solar wind can be caused by the disturbing effect of the magnetohydrodynamical wake of the Moon, appearing on account of the process of flow-around the Moon from the solar wind with a superAlfvenic velocity.

The analysis of the periods (–1, +1 day) when a maximal effect can be expected of the lunar plasma wake on the Sun — Moon — magnetosphere line showed another peculiarity. At these very moments the tendency of "reversion" of the IMF polarity appears (A →T or T→A, A — from the Sun, T — to the Sun). A and T are sam-

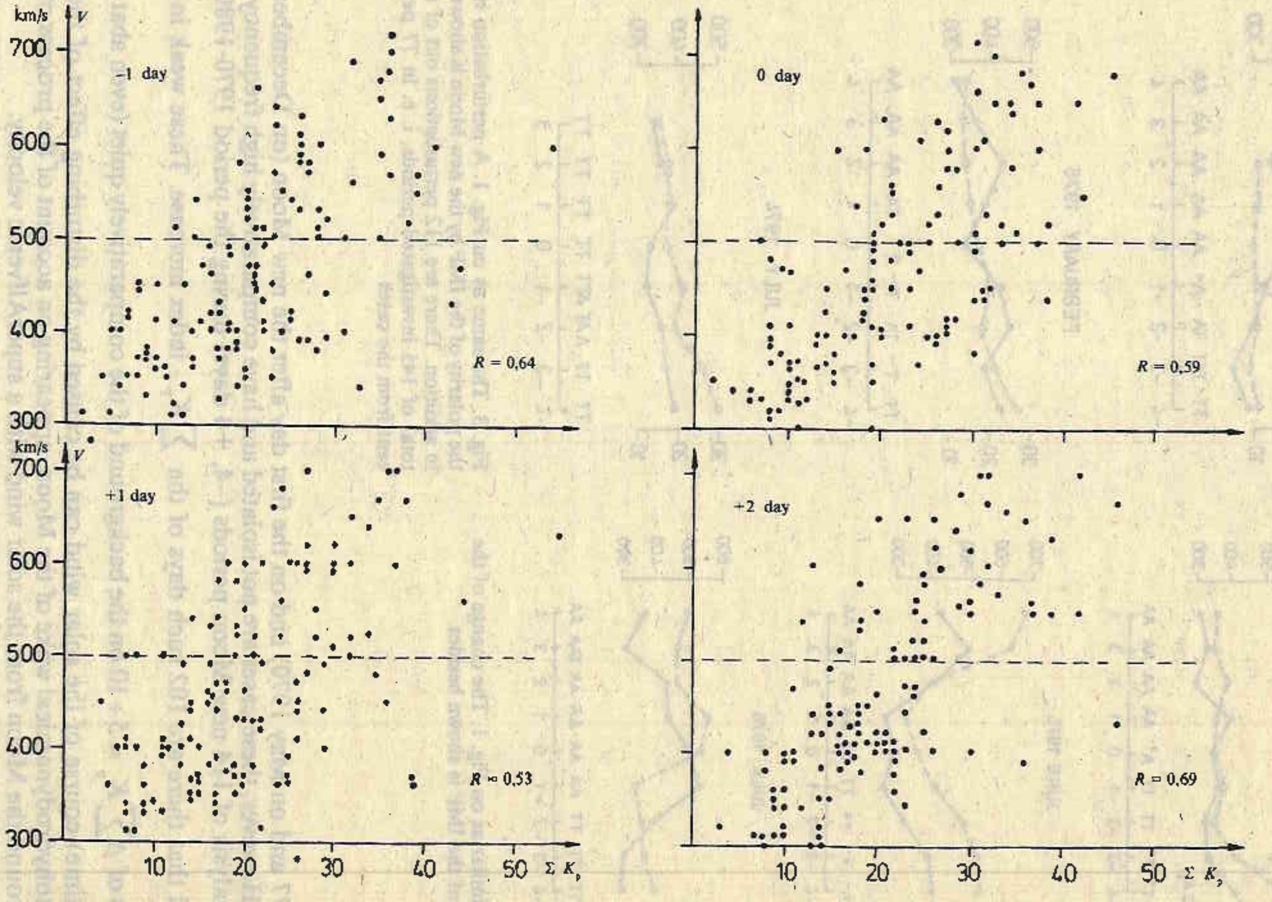

Fig. 4. Scatter plots of the solar wind velocity and of the geomagnetic index according to the lunar phase. The correlation coefficient *R* decreases by the new Moon and reestablishes then again

pled from the ground-based data [8]. For instance, 112 "reversions" or polarity disturbances of the A→AT→A or T→TA-T type of the investigated periods have been observed during 1972-1984. The frequency of 77 per cent is also an indication for the disturbing effect of the lunar pseudo-magnetosphere, which has an influence on the variations of the magnetic field components, measured for polar latitudes. Such three periods of sharp IMF polarity change on the zero day (on January 1977) and one day before the new Moon (on June and on July 1975) are demonstrated on Fig. 2. On Fig. 3 three periods are shown with more smooth T→TA→A inversion by the new Moon period, and in the last case (on July 1974) the lunar wake caused a perturbance in the polarity only.

3. Correlative analysis

As it is known, as early as in the 60-s a close relation between the phenomena observed in the solar wind and some geomagnetic processes was obtained. As basic characteristic we have chosen the three hour planetary K_p-index and its derivative $\sum K_p$. One of the first works, indicating the correlative relationship of the solar wind velocity V (km/s) to the magnetospheric activity [9] is the work, where:

$$\sum K_p = [V - (330 \pm 17)]/(8{,}44 \pm 0{,}74).$$

Subsequently, a number of other relations of the K_p-index to the parameters of the interplanetary medium was established [10, 11].

In this work we shall try to find the relation of the solar wind velocity V to $\sum K_p$, depending on the lunar phase in order to establish whether the magnetohydrdynamical wake of the Moon changes this relation by the zero day. For this purpose all diurnal periods (−4, +4 days) of the new Moon were analysed during the period 1970-1985 and the correlation coefficient R was determined of V to $\sum K_p$. Some of these results are shown on Fig. 4 for $\Delta=-1{,}0$ (new Moon), 1^{st} and 2^{nd} day. It is seen from this figure, that during the period of the new Moon and the first day after it R reaches its minimum, after which on the second day quickly reestablishes. The latter is shown more clearly on Fig. 5, where the results from all computations are presented. The correlation coefficients for high velocity fluxes of the solar wind (V>500 km/s) R_H and R_n for the normal solar wind (V<500 km/s) are represented separately (seen on Fig. 5). From Fig. 5 we come to a general conclusion that on days by the new Moon a change of the correlation relation of the solar wind velocity to the $\sum K_p$ geomagnetic index is observed, which is due to the perturbing effect of the lunar wake on the magnetosphere.

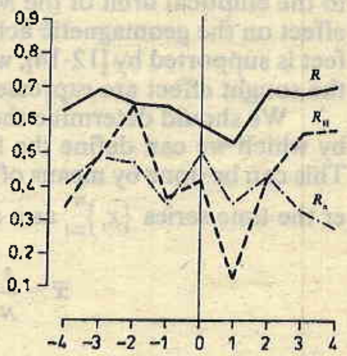

Fig. 5. Relationship of R to the lunar phase. R_H is the correlation coefficient for the high velocity fluxes of the solar wind V≥500 km/s, R_n for the normal solar wind

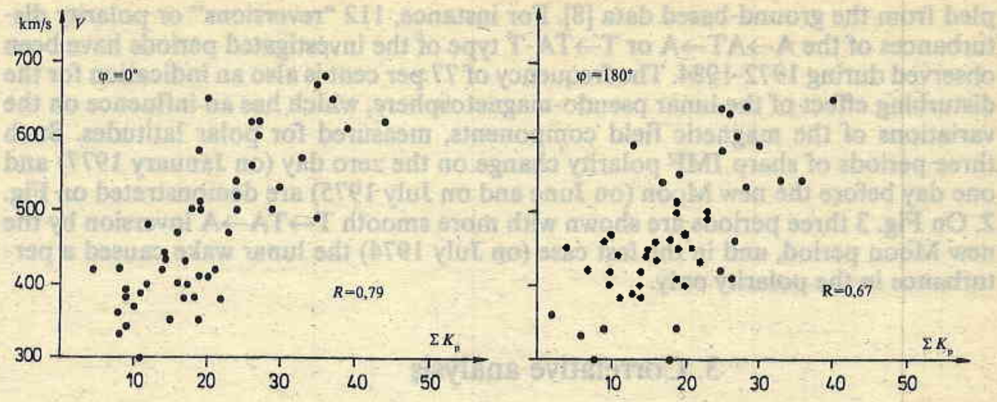

Fig. 6. Scatter plot as on Fig. 4 for two cases: parallelism (φ=0) and antiparallelism (φ=180°) between the IMF and the Sun—Earth line

An interesting result concerning the influence of the IMF direction on this relation is shown on Fig. 6, where these days are selected from the so indicated 9-day periods (Fig. 4, 5), in which φ=0° and 180°. The correlation coefficient $R(\varphi=180°)=0,67$ practically does not differ from the normal value of R on the days out of the new Moon period (−1, +1). But $R(\varphi=0°)=0,79$ exceeds to a large extent all the cases considered up to now, which indicates that the interaction of the solar wind with the Moon during the period by the new Moon is maximized in terms of parallelism of the B magnetic induction of the IMF and the line Sun—Moon—Earth.

4. Spectral analysis

The statistical proof of the lunar wake effect on the magnetosphere perturbations demands measurements of the solar wind velocity V before and after the Moon together. The problem is complex as all measurements have been done in practice after the Moon. For this reason it is more suitable to perform a spectral analysis of the perturbations, i. e. of the $\sum K_p$ series with a view eventually to indicate a periodicity of 29,53 days (this number varies from 29,25 to 29,83 days due to the elliptical orbit of the Moon). It should be pointed out, that the possible lunar effect on the geomagnetic activity has been discussed in a number of works. This effect is supported by [12-14], while in [15, 16] an uncertainty and the insignificance of the sought effect are expressed.

We should determine the length N of the series before discussing the methods by which we can define the frequency characteristics of the considered processes. This can be done by means of confidence intervals. For this purpose we shall consider the time series $\{x_i\}_{i=1}^{N}$ as a casual process, and the distribution of the parameters

$$\bar{x}=\frac{1}{N}\sum_{i=1}^{N}x_i,\quad S^2=\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i-\bar{x}\right)^2$$

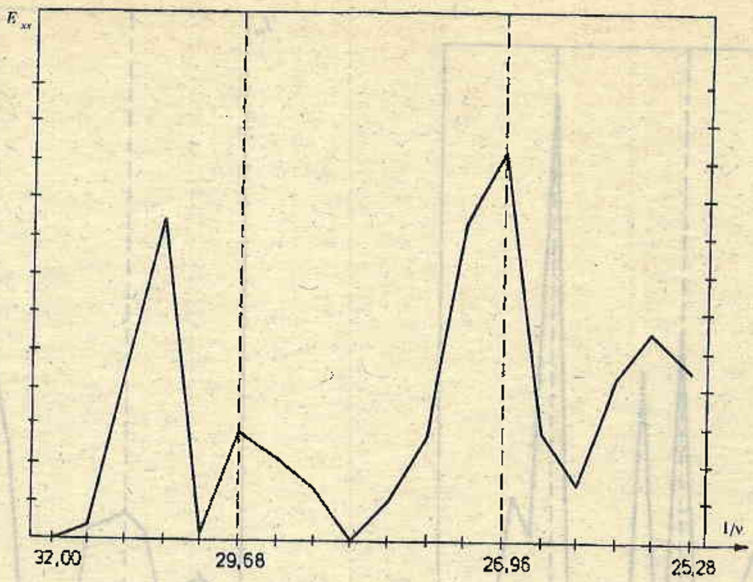

Fig. 7. Spectral density distribution for frequences corresponding to periods of 25,28 to 32,00 days. The distinctly expressed 27-day solar variation and the more weak lunar one are seen

is normal and they have a probability distribution as:

$$P_x(\varepsilon) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(\varepsilon-\mu)^2}{2\sigma^2} \right]; \quad \forall\varepsilon \in (-\infty, +\infty).$$

The necessary amount of the data sample is conditioned by

$$N = \left(V_{1-\alpha/2}\, S/\varepsilon\right)^2$$

and by the condition that the distance between the mean of the sample $\bar{x}$ and the mathematical expectation of the totality to be of the order of 0,5 units at confidental probability 95 per cent. Let we have $\alpha=0{,}05 \rightarrow V_{1-\alpha/2}=1{,}96; S^2=71{,}676; \varepsilon=|\mu-\bar{x}|\sim 0{,}5$. Therefore the amount of the sample is of the order of 1000 observations. But as we need $N=2^S$ with a view to apply the Fast Fourrier Transformation (FFT) the amount to be selected is 1024 ($S=10$). In our case this is the period from 01.06.1965 to 28. 06. 1968. Then a stationarity examination was made which gave positive results. The results obtained are shown on Fig. 7, where the distribution of the spectral density is given for frequencies corresponding to periods from 32,0 to 25,3 days. Here it is seen clearly expressed periods of 27 days and slight expressed one of 29,6 days. Data were filtered in order to eliminate the influence of the frequency corresponding to a period of 30,6 days. Low frequency filter was used for this purpose. Then the data obtained were filtered to eliminate the determinantal component (27-day solar variation). This was done by usingd determinantal filter. The data filtered this way were let pass trough the FFT and the spectral density was determined (Fig. 8) and

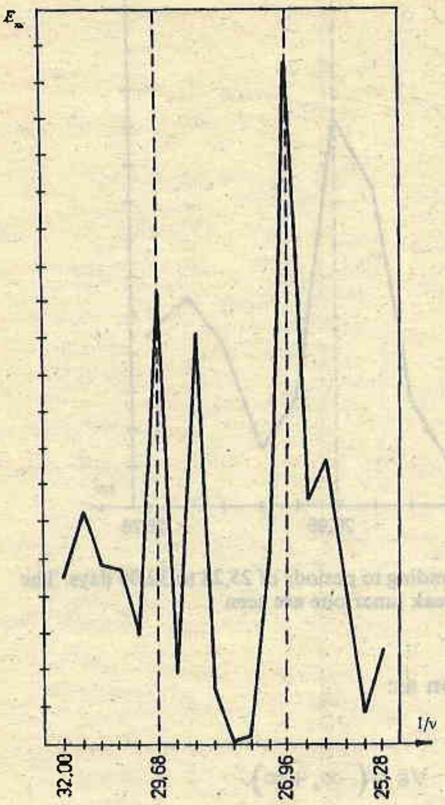

Fig. 8. The same as on Fig. 7 after filtering to eliminate the deterministical component (27 days) and the influence of the period of 30,6 days

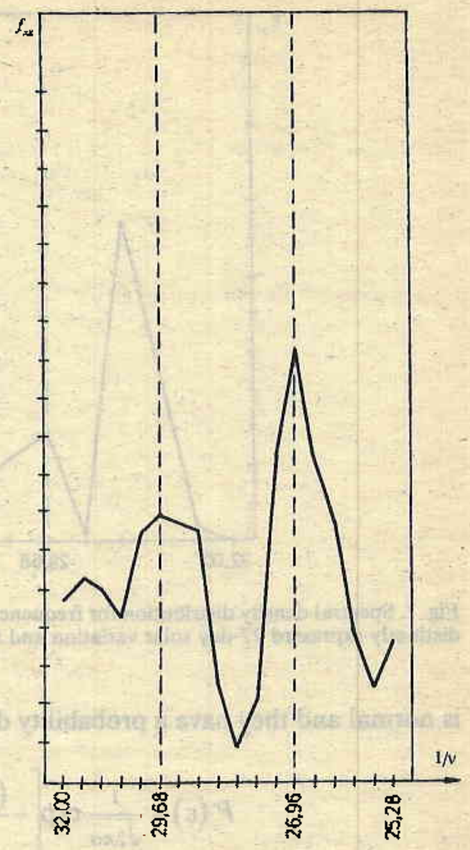

Fig. 9. Smoothed estimation of the spectral analysis. The previous results are averaged by three points to enhance the stability of the spectral density

then the smoothed estimation was obtained (Fig. 9). In the last figure the result is averaged by three points. This leads to an enhancement of the stability of the spectral density estimation.

In fine it is necessary to determine the interval of confidence of the estimation obtained for the spectral density. We take a confidental probability $\gamma=0,50$, and for the interval of confidence 50 per cent we receive $0{,}525.10^{-8} < f^{*}_{xx} < 1{,}019.10^{-8}$. From the 50 per cent interval of confidence a conclusion may be drawn that there exists an effect of the lunar wake, but it is comparatively slight.

5. Theoretical model

In the model of Spreiter, Marsh and Summers [17] the Moon is considered as a nonconducting sphere, which fully absorbs the falling particles. The equations of the ideal magnetichydrodynamics under the assumption of $V \| B$ re-

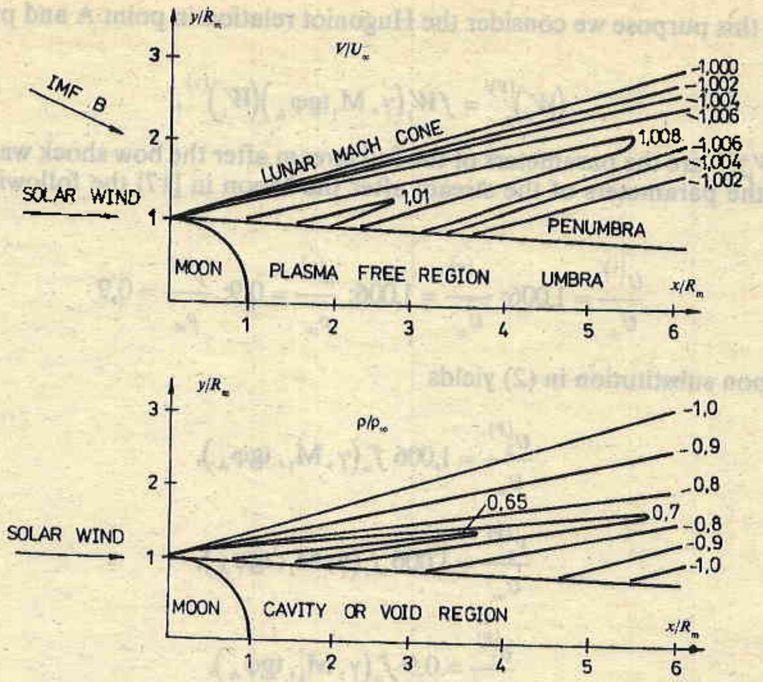

Fig. 10. The results obtained by Spreiter, Marsh and Summers [17], which have been used as initial conditions for the our theoretical model

duce to the effective gas-dynamical equations. The problem is solved in an axis symmetrical approach. The cavity or void formed behind the Moon is limited by the tangential discontinuity

$$V_n = 0, \quad B_n = 0, \quad \left\{p + B_t^2/8\pi\right\} = 0$$

where the internal magnetical pressure attained in terms of conservation of the magnetic flux and full pressure from the outer side are balanced. After passing from gas to pseudogas in [17] we get the correlation of the characteristics

$$\text{(1)} \qquad d\theta \pm \left[\left(\frac{V^*}{a^*}\right)^2 - 1\right]^{1/2} \frac{dV^*}{V^*} = 0, \quad \frac{dy}{dx} = \mathrm{tg}\left(\theta^* \pm \mu^*\right)$$

where V^* is the modul of the pseudogas velocity, θ^* — the angle between the line of the current and the axis Ox (actually the Sun — Moon line), a^* — velocity of the sound, $\left(a^*\right)^2 = \left(\partial p/\partial \rho\right) S^* = \text{const}$, μ^*— the angle of Mach, $\mu^* = \arcsin\left(1/M^*\right)$, M^* — Mach number. The results obtained in [17] by equating the system (1) and reduced from pseudogas to gas are shown on Fig. 10. By using these results and the method mentioned in [18], an estimation can be made of the effect of the small irregularities occurring due to the plasma wake of the Moon. We have done computations in the meridional plane only in the plase of the new Moon. This enables us to give small irregularities only in the elliptical part of the magnetosheath region (Fig. 11).

For this purpose we consider the Hugoniot relation in point A and present it in the form

$$(W_i)_2^{(F)} = fW_i(\gamma, \mathrm{M}_1 \mathrm{tg}\varphi_A)(W_i)^{(v)}, \tag{2}$$

where $(W_i)_2^{(F)}$ are the parameters of the full stream after the bow shock wave. We obtain for the parameters of the stream after the Moon in [17] the following estimations:

$$\frac{U^{(v)}}{U_\infty} = 1{,}006; \ \frac{V^{(v)}}{U_\infty} = 1{,}006; \ \frac{\rho^{(v)}}{\rho_\infty} = 0{,}9; \ \frac{p^{(v)}}{p_\infty} = 0{,}9$$

which upon substitution in (2) yields

$$\frac{U_2^{(F)}}{U_\infty} = 1{,}006\, f_u(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A),$$

$$\frac{V_2^{(F)}}{U_\infty} = 1{,}006\, f_v(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A),$$

$$\frac{\rho_2^{(F)}}{\rho_\infty} = 0{,}9\, f_\rho(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A),$$

$$\rho_2^{(F)} = (0{,}9)^\gamma\, f_\rho(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A).$$

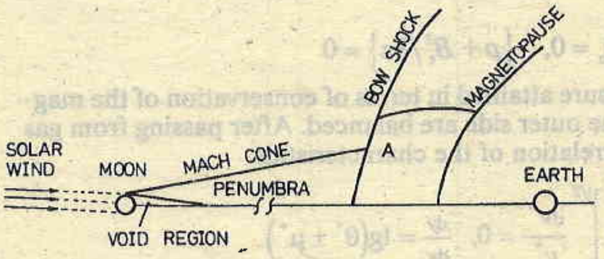

Fig. 11. Geometry of the theoretical model in the meridional plane in a phase of a new Moon. The small irregularities due to the plasma wake of the Moon are given in the elliptical part of the magnetosheat only

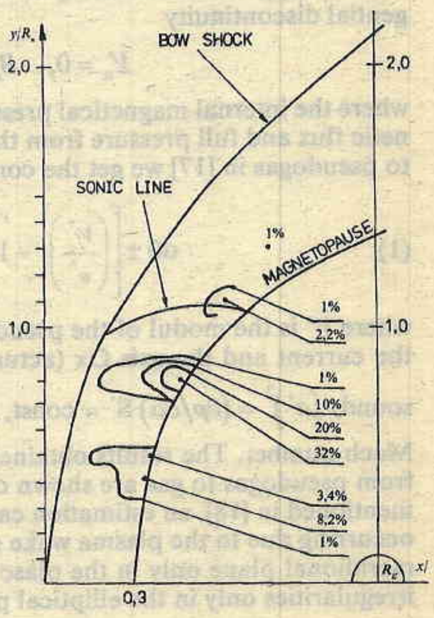

Fig. 12. Results obtained by the numerical solution of the hydrodynamical equations system at the initial conditions from Fig. 10, i. e. small irregularities due to the plasma wake of the Moon

We present the full stream as $W_2^{(F)} = W_2^0 + \tilde{W}_2$ (W^0 is the base flux, and $\tilde{W}$ — the irregularities, as $\tilde{W} << W^0$) and receive for the velocities ($V_x = U$, $V_y = V$), the density and the pressure of the small irregularities after the bow shock wave the expressions as follows:

$$\frac{\tilde{U}_2}{U_\infty} = 0{,}006\, f_u\left(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A\right), \tag{3}$$

$$\frac{\tilde{V}_2}{U_\infty} = 0{,}006\, f_v\left(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A\right), \tag{4}$$

$$\frac{\tilde{\rho}_2}{\rho_\infty} = -0{,}1\, f_\rho\left(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A\right), \tag{5}$$

$$\frac{\tilde{p}_2}{p_\infty} = \left[(0{,}9)^\gamma - 1\right] f_p\left(\gamma, \mathrm{M}_1, \mathrm{tg}\varphi_A\right). \tag{6}$$

The results obtained by solving the equation system in [18] under initial conditions (3)—(6), i. e. at small irregularities, being due to the plasma wake of the Moon are shown on Fig. 12.

This consideration is naturally simplified, as the irregularities in the lunar wake are not stationary. Moreover, the condition $V_{n/m} = 0$ of the magnetopause can no longer be considered as fulfilled in case of inhomogeneities. The latter can be involved and absorbed in the magnetosphere in a manner already discussed in [19]. Hence the condition $V_{n/m} = 0$ should be substituted by the conditions $V_{n\uparrow\uparrow} \neq 0$ and $V_{n\uparrow\downarrow} = 0$, where the arrows indicate the most favourable orientations of the magnetic moments of absorption and reflections of these irregularities [17], which occur in the lunar wake and enhanced in the magnetosheath region (3)—(6). The conductivities in the polar ionosphere exert an influence on this effect of penetration, where the field lines are projected from the equatorial magnetopause.

It can be supposed that in a nonstationary case the disturbations of the Alfvenic waves type will be enhanced, as the irregularities in the velocity components lead to more large deviations in the base stream (in the magnetosheath region) compared with the irregularities and parameters of the pressure p and density ρ. Whether and how would they distribute within the magnetosphere is a problem, which could not be solved adequately, without specifying boundary conditions of the magnetosphere (magnetopause). This will be an object for detailed future studies.

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References

1. Ness, N. F., K. W. Behannon, C. S. Scearce, S. C. Cantarano. — J. Geophys. Res. 72, 1967, p. 5769.
2. Ness, N. F., K. W. Behannon, H. E. Taylor, Y. C. Whang. — J. Geophys. Res. 73, 1968, p. 3421.
3. Siscoe, G. L., E. F. Lyon, J. H. Binsack, H. S. Bridge. — J. Geophys. Res. 74, 1968, p. 59.

4. Colburn, D. S., R. G. Currie, J. D. Michalov, C. P. Sonett. — Science, N. Y., **158**, 1967, p. 1040.
5. Ness, N. F. Lunar Explorer 35, Space Research IX, Eds. K. S. W. Champion, R. A. Smith and R. L. Smith — Rose, North Holland, Amsterdam, 1969, p. 678.
6. Ness, N. F. NASA — Goddard Space Flight Center. Preprint X-692-70-141, (1970). Invited review presented at STP Symposium — Leningrad, May 1970.
7. King, J. H. Interplanetary Medium Data Book 1963-1975 (1977); Supplement 1, 1975-1978, (1979); Supplement 2, 1978-1982 (1983), NSSDC/ WDC- A- R d. S, NASA — GSFC.
8. Solar-Geophysical Data, promt rep., WDC- A, Boulder, Colorado (1970-1985).
9. Snyder, W., M. Neugebauer, R. Rao. — J.Geophys. Res., **68**, 1963, p. 6361.
10. Wilcex, M., H. Schatten, N. F. Ness. — J. Geophys. Res., **72**, 1967, p. 19.
11. Balif, Jones, Coleman. — J. Geophys. Res., **74**, 1969, p. 2289.
12. Suckdorff, E. — Geophysica Helsinki, **5**, 1956, p. 95.
13. Bigg, E. K. — J. Geophys. Res., **68**, 1963, p. 1909.
14. Bell, B., R. J. Defouw. — J. Geophys. Res., **69**, 1964, p. 3169.
15. Michel, F. C., A. J. Dessler, G. K. Walters. — J. Geophys. Res., **69**, 1964, p. 4177.
16. Rassbach, M. E., A. J. Dessler, A. G. W. Cameron. — J. Geophys. Res., **71**, 1966, p. 4141.
17. Spreiter, J., M. Marsh, A. Summers. — Cosmic Electrodin., **1**, 1970, p. 5.
18. Popov, A., I. Mastikov, M. Kartalev. — Space Res. in Bulgaria, **8**, 1986.
19. Lemaire, J. — Aeronomica Acta, Brussel A- N 207, 1979.

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Процесът на обтичане на Луната от слънчевия вятър като източник на магнитосферни смущения

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(Резюме)

За откриване на ефект от магнитохидродинамичната лунна следа, дължаща се на процеса на обтичане на Луната от слънчевия вятър, е извършен анализ на около 150 периода на новолуния (–4, +4 дена) през 1970—1985 г. За тази цел са сравнени параметрите на междупланетната среда (според Каталога на Кинг) и на магнитосферната активност. Установено е, че: а) в 89% от периодите са наблюдавани дни с увеличен геомагнитен *K*-индекс (дори при намаляващи по време стойности на скоростта *V* на слънчевия вятър); б) в 77% от случаите е наблюдавана смяна на полярността (или смущения в полярността) на междупланетното магнитно поле (ММП) в дните —1 до +1 около новолуние; в) корелационният коефициент *R* между *V* и K_p зависи от фазата на Луната и има различни значения при спокоен слънчев вятър и при високоскоростните потоци на слънчевия вятър (V>500 km/s); г) корелационният коефициент *R* зависи също и от ъгъла между ММП и линията Слънце—Луна—Земя като *R* (0°)=0,79, *R* (180°)=0,67; д) построен е теоретичен модел за въздействието на дребномащабните нееднородности на лунната следа върху външната магнитосфера и по-специално върху магнитопаузата.