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National Aeronautic and Space Administration
Goddard Space Flight Center
Contract No.Nas-5-12487

ST-SP-10727

INVESTIGATION OF MAGNETIC FIELDS ON THE SUN

By

B.A. Ioshpa
&
V.N. Obridko

(USSR)

12 JULY 1968

ST-SP-10727

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Vestnik Akademii Nauk SSSR,
Tom 4, pp 46-50,
Moscow, April, 1968.

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SUMMARY

This review paper considers studies of magnetic fields on the Sun as a major contribution to the explanation of the multitude of events in the Sun, these influencing in their turn, those near the Earth.

First the history is given of investigations of magnetic fields on the Sun, particular attention being paid to sunspots. The authors then describe the use by IZMIRAN since 1962, of photoelectric magnetographs for the determination of the field component along the visual ray, with the assumption that beyond the spot penumbra the magnetic field drops sharply to zero. The measurements were conducted since then by means of a circular polarization analyzer, the distance measures between the Zeeman components yielding the magnitude of the magnetic field at the investigated point.

Two trends in the studies are emphasized for the last decade: the study of local magnetic fields with high resolution and the refinement of macroscopical regularities and of structural interrelation of various characteristic dimensions.

The mechanism of solar flares is examined and the latter's structure is found to be very irregular. Filaments, prominence, faculae and flocculi are studied alongside with the chromosphere in general.

In the final resort it is concluded that the relationship between all the elements of the structural hierarchy and active events on the Sun deserve further detailed study.

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The processes taking place near Earth are influenced in one or another way, by practically all the events on the Sun. In view of this, the investigation of the mechanism, binding into one all the diversified events of solar activity, i.e. the magnetic fields on the Sun, is of particular importance.

The first investigations of magnetic fields on the Sun were carried out at the turn of our century by the American scientist G. Hale. In the course of the following three decades, such investigations were conducted exclusively at the Mount Wilson Observatory (USA). They enabled us to obtain a series of results, concerning the ascertaining of statistical mechanisms of magnetic fields' structure and evolution. Particular attention was paid to one of the most powerful manifestations of solar activity, namely to sunspots. However, on account of rather low spatial resolution, the results obtained gave only an averaged pattern of spot field distribution.

It was discovered, that sunspots from the so called bipolar groups, which consist of two spots or two other spot groups, are divided along the latitude and have an opposite magnetic polarity. The distribution of the latter is subject to the mechanism established by Hale, i.e. the reciprocal position of area layout with different magnetic polarities in the bipolar groups in the northern and southern hemispheres is opposite: the whole polarity system remains invariable in the course of a given 11-year cycle of solar activity, changing, however, at the commencement of the following cycle. The investigation of the magnetic field led to the representation of a fan-shaped structure of magnetic lines of force in the spot, whereupon it was assumed that beyond the spot penumbra, the magnetic field drops very sharply to zero.

In the middle of past decade, the first photoelectric magnetographs for the determination of the field component along the visual ray were constructed first in U.S.A. and then in the Soviet Union. This immediately led to a sharp increase (by 2-3 orders) in the sensitivity of magnetic longitudinal field measurements. At the beginning of the current decade, we designed and built photoelectric magnetographs of the total vector, which enables us to investigate the magnitude as well as the orientation of local magnetic fields.

Photographic and photoelectric measurements of solar magnetic fields have been conducted at the Institute of terrestrial magnetism, ionosphere and radiowaves of the USSR Academy of Sciences (ISMIRAN) since 1962. The Zeeman splitting pattern in one of the solar spectral lines is photographed by means of circular polarization analyzer. The distance measurement between the Zeeman components gives the magnitude of the magnetic field H at the investigated point. The improved Hale's method consists in the utilization of a special monochromatic photographic guide, which allows the tying with great precision of magnetic field measurements with the details on the Sun and the materialization of detailed measurements inside the spot.

The photoelectric magnetograph built at IZMIRAN offers the possibility of determining simultaneously all the magnetic field components on the Sun. The principle of the method is based upon the emission modulation in the wing of the solar spectral line by means of an electro-optical modulator and the separation of the first two photocurrent harmonics. The measured signals enable us to fully determine all the polarisation parameters of the magnetosplit line, and consequently, the magnitude and the direction of the field.

In the works of last decade, it is possible to single out two tendencies: the investigation of local magnetic fields with high sensitivity and high resolution; the refinement of macroscopical regularities and of the structural interrelation of various characteristic dimensions.

The very first investigations with high resolution (Crimean Astrophysical Observatory of the USSR. Academy of Sciences and IZMIRAN, have already shown, that the magnetic field of even ordinary sunspots, differs very much from the classical representation of the line of force fan, and has a much more complex character. Only in the very center of the spot does the field approach a vertical character. While receding from the center, the lines of force, decline so strongly from the normal that the field is practically entirely horizontal as early as in the penumbra. At the outer boundary of the penumbra the field does not drop to zero at all, but continues far beyond its borders. Practically in all the formations of active regions near spots (in faculae, flocculi, near chromospheric filaments) the field reaches considerable magnitudes (50-300 gauss) and mostly horizontally (IZMIRAN, SIBIZMIRAN). The series of works carried out at IZMIRAN, point to the fact that the structure of the magnetic field in active formations is close to force-free(E.I. Mogilevsky). At high averaging the distribution of the entire field magnitude in the spot basicaly satisfies the dipole principle, but in details, considerable deviations are revealed. Numerous local maxima and minima in the field of the spot and regions of sharp polarity changes are observed. Still more substantial anomalies are made apparent during the investigation of field directions in the spot.. The sharp variations in line of force directions and crossing regions, the presence of irregular azimuthal component, are typical of the majority of spots (A.B. Severnyy). It was revealed, that spots are regions of existence of strong currents. Measurements on several levels in solar atmosphere show great heterogeneities of the magnetic field in depth. At observations on several levels isolated fields in the chromosphere were established near the spots, having in several separate cases even an opposite sign by comparison with the underlying field

Lines of neutral as well as ionized elements are simultaneously observed in sunspots. This is evident, that regions with very distinct physical conditions, temperature and density-wise, apparently coexist in the spot. Investigation of magnetic fields shows that in hotter regions, the field is substantially smaller than in the colder ones. The physical conditions in warmer regions apparently are close to those in the undisturbed photosphere. Evidently, these regions constitute impregnations of photospheric matter. The accounting of a small quantity (2-5 % by surface) of dense photospheric matter impregnation allows us to construct as an average a rarefied but optically dense model, in which a series of rarefied model difficulties are eliminated (V.N. Obridko).

From the standpoint of theory the existence of considerable heterogeneities in the spot and in the chromosphere, is not unexpected. In connection with the magnetic field energy prevalence over other forms of energy, the magnetic field in the spot and in the chromosphere should tend to acquire a froce-free structure. In accordance with computations (F.A. Yermakov), the emergence in such conditions of a heterogenous structure is possible; in it the field desintegrates in separate tiny formations with a force-free magnetic field, i.e., subgranules, surrounded by quasihomogenous currentless field with considerably reduced intensity,

The decreased spot brightness is explained by the fact that convection, transferring heat from lower solar regions into the atmosphere, is arrested in the spot by an intense magnetic field. However, direct observations in continuous spectrum, showed the presence in the spot penumbra of brightness heterogeneities, which by shape, dimensions and character of temporal variations, suggest very strongly the results of convection activity. Besides, with the full halt of convection in the spot, the temperature inside should be considerably lower than that observed. The computations carried out at IZMIRAN and (Institute of Physics in the name of P.I. Lebedev, of the USSR Academy of Sciences (Yu.D. Zhugzha, S.I. Syrovatskiy)), established that there takes place in the spot a new type of convection - the vibrating convection. Contrary to the usual circulation, at which one and the same liquid element first rises upwards, cools with heat liberation and then drops down, in vibrating convection the floating of one element is attended by the descent of the adjacent one. Such a convection may exist in as strong a field as desirable and it apparently leads to the emergence in it of strong field heterogeneities.

The structure of solar flares is also very irregular. The last investigations showed that a flare is apparently composed of filaments only 10^5 - 10^6cm thick. The flares show a tendency to arise in the region of sharp variations in the magnitude and the azimuth of the field; even crossing of lines of force was noticed in numerous cases (A.B. Severnyy).

Field measurements in prominences and filaments on the disk led to several unexpected results. The field in prominences, located rather high above the active region (10-20 thousand km), reaches considerable magnitudes - from some tens to some hundred of gauss. In a series of cases a field of $\sim$ 100 gauss was measured in prominences not having any apparent relation to the active region on the disk. This result is interpreted as evidence of the presence of an internal prominence field tied up with a field below at the ends of filament. The field variation with altitude in series of prominences is not monotonic. The maximum field value is frequently observed in the central part of a prominence. The field near chromospheric filaments reveals signs of a double structure: it constitutes a combination of an external field, at whose arched structure apex lies the filament, and an internal field directed along the filament (B.A. Ioshpa). Such a structure, possibly, creates more advantageous conditions for the maintenance and the stability of the filament.

The question about the magnitude of magnetic field intensity above the spot is important for the interpretation of polarized radioemission on centimeter waves. It appeared, that radio sources are very accurately disposed above the sunspot nuclei, and have an area comparable to them. Usually this radiation is explained by a magnetic bremmstrahlung mechanism. Such a mechanism requires extremly great intensities at the radiation formation level (1000-1400 gauss), which is generally considered to be equal to 10-20 thousands km. The existing sunspot models do not yield such intensities at the indicated altitude (according to the standard dipole law the intensities are 3-5 times lower even on the sunspot axis). It is very difficult to assume that the tube of force reaches such altitudes almost without widening, inasmuch as there is no force in the chromosphere and corona that could have stopped it from expanding. That is why it is necessary to discuss once again the possibility of employing other radiation mechanisms. Another approach was demonstrated by M.A. Livshitz, V.N. Obridko and S.B. Pikel'ner. They showed that above the sunspot the corona is lowered. At that, the outlet level of polarized centimeter emission is located at 3-5 thousand km. The values of the field N $\sim$ 1000 gauss at the given altitude is quite true. For such a model, it is possible to explain the spectrum, the polarization and the variation; the center being the edge for radiosources. (?)*

For the investigation of the general field of the Sun the discovery of its fine structure is of particularly great significance. According to the first observations carried out by G. Babcock (USA) in the magnetosphere with high sensitivity, but with low spatial resolution, the intensity of the total field averaged around 2-4 gauss, which is considerably less than the value initially derived by G. Hale. The whole field varies with the 22-year period, but

* [The Russian text here is very foggy].

the phase of these oscillations is shifted by one fourth of the period by comparison with the usual cycle of solar activity, determined by the number of sunspots and the laws of magnetic polarity. Such variations bear an irregular character and in some years the polarity of the field had one and the same character at both poles of the Sun. The observations of general field with high resolution at Crimean Astrophysical Observatory, immediately led to the discovery of its delicate structure. It was revealed that on the very same pole there are regions of different polarity with a rather extended field (up to several tens of gauss). The characteristic dimensions of these regions differ within a quite broad range (5-30"). The fields frequently vary in volume and sign. The field streams of different polarities are not balanced; the causes of this phenomenon are still unclear.

The discovery of magnetic field's fine structure as a typical characteristic of solar plasma opens a way to solve a series of difficult problems of solar-physics. In the first place it concerns questions regarding temporal variations in solar plasma; the latter being frozen-in into the magnetic field should be slow-acting in its variations. The ohmic dissipation time t_D is $\frac{\sigma l^2}{c^2}$ (СГСЭ).

With the decrease of characteristic dimensions by 1-2 orders, the time of ohmic dissipation, is substantially curtailed.

In recent years there also appeared some works on macroscopical regularities of distribution of magnetic fields on the solar disk and on the relationship of local fields with the general field of the Sun. Observations with high-sensitivity by V. Boomba (Czechoslovakia) and R. Howard (USA) have shown that the bulk of solar surface is occupied by magnetic fields exceeding several gauss. This continuously existing magnetic background was generated as a result of the decay of old active centers. The background fields are grouped inside separate longitudinal zones and can be traced sometimes in the course of a whole year, although their contours continuously undergo slow variations. As a result of expansion and Sun's differential rotation effect, (with the decrease of latitude, the rotation velocity increases) these large-scale background fields are extended and shifted to the poles. In each hemisphere mostly regions with polarity corresponding to the one of the eastern bipolar group, drift toward the pole.

The expansion mechanism of magnetic field's region was suggested by R. Leytton (USA). According to this mechanism, the magnetic region represents a combination of separate magnetic tubes, undergoing "random" Brown-type shifts. The magnetic tubes are tightly connected with supergranulation cells well visible in the light of the ionized calcium K-line forming the so called chromospheric net, which covers all the "quiet" surface of the Sun. The mean diameter of the cells is around 30 thousand km. The motions inside the cells is predominantly horizontal and directed from the center of the cells to the edges; the mean velocity is about 0.5 km/sec. Apparently, these motions lead to the concentration of magnetic lines of force at the edge of cells. Every magnetic tube, connected with such a cell, can be considered as a separate magnetic element ("atom"), participating in the diffusion which is determined by the nonstationary state of the photospheric field velocities.

As a result of diffusion spreading, the region of magnetic field expands, while the mean intensity decreases. The superimposition of differential rotation on this effect causes the emergence in the polar regions of the Sun, of fields with an intensity of about one gauss, changing sign during the period of solar cycle maximum. Thus, the works of later years, enabled us to establish genetic dependence between local magnetic fields on the Sun and the field in polar regions (the so called general field of the Sun). Apparently, in the general representation there is no idea of the general field of the Sun (i.e. dipole field, connected with currents in the deep-seated solar regions), or else it is too small to detect by the existing methods. The superficial character of the polar field and its relationship with local fields' expansion, helped to eliminate the contradiction whereby the time of essential variation of the dipole field should be around 10 billion years, while the period under observation of polar field variation is of $\approx$ 22 years. On the other hand, for the emergence of magnetic fields in active regions, and particularly of magnetic fields in the spots, the presence of "baying" field, the nature of which is still not clear, is apparently necessary. That is why the question about the existence of a general field of the Sun and its physical nature are not definitely elucidated.

The concentration of background fields inside certain longitudinal regions is apparently connected with an interesting fact, that the new active centers appear in the regions, where there is already a background field (V. Boomba, R. Howard). Thus, there exists a successiveness, the genetic connection between the old and the new active centers, the investigation of which should bring to a better understanding of the reasons of the emergence of active regions on the Sun.

In recent years some works appeared (V.Boomba), which enabled to assume the presence of a deep internal dependence between supergranular structure of chromosphere and other active formations on the Sun, among them the sunspots. It has been shown, that the spot begins to develop in the space between supergranules - there, where the magnetic field is higher. Gradually the spot inundates the supergranules. The spot was found to be steadier, when its area is equal to that of several supergranules. There is a definite connection between the site of filament flare emergence and the supergranular structure.

Analyzing the character of magnetic field distribution on the solar disk, it is possible to reach the conclusion about a certain structure hierarchy of the magnetic field and of the velocity field on the Sun. The photospheric granule corresponds to the lower stage of this hierarchy, the supergranule - to the middle, and the hypothetical gigantic granule to the upper, the dimension of which constitute approximately 400 thousand km. The dimensions of consecutive elements of hierarchy as well as their life-times differ approximately by one order. The connection between the elements of such an hierarchy and active occurrences on the Sun deserve a further detailed investigation.

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Contract No.NAS-5-12487
Volt Technical Corporation
1145 19th Street, N.W.
Washington, D.C. 20036
Telephone: [202] 223-6700 - X 36,37.

Translated by
Ludmilla D. Fedine
July 9, 1968
Revised by
Dr. Andre L. Brichant
July 11, 1968.

ALB/ldf