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DYNAMICS OF THE SOLAR ATMOSPHERE

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INTRODUCTION

THE energy in a star is evolved by thermonuclear reactions in the core and it leaks out in the form of quanta of gradually decreasing frequency. However, stars are not dead globes; they do not just emit thermal energy. Some stars pulsate; in cold stars, complex changes take place, gas is set in motion, and the conditions in their atmospheres differ strongly from thermodynamic equilibrium. Sometimes, shock waves are observed which eject the stellar envelope material. Some stars have strong magnetic fields, which are usually variable, and the field variations are associated with changes in other parameters including the chemical composition. Our Sun is a quiet star and, at large distances, it would be difficult to notice any changes in it. A. Eddington once said: "There is nothing simpler than a star." However, studies of our nearest star—the Sun—have shown that it has a complex existence, that numerous effects take place in it, and that the number of such effects known to us increases as new observational methods are introduced; many of these effects are still not accounted for theoretically.

On the surface of the Sun—in the photosphere—vertical small-scale motion is observed with a clearly defined period. Moreover, horizontal motion is observed in large-scale cells. Meridional circulation and differential rotation—the increase in the angular rate of rotation as one approaches the solar equator—are motions on an even larger scale. These photospheric motions generate waves which are propagated upward and are dissipated. Although the energy flux of the waves represents only about 10^{-4} of the solar radiation, and not more than 10% of this flux reaches the upper layers of the chromosphere, even such a relatively small amount of the energy causes a strong deviation from local thermodynamic equilibrium in the upper layers. I. S. Shklovskiĭ has shown that these upper layers emit little because of their low density and therefore even small dissipation of the mechanical energy can shift them to a high temperature which, in the upper chromosphere, is measured in terms of tens of thousands of degrees, and in the corona it exceeds 1 000 000°. Because of their high temperature, these layers emit, in the ultraviolet and x-ray regions of the spectrum which are responsible for the terrestrial ionosphere, much more energy than the photosphere although the total radiation of these transparent rarefied layers represents only 10^{-5} of the total solar radiation. In the radiowave region, particularly at meter wavelengths, the radiation is also affected by the corona. The heating of the corona leads, moreover, to the appearance of the solar wind, which is a flow of gas at the rate of 500 km/sec. This solar wind and its variation, as well as the occasional appearance on the Sun of hard particles with energies up to hundreds of MeV, are closely associated with the radiation belts and other phenomena observed in the vicinity of the Earth. Moreover, the magnetic fields carried by the solar wind cause variations of the cosmic rays and prevent the penetration of the soft cosmic rays into the solar system.

Departures from thermodynamic equilibrium conditions in the upper layers of the solar atmosphere are associated with the fact that not only the thermal but also the mechanical energy flows upward from the photosphere. Consequently, the Sun should act as a heat engine, converting its radiation energy into kinetic energy. The source of the mechanical energy in the Sun is the convective motion in a thick layer extending from the photosphere to a depth of 0.2—0.3 solar radii. This convection takes place in a zone where hydrogen or helium is partially ionized. The result is a series of levels, each of which is manifest in various types of motion. The convection, and the differential rotation supported by the convection, generate magnetic fields and these fields are of a cyclic nature with a period of 22 years. Thus, the Sun also acts as a dynamo. The emergence of the fields on the surface of the Sun affects the motion, decreases the magnetic viscosity, increases the velocities, enhances the generation of waves and the heating of the corona, and intensifies the solar wind. In sunspots, the fields become so strong that they suppress convection, reduce the energy transport and lower the photosphere temperature. In some cases, strong complex fields cause discharges and chromospheric flares in which cosmic rays and x-ray radiation are produced, and a shock wave is generated which ejects gas streamers at velocities higher than 1000 km/sec. This gives rise to a number of effects on the Earth and its vicinity.

Investigations of solar phenoma lead us to a better understanding of the more powerful phenomena taking place on a much larger scale in nonstationary and magnetic stars, which cannot be observed in as great detail as the Sun. The solar and stellar phenomena have much in common and they should be studied simultaneously.

In the last few years, much new qualitative information has been gathered on the various types of motion, some of which have been interpreted theoretically. In the present review, we shall consider the convective motion and its effects on the surface (Sec. 1), the differential rotation and the meridional circulation (Sec. 2), magnetic fields (Sec. 3), waves in the solar atmosphere (Sec. 4), and the phenomena in active regions associated with magnetic fields (Sec. 5).

1. CONVECTION AND THE MOTIONS ASSOCIATED WITH IT

The main mechanism which converts some of the solar radiation energy into mechanical energy is convection. The convective instability appears in layers in which hydrogen is partially ionized. For these layers, the adiabatic exponent is

$$\gamma = \left(\frac{d \ln p}{d \ln \varrho}\right)_S \approx 1,$$

because when an element is compressed, the energy is used not so much to raise the temperature as to ionize the hydrogen. At the same time, the absorption coefficient of partially ionized hydrogen is large. Therefore, the radiative logarithmic gradient is greater than the adiabatic exponent:

$$\nabla \equiv \frac{d \ln T}{d \ln p} > \nabla_S \equiv \left(\frac{d \ln T}{d \ln p}\right)_S \equiv \frac{\gamma - 1}{\gamma}, \tag{1}$$

or $\gamma_r > \gamma$, and convection should take place. The theory of the convective zone is based on the following main ideas.[1-3] It is assumed that an element of gas is transported, by the convective motion, a distance L, which is of the order of the height of a uniform atmosphere, and then the element mixes with the surrounding medium. The velocity V of an element is governed by the work done by the convective lifting force in a column L, and it is assumed that about half the energy is lost in turbulent friction, because the Reynolds number of the convective cells is very high. The lifting force depends on the temperature difference $T' - T \sim \nabla' - \nabla$, where the gradient ∇' in the element differs from ∇_S because of the radiative thermal conductivity. The same temperature difference governs the convective energy transfer which, together with the radiative flux, is equal to the total flux from the surface of the Sun. The solution of this system gives a model of the convective zone.

The thickness of this zone, allowing for the ionization of helium, is of the order of $0.3R_\odot$.[4] The velocity of motion in the upper thin layer reaches 2km/sec and decreases in the downward direction approximately as $\rho^{-1/3}$. The distribution of the specific entropy of the gas with depth[1] is shown in Fig. 1.* In

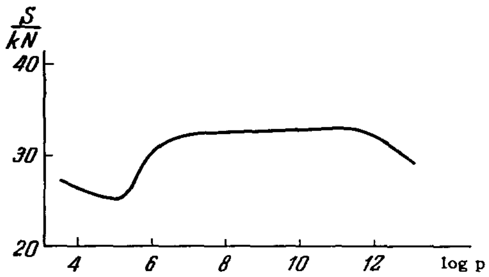

FIG. 1

the main part of the zone, the specific entropy is constant, and the energy transport is by convection, the radiation playing a negligible role. In the upper layers of the convective zone, approximately 400 km thick, the entropy decreases since some of the energy is carried away by radiation. In these layers, the convective instability is particularly strong and, therefore, the rate of convection has its maximum value. In layers lying still further away, the convective transport process is unimportant because here the energy exchange between an element and the surrounding medium is large because of the lower absorption coefficient. This energy exchange is difficult to calculate because it depends strongly on the convective element parameters. According to an estimate given in[1], it represents 2–5% of the total flux in the photosphere. This indeterminacy has little effect on the structure of the upper layers. There, the temperature is governed by the radiative transfer and the specific entropy increases in the upward direction. The visible part of the photosphere represents this particular level; the upper part of the convective zone is not directly visible. The layer where entropy arises is convectively stable, i.e., no motion should take place in it. However, a rising convective element, formed in the unstable zone, will be hotter than the surrounding medium and it will rise even when it finds itself within the stable zone. It is represented in Fig. 1 by a point moving almost horizontally with a downward slope due to the de-excitation. The lifting force acts on this element until its path intersects the curve representing the limit of the stable region. Then, it still continues to move by inertia, but the temperature difference, which is small because of the radiative transfer, now has the opposite sign. A specific entropy minimum explains why the granules observed in the stable region and moving upward have, nevertheless, a higher temperature. In the upper layers, the correlation between the velocity and brightness has, according to some data, the opposite sign, i.e., the rising elements are colder than the surrounding medium.

The granules are not convective cells. However, it can be assumed that their dimensions and some other parameters reflect the parameters of cells in the upper layer of the convective zone. The observations of the granulation are difficult because of the

*The depth of 1000 km corresponds to log p ≈ 6, and 100 000 km to log p ≈ 11.5.

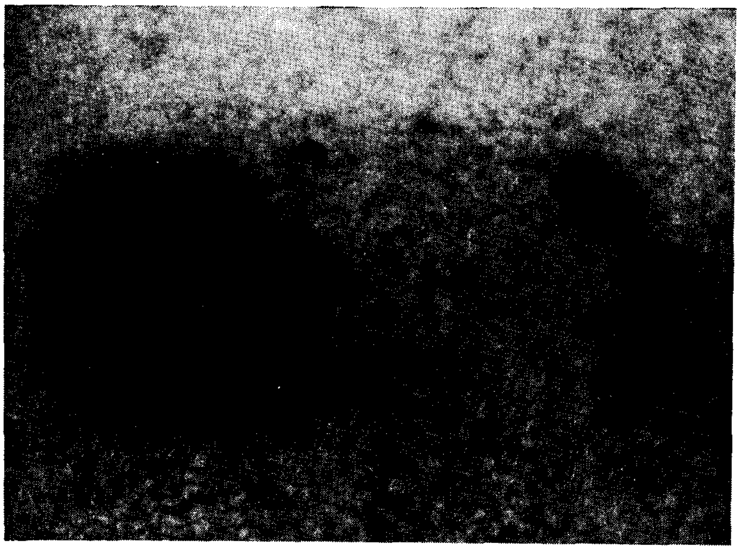

FIG. 2

influence of the terrestrial atmosphere. Using special apparatus, which suppresses the convection inside a telescope, and employing periods of good atmospheric conditions, as well as telescopes borne into the stratosphere, it has been possible to obtain good photographs of the granulation which resolved 0.4″, i.e., 300 km on the surface of the Sun (Fig. 2). It is clear from these photographs that the granules are irregular polygons of various dimensions separated by finer dark spaces. Their average dimensions are 700 km, and the distance between cells is ≈ 2000 km; their lifetime is 8–10 minutes. During this period the granules change their form, grow, and frequently split up. The granules are about 500° hotter than their background and a noticeable contrast is observed in the upper layers to an optical depth $\tau \approx 0.3$. As a rule, the bright granules rise upward.

The granule dimensions correspond approximately to the expected dimensions of convective cells formed in a layer about 200 km high. Their irregular form and short lifetime, during which the gas in a cell is capable of rotating only once, indicate the non-stationary but not fully turbulent nature of the convection. This means that the Rayleigh number, calculated making allowance for the turbulent viscosity, exceeds the critical value by not too large an amount. In such convection, the horizontal cell dimensions may be 5–10 times greater than their thickness.

In a convective element, the matter at the center rises, spreads outward toward the edges, and then sinks. Since the granules are not convective elements, the nature of the motion in them may be different. Observations carried out using a new sensitive method have shown an unexpected feature of the velocity field in the upper photosphere and in the lower layers of the chromosphere.[5,6,3] It was found that there was practically no horizontal small-scale motion. After its appearance, a bright granule began to move upward at the rate of 0.3–0.4 km/sec. The maximum velocity was reached about 40 sec after reaching the maximum brightness,[6] i.e., this velocity was reached in the upper layers. There was a direct correlation between the additional brightness and the value of the velocity. This could have been due to the fact that the bright elements, having a larger entropy and being acted upon by stronger lifting forces, acquired higher velocities, and produced a greater impact on the upper layers.

The characteristic feature of the vertical velocities is their periodic nature.[3,7] After 2.5 min from the first observation, the velocity pattern is usually repeated but with an opposite sign of the velocity and much smaller contrast for the same elements. After a further 2.5 min, the pattern returns to its initial form. The period in the upper photosphere is very definite and equal to 296 ± 3 sec. After 2–4 oscillations, the correlation disappears completely. The dimensions of the oscillating elements are greater than those of the granules—they reach thousands of km. Obviously, this is the result of the interference of perturbations due to several granules.

Quantitatively, the process is described by the correlation function[7]

$$C(\tau)=\frac{\iint v(r,\ t+\tau)\, v(r,\ t)\, d^2r}{\iint v^2(r,\ t)\, d^2r}. \tag{2}$$

This function may be approximated by the expression

$$C(\tau)\approx e^{-\frac{\tau}{342}}\cos\frac{2\pi\tau}{300}. \tag{3}$$

The parameters of the oscillations at various levels can be found by determining the radial velocities from the spectral lines of various intensities formed at different depths. The oscillations take place not only in the upper photosphere but also in the chromosphere right into the middle layers of the latter.[7] The oscillation period decreases somewhat with height; for example, the core of the yellow Na line, which is formed in the lower chromosphere, indicates that the period is 286 sec, while the Ca II 3934 Å line, formed in the middle chromosphere, indicates 175 sec. The velocity amplitude increases with height. For example, in the middle chromosphere (core of the H_α line) the oscillation velocity is 1.6 km/sec. The dimensions of the elements also increase somewhat with height.

The oscillatory motion indicates that the layer in which the oscillations take place has a natural frequency. Even in an isothermal atmosphere, free oscillations may take place with a period [8]

$$P \doteq \frac{2\pi\zeta}{V_s}, \tag{4}$$

where ζ is the scale height, and V_S is the velocity of sound. In the photosphere, the temperature decreases as the height increases and the opposite applies in the chromosphere. Therefore, in the upper layers of the photosphere and in the lower layers of the chromosphere, the velocity of sound has its minimum value; in that region the sound should suffer refraction and reflection at the boundaries and stable oscillations may take place. The period of these oscillations should be of the order of 5 min. However, this hypothesis does not explain why oscillations are observed in the middle chromosphere and it does not allow for the large difference between the densities in the photosphere and chromosphere.

A different hypothesis, which seems more likely to be true, is based on the large differences between the densities of the photosphere, chromosphere, and corona.[9] The oscillating layer is assumed to be the chromosphere, bounded from below by an apparently solid surface, and having an almost free boundary at the top. The gas motion is assumed to be isothermal, since oscillations have a fairly long period. The equation of motion allows also for the gravitational force. The solution is sought in the form of a standing wave of complex frequency and a displacement amplitude ζ, depending on z. The equation for the amplitude has the form

$$V_s^2 \frac{d^2\zeta}{dz^2} - g\frac{d\zeta}{dz} + \omega^2\zeta = 0. \tag{5}$$

The amplitude increases with height because of the influence of the gravitational force (second term). To solve this equation, it is necessary to specify $V_S(z)$ and the boundary conditions which give rise to standing waves of the required period. Bahng and Schwarzschild [9] considered three models. In one, the temperature of the photosphere was assumed to be constant and equal to 6000°, while that of the chromosphere was taken to be rising linearly from this value upward. The characteristic equation was obtained by matching the solutions at the boundaries of the layers. It was found that a gradual transition from the photosphere to the chromosphere could not explain the observed oscillations.

In a second model, it was assumed that the chromosphere was an isothermal layer having a temperature T_2 and a density differing sharply from the densities of the photosphere and the corona. For solutions with a period of 5 min to exist, the temperature of the photosphere should be $T_1 < 6000°$, while that of the corona (or the temperature of the upper chromosphere) should be $T_3 > 100\,000°$. The solution gave, for various T_3, the dependence of the thickness of the chromosphere on T_2 for which the period had the required value. When T_2 was varied from 8000 to 30 000°, the thickness varied from 1200 to 1700 km, which represented roughly the lower part of the chromosphere. The temperature of these layers was, in fact, less than 8000°. The oscillation amplitude increased with height, reaching its maximum at the upper boundary.

In a third model, it was assumed that there was a gradual transition from the chromosphere to the corona, i.e., the temperature rose linearly in the upper region from the value T_2. Here again, oscillations were possible and the most favorable temperature of the chromosphere for these oscillations was about 6600°. Thus, in a rough approximation, it was shown that standing waves could exist in the chromosphere if the chromosphere differed sufficiently from the photosphere. Since the scale height in the upper photosphere was small, this assumption seemed plausible. It has not yet been possible to obtain a solution for a real model. However, even the model of the chromosphere has not yet been established convincingly.

Apart from the aforementioned vertical motion, observations have revealed a horizontal motion of the large-scale cellular structure. The gas flows at a velocity of 0.3—0.5 km/sec from the center of a cell to its periphery.[5,7] The cells resemble the convective cells but their dimensions are from 20 000 to 50 000 km, i.e., they are larger by a factor of several tens than the granules, and their lifetimes are about one day. Therefore, they have been called supergranules. In an atmosphere whose thickness is considerably greater than the scale height, the convection should split up into layers, each of which should have a thickness close to the scale height at a given level.[10] The supergranules are cells lying below those which give rise to the conventional granulation. Their thickness should be 3000—8000 km. In a polytropic atmosphere, the scale height is approximately equal to half the distance from the surface. The convective zone is almost isentropic, and in its upper layers this ratio is, according to the model, equal to 0.8. Consequently, the basis of the supergranular cells lie at a depth of 4000—10 000 km.[11] At this depth, the rate of convection is several hundred m/sec, so that during its lifetime the gas in a cell is able to rotate about once. Below the supergranules there should be a layer of still larger cells, and so on, right down to the bottom of the convective zone.

The cellular structure appears not only in the motion. Over the whole solar surface there is a magnetic

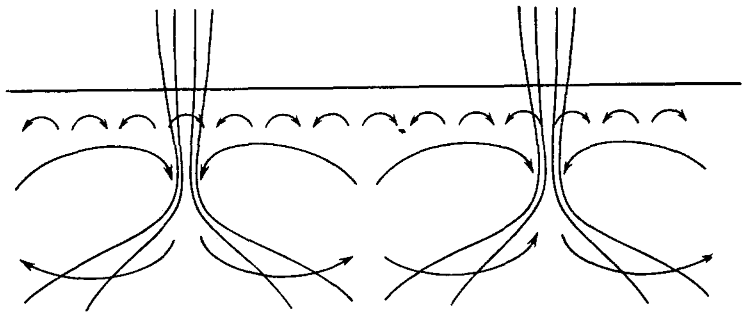

FIG. 3

field of 0.3—1 Oe average intensity in the unperturbed regions and of 5—50 Oe intensity in the active regions. High-resolution observations have shown that this field has a fine structure.[12-14] The field intensity varies considerably over short distances, sometimes even distances of 1000 km. The field structure associated with the supergranules was the first to be investigated. The field is enhanced to an intensity of tens of oersteds in a thin layer along the periphery of a cell, while in the interior of the cell the field intensity is considerably less or even zero, within the limits of the experimental error.[7,11] Since the field is frozen into the gas, the lines of force naturally move together with the gas and are denser at the cell peripheries.

The mechanism of the transfer of motion from the supergranular cells lying at greater depths to the photosphere may be associated with magnetic fields.[15] The lines of force dragged by the gas flowing from the center of a cell become compressed at the periphery and, in tending to straighten again, they set in motion the surface layers, making them repeat the motion of the lower layers with a phase lag. In other words, a wave, similar to the Alfvén wave, is propagated outwards and tends to compress the lines of force (Fig. 3). If the reflection and damping are weak, the amplitude of the wave propagated upwards increases because of a reduction in the density. However, we can show that, in such a case, the wavelength with a period of about one day is comparable with or greater than the scale height. The energy flow is then not conserved, but the velocity amplitude remains approximately constant.[16] This agrees with the fact that the observed velocity of the horizontal motion is approximately equal to the calculated convective velocity.

The horizontal motion should compress the gas at the cell peripheries. However, this presents no great resistance to the motion because here the main part of the atmosphere is convectively unstable and the compressed gas sinks downward without energy loss. Thus, the magnetic forces favor the translation of the large-scale convection to the upper layers.

According to a different point of view,[17,11] the observed motion is simply the continuation of the supergranular motion, i.e., the large cells extend right up to the visible photosphere and the small-scale convection and granulation are generated against a background of large-scale motion. Then, the lines of force are passively dragged toward the cell boundaries. Since there is, as yet, no theory of convection in a thick atmosphere, it is difficult to decide between these possibilities. The viscosity of the solar atmosphere, due to the small-scale convection and granulation elements, is sufficiently high for the upper layers to repeat the motion of the lower layers without any magnetic forces, although such forces act in the same sense as the viscosity. However, in the active regions, the fields reach 100 Oe. Then the magnetic energy is greater than the kinetic energy of the horizontal motion in the photosphere. Obviously, the field then plays an active role; otherwise, the magnetic pressure would have prevented compression. It is most likely that both factors—the viscosity and the magnetic forces—act simultaneously.

The relatively uniform nature of the supergranules presents a new problem in the theory of solar convection. We have stated that the convection should take place in layers of cells. However, this statement followed directly from the fact that there could not exist a cell in which the density would fall rapidly since the velocity of the main flow and of the perturbations would, in such a case, increase as the height increased and the motion would be unstable. However, the supergranulation shows that there are well-defined layers with approximately the same cell height. The convection theory cannot yet explain the reason for this situation.

Under the supergranules, there should be another layer of cells in which the gas velocity should be less than 0.1 km/sec. Their presence can, in principle, be detected by an investigation of the statistical properties of the supergranules. In fact, the lower cells should have some dispersion in their thickness. Above a thicker cell, the supergranules should lie higher and should therefore have smaller dimensions than those above a thinner cell. In this connection, it is interesting that in the active region the network has a somewhat different structure from that in the inactive parts of the Sun. However, a special investigation is needed to draw definite conclusions.

Convection is an effective method of mixing a substance. Therefore, we may expect the convective zone to have a relatively uniform chemical composition. On the other hand, the mixing between the convective and stable zones should be slight. At the same time, the low content of Li in the solar atmosphere indicates that a considerable fraction of the gas in the convective zone has passed through deeper layers with temperatures $T \approx (3-4) \times 10^6$ °K, sufficient to burn out Li. The general circulation of matter in the Sun, as shown in the next section, is not very effective. In this connection it is interesting to note that individual convective elements, particularly those having large horizontal dimensions, can penetrate to the base of the convective zone and pass into the stable layer.[18]

Apart from the layered structure, convection in the Sun differs from laboratory convection in two respects: the important role played by radiation and the presence of magnetic fields. In the presence of radiation the convective instability criterion, given by Eq. (1), has to be calculated sometimes for elements which rise nonadiabatically.[19] This may change the result, particularly in the case of the upper layers. The magnetic field may also change the stability criterion, making convection more difficult. The correction to γ_r is approximately equal to the ratio of the magnetic and gas pressures at the base of the convective zone.[20] In the case of the Sun, it is unimportant but it may feature in magnetic stars. The magnetic field, as already mentioned, may affect the convection indirectly, through a change in the turbulence. However, there is as yet no exact theory of convective turbulence. Investigations of this turbulence in the nonmagnetic[21] and magnetic[22] cases are based on semi-empirical equations which are only rough approximations.

2. ROTATION OF THE SUN AND MERIDIONAL CIRCULATION

Apart from the motion associated directly with convection, regular movements are observed on the Sun extending over a considerable part of its surface. These movements are the differential rotation and the meridional circulation. The differential rotation is represented by a dependence of the angular velocity of the surface layers on the latitude φ approximately in accordance with the law

$$\Omega = 2.9 \cdot 10^{-6} - 0.56 \cdot 10^{-6} \sin^2 \varphi. \qquad (6)$$

The meridional circulation is manifested by a slow drift of long-lived high-latitude ($\varphi > 30°$) quiet prominences and some other features, for example, the polar "plumes" in the corona, all moving toward the poles. The boundary separating magnetic fields of opposite polarities drifts in the same way. The motion from middle latitudes to the pole takes about 6—7 years, so that the circulation velocity is about 3 m/sec. Changes in the sunspot latitude during a cycle indicate that at low latitudes ($\varphi < 30°$) the circulation is directed toward the Equator.

One of the causes of the meridional circulation may be the spheroidal shape of the rotating Sun, giving rise to rotation of a baroclinic nature. The condition of hydrostatic equilibrium requires that the density and pressure, and consequently the temperature, should be constant on equipotential surfaces, which include the centrifugal force potential. At the same time, the temperature is governed by the diffusion of radiation. Along the short axis, the radiation flux is relatively stronger so that on the same equipotential surface the polar regions are hotter than the equatorial regions. Circulation from the poles to the equator appears, with flow paths closed in the inner layers.

The velocity of this circulation is determined as follows (cf., for example,[23]). The form of the equipotential surfaces is governed by the law of rotation and is independent of the slow circulation. Its equation has the form

$$r = \bar{r}\,[1 + c_2(\bar{r})\,P_2(\theta)], \qquad (7)$$

where $\bar{r}$ is the average radius of an equipotential surface, θ is the angle between the radius vector and the axis of rotation, P_2 is a Legendre polynomial of the second degree, $c_2(\bar{r})$ is a deformation function, governed by a second-order differential equation, including the rotation law. The equilibrium condition gives, approximately, the temperature distribution along the radius as some function of the density. For this distribution, the divergence of the radiant energy flux is somewhat different from zero and it has different signs at the poles and at the equator. The circulation velocity is governed by the condition that it should compensate the inconstancy of the flux, i.e., that the divergence of the convective flux of heat should differ only in sign from the divergence of the radiant flux. Finally, the circulation velocity is given by

$$V = \frac{\Omega^2 R}{g}\,\frac{L_*}{Mg}\,v^*\left(\frac{\bar{r}}{R}\right) P_2(\theta). \qquad (8)$$

Here, L_* is the brightness of a star, R and M are the radius and mass of a star, v^* is a dimensionless function depending on c_2, the density distribution, and the polytropic index. In the case of rigid rotation, the value of this function increases from the center to the surface, approximately from 0.1 to 6. Substituting the parameters of the Sun into Eq. (8), we obtain $V \approx 10^{-9}$ cm/sec.

This means that the time of mixing is longer than the age of the Sun, i.e., such circulation has no cosmological meaning.

Apart from the circulation due to the baroclinic nature of the rotation, there may be circulation due to the fact that the curl of the inertial acceleration may not be equal to zero in some part of a rotating star. In a rigidly rotating star and, in general, if Ω depends only on the distance from the axis, this curl is equal to zero. Under steady-state conditions, the rotation will be rigid if the transfer of the angular momentum takes place through the viscosity or some other isotropic process, described by a scalar coefficient. If the process of momentum transfer is not isotropic and is described by a "viscous" tensor with unequal diagonal components, then the steady-state rotation has a non-uniform angular velocity. For example, if the transfer of the momentum is only one-dimensional, i.e., radial, the specific angular momentum $r^2\Omega \sin\theta$ of moving elements will be conserved and so will the angular velocity $\Omega \sim r^{-2}$.*

The radiation flux transfers the momentum anisotropically. However, under solar conditions, its effect is slight. Much more important is the convection. The lifting force acts on a gas only in the vertical direction and, therefore, the convective motions are not isotropic: they transfer the momentum predominantly in the radial direction.[24] This should reduce the angular velocity as the height is increased. In spherical coordinates, the nondiagonal components of the viscosity tensor η^i_k are equal to zero, and the diagonal components can be written in the form

$$\eta^r_r = \eta = \varrho l v_t, \qquad \eta^\theta_\theta = \eta^\varphi_\varphi = s\eta, \tag{9}$$

where s is an anisotropy parameter, governed in our model by the condition $0 \le s \le 1$. In the case of pure rotation, the motion of a given layer is governed by the equation[25]

$$\frac{\partial}{\partial r}\left(r^4\eta\frac{\partial\Omega}{\partial r}\right) - 2(s-1)\frac{\partial}{\partial r}(r^3\eta\Omega) = 0, \tag{10}$$

whose solution, when the angular momentum does not cross the boundary of the convective zone, has the form

$$\Omega = \Omega_0 r^{-2(1-s)} \qquad (\Omega_0 = \mathrm{const}). \tag{11}$$

When $s = 1$, we have rigid rotation; for $s = 0$, we have $\Omega \sim r^{-2}$.

The reduction in the angular velocity in the upward direction makes the curl of the inertial acceleration vector at a latitude φ

$$\mathrm{rot}\,[\Omega\,[\Omega \mathbf{r}]] = 4(s-1)\,\mathbf{r}^{4s-2}\sin\varphi\cos\varphi \tag{12}^\dagger$$

not equal to zero when $s \neq 1$.

The gravitational acceleration is of the potential kind and it cannot compensate the vortical component. The acceleration due to the baroclinic nature of the rotation is vortical and acts in the opposite direction, but its influence, as can be seen from Eq. (8), is slight, except in the uppermost layers. Therefore, there appears a circulation, which is directed toward the equator at the base of the convective zone and toward the poles at the solar surface. Its velocity is governed by Eq. (12) and by the viscosity. The latter may be controlled by the convective motion, or, in the case of the fast circulation that generates turbulence, by the corresponding turbulent motion. A numerical calculation for the Sun and $s = 0.5$ gives, for the vertical circulation velocity, the value $V \approx 10^2$ cm/sec. The horizontal component of the velocity may be ten times as large.[25] Obviously, this circulation is responsible for the aforementioned drift of the high-latitude features toward the poles. In rapidly rotating hot stars with a thin convective zone, the velocity of the meridional drift may be several km/sec. The instability of such flow at high Reynolds numbers explains the strongly turbulent motion in atmospheres of such stars.[26]

The meridional circulation depends mainly on the variation of the angular velocity with height. The dependence of Ω on the latitude, for example, in the empirical law of the differential rotation, has less effect but it should still be allowed for. On the other hand, the circulation itself, transferring the angular momentum, makes the rotation nonuniform. Therefore, the steady-state solution requires some law of differential rotation.[27] Such a solution of the Navier-Stokes equation and the curl of this equation have been obtained for the convective zone by the method of successive approximations.[28] It was found that the circulation moving toward the poles at the surface gives rise to an increase in Ω with latitude, which is contrary to observations. In view of this, calculations have been made for $s > 1$, i.e., for those values of the viscosity which transfer the momentum mainly in the horizontal direction. In this case, the circulation at the surface should be directed toward the equator and the angular velocity should increase in this direction in qualitative agreement with observations. It was assumed in[28] that $s > 1$ was possible for convection because the laminar modes of the nonstationary convection corresponded mainly to the horizontal motion. To obtain numerical values, it is necessary to solve the same equations in the nonlinear approximation, which has not been done so far. Another possible explanation of the direction of the low-latitude circulation is that the circulation in one direction, taking place in deep layers, may through friction cause an opposite circulation in higher layers, as in the case of two mating gears. An opposite circulation should result in work being done against inertial forces. This hypothesis has not yet been tested quantitatively.[29]

In the stable zone of the Sun, where there is no convection and neither the meridional circulation nor the radiative flux is important, there are no agencies which would maintain the differential rotation. On the other hand, the dissipative processes are weak in that zone, so that the time for the establishment of the steady-state rigid rotation is longer than the age of the Sun, unless it is assumed that the inner layers rotate very rapidly. Therefore, the law of rotation of

*The properties of the anisotropic viscosity are, in some respects, very different from the conventional viscosity; the former is related in a more complex way to dissipation. In particular, the differential rotation (along the radius) transformed from uniform rotation implies an increase of the total energy of rotation for the same angular momentum.

†rot ≡ curl, $[\Omega\, \mathbf{r}] \equiv \Omega \times \mathbf{r}$.

the stable zone should obviously be governed by the initial conditions at the time when the Sun was formed and these layers ceased to be convective. However, if there is a magnetic field in the stable zone, the angular velocity of rotation under steady-state conditions should be constant along the lines of force. Such a law of rotation is known as "isorotation."[29,30] Since the transfer of the momentum from the stable to the convective zone is slight, the observed law of rotation of the surface layers is independent of the movements in the stable zone and is governed only by the conditions in the convective zone. Here again, it is assumed that the magnetic coupling between the stable and convective zones is unimportant. Since the observed "general" solar field changes its sign with the solar cycle, it is therefore associated not with the deep layers but with the convective zone, so that our assumption is justified. On the other hand, had there been a close coupling between the stable and convective zones, the dissipative processes in the convective zone would damp the differential rotation of the inner layers. Therefore, in all cases, there should be a process maintaining the velocity difference in the outer layers. The main source of the mechanical energy in the Sun is the convection, and, therefore, further investigations are needed on its influence in the presence of rotation, circulation and, possibly, magnetic fields. If the asymmetry of the viscosity tensor is insufficient, finer effects should be looked for.

3. MAGNETIC FIELDS ON THE SUN

Magnetic fields play an important role in the movements of the solar atmosphere. They were first discovered in sunspots, in which the magnetic field intensity is 2000—3000 Oe. Sunspots usually occur in groups, and a typical group contains two large sunspots of opposite polarity as well as a number of smaller sunspots. The leading sunspots in the northern hemisphere of the Sun have one polarity, while in the southern hemisphere these spots have the opposite polarity. The polarities are reversed in successive eleven-year cycles. Sunspots occur in bands parallel to the equator. The latitude of these bands during a cycle shifts from about 30° to 5—8°. More detailed investigations have shown[31] that there are two "waves" of activity: one concentrated in latitudes near 25°, and the other lagging three years in phase and concentrated at 15°. The simultaneous effect of these two "waves" gives rise to an apparent continuous motion of the sunspot zone toward the equator. The sunspot bands contain active regions with fields of 5 to 100 Oe intensity, usually around sunspots. In most cases, these regions are bipolar and the relative positions of the polarities are the same as for the sunspots.

An active region is characterized by a number of distinguishing features, which will be discussed below. The emergence of a field on the surface is preceded by an enhanced motion in the photosphere. During a week, a field of a typical active region becomes stronger and spreads to a greater area and the magnetic flux increases. At the same time, sunspots appear and the region becomes most active. During the next month, the area of the region continues to increase but the field intensity decreases, the activity becomes weaker, and the magnetic flux spreads out and remains approximately constant. Next, the region spreads out even further, one of the polarities practically disappears, and a unipolar region remains whose lines of force are closed in the neighboring regions of the photosphere. Such a unipolar region continues to spread out and disappears after several months.

Outside the active regions, there is a weaker field of average intensity 0.3—1 Oe, which covers practically the whole surface of the Sun. This field is somewhat stronger at polar latitudes, and in each hemisphere there is a dominant polarity concentrated in certain regions. This field is sometimes called the general field of the Sun since its nature resembles the dipole field of the Earth. The sign of the high-latitude field reverses at the period of maximum activity. In this respect, the Sun is similar to a magnetic star with a variable field.

As already mentioned, the magnetic field has a fine structure. In the unperturbed regions, the main element of the structure is an assembly of supergranular cells. The field is concentrated along the cell peripheries and forms a network. The active regions contain, apart from this network, some isolated "poles" which are regions of stronger field. Magnetic charts, particularly those obtained using high-resolution apparatus, are usually complex.[13,32,33] Regions of opposite polarity are frequently very close to one another. Even within the limits of the periphery of a single convective cell, in the same part of the network, we find lines of force of opposite directions.[14] Inside a cell, the field is sometimes opposite in direction to the field at the periphery.

The spreading of the active regions with time and the mixing of fields of various directions is explained by the supergranulation. The convective motions at the second level transport the lines of force across distances of the order of the cell radius. After the breakup of a cell, a new cell is formed and its center has a location which is random with respect to the center of the old cell. The same line of force is now transported some distance in a different direction. Thus, we have a form of two-dimensional diffusion of the lines of force, involving the diffusion coefficient[34]

$$D \approx \frac{1}{2} lV \approx \frac{1}{2}\cdot 10^9 \cdot 2\cdot 10^4 = 10^{13}\ \mathrm{cm}^2/\mathrm{sec}. \qquad (13)$$

The active regions diffuse in this way. The radius of a small region increases as $t^{1/2}$. As the dimensions increase, the differential rotation of the Sun begins to stretch a region in the longitudinal direction. Since the latitudes of the N- and S-polarities of a bipolar region are usually different, these polarities drift apart with time. The diffusion mixes the lines of force, which explains the structure of the field and the reversal of the sign over small distances. The presence of a field over the whole surface of the Sun may also be associated with the spreading of the active regions, since a given region should spread over a considerable part of the solar surface in $t \approx 5$ years. The reversal in the polarity of the lagging active regions at higher latitudes during a cycle should then change the sign of the "general" field with time, and the boundary between the polarities should move from middle to high latitudes due both to the diffusion and to the meridional circulation.

The supergranulation bunches the lines of force along the cell peripheries. Similarly, deeper cells should collect fields from a greater area and concentrate them into tubes with a relatively strong flux.[35] Such tubes may explain the strong fields of the sunspots in the active regions occupying a relatively small part of the solar surface. The emergence of the tubes on the surface is due to the fact that at equilibrium the total pressure - magnetic and gas - is constant. The presence of a field reduces the pressure and, consequently, the density of the gas; the Archimedes force appears.[36] This effect is important in the upper part of the convective zone since in the interior of this zone the magnetic pressure is considerably less than the gas pressure.

One of the principal problems of solar physics is the problem of the formation of fields in the active regions and their cyclic variations in magnitude and sign. Compression by the convective movements does not solve this problem since it simply redistributes the lines of force. The presence of active belts and the relative positions of the N- and S-parts of a bipolar region indicate that the field above the surface is toroidal and that its direction varies from cycle to cycle and is opposite in the two hemispheres. A toroidal field may be generated from a poloidal field (in which the lines of force lie in meridional planes) by the differential rotation. The field variation in a conducting medium is given by the equation

$$\frac{\partial \mathbf{H}}{\partial t} = \operatorname{rot}[\mathbf{VH}] + \nu_m \nabla^2 \mathbf{H}; \qquad (14)$$

H_φ may increase for a time if the magnetic viscosity ν_m has a sufficiently low value and the differential rotation is constant. However, the poloidal component does not increase but decreases exponentially and therefore H_φ also begins to decrease with time and tends to zero.

The formation of a field due to the motion of a conducting medium is called the dynamo process. It is investigated using Eq. (14); in the kinematic theories the motion is assumed to be given, while in the dynamic theories the influence of magnetic forces on the motion is allowed for. Simple two-dimensional or planar motion cannot maintain a steady-state field.[37,38] The motion must be basically three-dimensional, which makes it impossible to solve the problem in its general form; only certain special forms of motion can be considered and even they can only be treated qualitatively.

For the process of the twisting of a field to be stationary, it is necessary to maintain a poloidal field and to make good the dissipation due to the formation of a toroidal field. The toroidal field may be rotated, for example, by the Coriolis forces in the convective motion.[36] A rising stream pulls up a loop of the toroidal field and the Coriolis forces, which appear when the gas flows toward the axis of a cell, rotate the plane of the loop so that, under certain conditions, it may approach a meridional plane. Owing to dissipation, the loops may become separated from the main toroid and, merging, they may form a large poloidal field loop. The growth of the field is restricted by the feedback effect of the magnetic forces on the motion. Using variants of this idea, it is also possible to explain qualitatively the shift of the toroidal field toward the equator. To explain the polarity reversal, it is assumed in[36] that the fields at the surface and in the interior of the convective zone differs in sign. Theories relating the formation of the field to the rotation and convective motion have been developed in detail for the Earth[39-41] but it is still not clear whether these ideas can explain the more complex, varying field of the Sun.

The existence of feedback between the twisted toroidal field and the poloidal field means that the fields in the active regions form finally the "general" field of the Sun. This can explain also the change in sign of the general field, which-in turn-causes a change in sign of the twisted toroidal field. Such a hypothesis has been developed in[42]. It is assumed that the general field does not pass through the stable inner core of the Sun but is mainly located at the base of the convective zone. The toroidal field increases to a critical value at which it becomes sufficiently buoyant and emerges on the surface giving rise to the active regions in sunspots. At the same time, the field continues to grow at lower latitudes. Assuming an acceptable distribution of the field and latitudinal rotation, one can deduce the observed law of the active region shift. As indicated by observations, the motion in the active regions is such that the leading part shifts toward the equator and the lagging part, which has the opposite polarity, moves toward the poles. It is assumed that the motion continues also after an active region spreads so much that it is no longer observed. Consequently, the opposite fields of the "leaders" of two regions merge at the equator and disappear so that a large arc is produced coupling both hemispheres (Fig. 4). Owing to diffusion and meridional circulation, the bases of the arcs move

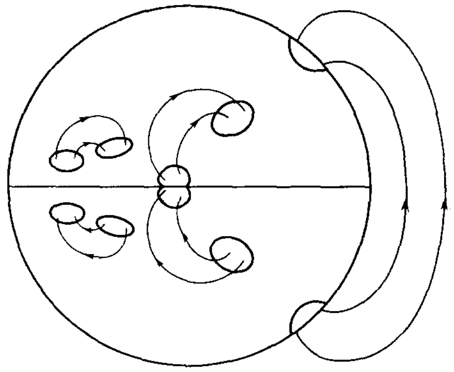

FIG. 4

toward higher latitudes and part of the general dipole field is formed. The arc initially extends to the "leader" of the next active region in the same hemisphere and the same longitude. When the leaders of these regions merge, the arc closes under the photosphere. The sign of the new dipole field differs from the previous field and the twisting process is repeated but in a different direction of the toroidal field. The hypothesis presented in [42] explains qualitatively the main features of the solar activity but it is still not fully developed. It does not explain the constancy of the period, the causes of the rotation of the active regions, and a number of other features. Another possible mechanism of the reversal of the sign of the toroidal field postulates torsional oscillations of the equatorial belt.[43,44] The sign of the differential rotation remains constant but its magnitude changes slightly so that oscillations take place with respect to some average system with which the lines of force are associated. At the edges of an oscillating belt, where gradients of the angular velocity are considerable, the toroidal field should become twisted. Changes in the angular velocity of the rotation of the Sun have not been observed directly, but oscillations along the latitude have been found, having an amplitude of 5.5° and a period of 23 years.[45] In the presence of the differential rotation, these oscillations are equivalent to torsional oscillations: the mass of gas changes its latitude and the velocity of rotation. According to estimates given in [40], the amplitudes of torsional oscillations of this type reach 170°, i.e., their linear velocity varies by about 100 m/sec. The magnetic flux of the toroidal field is then approximately equal to the poloidal field flux, which does not contradict observations. The poloidal field is not generated and is assumed to be already present.

Torsional oscillations may be caused by inertial and magnetic forces. However, they should be strongly damped due to the turbulent viscosity, which ought to be considerable in the presence of large-scale and small-scale convection. Therefore, the main problem in the hypothesis of torsional oscillations is how these oscillations are maintained and what is the nature of the oscillatory instability. This problem was considered in [46]. In the steady state, the angular velocity of all points on a single line of force is the same, although it may be different for different lines of force. This constant velocity of rotation determines the system with respect to which oscillations may occur. Let one of the ends of a tube of force, for example, the surface end, be displaced along the latitude. It then enters a region of different angular velocity and, therefore, begins to shift along the longitude as well. The oscillations of the end of the tube along the longitude will begin when the end of the tube oscillates along the latitude. This process differs considerably from the usual inertial torsional oscillations. To maintain the oscillations there should be feedback between the oscillations in the longitudinal and latitudinal and latitudinal directions, i.e., the motion along the coordinate φ should generate the motion along the meridian in a suitable phase. In this case, the source of the field energy and the oscillation energy is the differential rotation, which, in its turn, is supported by the convection.

The motion along the parallels and meridians may be coupled because when the velocity of rotation varies, the centrifugal force, directed along a meridian, changes as well. Moreover, an increase in the velocity of rotation additionally twists the field, makes H_{φ} stronger, and, therefore, the magnetic force in a meridional plane changes. All we need to establish is that the negative dissipation due to these effects is greater than the positive dissipation due to the viscosity. The relationship between these dissipations depends on the assumed parameters and needs quantitative investigation.

Magnetohydrodynamic equations become linear for the axial symmetry and, because of the considerable viscosity, the motion is assumed quasistationary, i.e., $\partial V/\partial t$ is neglected. The system may be solved on the assumption that the coefficients which are associated with the components of the velocity and the field are constant. This means that we assume not only that the perturbation amplitude is small, but that the scale of the perturbation is small, so that the parameters of the unperturbed motion in the investigated region are independent of the coordinates. For certain relationships between the parameters the solution of the characteristic equation may give the oscillatory instability and the oscillations should be basically nonlinear.

For the period to correspond to the 11-year cycle, we should have $H_{\varphi} \approx 0.1-1$ Oe, which is acceptable. Instability does indeed occur. In view of the large number of simplifications, the calculation does not prove the presence of oscillations but it does give grounds for assuming that such oscillations are possible. In the determination of the spectrum of oscillations, it is important to note that the small-scale oscillations have longer periods than the large-scale oscillations. Therefore, we may expect that the small-scale oscillations do not appear in general, especially as these oscillations are damped more strongly by the magnetic viscosity.

In the explanation of the cycle by torsional oscillations, we must bear in mind that a toroidal field has comparable intensity but different sign in successive cycles. Consequently, the variable component is much greater than the constant toroidal field ensuring isorotation. At the same time, the nature of the rotation does not change greatly. This means that the isorotation is maintained practically without the participation of the field, i.e., the average positions of the lines of force coincide with surfaces of the same angular velocity and the rotation itself is more likely to be governed by hydrodynamic rather than magnetic effects. This restriction is important. It is not at all clear how well the linearized solution describes the oscillations that involve a change in the sign of H_φ. On the whole, we may say that the problem of solar activity is far from being solved.

4. WAVES IN THE SOLAR ATMOSPHERE

The convective motion generates waves of various types which are propagated and dissipated in the solar atmosphere, and heat the chromosphere and corona. The periods of these waves should be of the order of the characteristic time of the convective motion, i.e., of the order of several minutes. As already mentioned, these waves may be partly responsible for the velocity and brightness fluctuations observed in the photosphere, and their role is particularly important in the upper layers. The main types are the accelerated and retarded magnetosonic waves, the Alfvén waves, and the internal gravitational waves. The theory of these waves should deal with their generation, interaction, and damping. One should bear in mind that in the photosphere the velocity of sound is higher than the Alfvén velocity, while at some height in the chromosphere the Alfvén velocity is the greater, particularly above the active regions. The generation of acoustic waves was considered in[47] for isotropic turbulence and low values of the Mach number $\mathbf{M} \ll 1$. Since there are no external forces in a turbulent mass and the internal action and reaction are balanced at low Mach numbers, the dipole radiation of sound in the wave zone is equal to zero. The sound generation is quadratic and is governed by fluctuations of the momentum flux $\rho v_i v_j$. Retaining the corresponding term in the equation of motion, we can obtain an analog of the wave equation

$$\frac{\partial^2 \varrho}{\partial t^2} - V_S \nabla^2 \varrho = \frac{\partial^2}{\partial x_i \, \partial x_j} (\varrho v_i v_j), \qquad (15)$$

which can be solved in terms of retarded potentials. An approximate calculation on the assumption of isotropic disturbance gives the following amount of acoustic energy radiated per unit volume in 1 sec:[48]

$$E \approx 40 \frac{\varrho V^8}{V_s^5 l} \text{ erg} \cdot \text{cm}^{-3} \cdot \text{sec}^{-1} = \alpha \varepsilon \mathbf{M}^5, \qquad (16)$$

where V and l are the velocity and scale of the main turbulent element, and ϵ is the turbulent dissipation. The numerical factor α in Eq. (16) reflects the fact that the generation is most effective for scales slightly less than the principal scale, so that the velocity is less but the velocity gradient is greater. The generation of waves is an additional source of dissipation of the turbulent energy, whose role increases markedly when the Mach number is increased.

In the presence of a magnetic field, all three types of magnetohydrodynamic wave are generated. The coefficients of the quadrupole radiation are cumbersome and include many tabulated functions;[49] they will not be given here. After making some simplifications, the power of the generated magnetoacoustic waves can be represented in the form

$$E_H \approx \alpha \varepsilon \mathbf{M}^5 (1 + a\gamma^2 + b\gamma^4); \qquad (17)$$

here, $a \approx 8$, $b \approx 1$, γ is the ratio of the magnetic energy of the waves to their kinetic energy. The value of this ratio is $\gamma \approx 1$ if $V_A \geq V$ and $\gamma < 1$ if the energy of the unperturbed field is less than the kinetic energy. In the active regions with strong fields, $H > 50$ Oe, the generation of the accelerated and Alfvén waves is stronger. However, one must bear in mind that a strong field may reduce the velocity of the convective motion.

The dipole radiation of sound is unimportant only under isotropic conditions. In fact, there are several factors which disturb the isotropy. The density fluctuations in a turbulent medium are subject to the gravitational force, which is not compensated by the Archimedes force. This produces a dipole radiation whose power is

$$E_g \approx 1{,}4 \cdot 10^{-2} \varrho g^2 l \frac{V^6}{V_s^7} \text{ erg. cm}^{-3}\text{. sec}^{-1}. \qquad (18)$$

For not too low Mach numbers ($\mathbf{M} \geqslant 0.1$), we have $E_g \leqslant E$. Another anisotropy-inducing factor is the magnetic field. The dipole radiation power is[52]

$$E_m \approx \frac{\varrho V_A^2 V^4}{12\pi V_s^3 l} \text{ erg.cm}^{-3}\text{.sec}^{-1}; \qquad (19)$$

it is small compared with E, everywhere except in the sunspots. Thus, under normal conditions, the generation is governed by Eq. (16), but in the parts of active regions with particularly strong fields, it becomes somewhat stronger, in accordance with Eq. (17).

The calculations of the energy generation have been made for isotropic turbulence. Since the Reynolds number for the convective flow is large, turbulence develops in such a flow. However, its velocity is low and the energy generated depends greatly on $\mathbf{M}$. Therefore, waves are generated by the convective motion itself, especially in the strongly unstable layer (Fig. 1), where $V \approx 2$ km/sec. The thickness of this layer is of the order of l, which is the height of a convective cell. The total energy flux in the waves is $F \approx 10^7$ erg.cm^{-2}.sec^{-1}, and this value is 5–10 times larger for an active region.

The variation of the energy flow with height is governed by the process of reflection, refraction, and absorption. The reflection takes place when the geometrical optics conditions are not satisfied and the wavelength is greater than the scale height. The photosphere, whose scale height is least, reflects waves of periods longer than 3 min, but a considerable part of the energy is transferred to the chromosphere. The refraction of waves having an isotropic phase velocity V_F reduces the energy flow proportionally to V_F^{-2}. As long as $V_F \approx V_S$, the refraction is not very important since V_S increases slowly with height. The Alfvén velocity increases more rapidly and $V_A \approx V_S$ at the $h \approx 5000$ km in the unperturbed regions, and at $h \approx 750$ km in the active regions. Above these heights, the accelerated wave moves at the velocity V_A and suffers strong refraction, particularly in the active chromosphere.[52] This presents difficulties in the explanation of the observed heating of the chromosphere. In fact, one must not consider the propagation of simple waves of different types. Because these waves are generated by different convective elements, which are separated by distances comparable with the wavelength at some height, the geometrical optics conditions are not obeyed and the different types of wave interact.[16] The interaction is also due to a gradient in the atmospheric density, to nonlinear instability, and to other causes. Therefore, we must consider the propagation of an ensemble of waves, between which energy is continually exchanged. Since the refraction and reflection are less important for the Alfvén and retarded waves, such an ensemble may reach the upper chromosphere and the corona, retaining sufficient energy to maintain high temperatures in the latter.

In the absence of damping and reflection, the energy flow is $F \approx \rho_V{}^2 V_F = \text{const}$. Therefore, the amplitude v of an acoustic wave moving upward increases and the wave becomes a weak shock wave, especially since its amplitude is finite at the generation stage. A self-similar solution was obtained in[52a] for a wave emerging from the deep layers of a star. The conditions of the shock wave formation were considered in[53]. The velocity of propagation of a weak shock wave remains V_F but the damping becomes much stronger and compensates any further increase in the amplitude. Therefore, the wave remains weak. The damping can be easily estimated on the assumption that the density decreases behind the shock-wave front, returning to its normal value in a time $t_0 \approx 10$ sec in the lower chromosphere. The coefficient of absorption of a wave of amplitude v is[54,52]

$$\varkappa_s = \frac{1}{F}\frac{dF}{dh} \approx \frac{\gamma+1}{12}\frac{v}{V_S^2}\frac{1}{t_0\nu}, \qquad (20)$$

where ν depends weakly on the density distribution behind the front and it is equal to $5/3$ for a sawtooth wave. Allowance for the refraction and absorption makes it possible to find the variation of the energy flow with the height and the dissipated energy which heats the atmosphere.

We have not allowed for gravitation because it is not important at high frequencies. If gravitation is included in the equation of motion, then the characteristic equation becomes separable. In the region $\omega > \omega_1 = \gamma g/2V_S$ the waves are nearly acoustic or magnetoacoustic. At low frequencies

$$\omega^2 < \omega_2 = g\left(\frac{\gamma-1}{V_S^2}g + \frac{d\ln T}{dz}\right) \qquad (21)$$

the internal gravitational waves are propagated. If the atmosphere is isentropic, as, for example, in the convective zone, then $\omega_2 = 0$, i.e., the gravitational waves are not propagated. Physically, it means that the displacement of an element does not give rise to a restoring force, since its density changes in the same way as the atmospheric density. In the chromosphere, where the temperature increases with the height, conditions are favorable for the generation of the gravitational waves. These waves, generated by the vertical motion in the photosphere, are propagated both along the solar surface and in the upward direction. The granulation and some types of the photospheric motion may be associated with the gravitational waves.[55] The same waves account for the perturbations propagated along the surface of the Sun at a high velocity.[56] The gravitational waves decay due to the thermal conductivity, which removes energy from the compression region. Since the thermal conductivity is high in the corona, these waves are important in the heating of the corona.[57]

The temperature of the atmosphere is governed by the balance between the heating by weak shock waves and gravitational waves and the cooling by radiation. Since the density and radiation both decrease with the height, the temperature increases, reaching 10^6°K in the corona. This value is governed by the condition that the thermal velocity of a proton is comparable with the parabolic velocity at this level so that the corona is dissipated into space, and the excess energy is lost in this way.[58] Part of the thermal energy of the corona goes back to the chromosphere by thermal conduction.

The dissipation of the corona, or the "solar wind," was considered in detail in[58] in the hydrodynamic approximation without a magnetic field. The flow was assumed to be steady-state, the velocity in the lower layers to be low, and the density distribution to be little different from the hydrostatic distribution. The velocity was assumed to increase away from the Sun, reaching a limit, which depended strongly on the thermal conditions of flow. It was assumed that, due to the high thermal conductivity of the corona, the temperature was constant up to a certain distance and then it decreased adiabatically. In this way, it was easily possible to obtain a velocity $V \approx 300$ km/sec, found in streams observed in the interplanetary space. The density of the wind at the Earth's orbit is several particles per cm^3.

5. EFFECTS IN THE ACTIVE REGIONS OF THE SUN

The active regions are those where magnetic fields emerge on the surface, the emergent fields being denser and stronger that the general field spread over the whole surface. The most remarkable features in the majority of the active regions are the sunspots (cf. Fig. 2). The temperature in the umbra is about 4300°K and in the surrounding penumbra about 5400°K, while the photospheric temperature is 5800°K. The field intensity in the umbra ranges from 1000 to 3000 Oe for the majority of sunspots. In some cases, the field has a fine structure.[13] The low temperature of a sunspot is due to the fact that the field supresses the convection in the upper part of the convection zone to a level at which the magnetic and kinetic energies are comparable. Since the convection transports the main part of the energy, this results in the cooling of the upper layers. However, had the energy transfer been due to radiation alone, sunspot temperature would be lower than actually observed. At the base of a sunspot, there must be an additional transfer which is stronger than the radiative one.[60] This transfer is partly due to the magnetohydrodynamic waves. The waves are generated at the level where the energies of the Alfvén waves and the partly retarded waves are equal.[61] The greater part of their energy is reflected without reaching the surface but part of it emerges and heats the chromosphere. The dissipation of the transmitted and reflected waves may heat a sunspot but such heating is found to be insufficient. There is as yet no quantitative theory. The motion observed in the umbra of a sunspot (cf. p. 473 in[3]) may also be associated with the emergent waves.

The penumbra of a sunspot usually has a radial structure consisting of bright filaments on a darker background. These filaments are convective cells elongated along an inclined field. The gas moves along them in the outward direction at a velocity of about 2 km/sec and at the edge the flow turns sharply downward and the motion stops. The theory of such convection has been considered in[62]. The circulation of the gas above a sunspot has been observed also in higher layers: the gas flows toward the axis, sinks there, and then spreads out. The reason for this circulation is not yet clear.

The photosphere in an active region is known as a facula. It is distinguished from the normal photosphere by a lower temperature gradient because the upper layers are hotter, and the lower layers are colder than the corresponding layers in the rest of the photosphere. This means that the energy is transported not only by radiation but also by convection. The enhancement of the convection in the faculas is caused by the magnetic field of the active region. This field is weaker than the sunspot field. It cannot stop convection but makes the convective motion stable in spite of the large Reynolds number. It apparently suppresses turbulence, reduces turbulent viscosity and thus increases the velocity of the convective motion and of the elements floating up through the region of minimum entropy.[63]

The chromosphere in the active region is denser and hotter than normal; the emission lines in such a region are brighter. This is because the faster convection motion generates a stronger stream of waves.[63] Moreover, the presence of a magnetic field also increases the efficiency of the generation of sound. The stream of waves emerging from the chromosphere into the corona is also enhanced and, therefore, the corona above the active regions is denser and somewhat hotter. The temperature is increased only slightly because heating intensifies strongly the "solar wind," which carries away the excess energy. Because of this, stronger streams of gas flow from the active regions, associated with some types of geomagnetic perturbation.[64,65]

In the active regions, particularly those close to large groups of sunspots of complex structure, chromospheric flares are sometimes observed. During these flares, the chromospheric line emission is enhanced, the motion of matter becomes faster and massive prominences (flare ejections) are observed. A large number of relativistic particles is generated in very strong flares.

The bremsstrahlung radiation of relativistic electrons gives rise to x rays and γ rays. However, at densities less than 10^{12} cm^{-3} the radiation due to the inverse Compton effect is more important; this effect involves the interaction of thermal photons with relativistic electrons. The pressure of cosmic rays causes an explosion, with gas being ejected at velocities up to 1500 km/sec. A collisionless shock wave is propagated in the corona; plasma waves are generated at its front, which are transformed into electromagnetic waves giving rise to a radiowave burst. The relativistic electrons behind the shockwave front generate magnetodamping radiation. Sometimes, they escape from the trap and move into the upper layers of the corona, giving rise to radiowave bursts of rapidly varying frequency.[66] In the interplanetary gas, i.e., in the solar wind, a shock wave is formed which reaches the Earth after several days, giving rise to a magnetic storm. At the same time, a large number of soft cosmic rays, carried by a magnetic trap, reaches the Earth. The more energetic particles leave the trap earlier and reach the Earth before the shock wave. The total energy of a strong flare, which is carried away mainly by cosmic rays, may reach 10^{32} erg. The energy of weak flares may be considerably less, and not all the effects described take place during such flares.

The magnetic field is the source of the flare energy. This is indicated by the positions of the flares and the observed changes in magnetic fields during the flares.[67,68] The flares are observed at points of high potential gradients, near neutral lines separating regions of opposite polarities in complex field configurations. There are several hypotheses which associate the flares with discharges near neutral lines or with shock waves (caused by the magnetic pressure due to a gradual change in the field because of dissipation, or by the motion in the photosphere). The generation of cosmic rays may be associated also with the acceleration between converging waves or the acceleration by plasma waves generated by a magnetohydrodynamic instability. These various hypotheses cannot as yet explain all the observed effects. One of the difficulties is the suddenness of a flare, while the dissipation and field variation in the photosphere are relatively slow.

Effects similar to flares but much smaller in scale are "whiskers." In most cases, they appear during flares but they can also be found in active regions without a flare. "Whiskers" are very small structures giving rise to bright and very broad lines.[69] Their widths are governed by the Doppler effect and the velocities reach several hundreds of km/sec. They last for several minutes. The cause of the appearance of "whiskers" is unknown; they are probably also associated with magnetic forces.

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