SOVIET PHYSICS

USPEKHI

A Translation of Uspekhi Fizicheskikh Nauk

SOVIET PHYSICS USPEKHI (Russian Vol. 88, Nos. 1 and 2) JULY-AUGUST 1966

523.038

MAGNETIC FIELDS OF THE SUN AND STARS

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Usp. Fiz. Nauk **88**, 3-50 (January, 1966)

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INTRODUCTION

THE discovery by G. E. Hale in 1908[1] of the Zeeman splitting of dark (Fraunhofer) lines in the spectrum of sunspots is undoubtedly one of the most important events in astronomy: from it began a systematic study of magnetic fields on the Sun and the search for magnetic fields of other astronomical bodies (stars, galactic nebulas, etc.). Until this discovery, the only example of a magnetic field in the cosmos was the magnetic field of our Earth. Thanks to the work of H. W. Babcock[2] in the last 20 years it has become established that numerous stars also have magnetic fields, the intensities of which reach, on the average (over a stellar surface), several kilogauss and are, therefore, considerably stronger than the solar magnetic fields, which are of the same order but are concentrated mainly in sunspots. If we could investigate the Sun as a star, the solar magnetic fields would be hardly detected because the solar regions accompanied by considerable magnetic fields (m.f.) do not contribute more than 0.1% to the total brightness of the Sun.

Over 50 years have passed since Hale's discovery; during this time, a wealth of data on the solar and stellar magnetic fields has been accumulated, but the nature of the magnetism of the Sun and stars remains very puzzling. There is no theory which can explain successfully the various phenomena, and the observations frequently lead to contradictory conclusions. For example, theoretical considerations would suggest that, due to the very high conductivity of the stellar plasma and the very large characteristic dimensions with which we are dealing in the case of stars, the stellar magnetic fields should not decay. However, the observations frequently show strong and "spasmodic" changes of m.f. which are accompanied by other extremely rapid changes in the state of the stellar plasma (changes in the velocity field, etc.). Colossal and extremely fast changes in m.f. are observed in magnetic and variable stars: here, sometimes, a complete redistribution of the field and even a reversal of the polarity are observed during a period of the order of days.

The role of magnetic fields in the maintenance of the equilibrium or the steady state of a star is also important if we consider, for example, such stars as HD 215441, for which Babcock found a field intensity of 34 kG.[3] In this star, the magnetic pressure may reach 50 atm, which greatly exceeds the normal gas pressure (and obviously the radiation pressure).

The problem of the chemical composition of stars is very closely related to their magnetic fields. The exceptionally long diffusion time necessary for the mixing of elements in the presence of a magnetic field, in the case of dimensions characteristic of those met with in stars, does not exclude the possibility that the chemical composition of the magnetized parts (for example tubes or rings) of the stellar plasma may differ from the composition of the remainder of the star. This may, in particular, apply to the sunspots with their strong magnetic fields. In principle, as pointed out by Alfvén,[4] the magnetic spots may retain a memory of the distant past of a star and may indeed be fragments remaining after earlier stages of its evolution.

The present review attempts to summarize the results of the experimental investigations of the magnetism of the Sun and stars. The theories of magnetic phenomena in astronomical bodies will be practically ignored since it would have been difficult to present in a single review both the experimental and theoretical studies of the problem, especially as the theoretical problems belong more to the field of theoretical magnetohydrodynamics.

The difficulty of producing in a terrestrial laboratory a plasma with the same characteristic properties and relations between the parameters as those in the Sun and stars makes the whole problem of stellar magnetism very special, to the extent that we are not yet able even to formulate clearly the physical meaning of the phenomena being discussed—something which is frequently due to the insufficiency of the experimental data and the lack of theoretical analyses.

1. METHODS AND TECHNIQUE OF MEASURING MAGNETIC FIELDS

In the case of strong fields, the determination of the absolute value of the magnetic field intensity H is based essentially on measurements of the value of the magnetic splitting of a spectral line with a given wavelength λ:

$$\Delta\lambda_H = \pm H \frac{\mu\lambda^2}{hc} (m_2 g_2 - m_1 g_1), \tag{1}$$

where m_2 and m_1 are the magnetic quantum numbers of the upper and lower levels, which vary from $-J$ to $+J$ and the value of the Landé factor is given by

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}. \tag{2}$$

The Zeeman splitting pattern of any line can be found by calculating g for the upper and lower levels (g_1 and g_2); then for each term we write down the series of allowed mg and calculate the differences using the selection rules ($\Delta m = 0$ for the π-components and $\Delta m = \pm 1$ for the orthogonally polarized σ-components). The Zeeman splitting patterns for all the usual transitions are tabulated in [5]. In the simplest case of lines having the triplet splitting we have $g_1 = g_2 = 1$ for a normal triplet, but the value of g reaches 2.5 or 3 for some lines which are very important in practical applications, such as the iron lines λ = 6302, 6373, 5250 Å, which are used most frequently in the measurements of the solar m.f. If g_1 and g_2 are unequal, an anomalous pattern is obtained: the π- and σ-components, which have different intensities, merge into groups ("blends") from which we can calculate the effective shift represented by the quantity z (which is the average value of $m_2g_2 - m_1g_1$, weighted for all the intensities); these quantities are tabulated in [6] for about 1500 lines used in stellar spectra. For typical anomalous patterns see [7]. In simple triplets, which are symmetrical on both sides of an undisplaced π-component, the σ-components are located at

$$\Delta\lambda_H = \pm 4.67 \cdot 10^{-5} g \lambda^2 H, \tag{3}$$

where λ is in cm and H is in G. In a purely longitudinal field, the π-component is known to be absent and both the σ-components are circularly polarized in the right-handed and left-handed sense, respectively, so that in a purely transverse field the π- and both σ-components are plane-polarized at right angles to one another. Because of the relatively strong broadening of the lines in the spectra of stars and the Sun (mainly due to turbulence and rapid rotation), their width $\Delta\lambda$ is considerably greater than $\Delta\lambda_H$ and we have a "blend" of overlapping components of the Zeeman pattern. Therefore, in astrophysics, it is preferable to work almost exclusively with a circular polarization analyzer, i.e., use only the longitudinal Zeeman effect in which the π-component is absent (it is easier to measure the splitting than a small change in contrast within a given line).

In the case of a field inclined at an angle γ to the line of observation, the relative intensities of the components of a triplet after passing through a circular polarization analyzer were shown by Seares[8] to be given by the expressions

$$\sigma_1 = \frac{1}{4}(1 - \cos\gamma)^2, \quad \pi = \frac{1}{2}\sin^2\gamma, \quad \sigma_2 = \frac{1}{4}(1 + \cos\gamma)^2, \tag{4}$$

if the emission line is optically "narrow." The diagram in Fig. 1 illustrates the variation of the intensities of the various components with the angle γ. From obvious energy considerations, it follows that the strongest intensity (equal to 1) of each of the components represents half the intensity* of the total emission of two mutually orthogonal oscillations, appearing in the presence of a magnetic field and incident on an analyzer (such oscillations are independent and the squares of their amplitudes can be added). In practice, however, since $\Delta\lambda_0 \gg \Delta\lambda_H$ (particularly in the case of weak fields), the components of the spectrum overlap, and this is the cause of a characteristic interaction between them: the intensities (or absorptions) can be added only in the case of an optically thin layer. In the case of an optically thick layer, the emission of the σ_2-components (when $\gamma = 90°$) is absorbed by the σ_1 component but is not absorbed by

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*When we speak of the intensity, we mean the integral over the spectral line profile.

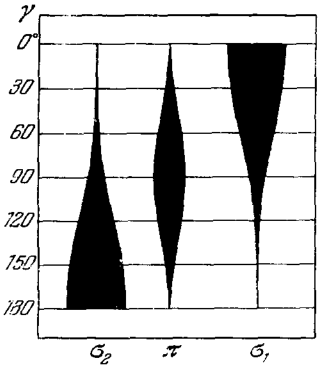


FIG. 1. Relative intensities of the σ_1, π, σ_2 components (n_V, p_V, n_r) as a function of the angle γ, in accordance with [8].

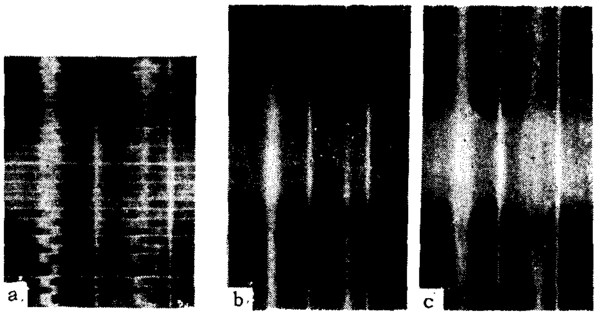


FIG. 2. Polarization spectrum of a large sunspot, recorded using a polaroid mosaic (a polaroid and a quarter-wave plate) (a) and a polaroid by itself (b and c), adopting different positions of the extinction axis (0 and 45° for b and c, respectively); the depolarization effect is clearly visible in this sunspot.[84]

the π-component orthogonal to it. In general, the state of the polarization at each point of a magnetically split line, in the case of the superposition of its components, is a state with an elliptical polarization, symmetrical with respect to the center of the line; for instances of such distributions, for various values of γ from 0 to 90°, see, for example,[9].

To measure strong fields on the Sun and in stars, it is usual to employ a spectrograph of the highest possible dispersion, with an analyzer placed in front of its slit. The Zeeman pattern in the spectrum is recorded photographically or observed visually (the latter only in the case of the Sun) for two opposite states of polarization. The analyzer consists basically of a crystal plate, introducing a path difference $(2n + 1)\lambda/4$ between the oscillations along the ordinary and extraordinary axes, and polarizers, which are usually placed at ±45° to these axes.

For the solar observations, it is preferable to place, between the quarter-wave plate and the slit, a polaroid mosaic consisting of narrow polaroid strips whose extinction axes alternate making angles of +45, −45, etc., with the plate axes (Hale—Nicholson plate). This allows us to obtain directly a distribution (which is discrete with steps equal to the strip width) of m.f. in one measurement over a segment corresponding to the spectrograph slit image, which usually covers a distance of 3—5 angular minutes on the solar disk (diameter ≈30′). Figure 2 shows a photograph of the Zeeman effect in the spectrum of a sunspot (the bright band along the spectrum), recorded with a mosaic analyzer at the Crimean Astrophysical Observatory.[10] The sensitivity of this method usually does not exceed 100—200 G. The method was developed further recently[11] by the use of a spectrograph with a "jumping" entry slit (as well as a polaroid mosaic and a quarter-waver plate) and a relatively wide (width of the order of the greatest splitting) exit slit in the focal plane of the spectrograph, moving discretely and synchronously with the entry slit. A photographic plate placed in the focal plane of the spectrograph gives a discrete sequence of images of a magnetically split line for various parts of the Sun's surface, both along and at right angles to the spectrograph slit, i.e., a discrete field distribution is obtained along two dimensions.

Leighton[12] developed a method for determining a continuous distribution of the field along two dimensions on the solar disk by applying the principle of a spectroheliograph, which is an instrument giving a monochromatic image of the Sun in the light of a selected spectral line. The essence of this method is briefly as follows: if a narrow exit slit of a spectrograph is placed at an edge (in a wing) of a spectral line subjected to magnetic splitting, and a circular polarization analyzer is placed in front of the entry slit (the analyzer consists of a quarter-wave plate and a polarizer making an angle of +45° with the plate axis), those regions of the Sun which have a magnetic field exhibit, for example, a dark σ_1-component in the exit slit; therefore, the intensity of light in that part of the slit decreases. If the image of the Sun is moved relative to the entry slit and the photographic plate placed behind the exit slit is moved in synchronism, the photographic plate will record a series of bright and dark regions, corresponding to the sequence of the magnetic and nonmagnetic regions on the Sun. In fact, because of the presence of a σ_2-component, we obtain (by beam splitting) two images of the Sun (in σ_1 and σ_2), which are then superimposed, making it possible to intensify the contrast in the final print. A similar method may, of course, be used to determine the radial velocities over the solar disk causing similar shifts in the lines due to the Doppler effect. The great advantage of the method is its ability to obtain rapidly (in 10 min) a m.f. distribution over the whole solar disk; the disadvantage of both methods is their relatively low sensitivity (the errors are not less than 50 G).

Several ingenious but complex interferometric methods,[13-16] intended mainly to measure the general m.f. of the Sun (far from sunspots and other active regions), have been proposed with the aim of reducing the errors in the photographic method of determining m.f. on the Sun. However, weak fields are measured most effectively by a photoelectric method, first introduced in[17] and then developed in[18] in its most successful modification. Further applications and improvements of this method were reported in[19-21].

The principle of the photoelectric method (the magnetograph) is very simple. If a magnetic field is weak, then, due to the strong overlap of the components, the separation between them cannot be measured in practice, but if we modulate the state of polarization of the beam incident on an analyzer (for example, by varying the delay within the limits of $\pm\frac{1}{4}\lambda$), then the resultant intensity fluctuations in the blended Zeeman pattern and the photoelectrically measured amplitude of these fluctuations should depend in a definite way on the m.f. intensity. The polarization modulation is carried out most effectively by means of an ammonium dihydrogen phosphate (ADP) crystal, cut parallel to its principal axis, and both sides of which are covered with a conducting layer and subjected to an alternating voltage (of about 4 kV) which makes it possible to obtain a path difference of $\pm\frac{1}{4}\lambda$. A polarizer behind (in the direction of travel of the beam) the ADP crystal transmits alternately the σ_1- or the σ_2-component of the longitudinal field (cf. Fig. 3 for a schematic diagram of the main elements of a magnetograph). If two slits are placed symmetrically with respect to the center of a weakly split line and within the limits of this line, and if photomultipliers are placed behind the slits, then both channels give photocurrent fluctuations equal in magnitude and opposite in phase, which are added electrically so as to double the signal. After preliminary amplification, the signal is passed on to a synchronous phase detector (a polarized relay), which "memorizes" the signal amplitudes and adds them (the method of addition of the signal is shown in Fig. 4a), so that if I_- and I_+ are the intensities of light in the slits for the phases $+\frac{1}{4}\lambda$ and $-\frac{1}{4}\lambda$, the signal will be given by

$$\delta_{\parallel} = 2(I_+ - I_-) \approx 2\frac{\partial I_\lambda}{\partial\lambda}\Delta\lambda_H \tag{5}$$

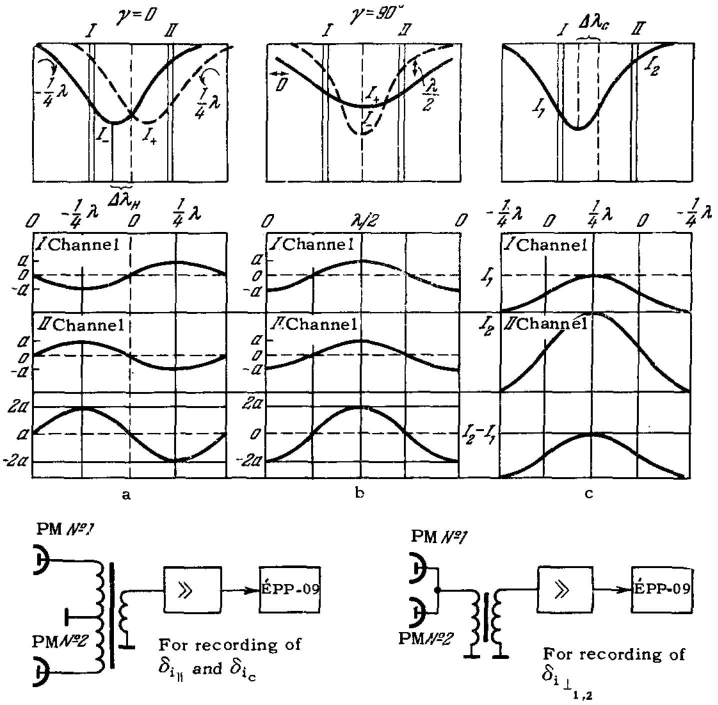


FIG. 4. Method of generating the longitudinal (a) and transverse (b) field signals, and of the calibration signal (c). I and II are photometer slits. The photocurrent variation in channels I and II is shown in the middle of the figure. The lower part of the figure gives the circuits used to subtract (on the left) and to add (on the right) the signals produced by the two channels.

in the case of small shifts $\Delta\lambda_H$ of a line profile which may be approximated by a triangle. The value of $\partial I_\lambda/\partial_\lambda$ for each line may be calculated and, therefore, in accordance with Eq. (3) the value of the signal is proportional to the intensity of a longitudinal m.f. at not-too-high values of H. The accuracy of the method is governed not only by the photomultiplier and circuit noise (time constant of the recorder), which usually amounts to several gauss, corresponding to contrast oscillations of ≈0.01% in the Zeeman pattern. Instead of a double-slit photometer, we can use a photometer with one slit and one multiplier and apply alternately, to this slit, by an optical method (oscillation of a

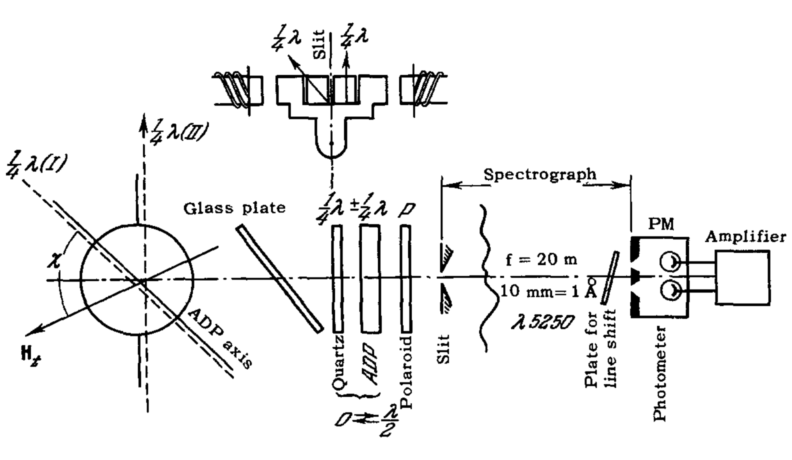


FIG. 3. Arrangement of the main parts of a magnetograph.[24,27] H_t is the transverse vibration vector; χ is the angle which this vector forms with the axes of a composite quarter-wave plate. The modulation of the directions of these axes makes it possible to record simultaneously both components of the transverse field (the composite plate is attached to the armature of a relay placed in front of the spectrograph slit; details are shown at the top of the figure). ADP – ammonium diphosphate crystal; PM – photomultipliers.

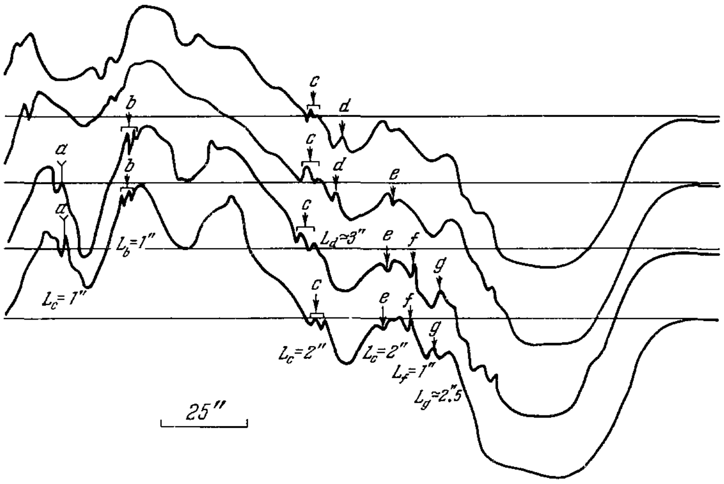


FIG. 5. Consecutive recordings of the longitudinal field $\mathbf{H}_\parallel$ for the same section in a group of sunspots observed on July 17, 1958, indicating the presence of a fine structure of the field (the field peaks a, b, etc., are localized in the regions L ≈ 2-5" on the Sun).[84]

glass plate), the images of the right- and left-hand sides of the Zeeman pattern, as was done in[20].

Figure 5 shows an example of an electronic-potentiometer recording of a longitudinal field in the region of a sunspot group.

To measure the transverse field, the following modification of the photoelectric method (Fig. 4b) was first proposed in[22]. If a crystal plate with a fixed path difference of $+\frac{1}{4}\lambda$ (cf. Fig. 3) is placed in front of an ADP modulator, the device becomes a linear polarization analyzer with a modulation of the path difference from $\frac{1}{2}\lambda$ to zero. Since signals entering channels I and II of the slit are now identical in phase and magnitude, they do not have to be subtracted but simply added. We obtain a pulsating photocurrent (the constant component of which is subtracted by the circuit) and the signal is given by an expression similar to Eq. (5):

$$\delta_\perp = 2(I_- - I_+), \tag{6}$$

where I_- and I_+ are intensities for the phases $\frac{1}{2}\lambda$ and 0. In the case of a transverse field (mutually orthogonal plane-polarized oscillations) the value of the signal which has passed through an analyzer will obviously depend also on the mutual positions of the quarter-wave plate and ammonium phosphate crystal axes and of the plane of oscillation (cf. [23]). In the simplest case, when the axis of the quarter-wave plate coincides with the crystal axis, the signal is

$$\delta_{\perp 1} = 2(a^2 - b^2)\sin 2\chi,$$

but if these axes are crossed at 45°, the signal is

$$\delta_{\perp 2} = 2(a^2 - b^2)\cos 2\chi,$$

where a^2 and b^2 are the squares of the amplitudes of the mutually orthogonal (π and σ) vibrations, and χ is the angle between the crystal axis and the direction of the field $H_\perp$. The ratio of the signals $\delta_{\perp 1}/\delta_{\perp 2}$ fixes the azimuth of the plane of polarization and $\delta_\perp = \sqrt{\delta_{\perp 1}^2 + \delta_{\perp 2}} = 2(a^2 - b^2)$ defines the length of the oscillation vector. In the method proposed in[24], the signals $\delta_{\perp 1}$, $\delta_{\perp 2}$ are recorded simultaneously by modulating the quarter-wave plate orientation using two-quarter-wave plates, crossed at 45° and mounted on the armature of a relay placed in front of a slit (cf. Fig. 3). A special electronic device records the angle $\chi = \tan^{-1}(\delta_{\perp 1}/\delta_{\perp 2})$. The longitudinal field is recorded separately from the transverse field. One can, however, record the three components $\delta_{\perp 1}$, $\delta_{\perp 2}$, and $\delta_\parallel$ simultaneously, as proposed in[25], which halves the time for recording the total field. This is done by selecting the signal which has the doubled modulation frequency: when the modulation is $\frac{1}{2}\lambda \rightleftarrows 0$, the path difference $+\frac{1}{4}\lambda$ is produced twice, i.e., the circuit transmits at the doubled frequency only, for example, the right-handed circular vibrations σ_1 of the longitudinal component, which gives a longitudinal field signal half as strong as the signal in a single recording (cf. Fig. 4b) in which the left-handed circular component, σ_2, would also be recorded. Instead of the quantities $\delta_\parallel$, $\delta_\perp$, χ, we can record the Stokes parameters, as was done in[25].

A similar photoelectric method was recently proposed in[26] but the author measured photoelectrically not the polarization within a spectral line which was sensitive to a magnetic field but the polarization over a wide range of the spectrum (≈ 300 Å), selected by an ordinary glass filter, and the whole effect of the recorded polarization was ascribed exclusively to m.f. However, the polarization due to scattering processes associated with some spectral lines (particularly resonance scattering) may cause an effect fully comparable with the effect of m.f. (cf.[23] and[27]), and, therefore, the method proposed in[26] is hardly applicable to measurements of the transverse m.f.

The calibration of field signals is of fundamental importance in photoelectric measurements of m.f. Fig. 4c shows that the Doppler shift of an absorption line, relative to its normal position (for which the light fluxes are identical in both slits), leads to the appearance of a difference between the photocurrents in the two channels of a magnetograph, which can be modulated and measured as some equivalent longitudinal field signal. To obtain a "standard" known shift of a line, we can use the rotation of the Sun (2 km/sec velocity at the equator). To obtain modulation in this case, an additional polaroid and a fixed quarter-wave plate are placed in front of a circular polarization analyzer, so that the whole combination acts as an electro-optical shutter.

The line shifts due to the motion of gases on the Sun and to fluctuations of the refractive index of the atmosphere may distort the magnetic field signals. To eliminate these distortions, it is necessary to keep the line symmetrical with respect to the slits. For this purpose, a "self-adjusting" plane-parallel plate is placed in front of the slits and this plate is rotated by a motor energized by a current proportional to the difference of the light fluxes passing through two slits. Since the rotation of such a plate is proportional to the Doppler shift of the line, the device makes it possible not only to hold the line on the slit but also to record the radial velocity of the solar gases.

The calibration in measurements of the transverse field can be based on the theoretical dependence of the transverse field signals on the angle of inclination of the field γ and on the field intensity[22,30] using various assumptions about the mechanism of line formation (intrinsic absorption[28,29] or scattering[30]). We can also carry out this calibration by comparing the measured magnetograph signals $\delta_\perp$ with the splitting measured directly in Zeeman effect photographs (for the same region on the Sun).[31]

The sensitivity of the photoelectric method of recording m.f., governed by the signal/noise ratio, is ≈ 1 G for the longitudinal field and from 50 to 100 G for the transverse field.

Solar magnetographs capable of measuring only the longitudinal component of the field are used at the Mount Wilson Observatory,[18] at the Fraunhofer Institute (Western Germany),[32] at Cambridge University[33] and at Pulkovo Observatory.[21] Magnetographs capable of measuring both the longitudinal and transverse components of the field are used at the Crimean Observatory[19,22-24] and at the Institute for Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the U.S.S.R. Academy of Sciences (IZMIRAN) in Moscow.[20,25] Various recording methods are employed. For example, the Mount Wilson Observatory uses a special automatic scanning mechanism by means of which the $\delta_{||}$ signal can be recorded along 22 sections over the whole disk of the Sun. This mechanism is synchronized with the horizontal scan of a cathode-ray oscillograph and the longitudinal field signal, controlling the electron beam deflection, is applied to the vertical plates of the oscillograph. The cathode-ray oscillograph display is recorded on photographic film. An example of such a recording of fields over the whole disk is shown in Fig. 6. This method is convenient for the rapid examination of the distribution of magnetic fields over the whole solar disk. However, the resolving power (over the disk) of this method is low (1.5′) and the method is not very convenient for quantitative analysis, in particular, because of the overlap of the recordings of adjacent sections. Other observatories usually record individual limited regions of the Sun's surface by the relatively slow motion of the Sun's image across a spectrograph slit. An example of such a recording along one section of small dimensions is shown in Fig. 5. At the Institute for Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the U.S.S.R. Academy of Sciences, Moscow, it is also possible to obtain a recording by observing a region of the Sun in the hydrogen line H_α. Although these methods do not give immediately the field pattern over the whole solar disk, they allow us to investigate in detail (with high resolution, reaching several seconds of the arc) and quantitatively the magnetic fields in any given region. Figure 7 shows the pattern of the longitudinal and transverse fields in an active region of the Sun obtained using this method of recording.

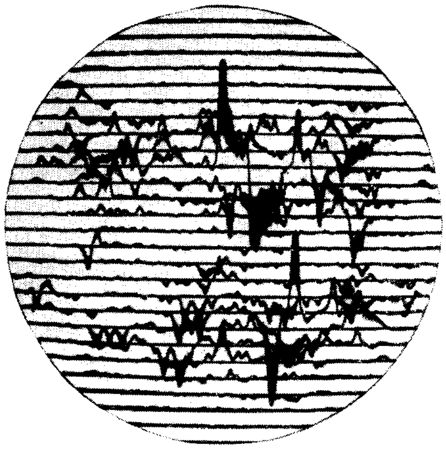


FIG. 6. Typical magnetograms for the whole solar disk, obtained at the Mount Wilson Observatory.[18]

In conclusion, we shall consider briefly the method of measuring m.f. of stars. Up to now, the stellar fields have been measured by a double or differential circular-polarization analyzer similar to that used by Zeeman for laboratory spectra. It consists of a mica quarter-wave plate (for λ about 4300 Å) in combination with a plane-parallel crystalline spar plate, producing ordinary and extraordinary (mutually orthogonally polarized) rays, which give two images of a star side by side on a spectrograph slit and, having passed through a spectrograph, form two parallel spectra one below the other, on a photographic plate. The axis of the quarter-wave plate bisects the right angle between the planes of polarization of light in the spar crystal (Fig. 8). Further measurements of the field are carried out on the photographic plate: the relative shifts are measured for about 30—40 lines in

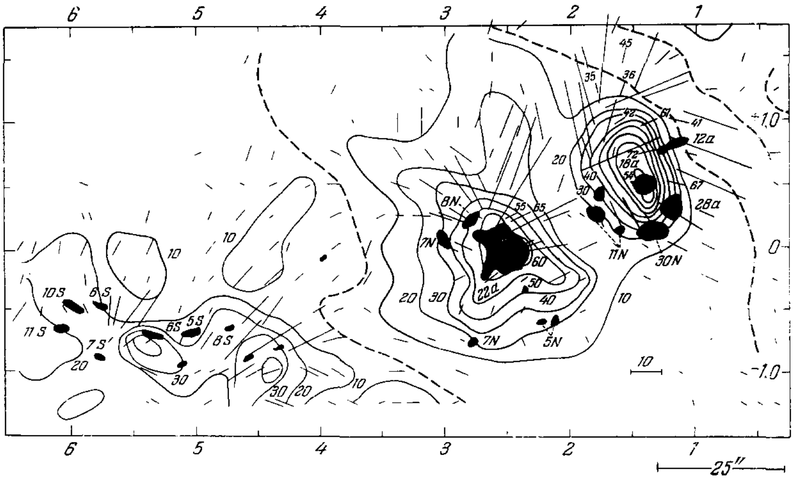


FIG. 7. Combined magnetic field chart for September 19, 1962, (Crimean Astrophysical Observatory [23]). The closed continuous curves are isogauss contours (1 division = 2.4 G); the dashed curves show the $H_{\|} = 0$ lines; the rectilinear segments represent the vector $\delta_{\perp}$, where the segment length is proportional to the magnitude of the vector and the direction of the segments is given by the angle χ. The black areas are sunspots; the intensities (in 100 G units) and polarities of the sunspot m.f.'s are given alongside these areas – they were measured using a polaroid mosaic and the λ5250 line. The letter a indicates the transverse field.

both spectra. The only measurements carried out so far are those of H. W. Babcock using the 200-inch telescope at the Mount Palomar Observatory.[34] He used a spectrograph with a diffraction grating (4.5 Å/mm dispersion) at the Coudé focus of the 200-inch telescope, and a large-aperture Schmidt camera with a focus of about 2 m. This apparatus can be used effectively to investigate m.f. of stars down to the 7th magnitude. By measuring the shifts Δs in the lines having different effective splittings z, the effective field H_e can be found from the relationship $\Delta s \propto z\lambda^2 H_e$, i.e., the longitudinal field component, assuming that the field is *uniform*. Initially[136], Babcock assumed a distribution of the field (for example, a dipole distribution) across a stellar surface, which required a knowledge of the distribution of brightness across the stellar disk and of other factors, but later he found that the dipole field assumption was unnecessary and incorrect.

2. GENERAL MAGNETIC FIELD OF THE SUN

a) Polar Field

The first spectroscopic investigations of the general m.f. of the Sun, carried out by Hale et al.,[35] showed that in 1913-1914 the Sun was similar to a uniformly magnetized sphere with its magnetic axis slightly inclined to the axis of rotation, and having polarity the same as the Earth's. The average shift of the spectral lines in the northern and southern hemispheres indicated a field intensity $H_p \approx -20$ G at the North Pole of the Sun. Hale et al. found that the field intensity decreased with altitude in the solar atmosphere and that the "true" field was found from the spectral lines generated in deeper layers (weak lines). Hale's spectrograms, and spectrograms obtained in 1922–1923, were analyzed in[36] (using the line λ5247.58, g = 2.5).

This analysis indicated clearly a change in the polarity on going from the northern to the southern hemisphere. The amplitudes of the shifts were ≈1 μ, which gave $H_p \approx -4$ G. Visual measurements, reported in[37] and carried out from September, 1933 through January 1934, gave +3.6 ± 1.7 G; another series of measurements from October 1, 1948, through April 1, 1949, gave a value $H_p = +2.0 \pm 2.8$ (for 45° latitude).[38]

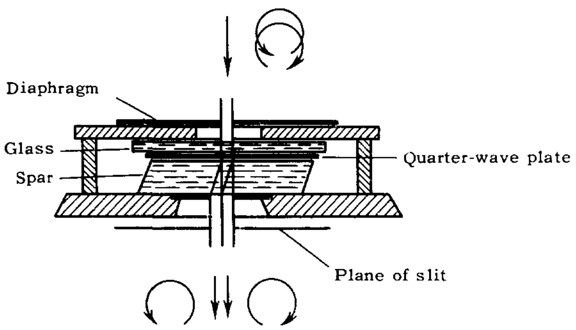


FIG. 8. Polarizing modification of a spectrograph slit used to determine stellar m.f.'s. The light collected by the 100"-mirror (F/30) comes from the direction indicated by the arrow.

H. D. Babcock[14] was the first to use the interference method to increase the accuracy of measurements of the general field (using a Lummer plate in combination with a spectrograph). At latitudes of ±45°, values ranging from −6 to −60 G were obtained for 18 cases investigated during 1940–1950, while in 24 cases no field was found or only a very weak positive field. During the same period, a similar method, used in August-September, 1949,[39] gave a value 1-2 G for these latitudes. A very complex interferometric technique employed in[13,40] gave + 1.5 ± 3.5 G in 1947–1948 for the same latitudes. In 1949, Thiessen obtained + 1.5 ± 0.75 G; in 1951, he found $H_p = +2.4 \pm 0.5$ G. A good review of the results of these measurements is given in[41]. The first attempt to make photoelectric measurements of the general field (reported in[17]) showed the presence of a fine structure of the m.f. far from sunspots, even when the resolving power was low (60″, which was the spectrograph slit length). The characteristic dimension of this structure was estimated to be ≈20″. No fields higher than 1 G were found at the poles.

H. W. and H. D. Babcock[42] used a magnetograph to observe a general field of ≈1 G intensity by averaging (with a ≈60″ resolution) over a large polar region with latitudes greater than ±55°. Between 1952 and 1955 the solar field was opposite in orientation to the Earth's. The Babcocks found that the intensity and polarity of the field varied in phase with the angle between the axis of rotation of the Sun and the Sun—Earth direction (this caused perspective contraction and expansion of the polar caps of the Sun and, possibly, magnetic flux oscillations). The measurements did not confirm the 30-day period which would be expected if the magnetic axis of the Sun were inclined to its axis of rotation. However, sometimes, the polar field increased by a factor of several times compared with the average value, while on other occasions it disappeared completely at one of the poles.

No changes in the polarity were found on passing through the solar activity minimum in September, 1959; the field was opposite to the Earth's (positive) between 1952 and 1955. In 1953, the values of the fective magnetic flux ($\int H_e \cos \gamma \, d\sigma$, where $d\sigma$ is an element of the disk area) varied from -0.1×10^{21} to 1.6×10^{21} maxwells. The Babcocks[42] estimated the total flux to be $\approx 8 \times 10^{21}$ maxwells for latitudes higher than 46°.

Later magnetograph measurements, carried out using 1′ resolution[43] at seven separate points in both polar regions and averaged in time, showed that the polarity of the general field was opposite to the polarity of the terrestrial field between 1956 and 1957; in the middle of 1957, the sign of the field at the South Pole was reversed and for about $1\frac{1}{2}$ years, up to November, 1958, the two poles had the same sign (in the spring of 1957, the field disappeared at both poles for several months). In November, 1958, the field at the North Pole reversed its sign almost suddenly from "+" to "−"; in 1959, the field was parallel to the Earth's field.

The separate consideration of the Wolf numbers for the northern and southern hemispheres of the Sun during the same period 1956—1959 showed that these numbers reached maximum in the southern hemisphere a year earlier than in the northern hemisphere which, according to[44], should be associated with the reversal of the polar field at the South Pole a year earlier than at the North Pole.

Between 1959 and 1964, the observations of the general m.f. were carried out more or less systematically using magnetographs at Mount Wilson, at Cambridge, and at the Crimean Observatory. According to[45], the poles had the same polarity beginning from the polarity reversal phase (1957-1958), and in some cases it was possible to find explicit indications of very weak fields at one or the other of the poles. Howard[46] was the first to report that the field at the South Pole probably disappeared in March, 1961. The Cambridge[47] and Crimean[48] measurements showed that, from the beginning of 1961 to the end of 1964, no measurable fields could be detected at the South Pole, but it was reliably established that a southern (negative) field of the order of several gauss was present at the North Pole.

Changes in the general (polar) m.f. during the whole period covered by observations (beginning from 1914) are given in Fig. 9 (cf.[49]) in accordance with the data referred to above. Although the results obtained up to 1952 are not very reliable, it is difficult to avoid the conclusion that the general m.f. of the Sun does indeed vary with time. The most reliable observation of the polarity reversal was that made in 1957-1958, but the two other reversals, in about 1927 and 1937, obviously also took place. We see that the epochs of the polarity reversal of the general field coincide more or less exactly with the epochs of the solar activity maximum M, while the epochs of the activity minimum m are "in phase" with the strongest negative or positive fields (except for the first determination of the general field reported in[35]). The agreement between the epoch of the field polarity reversal in 1957—1958 and the epoch of the activity maximum was first pointed out in[50]. Thus, a 20-year

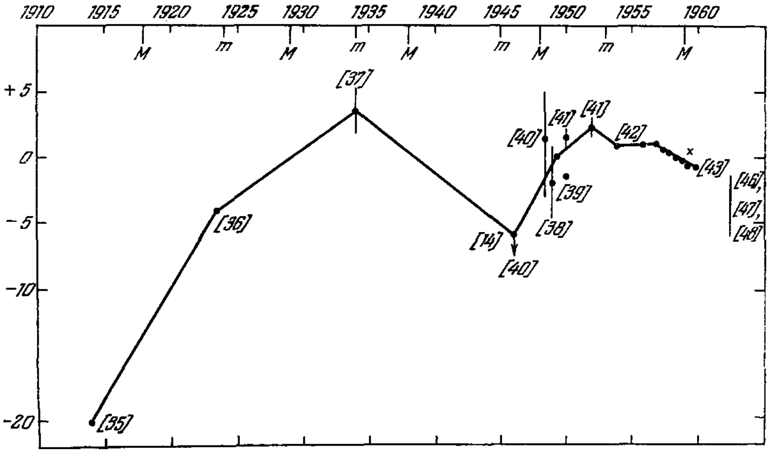


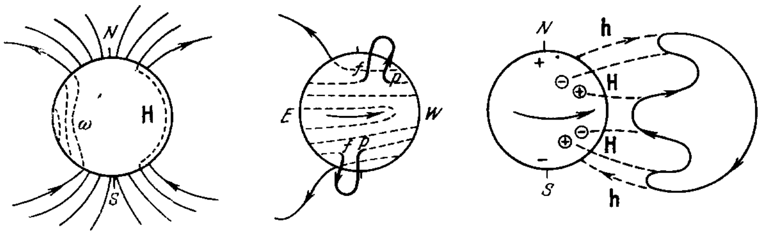
FIG. 9. Variation of the general m.f. of the Sun with time: M — maximum activity epochs, m — minimum activity epochs. The vertical lines represent the errors of individual measurements; the relevant literature references are given in brackets.

cycle of the general m.f., similar to that observed in the sequence of the sunspot polarity (see below), is very likely.

A possible explanation of this variation has been recently put forward in[51]. It starts from the assumption that the general m.f. of the Sun in its initial phase is an axisymmetric field of a dipole with lines of force lying completely in the meridional planes (Fig. 10). Assuming that the lines of force of this field penetrate to a small (approximately constant) depth below the solar surface (in the equatorial region), the differential rotation of the Sun (the equatorial zone rotates faster than the high-latitude zones) may cause the lines of force of such a field to intersect surfaces (cylinders) having different angular velocities, which are, however, constant over a given cylinder. Since the magnetic field is frozen into the Sun's matter, the part of a line of force closer to the equator will rotate faster and, due to the differential rotation, will stretch further and further to the west and will wrap itself around the equatorial zone as if on a drum. Thus, a toroidal field may be generated which may increase in strength. Individual parts of the tubes of force of this field may float above the Sun's surface (due to density fluctuations in the tubes) and form a structure similar to bipolar group of spots (stage 2 in Fig. 10). The process ends, according to Babcock,[51] with a special interaction between the fields of such groups and the initial poloidal field which destroys the initial field (because of the opposite directions of the two fields; cf. stage 4 in Fig. 10) and forms a new dipole m.f. of the opposite polarity.

The improbability of such a mechanism from the energy point of view was pointed out in[52]. In fact, the kinetic energy of the differential rotation of the Sun is not more than 10^{40} erg.[51] The energy stored in a sunspot (or a sunspot group) is $W = H^2 v/8\pi$, where v is the volume ($\approx 10^{10}$ cm^3) and $H = 2 \times 10^3$ G (on the average), so that $W \approx 10^{35}$ erg. Assuming the average lifetime of a sunspot to be ≈ 0.1 years, we find that the rate at which energy is consumed to form a single spot is $\approx 10^{36}$ erg/year. Hence, it is evident that the energy of the differential rotation of the Sun would be sufficient only to support this mechanism for at most $10^{40}/10^{36} = 10^4$ years; this is obviously insufficient. If we bear in mind also a number of artificial assumptions and inconsistencies in the representation of the general field as a dipole field (see below), we find that H. W. Babcock's explanation[51] of the 22-year cycle can hardly be regarded as satisfactory.

Moreover, a clearly defined fine structure of magnetic fields, in particular general field structure, found in recordings made at high resolving power,[49,53] forces us to view differently the earlier, frequently contradictory results and their explanations. Figure 11 shows the original recordings of the the transverse field using a resolving power of 5", which is ≈ 10 times greater than that used before: they show the concentration of the field in separate small elements (tubes of force) of different polarities, intensities, and dimensions. The "coherence" of consecutive recordings is affected considerably when they are separated by 5" (≈ 4000 km on the Sun): about 50% of the characteristic features of the field are not reproduced. A detailed statistical analysis shows that $\approx 35\%$ of the elements have dimensions of $\leq 5''$ (usually image oscillations due to terrestrial atmospheric turbulence amount to 2"). Figure 12 illustrates the influence of the resolving power used in recording the field on the values of the field intensity and the dimensions of the elements: we see that, on going over from low ($\approx 1'$) to high resolutions ($\approx 1''$), the general field intensity increases from several gauss to several tens of gauss while the dimensions of the elements decrease, but not nearly so much (by a factor of ≈ 2). This means that the field gradients obtained at higher resolutions may be 10 times greater which is in fact what is observed. Moreover, the regions of the Sun which are unipolar when observed at low resolutions become multipolar when observed at high resolutions (cf., for example,[49]). At low resolutions ($\approx 1'$), the Babcocks [42] recorded not less than 4–5 "incoherent" field distributions simultaneously, which led to very drastic averaging and a fictitious increase of the contribution of the largest field elements, which did not represent more than 30% of the total number. Thus the low-resolution measurements do not answer the question whether a field is "coherent," regular (dipole, etc.,) or is the result of averaging over a region with many magnetic spots. In fact, there is no uniform polar field of the dipole type or a uniformly magnetized sphere: only the averaging over a large (arbitrarily selected) area results in the predominance of one polarity over the other and gives an apparently uniform field.



Stage 1 Stage 2-3 Stage 4

FIG. 10. Explanation of the transformation of a poloidal dipole field (stage 1) into a toroidal field (stages 2-3) and the subsequent interaction of the resultant magnetic fields of sunspots **H** (loops) with the general dipole field **h** (stage 4), in accordance with [51]; ω is a schematic representation of the constant angular velocity on the surface.

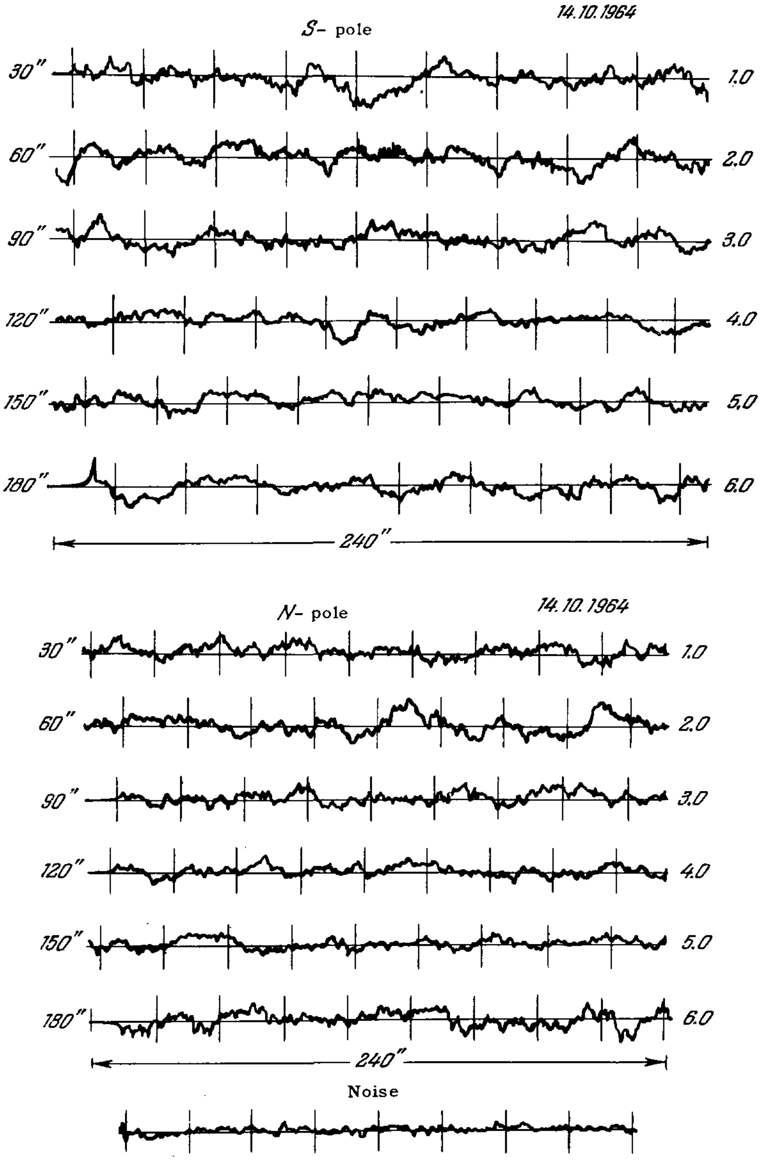


FIG. 11. Typical recordings of the polar field in λ5250 at the North and South Poles (latitudes 50-80°), indicating the fine structure of the field and the predominance of the S-polarity elements at the North Pole. A recording of the noise is given at the bottom of the figure; individual recordings are separated by 12.5" on the Sun.[53]

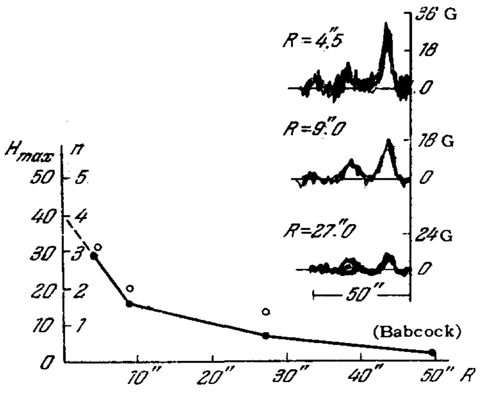


FIG. 12. Effect of the resolving power R on the determination of the value of the maximum magnetic field intensity (H_{max}, black points) of field elements and of their number (n, open circles). The right-hand side of the figure shows original repeated recordings of the same part of the polar field using different resolutions R.[53]

The histograms of Fig. 13 give the relative frequency of elements of different intensities and polarities at the North and South Poles during the first half of 1964.[54] They indicate clearly the statistical predominance of the S-polarity elements at the North Pole of the Sun and the absence of such an effect at the South Pole. It is interesting that about 20% of the elements have strong fields ≥ 16 G (when corrected for the resolution R = 9") and these are eliminated in low-resolution recording. This indicates that individual elements of solar and stellar m.f. may have fields 5—10 times stronger than those assumed so far. This follows also from the spectrum of the Fourier amplitudes of the correlation function of m.f. fluctuations and dimensions of the elements, which was obtained recently[55] using high resolution. The rms amplitude of these fluctuations reaches ±16 G for small elements in a magnetically "quiet"

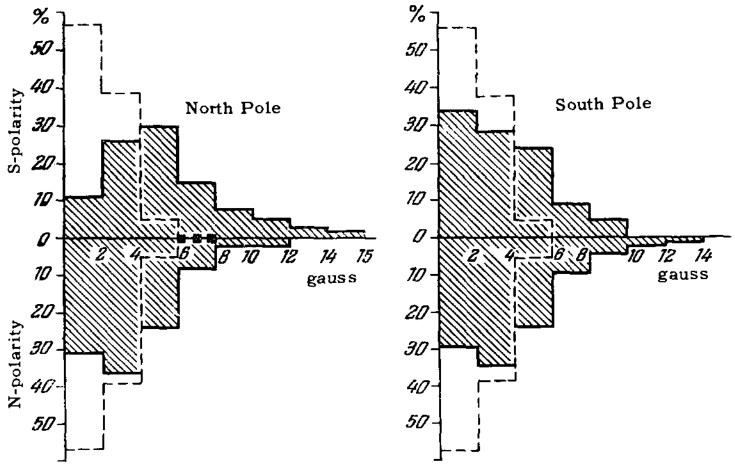


FIG. 13. Histograms of maximum intensities of the polar field elements: the S-polarity elements are shown above the abscissa, and the N-polarity elements below it. The dashed histograms give the noise distribution for a magnetograph (in accordance with [53]).

region at the equator (see below). A similar value was reported in[56]. If we bear in mind that the fields measured in sunspots reach 40 G and that in stars they reach several tens of thousands of gauss, the application of these considerations leads to the conclusion that individual elements of m.f. may reach intensities of $\approx 10^4$ G for the Sun and $(5-10) \times 10^4$ G for stars. Should the existence of such powerful m.f. be confirmed by observations, a number of difficulties will be resolved that are associated with the generation of cosmic rays and radio waves in the Sun and stars.

What we are recording as an average field at a given latitude φ on the Sun is obviously

$$\bar{H}(\varphi) = \frac{1}{l}\int_0^l H(s)\,ds = \frac{1}{l}F(\varphi), \tag{7}$$

where l is the length of the investigated region. The quantities F give us a measure of the magnetic flux at a given latitude. While the ratio of the average total fluxes of the S- and N-polarities is equal to 1 for the South Pole, it is 6.4 for the North Pole; this strange effect has not yet been explained; it is possible that many of the lines of force starting from elements at the North Pole are closed somewhere near the equator.*

If the average field of Eq. (7) is dipolar, the longitudinal component (along the line of sight) should obey the law $\bar{H}_{||} \propto C \cos\varphi$, where the quantity $C = (2a/R^3)\sin\varphi$ is practically constant at high latitudes $\varphi \geq 60°$, where, in fact, the measurements are carried out. However, observations reveal a behavior which is opposite to that expected for the latitude dependence of the field intensity of a dipole (or a uniformly magnetized sphere). Thus, even the average polar field cannot be represented as the field of a dipole. A similar conclusion is obtained also by analyzing low-resolution magnetograms.[57]

b) Fields at Low Latitudes

One of the best established facts about the magnetism of the Sun is the exact correspondence between the positions of the magnetic elements and the bright clouds in the solar chromosphere, observed in light of ionized calcium Ca II (the H and K lines in the solar spectrum[12,42,58]). In particular, Leighton[29] observed this correspondence right down to the smallest bright elements, which are regions in the calcium chromosphere, visible at the resolving power threshold ($\approx 2''$ and smaller). The existence of this correspondence is also supported by the fact that the correlation function "field–element dimensions" is similar for the correlation "intensity–dimensions".[58] Initially, the correspondence was found for bright clouds, known as calcium floccules, characteristic of the active regions of the Sun, and having relatively strong fields (tens and hundreds of gauss). According to[58] and[60], the isophot curves of these floccules followed closely the isogauss contours in charts of the longitudinal component of the field $H_{||}$: the 10 G isogauss enclosed the floccule edges in most cases. Figure 14 illustrates the correspondence between calcium floccules and the field. Stepanov and Petrova[60] reported, moreover, that the brightness of the faculas increased with the field intensity $H_{||}$ right up to $H_{||} = 70$ G; for $H_{||} > 70$ G, a maximum was followed by a decrease of the brightness. All this shows that the chromospheric emission and chromospheric faculas are the "unavoidable consequences of the ef-

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*Recent detailed recordings of the equatorial fields showed, however, that this was not true: a flux of the S-polarity predominated also at the equator, but to a lesser degree than at the North Pole. Thus, over the whole northern hemisphere of the Sun there was a flux predominantly of the S-polarity, and, since at the South Pole the S- and N-polarities were balanced, the departure from the flux balance ($\int H_n d\sigma \neq 0$) for the Sun as a whole was perplexing.[53] A similar observation was recently made for the developing active regions (according to a private communication from V. Bumba). It is possible that if an even higher resolution were used, an even stronger concentration of the field would be found, especially in separate elements of the N-polarity, and the "magnetic asymmetry" of the two solar hemispheres would disappear.

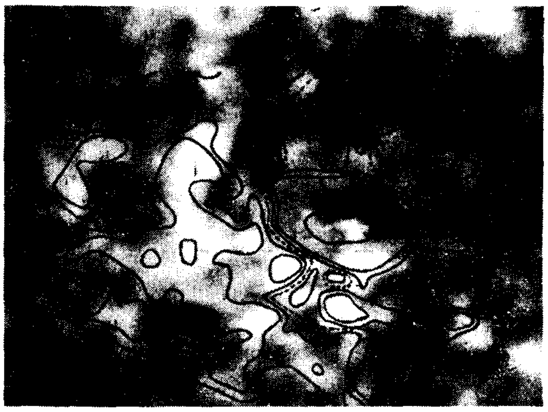

FIG. 14. Calcium floccules (bright clouds) and isogauss curves for the longitudinal field (continuous and dashed lines) as a function of the polarity.

fects of the magnetic field.''[12] In this connection, we ought to mention the theory of emission from floccules, developed in[61] on the basis of the effect of magnetic fields on the convection which is actually observed everywhere in the solar atmosphere. According to[61], a magnetic field damps turbulence more rapidly than convection and, therefore, if a magnetic field appears and increases in magnitude then, having suppressed turbulence, the field makes it easier for hot convective columns to rise upward, which gives rise to an additional flow of energy to the upper layers and strengthens the emission in individual lines. These considerations help us to understand the causes of the formation of floccules. However, a recent more detailed investigation[62] shows that there is no clear maximum in the dependence of the brightness on the magnetic field intensity. Moreover, the dependence of the brightness on the transverse component of the field is even less clear than in the longitudinal case. Contrary to expectations, in this case the upward rise of a column seems to be slowed down as the field increases.

The question arises whether this generally good correspondence between bright formations in the calcium chromosphere and the elements of the field means that the field penetrates the upper chromospheric layers (up to 10^4 km) of the solar atmosphere. Some useful information on this point is provided by a comparison of the m.f. charts, recorded by means of the lines which are usually emitted at great depths in the photosphere, with the lines (more exactly, with the cores of strong lines) which are generated in the chromosphere (above the photosphere), such as, for example, the H_β line of hydrogen, or the H and K lines of calcium. Figure 15 illustrates such a comparison, indicating a very close correspondence between the details of the field chart in the photosphere and at a height of $(1.5-2) \times 10^3$ km above it, in the lower chromosphere (where the core of the H_β line is generated): usually, all the details of the "chromospheric" field chart can be found in the "photospheric" chart but the reverse is not true; the photosphere has details not visible in the chromospheric charts. This may also be associated with the lower magnetic sensitivity of the H_β line. It was reported in[63] that there were details in the chromospheric chart which were not visible in the photospheric pattern. Although the correspondence between the photospheric and chromospheric charts is observed in strong fields (≥ 25 G), in weak fields the pencils of lines of force starting from the photosphere may be everywhere more or less radial, penetrating the chromosphere and extending even above it. It is also possible that the fine structure of the solar corona is also closely related to these m.f. although this relationship has not yet been investigated because it is not possible to measure weak m.f.'s in the corona. Information on this point is provided by comparisons of the charts of the longitudinal component $H_{\|}$ and of the chromospheric structure observed in the H_α light (spectroheliograms, filtrograms), reported in[42,64]. In particular, the dark filaments (prominences visible in projection on the disk) frequently lie along the $H_{\|} = 0$ boundary between two field polarities in the region of weak fields < 20 G.[64] In the strong-field regions (between spots), these filaments may intersect the $H_{\|} = 0$ lines. Active filaments (those moving and changing rapidly) frequently join sunspots or solar field maxima to certain points ("centers of attraction") which have strong fields without sunspots. For example, it was found[64] that small dark filaments in the chromosphere visible in the H_α light—in particular, chains of such filaments—were oriented approximately normally to the isogauss

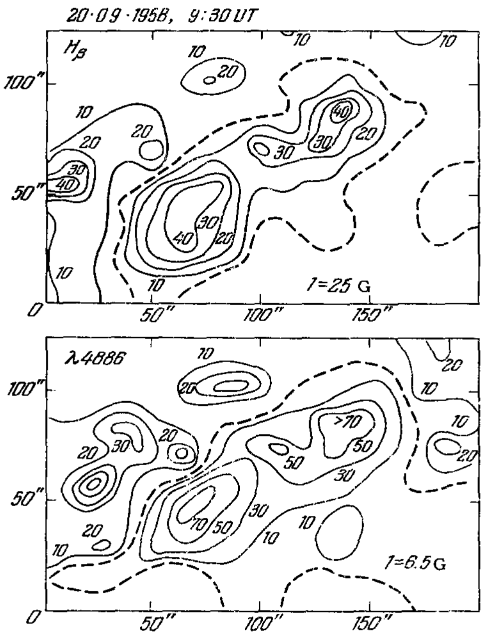

FIG. 15. Comparison of the longitudinal m.f. charts in the chromosphere (top of the figure) and in the photosphere (bottom of the figure).

curves. These quite stable chains sometimes joined magnetic field maxima of opposite polarity in charts of the longitudinal field $H_{||}$ as if they intersected lines of force at very great distances (up to 300 000 km). All this indicates a close relationship between the structure of the hydrogen chromosphere and magnetic fields.

The same problem of field propagation to various heights in the solar atmosphere may be approached directly by investigating field gradients. The first observation of a field gradient was reported in [35], giving various values of the field from zero to 20 G for absorption lines of various intensities appearing at different depths in the photosphere, ranging from zero to ≈ 500 km. This gives a gradient of ≈0.04 G/km. Longitudinal field magnetograms were reported in [65] at two distances from the center of the sodium D-line, which gave the author of that paper a value of 0.03 G/km far from strong fields. If we now assume that on the surface of the photosphere the field is ≈30 G, it would follow from these gradients that this field would disappear even before reaching the lower chromosphere (10^3 km). These results contradict both the direct comparisons of the photospheric and chromospheric charts and the correspondence between the calcium chromosphere structure (average height 3000 km) and the magnetic "relief" in the photosphere.

This contradiction between the data on the field gradient in the photosphere and the strong "controlling action" of the field on the chromosphere is a serious problem which needs to be dealt with. It may be related to some fundamental difference between m.f.'s in the photosphere and m.f.'s in the chromosphere and the corona. In the lower photosphere (where $H^2/8\pi$ is less than the gas pressure), the magnetic fields participate passively in the general turbulence of the atmosphere, which is governed by magnetic forces. These magnetic fields may be forced out of the photosphere by convection. In the upper chromospheric layers and in the corona, the fields are limited only by one condition, i.e., that there are no important forces apart from the magnetic force ($H^2/8\pi$ is considerably greater than gas pressure), and this proves the conclusion that field configurations above the photosphere should belong to the class of force-free fields, i.e., with currents flowing along force lines ($[\text{curl } H \times H] = 0$).[66]

Attempts to measure directly these "passive" fields in the photosphere, which may be ejected upward by convection, meet with a number of difficulties since it is necessary to measure accurately fields and elements having dimensions of 1—2", i.e., in individual solar convection cells or granules. The conclusion[42] that the granule fields cannot be greater than 2 G should be reviewed in the light of the strong influence of the resolving power on the true field pattern, as discussed above. An attempt to measure photographically the fields in individual granules[67] showed that their m.f. did not exceed 50 G, i.e., the limit which is usually set by the turbulence of air in the spectrograph. Another such attempt[68] gave 24 G for the granule fields and it was based again on the measurement of a slight broadening of the iron line in spectrograms obtained using good images exhibiting granular structure. However, this result may have been distorted by the effect of relatively strong local fields. The graph (Fig. 12) of the dependence of the field intensity on the instrument resolution shows that fields with intensities stronger than 50 G can hardly be expected; however, the dimensions of the "magnetic elements" are considerably greater than the dimensions of the granules and this is only partly due to the influence of the resolving power. These elements are more likely to correspond to the supergranules described in [69]; they are relatively stationary in time: they do not show changes in the dimensions and field intensity for at least 4—5 hours or longer, so that the ≈10-hour lifetime, reported in [69], as characteristic of supergranules is probably correct (the lifetime of ordinary granules is several minutes). It is interesting that a histogram of the magnetic element dimensions shows a secondary maximum (at a characteristic length of 26"), which is almost exactly double the length (10—12") characteristic of the stronger primary maximum; this "harmonic" appears also in the correlation function[55] for approximately the same length. It is possible that the appearance of such "harmonics" is associated with a characteristic fluctuation state of the solar surface so that the magnetic elements reflect the appearance of some quasi-stationary fluctuations on the surface of the Sun.

It should be mentioned also that no theory has yet been developed to account for the formation of lines in the presence of random small-scale magnetic fields when a mixture of field elements of different intensities or orientations may act along the line of sight, as would be expected in the case of turbulence in the strongly conducting solar plasma. In this case, it is not clear what should be the nature of the dependence of the intensity of the emergent polarized light on the field intensity and orientation.[70]

In conclusion, we can mention one more fact which refers to the geometry of the general m.f.

Careful comparison of the positions of the bright calcium floccules and sites in the chromospheric network with the positions of the "hillocks" in the magnetic relief shows a statistically small easterly shift (about 3") of these chromospheric formations, with respect to the magnetic structure. The same shift is exhibited by the hillocks in the chromospheric chart when compared with the hillocks in the photospheric magnetic relief. This indicates that the axes of the tubes of magnetic force are inclined to the East, as expected, due to the Coriolis force, if we assume—in accordance with[69]—that the chromospheric gases descend almost exactly along these tubes. The field along the Sun's equator is thus similar to a brush whose bristles are inclined to the East.

3. STRONG MAGNETIC FIELDS IN ACTIVE REGIONS OF THE SUN

a) Magnetic Fields of Sunspots

A sunspot consists of a dark core, the "umbra," and a brighter "penumbra" surrounding the core. The fine structure of the penumbra (almost radially directed filaments) can be seen using high resolutions; the fine structure of the core will be described below. The temperature of the umbra is about 4300°, which is over 1000° less than the temperature of the surrounding photosphere (5740°). The sharpness of the outer boundary between a sunspot and the photosphere, and of the boundary between the umbra and penumbra, indicates that the layer in which cooling takes place is shallow (of the order of several thousand km), for otherwise the edges would have been broadened by the radiation coming from below. It is assumed that a relatively cold layer is located where convection is active in the solar atmosphere; m.f.'s which unavoidably give rise to spots, retard the convection: a spot is dark because the convective heating, which takes place everywhere in the solar atmosphere (the granulation effect), is impeded by m.f. The strongest m.f.'s reaching 4000 G, are concentrated in sunspots. The magnetic flux in a sunspot may range over wide limits from 10^{20} to 10^{23} maxwells; on the average, it is 10^{21} maxwells. In the majority of cases, sunspots form bipolar groups, which are systems of two spots in which the leading spot (the direction of motion is taken with respect to rotation of the Sun), known as the leader or the p-spot, has a polarity opposite to the "tail" spot (the f-spot). For the majority of spots, the p- and f-spot polarities are opposite in the northern and southern hemispheres (Hale[71]) and these polarities are reversed in each consecutive 11-year cycle. Hence, it has been concluded that the total "magnetic" solar cycle of the Sun is 22 years. In the latest 1954-64 cycle with a maximum in 1958, the p-spots in the northern hemisphere (and the f-spots in the southern hemisphere) had the positive (north) polarity. According to[72], the dimensions of the p-spots are greater and they live longer than the f-spots; the ratio of the magnetic fluxes in the p- and f-spots is on the average ≈3:1. A typical dependence of the sunspot area and the field intensity on time is shown in Fig. 16 (according to[73]).

The distribution of the magnetic field intensity may be obtained from spectral measurements of the Zeeman splitting at various distances from the center of the spot. According to the data reported in[74-76], the field intensity is practically constant in a spot but it may decrease rapidly at its outer boundary. Broxon[74] proposed the law $H = H_m[1 - (r^2/b^2)]$, where H_m is the maximum field intensity along a spot axis, and b is the radius of the spot; however, later measurements showed that this formula is unsatisfactory: the distribution of H depends on the type of spot; the distributions differ considerably for unipolar and bipolar spots, since in the latter case the lines of force are closed mainly in the neighboring spot. It was later observed that fairly strong fields are found near a spot and according to[77], the field distribution near a spot is given fairly well (for single spots) by the dipole formula $Hr^3 = \text{const} = m$, where m is the magnetic moment ($= H_m b^3$), which ranges from 10^{27} to 10^{30} G/cm^3 (for large spots), and m and H_m are related by the empirical expression $\log H_m = 0.27m - 4.82$. For more complex spots, the decrease in H is slower.[78]

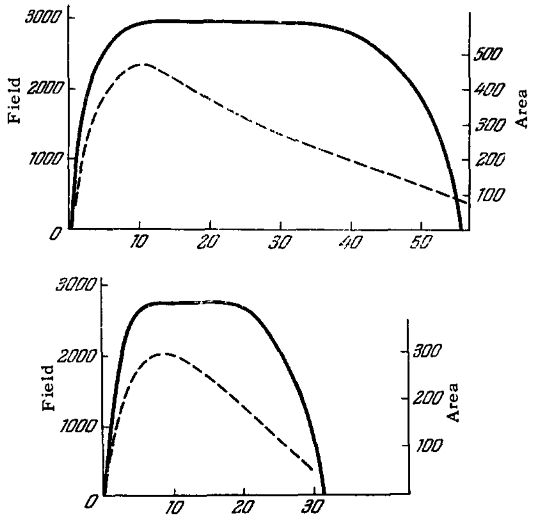

FIG. 16. Variations in the m.f. intensity (dashed curve, in G) and area (continuous curves) of long-lived (top of the figure) and short-lived (bottom of the figure) sunspots. The abscissa gives the time in days, and the ordinate on the right gives the area in units of 10^{-6} of the solar hemisphere (in accordance with [73]).

The inclination of the magnetic lines of force in a sunspot may, in the first approximation, be found using Seares's formulas (Sec. 1) from a comparison of the intensities of the π- and σ-components and from measurements of the orientation of the plane of polarization of the π-component near the edge of the solar disk, using a method described first in[79]. The results of such measurements of γ, given in[79], are described well by the formula $\gamma = \frac{1}{2}\pi r/b$, where b is the radius of a spot (cf.[80]). Similar results may be obtained using a magnetograph,[77] but then we also find a more detailed structure of the field in the form of invisible "satellite spots," which are hillocks of relatively strong field of opposite sign, observed in the neighborhood of the main spot and noticeable even when the spot is near the center of the solar disk. "Satellites" of 75 G or greater intensity have been observed at distances of 20—30" from the spots.[58]

These data lead, in the first approximation, to a representation of the sunspot field as being similar to the field at the top of a solenoid with its axis slightly inclined to the normal, as proposed in[73] and shown in Fig. 17. This model is supported by the following considerations. The lower temperature of a sunspot at a given gas density corresponds to a lower gas pressure than in the atmosphere surrounding the sunspot and the gas pressure difference is balanced by the magnetic pressure. Therefore, under a visible spot there should be a more or less vertical pencil of lines of force, whose pressure prevents the penetration of hotter gas into the interior of a sunspot and impedes the descent of the sunspot. For a sunspot with an associated field of 2000 G, the magnetic pressure is 1.5×10^5 dyn/cm^2, which is comparable with the pressure in the photosphere ($\approx 10^5$ dyn/cm^2). In the surface layers, the magnetic pressure is even stronger than the gas pressure outside and the field pushes away matter: strong fields are stretched outward, as shown in Fig. 17.

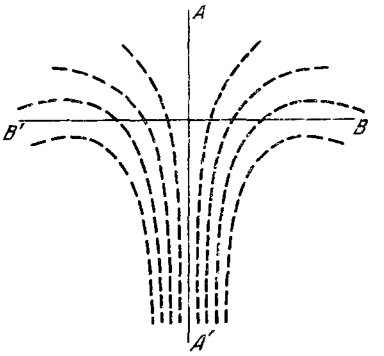

FIG. 17. Schematic representation of the m.f. lines of force in a sunspot (according to [73]).

Later, purely spectroscopic measurements (in particular those using interferometers) of the field intensity and the angle γ give somewhat contradictory results: thus, it was reported in[16] and[81] that the lines of force in a spot are strongly concentrated about its axis; for example, according to[16] ≈40% of the magnetic flux is enclosed in a solid angle of 1, while elsewhere[79] it was reported that only 20% of the flux is concentrated in the same angle. It was found that in the central part of a spot (the umbra) the angle between the field direction and the line of sight is never more than 30° (cf. also[82]). On the other hand, recent measurements[78] led to the conclusion that the field in the penumbra is almost everywhere horizontal.

All these results on the field structure are not free of serious objections. The scintillation of images at the spectrograph slits and the scattering in the optical system give rise to an apparent π-component which is a "continuation" of the Fraunhofer line of the surrounding photosphere into the region of the spot. The ratio of the π- and σ-component intensities is also strongly affected by the polarization caused by reflections in the telescopes themselves: an apparent σ-component is observed (cf.[16]). Secondly, formulas (4) of Sec. 1 are valid only in the case of an optically thin emission (or absorption) layer. In the real solar atmosphere, the intensity within the limits of a dark absorption line (apart from the extreme parts of its wings) comes from an optically thick layer and a theory needs to be developed to account for the formation of such absorption lines in the presence of a magnetic field, i.e., it is necessary to know the solutions of the equations of radiative transfer in the solar atmosphere, allowing for the polarization of the radiation. Such solutions were obtained in[28] for the special case of a spectral line produced by "pure absorption" processes (the scattering of photons by atoms was ignored). In particular, the results given in[78] and[81] on the inclination of the lines of force were obtained by applying the theory given in[28] to spectral measurements. A different solution was obtained in[9] by making the simplifying assumption that the equations of radiative transfer can be written separately for each of the mutually orthogonal polarization states (the possibility of the appearance of a state of different polarization due to scattering is ignored). The theory developed in[3] is much more free of arbitrary assumptions but it applies only to the case of an unsplit quantum state. A comparison of these theories reveals not-too-great differences in the theoretical line profiles, but the errors in the determination of γ may still be very serious.

Other serious sources of error lie in the real differences between the sunspot structures and, even more important, in the field structure variation within a sunspot (see below), which can be observed only using a sufficiently high resolution. The presence of transverse fields in the core of a sunspot was first reported in[83]. Others[31,48] reported "occlusions" of transverse fields in sunspots and other formations on the Sun occupied by a field of only one polarity. A very fine structure may be sometimes observed in sunspots when a high-resolution (about 2" of the arc) magnetograph is used: individual hillocks or peaks of the field in regions having dimensions of ≈2", in small regions with a zero longitudinal component, etc.,[84] all of which indicate a strong inhomogeneity in the field (Fig. 18). The field inhomogeneities may give rise to a disordered rotation of the plane of polarization both at different points on the surface and at points at various depths, as a result of which the radiation from a certain area, comparable with that selected by a spectrograph slit, may be depolarized. Such depolarization is sometimes observed.[84] The presence of characteristic inhomogeneities was indicated by long-lived granules in sunspot cores, reported in[85-87]. A detailed photometric study of sunspots, reported in[87], showed the presence of very

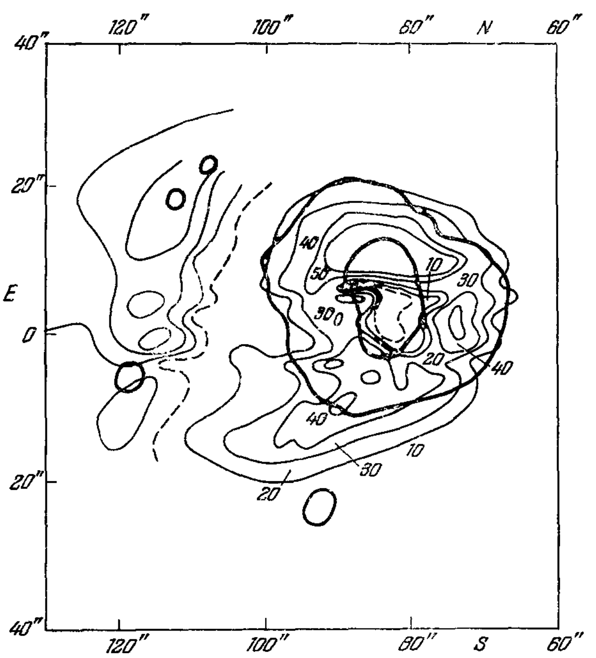

FIG. 18. Fine structure of the longitudinal $H_{\parallel}$ field. The sunspot shows field "hillocks" with dimensions of 2-5"; it is worth noting the $H_{\parallel} = 0$ contour in the core of the sunspot.[84]

dark small cores within the umbra of a spot, which could be ascribed to a local increase in the line of force density at points where the cooling of the gases in the spot was greater. New information on inhomogeneities can be obtained by measuring the transverse field with a magnetograph using the method described in Sec. 1 (cf. [23]). A characteristic of high-resolution recordings of the transverse m.f. is a very rapid rotation of the transverse field vector $H_{\perp}$ from point to point in different regions on the Sun's surface. This leads us to expect a similar rapid rotation of the vector $H_{\perp}$ with depth, which can be investigated by making recordings using different spectral lines generated at different depths in the solar atmosphere (we can also use different parts of the same line). A very strong rotation of the transverse field vector with depth, reaching 90° per 100 km depth, is indeed observed in some parts of spots and groups of spots.* This circumstance may, inter alia, explain the sometimes observed apparent intersection of the lines of force: the "coexistence" of fields having different directions at the same point (see below). Figure 19 illustrates the effect of the direction inhomogeneities both along the surface (lower figure) and with depth (upper figure).

The magnetograph recordings of the transverse fields allow us to take the next step in the investigation of the field structure in solar spots: using the longitudinal ($H_{\parallel}$) and transverse ($H_{\perp}$) field charts, we can plot charts of the magnitudes and orientations of the total field vector H in sunspots.[91] Figure 20 shows a combined chart of $H_{\parallel}$ and $H_{\perp}$ and a chart of the lengths and slopes γ of the total vector H (below) for a unipolar spot (shown above). The most important characteristic is the concentration of the field in tubes or bunches directed radially from the spot. The field is mainly longitudinal in the umbra and transverse in the penumbra, in accordance with the conclusions reported in [78] and [81]. Sometimes, a helical (vortex) m.f. structure appears near a spot, as first reported in [22]. It is interesting that such a structure follows closely the structure of the H_{α}-line vortices in the chromosphere, observed first by Hale (cf. [88]); the presence of a tangential m.f. component in a sunspot was recently reported also in [82]. The vortex field structure in a p-spot of a bipolar group was ascribed in [89] to the presence of an azimuthal field. In [89], the authors used their measurements to determine separately the radial (H_r) and azimuthal (H_{φ}) components and investigated their variation with the distance r from the center of the spot. The dependences of H_r and H_{φ} on r were found to be similar to that expected for a force-free field with cylindrical symmetry; from this, it was concluded that the sunspot fields should be force-free. (A similar field model with the corkscrew type lines of force was proposed in [90].) However, the helical structure is more likely to be the exception than the rule (according to [91], it is observed in one case out of 17–20; frequently it is found only in a small or restricted sector near a spot, as reported in [89]. On the other hand, an investigation of the hydrogen vortices in the chromosphere observed in the H_{α} light,[92,93] which were located (in agreement with [88]) along the $H_{\perp}$ directions, showed that in the northern hemisphere of the Sun vortices had always the same sense of rotation, which was opposite to the sense of rotation for the vortices in the southern hemisphere, irrespective of the 11-year cycle of the magnetic activity and of the magnetic polarity of sunspots. The sense of rotation of the vortices was always the same as that of the terrestrial cyclones, which definitely indicated the hydrodynamic nature of the vortices and, possibly, of the sunspots themselves although it was also likely that m.f.'s followed passively the hydrodynamic structure of a vortex.

The knowledge of both components of the field $H_{\parallel}$ and $H_{\perp}$ allows us to determine the electric currents responsible for the magnetic field of the spot and the vertical gradients of the field by the numerical solution of Maxwell's equations

$$\mathrm{curl}\,H = \frac{4\pi}{c}\gamma, \qquad \mathrm{div}\,H = 0. \tag{8}$$

The results of calculations of these quantities using an electronic computer are shown in Fig. 21.[91] The pattern of the vertical currents is very characteristic: similar, roughly speaking, to that which would be ob-

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*We note that, according to [23], the anomalous dispersion effect may rotate the plane of polarization by not more than 30°.

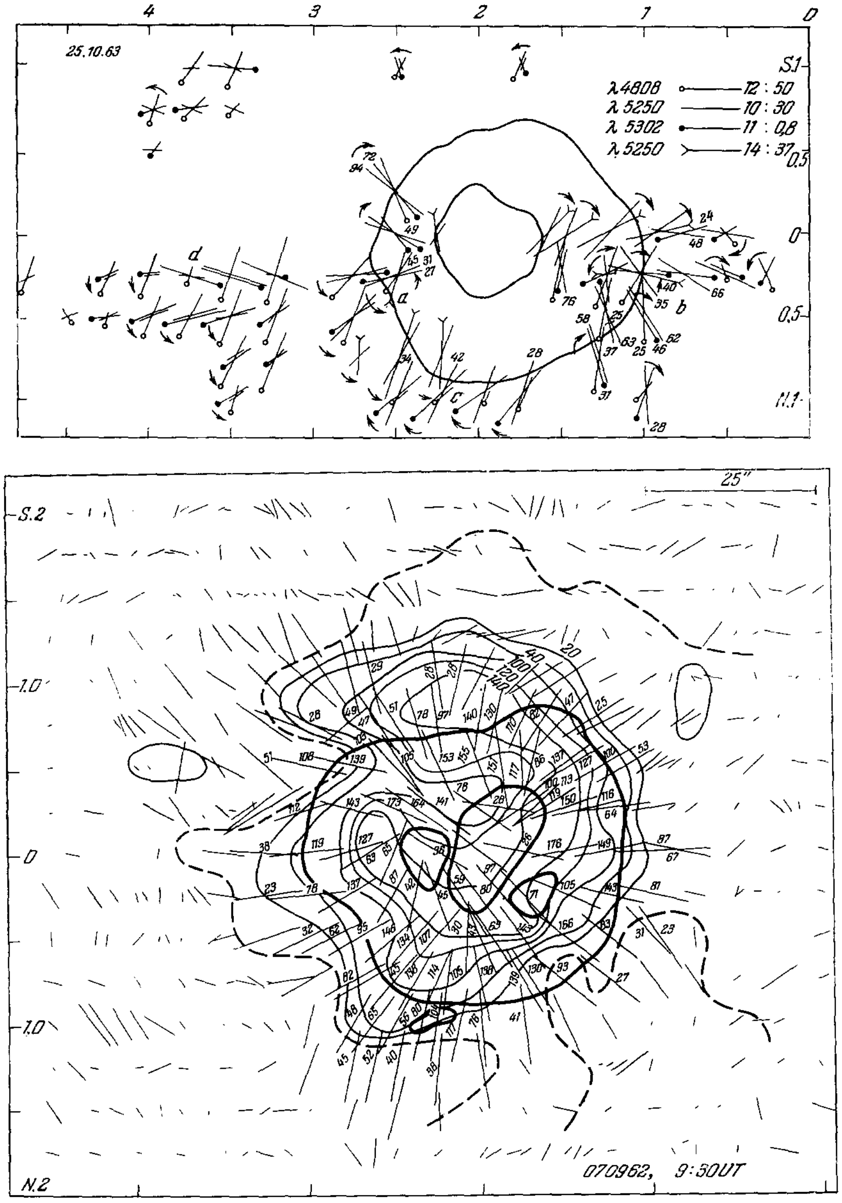

FIG. 19. Upper part of the figure shows the positions of the vector $H_\perp$ for spectral lines appearing at various depths: λ4808 in the lower layers of the photosphere, λ5250 in the middle layers, and λ5302 at the top of the photosphere. The recording using λ5250 was made twice to eliminate possible rotation of the vector with time (the time when the recording was made is given in the upper part of the figure together with the symbol used to represent the $H_\perp$ vector). Particularly strong rotation with depth in the photosphere can be seen in regions denoted by a, b and c. The curved arrows indicate the direction of rotation of the vector with depth. The continuous closed contours show the umbra and penumbra of the spot. The lower part of the figure gives a typical combined chart of the isogauss curves for the longitudinal field $H_\parallel$ and the directions and magnitudes of the vector $H_\perp$ (for large magnitudes of this vector, the lengths of the segments are given in figures). Strong rotation of the vector $H_\perp$ within a sunspot (shown by thicker lines in the lower figure) can be seen.[27]

served on viewing the stator coils of an electric motor along the axis of the motor. The origin of this structure is obviously associated with those tubes of approximately radial lines of force in which the m.f. is concentrated. Another interesting feature of the current pattern is the appearance of points of contact between very strong (up to 10^{11} A) oppositely directed currents, which is sometimes the result of very rapid rotation of the transverse field vector $H_\perp$.[23,91]

The variation of the field gradient with depth in a sunspot can be determined knowing the magnitude of the splitting of spectral lines generated at various depths. A gradient of about 3.0 G/km was found in[94] from the splitting of lines of various intensities. Attempts have also been made to find the gradient on the basis of a fairly arbitrary assumption about the divergence of the lines of force which gave values ranging from 0.5 to 2.5 G/km. However, all the estimates of the gradients lean very heavily on the assumption about the physical state of gases in a sunspot: different models of the sunspot structure give values differing by a factor of 10 or more.[77] Moreover, the lines of different elements in the spectrum of a sunspot yield substantially different results so that sometimes it is difficult to find any gradient at all.[96] The increase in the field with depth should give rise to an asymmetry of the spectral line since the central parts of one of the σ-components generated in the upper layers should show less splitting than the wings of these lines (if the other σ-component is absorbed by polarizers): the effect will increase in strength with the range of heights within which the line is generated.[97] The results of exact photometry of such asymmetric σ-components of the D-line of sodium are in very strong disagreement with the theoretical expectations.[98] In spite of this,

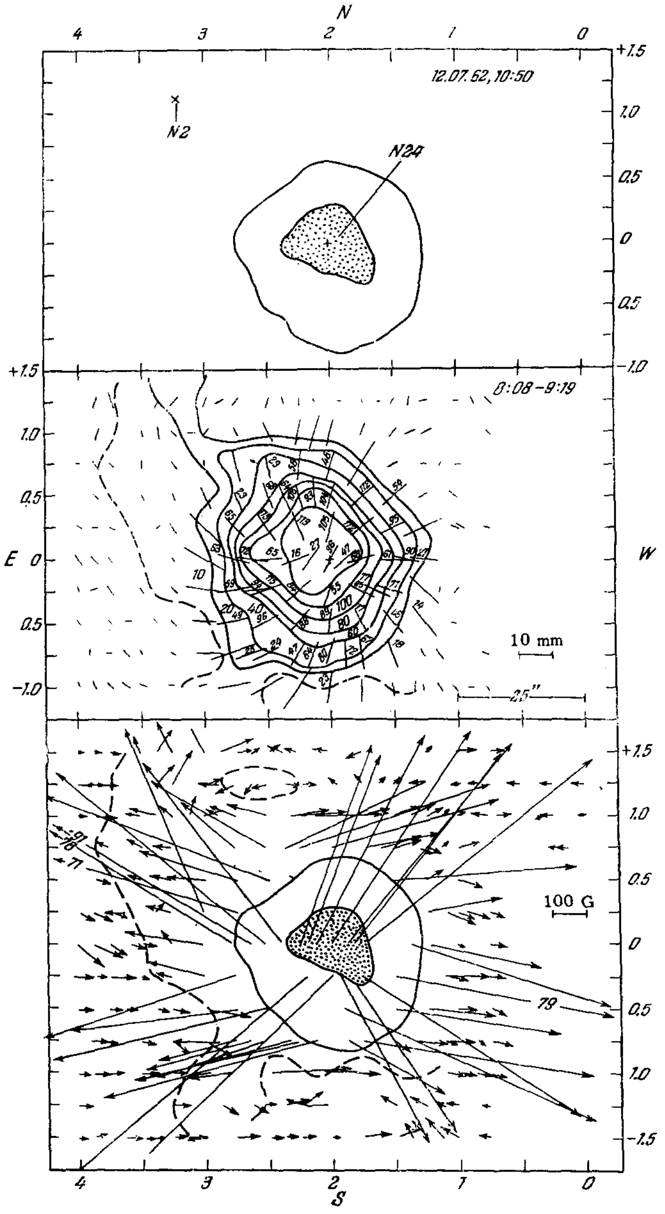

FIG. 20. Chart of the total-field vector (bottom part of the figure): the inclination of the arrows to the vertical is equal to γ; the orientation of these arrows in the quadrants is governed by the orientation of the vector $H_\perp$ in the combined chart (middle part of the figure). The lengths of the arrows are equal to $|H|$ expressed in G (the scale is given). The outline of the sunspot is at the top of the figure.[9]

the authors of[99] estimated a gradient of $\approx 1-1.8$ G/km, assuming the theory given in[98]. If the gradients are of the order of 1–5 G/km, the sunspot field of ≈2000 G should practically disappear at a height of ≈ 1000–2000 km above a sunspot, which disagrees with observations[100], which indicate that fields of 300–500 G are frequently recorded above a sunspot (the Zeeman splitting is observed in the cores of such strong lines as H_α and K of Ca II), and the longitudinal m.f.'s have been recorded reliably by a magnetograph for the core of the H_α line at heights of ≈3000 km. Measurements of the radiowave spectrum and of the circular polarization of radio waves give gyro-frequencies compatible with fields of 360 G even at heights of 50 000 km in the solar corona.[101] Fields of 600 G have been found at heights of $(20-30) \times 10^3$ km using a similar method.[102] It is possible that the field above the photosphere, in the chromosphere and corona, does not vary as rapidly with height as in the photosphere itself: there are indications that magnetic fields in the chromosphere decrease more slowly with height than would be expected for potential (dipole) fields.[63]

Figure 20 shows that regions of vertical gradients $\partial H_z/\partial z$ of opposite signs are adjacent in a spot and this probably indicates that in a given region of a spot the variation of the divergence of the lines of force with depth differs considerably from the variation in another region. This is one more indication of the complex inhomogeneous structure of the fields within sunspots. It may account for the considerable discrepancies between the field gradients determined by the spectral method, which would lead to drastic averaging.

Consideration of the nature of m.f.'s of sunspots from the observational point of view leads us at present to the conclusion that a sunspot exhibits a very strange "coexistence" of contradictory properties, typical both of potential fields of the dipole type (as mentioned first in[80]), when electric currents are absent, and of fields produced by a complex system of electric currents, in particular force-free fields in which currents flow along the lines of force. The observed twisting of the field, its inhomogeneities and fine structure are obvious indications contradicting the existence of potential fields.[23,91] Dependences of the intensity and inclination of the field on the distance from the center of a sunspot and certain other observations suggest the possibility of representing m.f.'s of sunspots by a potential field.[91] It is also very difficult to explain the occasional appearance of strong vertical electrical currents in regions containing a purely transverse field, if the force-free concept is used.

The similarity of sunspots to cyclones, referred to earlier, indicates a passive role of the magnetic field: the field follows hydrodynamic motion. On the other hand, the relationship between the m.f. and the velocity field in a sunspot is still not clear; a sunspot does not have a definite excess of magnetic over kinetic energy of motion or vice versa. In the core (umbra) of a sunspot, where m.f.'s are almost completely longitudinal, a transverse component of motion is observed,[103] while in the penumbra the inclination of the lines of force to the sunspot axis is considerably greater than the inclination of the currents flowing radially from the center of a sunspot, practically along the Sun's surface (Evershed's motion). On the other hand, in view of the expected high

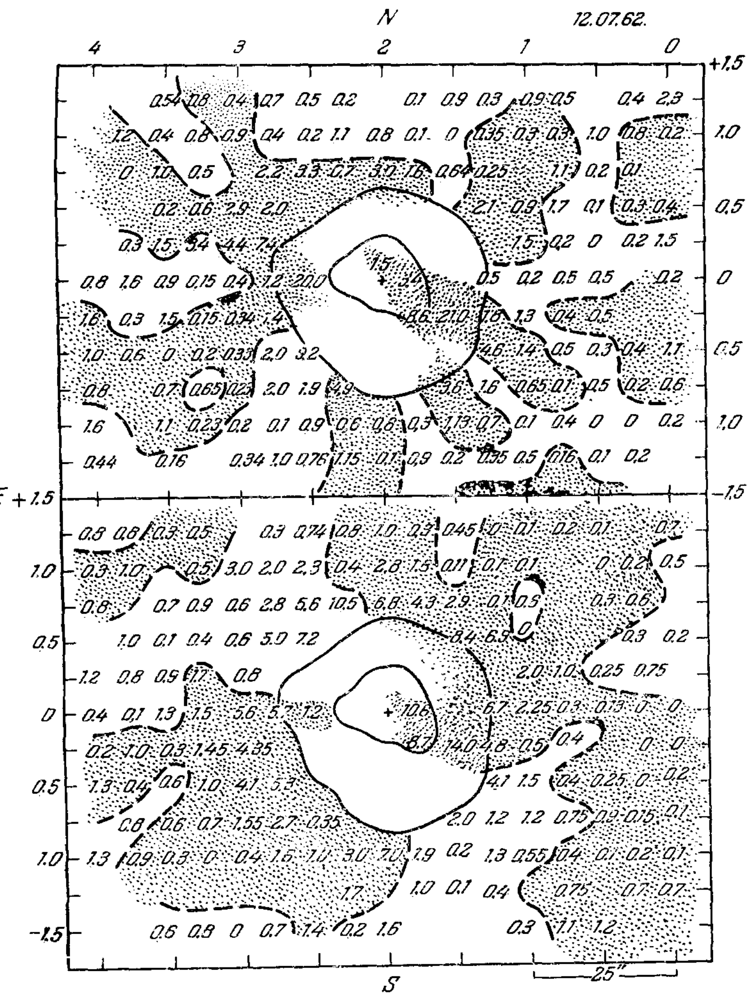

FIG. 21. Chart showing the vertical currents (top) and the gradients of the vertical component of the field around the sunspot shown in Fig. 20. The numbers give the values of the current j_z (or of $\partial H_z/\partial z$) in units of 10^{-2} G/km. The dark and light regions have opposite signs.[91,53]

conductivity of the plasma in a sunspot, the motion should be solely along the m.f. lines of force. Then, if there is some motion across the lines of force it will "push apart" the field in a time $\approx L/v$, where L is the dimension of a sunspot and v is the velocity of the aforementioned motion; when $L = 2 \times 10^9$ cm and $v = 1$ km/sec (such velocities are in fact observed), we have $L/v \approx 2 \times 10^4$ sec, i.e., about 5 hours, while sunspots exist as a rule for several days. This difficulty may be eliminated by the fine structure of a field in a sunspot, to which we have referred earlier: the motion involves leaks mainly through gaps between pencils of the lines of force, and gases flow through these gaps as if through slits in which the interaction between the field and the plasma motion is weakened.[104]

b) Fields and Their Changes in Groups of Sunspots and Active Regions

The magnetic fields on the Sun appear earlier and disappear later than the sunspots or groups of sunspots: the fields are closely associated with calcium floccules, and they appear and disappear at the same time as these floccules. According to[42], the weak fields associated with the development of an active region on the Sun usually form bipolar (BM) regions; some of them are multipolar (M), and only rarely unipolar (UM). In the bipolar case, the positive and negative magnetic fluxes approximately balance out. A small fraction of the lines of force is dispersed over a large region near a strong-field area.[42] BM-regions exhibit the same properties as sunspots, which represent the natural development of BM-regions in their earlier stages. Bright hydrogen clouds—floccules—and an enhanced emission of the solar corona are frequently observed above these regions. UM-regions do not exhibit a close correlation with the observed formations on the Sun's surface; attempts have been made to associate them with Bartels' M-regions, which are responsible for the generation of corpuscular currents, but Wood[105] showed that there is no correlation between geomagnetic disturbances and the passage of these regions through the visible spectrum of the Sun. One must remember also that, if high resolution is used, many UM regions are found to be multipolar.

The evolution of the magnetic field associated with the appearance and disappearance of a sunspot has not been investigated: there are cases when a sunspot with a field of the order of 1000 G appears in 6—8 hours and there are no data on the field before the appearance of a sunspot since it is not known in advance where a sunspot may appear; strong-field regions (up to 500 G and more) are observed (they are called "invisible" sunspots) where there are no sunspots at all. The positions of the "hillocks" of the usually recorded longitudinal component of the field do not always coincide with sunspots:[12,31] there is only a rough correspondence between the longitudinal field distribution and the observed structure of sunspot groups. The usual process of development of the field of a sunspot group involves an increase in the field intensity, the appearance of new polarities, the complication of the magnetic relief, and the appearance of deep "bays" of one polarity in a region of opposite polarity; a typical situation in a developed, usually multipolar, group with strong field gradients, is shown in the chart of Fig. 22. Under such conditions, solar flares are frequent (see below). Recently, it has become possible to measure the transverse field with a magnetograph and this allows us to supplement the information on the field pattern in active regions and groups; Fig. 23 shows an example of the field of a group in which, apart from the longitudinal field contours, arrows are used to represent the magnitude and direction of the transverse field. Figure 23 shows also a typical line of force pattern. In some cases, a strong transverse field is recorded on the neutral longitudinal field line $H_{\|} = 0$. On this line, and sometimes in regions of a strong positive or negative field, very interesting features are observed: they are places where transverse fields of different directions seem to intersect and oppositely directed fields are in contact. It is probable that this field intersection effect is associated with a very rapid rotation of the field on the surface and with depth, as described earlier. It is also found (Fig. 23) that there is a correspondence between the positions of these field features and the places on the Sun, recorded using the H_α light, at which flares, "whiskers,"* high-speed ejections of plasma, and other nonstationary or explosive processes are observed. Such deviations from the smooth progression of the lines of force (twisting of the field, rotation of the field vector, etc.), can naturally be associated with instabilities, which appear in the solar plasma in the presence of m.f.'s, because such states are not usually states of minimum energy. These regions are usually characterized by a strong rotation of the vector $\mathbf{H}_\perp$, i.e., they are regions of strong vertical electrical currents. Charts of these currents, calculated using the m.f. charts, confirm this: at points where flares and other instabilities occur, we frequently find contact between strong vertical currents flowing in opposite directions.[53] However, such contact is insufficient for the appearance of a flare.

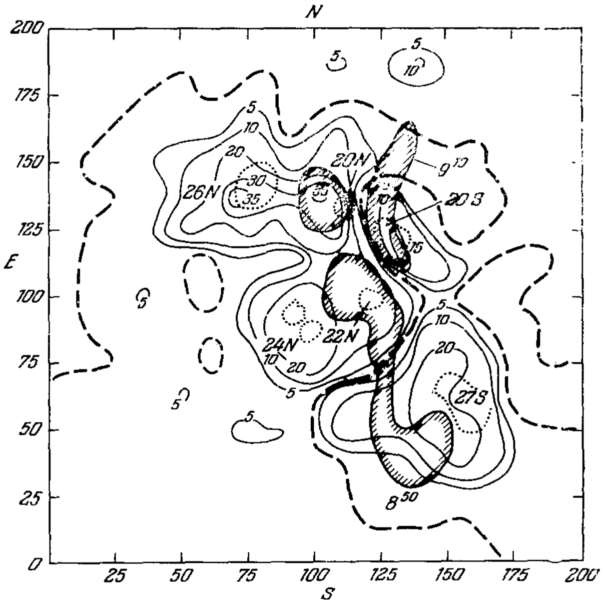

FIG. 22. Chart of the longitudinal field in a complex multipolar group on July 3, 1957, in which a strong flare of 3^+ magnitude was observed (the flare region is shown hatched internally). The sunspots are represented by dotted contours and the $\mathbf{H}_{\|} = 0$ line is shown dashed. One division represents 5.3 G.

We need more complete information on the nature of m.f.'s and their interaction with the solar plasma to understand the possible role of magnetic fields in such nonstationary processes as flares and other instabilities, which, incidentally, appear only in groups of spots and are accompanied not only by strong energy losses in the form of optical and radiowave radiation but also by the generation of cosmic rays, in particular protons of energies ≥ 100 MeV (cf.[106]). On the one hand, the measured fields of groups, as pointed out first in[80] and then in[107], show a general similarity with m.f.'s which can be produced in the laboratory by dipoles such as solenoids, after a suitable adjustment of the scale by a factor of 10^8—10^9 and of the field intensity by a factor of ≈10. This similarity follows from the invariance of the expression for the field intensity of a system of k dipoles with their ends at points 1 and 2

$$\mathbf{H} = \sum m_i \left(\frac{\mathbf{r}_{1i}}{r_{1i}^3} - \frac{\mathbf{r}_{2i}}{r_{2i}^3} \right), \qquad m_i = \frac{1}{4\pi} \int H_{1i}\, d\sigma$$

under similarity transformations $r' = \alpha r$, $m' = \beta m$, which yield the relations

$$H' = \frac{\beta}{\alpha^2} H, \qquad \frac{\partial H'}{\partial x} = \frac{\beta}{\alpha^3} \frac{\partial H}{\partial x}.$$

Models of groups consisting of dipoles, calculated using an electronic computer,[108] show not only a similarity with the observations but also predict the ap-

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*"Whiskers" are very wide emission wings appearing briefly in some absorption lines of the solar spectrum in very small "point" regions of an active area; cf. [123]

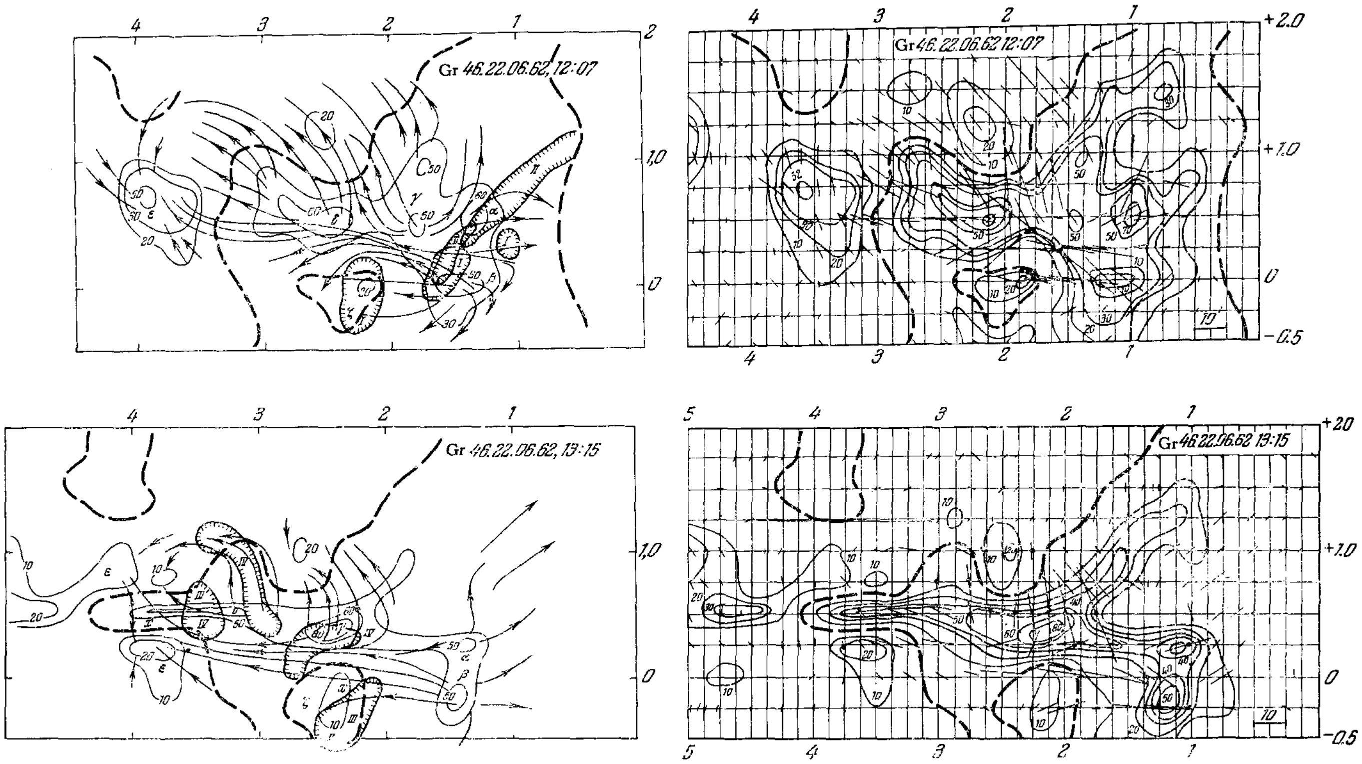

FIG. 23. Combined charts of the fields $H_\parallel$ and $H_\perp$ (on the right) before (above) and after (below) a flare of magnitude 2. The charts on the left show, in addition to the isogauss curves of the field $H_\parallel$, typical lines of force parallel to the $H_\perp$ vectors in the preceding charts. The flare considered is represented by the region shown with internal hatching (top left); bottom left shows flares observed after field measurements. Considerable changes in the field configuration can be seen in the charts before (top) and after (bottom) the flare.[31]

pearance of such singularities as the intersection of projections of the lines of force and the contact between the lines of force having opposite directions (this can be seen in the projection on the plane of the chart; cf. Fig. 24); if all these lines of force pass through a narrow layer in which the spectral lines are formed, we find the "coexistence" of fields of various directions, which is a phenomenon characteristic of magnetic charts near flares and other instabilities. However, a field generated by dipoles is a potential field in which currents cannot appear (curl $H = 0$), while direct measurements of the fields, as described earlier, show the presence of strong currents, particularly at points at which flares appear. The agreement between the magnetic fields measured in a group of sunspots and the dipole magnetic fields calculated using a model in which a group is represented by dipoles, is only a rough average agreement; details reveal serious contradictions, especially where the field has a fine structure or where the singularities referred to earlier (rotation of the $H_\perp$) are observed. The rough agreement probably means that, at a sufficient distance from a "source," any magnetic field is more or less similar to the field of a dipole. On the other hand, the representation of the field by a system of dipoles is difficult to reconcile with the very high conductivity of the solar plasma in which these dipoles are "immersed" (the plasma is deeply "frozen" into the field or the field into the plasma).

Changes in the fields with time are important for the understanding of our problem. The possibility of "spasmodic" changes in m.f.'s was first pointed out in [73] on the basis of observations of the magnetic fields of sunspots made at the Mount Wilson Observatory. The usual changes in the magnetic fields of long-lived sunspots do not exceed 10 G per day.[109] However, in the case of flares it was found that the values of the field before and after the occurrence of a flare differed considerably: a comparison of the

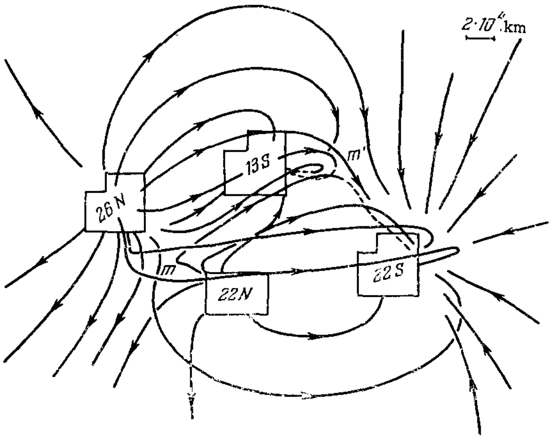

FIG. 24. Calculated lines of force of the magnetic field of a group observed on April 1, 1960, modeled by dipoles with appropriate areas, positions and intensities.[108]

charts obtained with a magnetograph showed that the structure of the field after a flare became simpler, the field gradients, and sometimes the fields themselves, decreased,[110] and the magnetic "hillocks" and sometimes the spots dispersed.[107,111,112] For example, if the longitudinal field gradients before a flare were 0.1 G/km, then after a flare they were only 0.02—0.03 G/km. Figure 25 shows, in accordance with[113], an example of changes in the field energy and gradients associated with a large flare on July 16, 1959, which was accompanied by a very strong flux of cosmic rays and a number of strong effects in the ionosphere and in the magnetic field of the Earth. (Changes in the field during this flare were not observed at first because of the low resolving power of the method used by Howard and Babcock[114], which led them to the conclusion that magnetic fields did not change during flares.) Sometimes, only a temporary change in the field was observed and after a time the field pattern returned to its initial pre-flare form.[115-117] Recently, it was also found that[118] the fine filamentary structure of the hydrogen chromosphere (visible in the H_α light and reproducing the structure of the field) is also subject to sudden large changes during a flare, but is re-established again after a flare.

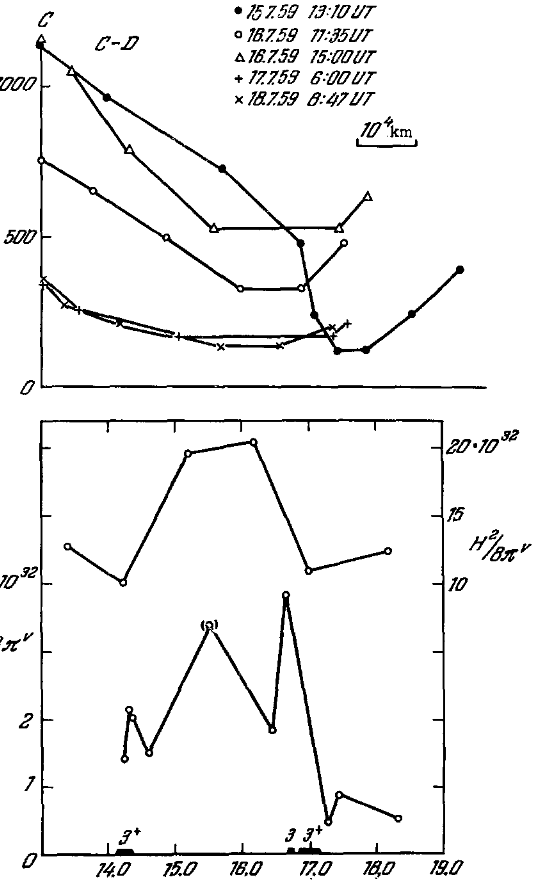

FIG. 25. Changes in the field gradients associated with a strong flare of magnitude 3^+ on July 16, 1959. The ordinate in the top part of the figure gives the field in gausses and the abscissa the distance from the pole C. The bottom part of the figure shows the changes in the total magnetic field energy of the group (upper curve) and the changes in $H_\parallel^2/8\pi$ (lower curve).

An analysis of the $H_\perp$ gradient before and after a flare, carried out in[107] using dipole models of sunspot groups, showed that these gradients depended on the magnitude of the flare and of the effects accompanying it, as listed in the adjoining table.

Flare magnitude and its effect	$\nabla H_\perp$, G/km		Number of cases
	before	after	
3^+, cosmic rays	0.73	0.25	13
3^+, polar blackout	0.46	0.27	11
3 and 2^+, no cosmic rays	0.18	0.13	12
2^+ and 2, without geophysical effects	0.054	0.038	15

The strong flares accompanied by cosmic rays listed in this table were all accompanied by powerful radiowave bursts of type IV. On the other hand, an investigation of flares accompanied by this type of radiowave burst showed that the probability of a flare with a radiowave burst of type IV or a polar blackout* increases as the ratio d/D gets smaller, where d is the distance between spots and D is their diameter, i.e., when the average field gradient in a sunspot group increases.[119] According to[120,121], the configurations and intensities of magnetic fields of the groups not accompanied by flares or accompanied by weak flares are not subject to great changes or do not change as much as the groups accompanied by strong flares.

An example of strong changes in the field is shown in Fig. 23; in this case, not only the field configuration and its intensity changed but also the vector $H_\perp$ was strongly rotated.

It should be mentioned that, in general, the measured changes in the magnetic energy (the value of $\int (H_\parallel^2/8\pi)\, d\sigma$ integrated over the whole active region where the field recorded by a magnetograph is not equal to zero) practically coincide, according to[113], with the estimates[106] of the total energy carried away by cosmic rays generated in a flare. The same estimate is obtained from the formula $\delta W = (3m_1m_2/R^3)(\delta R/R)$ for a change in the energy of interaction between dipoles if we take the value $\delta R/R = 0.3$ from the observations of shifts of sunspots during flares and if we assume that $m_1 = m_2 = HSh \approx 10^3 \times h = 10^{32}$, where S is the area, and h is the length of a dipole (which is of the order of $R = 10^{10}$ cm). Thus the energy considerations support the idea that the magnetic energy is converted into other forms of

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*Polar blackouts are caused by high-energy protons (> 100 MeV) produced by solar flares.

energy (mainly the mechanical energy of motion and the energy of cosmic rays) during flares.

However, one must bear in mind that in astronomical bodies the process of the conversion of the magnetic into thermal energy (due to the diffusion of fields and ohmic losses) is very slow and its characteristic time $\tau = 4\pi\sigma l^2/c^2$ is exceedingly long because of the large characteristic dimensions l and high conductivity. For example, according to[122], the time for the decay of a field in a sunspot ($l = 10^9$ cm) is $\approx 10^4$ years. For flares having dimensions of $l = 10^8$ cm, which appear in the chromosphere where σ can hardly be less than 10^{13}, this time cannot be shorter than 10^5 sec although, in fact, flares last usually not more than 10^3 sec. This difficulty is removed by allowing for the fine structure of the flares. As discovered in[123], the emission in active regions, irrespective of the type (flares, "whiskers," or faculas), is concentrated in small short-lived (up to 20 min) granules or cores, whose dimensions are comparable with the resolution of modern telescopes ($\approx 0.4'' \approx 300$ km). These cores generate nonstationary emission in separate spectral lines and in a continuum at rates of the order of several hundreds of $\mathrm{erg \cdot cm^{-3} \cdot sec^{-1}}$. Other considerations also lead to the same conlcusion about the fine structure of flares.[106] The reduction of the characteristic dimensions by a factor of 10 (to 10^7 cm) gives a reasonable value for the time of dissipation of the magnetic energy, particularly when the possible ambipolar diffusion[124] and turbulence (see below) are allowed for.

From among the possible mechanisms of flares satisfying these energy considerations, we must select that mechanism which would satisfy the main dynamical feature: the explosive motion which accelerates the plasma to high (supersonic) velocities and produces fine-structure elements. A considerable body of spectroscopic data indicates that, at the beginning of a flare, the plasma "collapses" within a small volume and this is followed by a shock wave propagated over almost the whole solar atmosphere both upwards and downwards. The possible reasons for such a collapse may be sought in the instability of the plasma near neutral points, as has been done in a number of papers.[110,125–129] The possibility of the plasma being rapidly compressed near a neutral point by the "external" fields of the sunspots and of a reflected shock wave was considered in[130], while Gold and Hoyle[131] considered a mechanism whereby two oppositely twisted tubes of a "free" (for example, force-free) magnetic field approached each other. If, due to plasma instability, fine structure vortices with oppositely directed fields are formed at the "epicenter" of an explosion, the mechanism of the conversion of the magnetic field energy into heat may be much faster than that in the case of ordinary diffusion: if the dimension of the vortex is D and its characteristic velocity of motion is ξ, the vortex surfaces are in contact for a time $\approx D/\xi$ and the dissipation during this time is restricted by a skin layer L, as given by the relationship $D/\xi = 4\pi\sigma L^2/c^2 = \tau$. The total dissipation time t_d is of the order of τ multiplied by the number of possible contacts for a given vortex, which is of the order of $\approx D/L$, so that the time

$$t_d = \left(\frac{4\pi\sigma D^3}{c^2\xi}\right)^{1/2}$$

may be comparable with the actual lifetime of 10^3 sec even for relatively large vortices of ≈ 100 km (which is the characteristic dimension of the observed fine structure), when the actually measured (using spectral line widths) turbulent velocity is $\xi \approx \approx 100$ km/sec.[132] A basically different mechanism was proposed in[133], where flares were considered to be due to the formation of a double layer in a current filament in which the current rose above a certain limit. The mechanism of the flare formation still remains partly unexplained although its electromagnetic nature (conversion of the magnetic into other forms of energy) is no longer in doubt. This also follows from the fact that the rapidly moving plasma in flares, as in prominences (which are in many respects similar to flares), is quite strongly magnetized, as shown by direct measurements of the fields in flares and prominences.[134,135]

4. MAGNETIC FIELDS OF STARS

The first measurements of the longitudinal magnetic fields were made on the star 78 Vir—which belongs to the spectral class A_{2p} (early hot stars) with sharp lines—using a circular polarization analyzer (Fig. 8).[136] The field of this star always has negative polarity and fluctuates irregularly from −140 to −1680 G.

As described at the end of Sec. 1, the measurements of the shifts Δs in the polarization spectra of stars are usually carried out for a large number (more than 100) of lines having different effective splittings z. This allows us to plot an empirical dependence of Δs on z and to find the magnetic field H from the slope of this rectilinear dependence (we note that in the case of a nonmagnetic star, the dependence of Δs on z is a straight line parallel to the z-axis). Figure 26 gives an example of such a dependence for the magnetic star 53 Cam. It should be mentioned that the measurement of fields by means of the line splitting is possible only if the lines in a stellar spectrum are Doppler-effect broadened by not more than ≈ 3 Å due to the rotation of the star and turbulence of its atmosphere. This follows from the fact that the splitting for a normal triplet is only 0.2 Å in a field of $\approx 10^4$ G, while most stellar fields are less than this value and the lines are rotation-broadened by more than 0.3 Å. The line broadening due to the rotation is given by the quantity $v_e \sin i$, where v_e is the

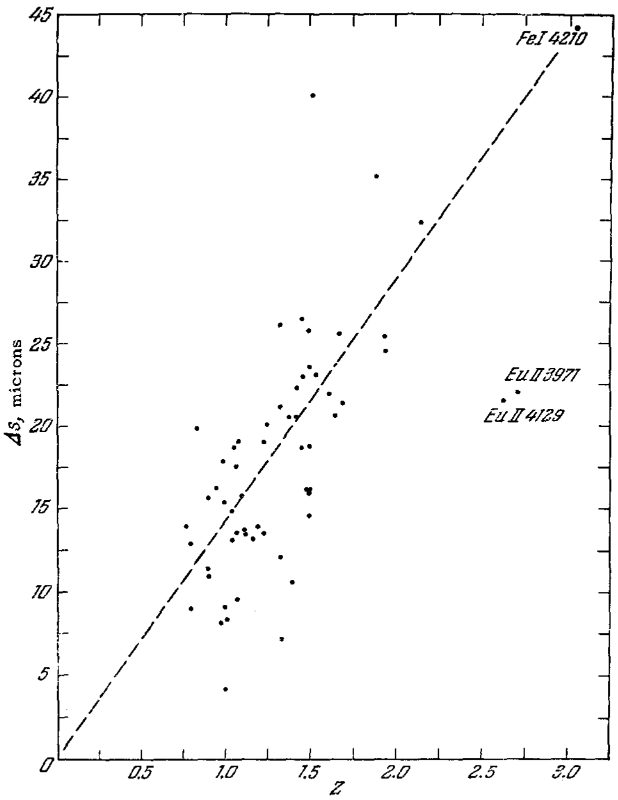

FIG. 26. Dependence of the shifts Δs on the effective splitting z for the star 53 Cam; $H_e \approx 3225 \pm 78$ G.

equatorial velocity of a star and i is the inclination of its rotation axis with respect to the direction of observation. When the inclination of the axis of a rapidly rotating star increases, the lines become broad and diffuse and the weak lines disappear altogether; the widths of the few remaining lines of metals are ≈4 Å, indicating velocities $v_e \approx 150$ km/sec. Assuming that the axes of rotation are distributed at random in space, we can estimate that only for about 0.6% of all stars with this velocity of rotation are the directions of their axes of rotation sufficiently close to the direction of observation for the total rotation broadening not to exceed 0.4—0.5 Å.

Babcock's[136,137,2] guiding assumption was that the magnetic fields of stars increased as their velocity of rotation increased. This assumption was made without reference to the nature of stellar magnetism, although similar suggestions of proportionality of the magnetic moment and the angular momentum had been made by physicists before.[138,139] (Babcock found that for three bodies: the Earth, the Sun, and the star 78 Vir, the ratios of their magnetic moments to their angular momentum were approximately the same: $u = 1 \times 10^{-15}$; the same ratio was found for γ Equi.[142]) Therefore, the search for strong fields has been concentrated on the rapidly rotating stars in the early spectral classes A and B.

A catalog of magnetic fields of such stars with detailed and interesting commentaries is given in[141]. This catalog contains information on m.f.'s of 336 stars. For 89 of these stars, the fields were definitely detected, for 66 their existence was suspected, while for 181 there are no data indicating the presence of a field. Most of the determinations of stellar m.f.'s were made on earlier (hotter) stars, but before we deal with them we shall note some interesting exceptions. It is very interesting to note the presence of strong m.f.'s (≈1000 G) in three giant stars (with radii of ≈100 times greater than the Sun's radius) of the later type M classes, with very slow rotation. Later, it was reported[3] that among "peculiar" A-stars, the star HD 215441 had an exceptionally strong field H = 34 400 ± 266 G. Some lines in the spectrum of this star are split into three components. The relative intensities of the π- and σ-components indicate that the average angle of inclination of the field to the line of sight is ≈50°. It is interesting to mention also the data obtained for a very hot star with the B_e class emission lines, HD 45677: its magnetic field, determined from the forbidden S II lines, is 1600 G. Since these lines appear in the extended envelope of this star, at a distance of several stellar radii, and the lines on the star's "surface" (photosphere) do not show marked splitting, which indicates a field of less than 30 000 G, we may conclude that the magnetic field of this star decreases with distance r from its surface much more slowly than r^{-3}, and possibly as r^{-2}.[142]

As far as the majority of magnetic stars are concerned, one must mention first of all their "peculiar" properties (anomalous ratios of the spectral line intensities for a given stellar temperature). H. W. Babcock[2] ascribes this to the fact that, by selecting stars of class A with sharp lines in order to measure magnetic fields reliably, we restrict ourselves to rapidly rotating stars (all class A stars rotate rapidly) observed almost along the directions of their axes of rotation. The point is that not only the width of the line but also the total absorption in a line should depend on the latitude in a rapidly rotating star. This follows from the fact that at the poles of a flattened, rapidly rotating star the acceleration due to gravity is greater and, therefore, the effective temperature and surface brightness at the poles are relatively greater than at the equator, which gives rise to the ionization and excitation of atoms different from that which is expected, on the average, for the great majority of stars in a given spectral class. The line spectra of such stars observed at the poles will correspond to hotter stars having greater pressures. However, the anomalies in the line spectra of magnetic stars cannot be accounted for solely by different physical conditions. Thus, for example, according to[143], the magnetic star α^2 Can Ven shows real differences in its average chemical composition, in terms of the relative abundance of elements (in particular the abundance of rare earths, strontium, etc.,), compared with a normal star of the same spectral class.

In general, stars of earlier classes (A_{0p}, A_{2p}, A_{3p}) with strong and rapidly varying fields (all stars of the type 21 Per, HD 173650) exhibit many anomalously enhanced lines (Si, Sr, Mn, Eu, Gd, Cr), while in "colder" subgroups in class A (A_{5p}-A_{7p}, F_0) only the lines of Sr, Cr, and of the rare earths are enhanced. The Fe and Mg II lines are relatively weak in all these cases.

Moreover, the majority of lines of various elements give, as a rule, similar values of the field intensity at a given time, with the exception of some stars with rapidly varying fields, which exhibit differences either between the field intensity measured using lines of certain elements and the average field intensity, or between the magnetic field intensities measured using lines of ionized and neutral atoms. This indicates some stratification of the field with depth in a stellar atmosphere. For example, the lines of chromium of the star HD125248 indicate a stronger maximum negative field than do the lines of other elements. In some silicon stars (K Cancri), the Si II lines give magnetic field value s different from those obtained using other lines.

It was initially assumed[136] that all m.f.'s of stars were axisymmetric dipole fields and that the observed fields were some effective fields H_e. Due to the darkening of a stellar disk toward its edges, the field H_e represents 0.3 of the field intensity at the pole[136] and has the same polarity as the polar field. Later it was found[2,137] that the stellar fields are not, in general, simple fields of the permanent dipole type. It was found that they vary and that these variations are in general irregular.

Stars may be divided into three groups in accordance with their magnetic variations: α, β, and γ, these designations being taken from typical stars α^2 Can Ven, β Cr Bor, γ Equi. Basically the α-group exhibits periodic variations of the field but with large departures from the average amplitude. The oscillations are not harmonic: a maximum of one polarity is usually wider than a maximum of the other (Fig. 27). The β-group is characterized by irregular fluctuations, which include polarity reversal. The γ-group (five stars only) exhibits irregular variations of a constant polarity field. The α-group is characterized not only by the highest amplitudes of the field oscillations, but also by changes in the line intensities in the spectra, which are synchronous with the magnetic variations. The oscillation periods in the α-group lie within the limits 4.0—9.3 days. Typical stars of the α-group show, in amplitude, an approximately symmetrical polarity reversal and the so-called "crossover effect." The crossover effect is understood to be the following phenomenon observed in some stars having strong fields: the width of the magnetically split lines depends sometimes on the sign of the circular polarizer: when the polarizer has the left-handed orientation the lines are sharper than they are for the right-handed orientation; this increase in sharpness may differ from one element to another, it may be different for different ionizations and even for the different members of a multiplet. The effect is usually observed in stars exhibiting strong fields and polarity reversal and it appears near the polarity reversal phase (for example, in the star HD 71866). To explain the effect, H. W. Babcock suggested[144] that there are two regions, A and B, on a stellar disk: both regions have the same (large) dimensions with fields of opposite polarity but they move at different radial velocities. Then, at a certain relative velocity of motion of these regions, it may happen that the two right-handed σ-components coincide and the left-handed components become separated by a distance more than double the Zeeman splitting. According to Babcock's estimates[144], the relative velocity of the regions need be only ≈10 km/sec for field intensities +4400 and −4400 G (star HD 71866). A similar explanation, if it is valid, would account for the strong inhomogeneity of stellar m.f.'s. Stars of the β and γ groups have, in general, lower variation amplitudes and usually do not exhibit changes in their spectra or the crossover effect. Typical field variations for these types of star are shown in Fig. 28. The average

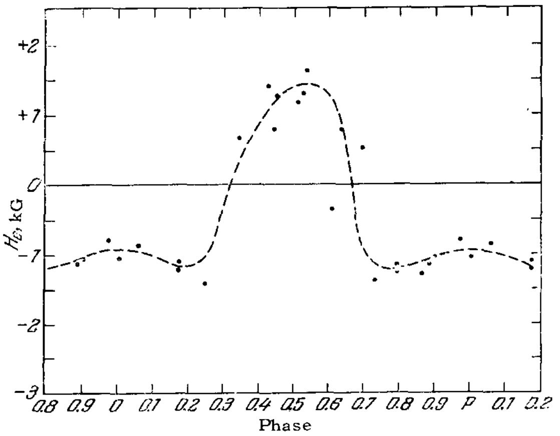

FIG. 27. Fluctuations of the field intensity for a typical star of the α-group: α^2 C Vn.

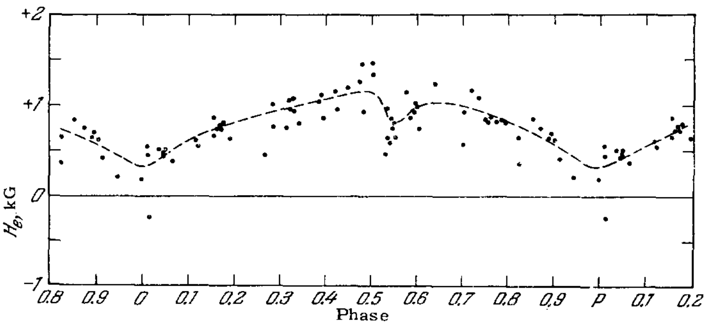

FIG. 28. Example of field fluctuations typical of groups β and γ (star HD 188041).

amplitude for the α-group is about 4000 G, for the β-group 1935 G, and for the γ-group 1140 G. The strongest field variations are observed in the earlier subclasses A_{0p}-A_{2p}. There is a possible tendency for the field fluctuations to slow down on going over to the later spectral classes.

The magnetic-variable stars also exhibit variations in their spectra. In the majority of stars of the α-group, these variations are periodic and synchronous with the field variations. The stars with irregular field variations (β- and γ-groups) do not exhibit variations in their spectra. However, a small δ-group has been found exhibiting irregular variations in the spectrum which are not associated with magnetic fluctuations. It is interesting to note the asymmetry of the K-lines of the Ca II ion, λ3933, observed in a number of magnetic stars (the asymmetry is in the form of a sharp edge on the red side), which indicates ejection of clouds or streams from the chromospheres of these stars. The α^2 Can Ven star and other magnetic hot stars exhibit, in addition to the anomalies in their chemical composition, variations in their chemical composition: a group of rare-earth lines (Eu I, etc.) and a group of metals (such as Cr) both exhibit periodic variations of the intensity and velocity in antiphase with each other but in synchronism with the field variations. At the same time, the iron and magnesium lines exhibit no fluctuations. It was shown in [143] that these fluctuations cannot be ascribed simply to changes in physical conditions. Therefore, it was suggested [143] that the anomalous abundances of the elements and the abundance fluctuations in magnetic A-stars result from nuclear reactions on stellar surfaces [145] produced by collisions of high-energy ions, accelerated in rapidly varying m.f.'s. On the other hand, the hypothesis of nuclear reactions [145] is incapable of explaining the exceptional abundance of europium, which is so characteristic of many magnetic stars. It is possible that in magnetic stars there is, in addition to the nuclear reaction mechanism, a mechanism of element separation, which may be associated with different diamagnetic forces acting on ions of different types and in different stages of excitation.

The theory of stellar magnetism faces two problems: one concerns the origin of magnetic fields and the other the nature of their fluctuations.

The simplest assumption that the magnetism of stars is due to their rotation has been found to be untenable. In fact, the rotation could give rise to a field if the separation between electrons and heavy ions (which would concentrate the former at the surface and the latter in the interior of a star) were considerable. However, such a separation is so negligible that the fields due to this effect would be less than 10^{-13} G.[146] Rapid rotation of ferromagnets also gives rise to a magnetic moment, but the stellar plasma does not have ferromagnetic properties. Attempts to associate the magnetic moment with the angular momentum by new "fundamental" laws of physics [138, 139, 147] have been disproved by experiment [148, 149] moreover, the magnetic moments of astronomical bodies are known to vary.

The enormous characteristic sizes of astronomical bodies tend to make the decay of magnetic fields extremely slow: for inner layers, the lifetime of the magnetic fields is comparable with the evolution periods (up to 10^{10} years), which suggests that these fields are due to events in the distant past and that they have been retained since the creation of the stars. The possibility of the generation of a field of $\approx 10^3$ G when a star condenses from interstellar matter was considered, for example, in [41]. However, the decay of a field can be strongly accelerated by convection and turbulence if a star passes through a convective phase in its evolution. The steady-state convection may simply transform a magnetic "filament" into a "filament" plus a "doughnut" without any marked dissipation.[150] The hypothesis of "intrinsic" magnetism also meets with difficulties when we consider the unusually rapid variations of the fields, including polarity reversal, in magnetic-variable stars. On the other hand, if we assume that the emergence of a field at the surface of a star is associated with a convective zone whose temperature is 10^5—10^6°K and whose characteristic dimension is $\approx 10^5$ km, we find that the decay time of magnetic fields of stars of the later classes is from 10^7 to 5×10^8 years, which is close to the age of old galactic star clusters (Hyades, etc.).[151] This is in agreement with the observations[152] indicating that the emission intensity of the H and K lines in the later stars of the main sequence decreases as the stellar age increases (if we assume that the fields and the formations emitting the K line are closely related, as in the case of the Sun; cf. Sec. 2).

A different point of view is based on the fact that electrons diffuse much faster from high-pressure regions than ions. Such a pressure effect gives rise to a current. In a spherically symmetrical star, this effect is negligible, since the separation of charge in such a star is practically impossible. The optimal conditions for the generation of a field in this way were considered in [153] and [154] but it was found that this effect did not give the necessary field magnitude or it required quite artificial assumptions.

Finally, a third possibility—"the self-excited dynamo theory"—explains the generation and maintenance of the field by currents which are induced in a star by the internal motion of the stellar plasma in m.f.'s. One example of such a mechanism, discussed in [155], is as follows: if matter at the center of a star flows toward the axis of rotation across the lines of force (the stellar field is assumed to be symmetrical with respect to the rotation axis), the direction of the currents about the axis is such as to maintain the field; however, if matter flows outwards at the poles, away from the axis of rotation, then the currents have the opposite direction; the currents at the center of a star are considerable because of the high conductivity. However, it was found[156,157] that this dynamo mechanism is impossible if the field and motion are axisymmetric: the whole effect of the motion reduces to a redistribution and displacement of the lines of force. In the case of asymmetric fields, we can find the types of motion which would increase the magnetic energy,[158,159] for example, the combination of nonuniform rotation and of the Coriolis acceleration with circulation (convection) which could be generated by thermal instability; [158] see also [160]. The dynamo mechanism is very effective, if it can be realized at all. Attempts to prove the dynamo effect for a completely disordered (turbulent) motion cannot be regarded as conclusive, especially if we bear in mind coherent large-scale forces (cf. [150]).

It is even more difficult to explain the variations of m.f.'s of the Sun and stars. The obvious explanation of the periodic variations by the rotation of an inclined dipole or some other stationary field oriented asymmetrically with respect to the axis of rotation (the inclined rotator hypothesis) was considered in [161]. According to this hypothesis, m.f.'s of stars are constant and the variations are due to their rotation: in the case of a dipole, the N and S poles periodically appear and disappear due to the inclination of the magnetic axis to the rotation axis. A harmonic analysis of field variations and line intensities, carried out in [161], gave distributions of the excited atoms and m.f. on the surface which were difficult to reconcile with observations. For example, using this theory it is difficult to understand why the Eu II atoms in α^2 Can Ven are concentrated at the South Pole and the Cr atoms at the North Pole, while in a similar star, HD 125248, these elements are concentrated in the opposite way.[41] Moreover, it is found that the rotation of magnetic stars (judging by the width of the "nonmagnetic" lines) is much faster than would follow from the period of magnetic fluctuations. It is also found that excessively large inclinations of the magnetic axis to the rotation axis are necessary to obtain a marked effect.[150] On the other hand, since the lines of force are almost completely frozen into the stellar plasma one would not expect any marked changes in the mutual positions of force lines with respect to the stellar surface during the period of a magnetic fluctuation. Therefore, if we exclude transfer of the lines of force from one hemisphere to the other by rotation, we have to assume that the stellar surface oscillates and that the lines of force oscillate together with the surface, exhibiting different "aspects" to the observer. In [162], it was assumed that a star is observed facing almost exactly one of its poles and that it oscillates between the shapes of prolate and oblate spheroids; the main effect is then not a change in the ellipticity but a horizontal motion toward and away from the poles. This theory cannot, however, explain the polarity reversal or the appearance of a principal oscillation with a period close to that observed.

The 22-year magnetic cycle of the Sun (cf. Sec 2) suggests the possibility of similar variations of m.f.'s in other stars, but with much shorter (by a factor of about 1000) periods. Figure 9 shows that the general polar field of the Sun disappears at the maximum activity epoch, when the strongest fields appear at the equator, i.e., when the toroidal component of the m.f. is strongest. The theory described in Sec. 2[51] predicts that an initially dipole poloidal field may be transformed into a toroidal field. The theoretical possibility of such oscillations between these two types of field was discussed in [163,164]: nonuniform rotation in the presence of a poloidal field produces a toroidal component; tubes of lines of force of the toroidal field rise upward and are twisted by the Coriolis force to form loops in meridional planes which, having the same direction of circulation and being additive, form again a poloidal field, etc. (a type of feedback mechanism). The migration of the toroidal field regions and their interaction with the polar field may be the cause of the destruction of the initial field and the appearance of a field of the opposite sign, as indicated by the periodic displacement of the sunspot zone toward the poles of the Sun. However, while there is evidence for the toroidal field at the equator, there is no evidence for a coherent poloidal field; on the contrary, the polar field consists of many elements of different sign (Sec. 2) and even the statistical average field is unlike a dipole field; moreover, the m.f. frequently disappears altogether at a pole, and sometimes both poles have the same sign. Furthermore, apart from the difficulties from the energy point of view, which were mentioned in Sec. 2, it is difficult to explain the N—S and S—N field reversals at the poles by a simple model of fields of opposite signs, due to the proposed migration of the toroidal field, because: 1) the time for migration is long; 2) the diffusion time for two opposite fields in contact can hardly be less than 100 years if the dimensions are of the stellar order.[150] In fact, the neutralization of fields in stars, if it does take place, takes several days, which would require a rate of migration of matter of about 1000 km/sec or more and concentrations of very strong fields in elements having dimensions of the order of 100 km. The fine structure of solar fields, referred to in Secs. 2 and 3, suggests that similar fine structure may be found in stars and this would make it very much easier to interpret such very rapid field variations.

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