METEORITE SWARM ENCOUNTERS AS A SOURCE OF MAGNETIC ANOMALIES ON THE LUNAR AND MERCURIAN SURFACES L. V. Starukhina, Astronomical Institute of Kharkov University, Sumskaya 35, Kharkov, 61022, Ukraine, starukhina@astron.kharkov.ua

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: $B_{max} = (8\pi nkT)^{1/2} \sim 10^4$ gauss, where $n \sim 10^{19}\text{cm}^{-3}$ and $T \sim 10^4$ 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_{max} which can be achieved in swarm impact exceeds B_{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.

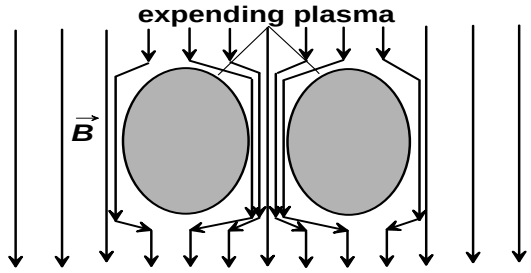

Fig.1. A scheme of compression of interplanetary magnetic field ***B*** by expanding plasma clouds after simultaneous meteorite impacts close to each other. External field ***B*** can have any direction.

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

$$M_s = J_r(1 - p)(\rho_r/\rho_{Fe})c_w H_r, \quad (1)$$

where ρ_{Fe} and c_w are density and weight concentration of iron, ρ_r, p, and H_r are density, porosity, and depth of magnetized material, respectively. Horizontal component B_y 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

$$B_y = -4R_xR_yM_s /[(R_y^2 + h^2)(R_x^2 + R_y^2 + h^2)^{1/2}]. \quad (2)$$

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

Table 1.

height, km	B_{north} measured, nT	B_y calculated, nT
17.6	-47.6	-46.7
33.6	-13	-12.2
39.2	-7.3	-8.4
0		-220

B_y calculated at c_w = 1 wt.%, $J_r = 0.18J_s$, p = 0.3, H_r = 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 extended 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.

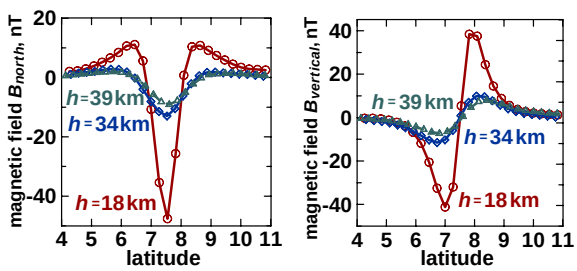

Fig.2. Magnetic field profiles over Reiner gamma (meridian 301.75 E)

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 successfully by crustal dipole model as well as surface "magnetic carpet" model presented above (Table 1). The depth of a magnetic dipole is determined by the topology of magnetic isolines (distances between zero lines or extreme points); the inclination and magnetic moment 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 horizontal 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.

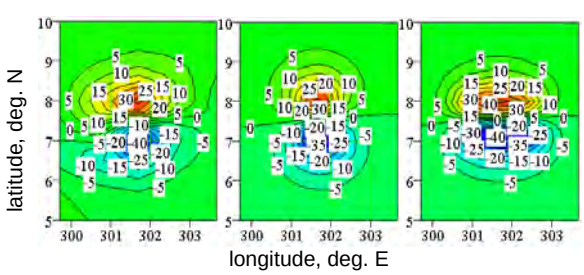

Fig.3. Contour lines of the vertical component B_z of magnetic field at a height of 18 km over Reiner-γ (left), and its simulations: the field over 9 km deep crustal dipole (middle), the field over 60x20km^2 magnetized regolith area (right); the center of Reiner-γ is in the centers of the pictures (7.5 N, 301.75 E)

(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 approximate 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, center). 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 regolith 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.

Acknowledgements: I thank Yu. G. Shkuratov for stimulating this work and M. A. Kreslavsky for providing the data on magnetic fields over the Moon. The work was partially supported by CRDF grant UKP2-2614-KH-04.

References: [1] Halekas J.S. et al. (2001) *JGR, 106*, 27841-27852. [2] Hood L.L. (1987) *GRL, 14*, 844-847. [3] Gold T. and Sotter S. (1976) *Planet. Space Sci., 24*, 45-54. [4] Crawford A. and Schultz P.H. (1993) *Intern. J. Impact Eng., 14*, 205-216. [5] Starukhina L. V. and Shkuratov Yu. G. (2004) *Icarus, 167*, 136-147. [6] Srnka L.J. et al. (1979) *Earth Planet. Sci. Lett., 42*, 127-137. [7] Hood L.L. et al. (2001) *JGR, 106*, 27825-27839. [8] Spudis P. and Pieters C. (1991) *Lunar Source Book*, 595-632.