Swirls and magnetic anomalies: The puzzling swirl patterns on the lunar surface are accompanied by most strong magnetic anomalies observed over the Moon (e.g., [1]). This suggests the same origin of swirls and magnetic anomalies. Field generation mechanisms in various impact events were proposed [2-4], but they did not explain complex albedo patterns together with complicated magnetic field distributions over swirls. One of the models of swirl formation is meteorite swarm encounter with the surface of an airless body [5]. Here generation mechanism of magnetic anomalies by dense meteorite swarm is presented.

Magnetization of regolith by impact of dense meteorite swarm: High-velocity impacts produce hot vapor clouds that are partially ionized plasma. Being a conducting medium, plasma expels external electromagnetic fields from its volume, compressing the force lines in the vicinity of the cloud, as indicated in [2,6]. On Mercury, such an external field for impact plasma is Mercurian magnetosphere; for the Moon, this is interplanetary magnetic field. However, field enhancement in a single impact is insufficient for substantial magnetization [6], as can be also concluded from the lack of magnetization around most young craters [1].

In case of almost simultaneous impacts of millions projectiles [5], compression of the external field between the expanding plasma clouds is much higher (Fig.1). The upper value is determined by the pressure of the nearest plasma clouds that are compressed by the clouds in the vicinity: \( B_{\text{max}} = (8\pi nkT)^{1/2} \sim 10^4 \text{ gauss} \), where \( n \sim 10^{19} \text{ cm}^{-3} \) and \( T \sim 10^6 \text{ K} \) are plasma concentration and temperature in the initial stage of expansion, and \( k \) is Boltzmann constant. Much less magnetic fields than that are sufficient for magnetization of all magnetic material (iron) to saturation values \( J_s \).

Note, that \( B_{\text{max}} \) which can be achieved in swarm impact exceeds \( B_{\text{max}} \) due to large antipodal impact [2], because, in swarm impact, field compression occurs at the initial stage of plasma expansion, when its density \( n \) is much higher than at the moment of arrival to the opposite side of the Moon.

At some depth under the plasma clouds, magnetic lines, repulsing from each other, return to their initial configuration (Fig.1) and the values of the external field return to the initial values. At lower depths, magnetic lines can be directed almost horizontally (Fig.1), which should result in nearly horizontal magnetization of the area under the plasma clouds. High magnetic field is relaxed mainly due to decrease of plasma density \( n \) in its expansion to space, diffusion of magnetic field into impact plasma being slower.

After removal of plasma and strong magnetic field, remanent magnetization \( J_r \sim 0.1J_s \) is left. Such magnetization affects, most probably, not deep crustal areas, but just regolith layers under the impact plasma. Obviously, the anomaly formed by magnetization of regolith should degrade with time, mixing of regolith destroying its magnetization. This implies that the anomalies formed in this way should be young. The age of such anomaly is less than the regolith mixing time for the lower boundary of magnetized layer.

The boundaries between the plasma clouds are very mobile and strong magnetic field captured there may constantly shift its position and direction during the lifetime of dense plasma. This may produce, in addition to horizontal magnetization mentioned above, arbitrary complex magnetic pattern as observed over Mare Ingenii and its neighborhood [7]. Complex structure and high values of magnetic field may result in complex trajectories of charged dust ejecta and contribute to complex albedo patterns of swirls.

Calculation of the swarm-impact-induced magnetic fields. Let us evaluate the magnetic fields that can be observed from Lunar Prospector (LP) orbits over magnetized regolith. Magnetization \( M_s \) per unit area of regolith is

\[
M_s = J_s(1-p)(\rho_\text{Fe}/\rho_\text{Fe})\rho_x H_x, \tag{1}
\]

where \( \rho_\text{Fe} \) and \( c_\text{Fe} \) are density and weight concentration of iron, \( \rho_x, p, \) and \( H_x \) are density, porosity, and depth of magnetized material, respectively. Horizontal component \( B_x \) of magnetic field at a height \( h \) over the center of horizontally (in \( y \)-direction) magnetized rectangle of sides \( 2R_x \) and \( 2R_y \) along \( x \) and \( y \)-axes is

\[
B_x = 4R_x R_y M_s \left( \frac{(R_x^2 + h^2)(R_y^2 + R_x^2 + h^2)^{1/2}}{\sqrt{R_x^2 + h^2}} \right)^{1/2}. \tag{2}
\]

Table 1 compares the values of \( B_{\text{north}} \) observed by Lunar Prospector over the center of Reiner-gamma and

7.4 m, magnetic anomalies can be reproduced rather success-
site, height dependence of the field in the centers of
topology of the patterns of magnetic field components.
height dependence of the field values, and (2) complex
difficulties in description of the observational data: (1)
magnetization of the Moon has to overcome two
of extremes are in accordance with each other, so they
are not due to noise, and further smoothing results in
loss of information about the magnetic field.

Lost of information about the magnetic field.

B_y calculated at c_w = 1 wt.%, J_t = 0.18J_w, p = 0.3, H_y =
7.4 m, R_x = 30 km, and R_y = 10 km. Close values of the
measured and calculated fields show that a thin but ex-
tended magnetized “carpet” can explain LP magnetic
observations. Note, that the value predicted at the same
parameters for magnetic field on the surface is about
the upper values measured by astronauts [8]. Here LP
data from PDS (Fig.2) were not smoothed as in [7],
which resulted in more than twice as high values for all
components of B in Table 1. PDS data near the points
of extremes are in accordance with each other, so they
are not due to noise, and further smoothing results in
loss of information about the magnetic field.

Fig.2. Magnetic field profiles over Reiner gamma
(meridian 301.75 E)

Crustal or regolith magnetization? Any modeling
of magnetization of the Moon has to overcome two
difficulties in description of the observational data: (1)
height dependence of the field values, and (2) complex
topology of the patterns of magnetic field components.

(1) For the present sets of orbital magnetic data,
with no more than 3 heights available for each lunar
site, height dependence of the field in the centers of
magnetic anomalies can be reproduced rather success-
fully by crustal dipole model as well as surface “mag-
netic carpet” model presented above (Table 1). The
depth of a magnetic dipole is determined by the topol-
ogy of magnetic isolines (distances between zero lines
or extreme points); the inclination and magnetic mo-
ment of a dipole are determined by the values of the
field components. E.g., magnetic field profiles along
301.75°E shown in Fig.2 are described by nearly hori-
tonal single dipole at a depth 9±0.2 km, which implies
B_y = 1230 nT on the surface. The lack of data at low
heights and at the surface does not allow us to use
height dependence of B_y in the center to distinguish
between crustal and surface magnetization.

(2) Complicated distributions of magnetic field
components over swirls, especially, in the region of
Mare Ingenii, completely exclude the model of single
crustal dipole. Too many dipoles should be used to ap-
proximate complex contour maps of B-components over
Mare Ingenii. In less complicated pattern over Reiner-
gamma (Fig.3, left), magnetic contours are enlarged in
east-west direction compared with rather circle-like
contours predicted by single dipole model (Fig.3, cen-
ter). This implies magnetized area extended to many
kilometers from east to west (Fig.3, right).

Conclusions: (1) Multiple impacts that occur in
encounter of a dense meteorite swarm with the Moon or
Mercury result in compression of the interplanetary or
local magnetic field, which strengthen it enough for
magnetization of the local material to saturation.

(2) Swarm-impact-induced magnetization of re-
golith can account for the observed values and complex
distributions of magnetic fields over swirls.

(3) Distribution of magnetic fields over magnetic
anomalies imply complicated magnetic models and
magnetization of areas with sizes of the same order as
the heights of observations.

Thus, meteorite swarm encounters with lunar or
Mercurian surfaces can provide the observed albedo
and magnetic field patterns typical of swirls.

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Impact Eng., 14, 205-216. [5] Starukhina L. V. and
Source Book, 595-632.

<table>
<thead>
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<th>Table 1.</th>
<th>Height, km</th>
<th>B_y measured, nT</th>
<th>B_y calculated, nT</th>
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<td>-7.3</td>
<td>-8.4</td>
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Fig.3. Contour lines of the vertical component B_y of
magnetic field at a height of 18 km over Reiner-γ
(left), and its simulations: the field over 9 km deep
crustal dipole (middle), the field over 60x20km² mag-
etized regolith area (right); the center of Reiner-γ is in
the centers of the pictures (7.5 N, 301.75 E)