PAPER 13

THE PROCESSES IN ACTIVE REGIONS ON THE SUN AND ELECTROMAGNETICS

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ABSTRACT

1. Brief summary of the dynamics of flare development, based on the analysis of moving picture and spectroscopic data. Some new spectroscopic data on the fine structure of emission in active regions, evidencing the peculiar character of motions in them: outbursts of corpuscules, ascending grains of continuous emission, explosive processes and shock-waves.

2. Summary of the observational data on the motions in prominences. Regular electromagnetic and turbulent motions, 'explosive' motions and their admissible interpretation. Some data on the coronal forms above active regions and on the possible rôle of hydromagnetics in their formation.

3. Some remarks on the role of hydromagnetics, admissible, from the observational aspect.

1. FINE STRUCTURE OF ACTIVE REGIONS

The high resolving power and dispersion of our new solar tower has permitted us recently to reveal the peculiar fine structure in the emission spectra of facculae, flares and prominences. The continuous and line emission were observed in the form of very narrow bright threads cutting the solar spectrum. In other words the emission of active regions is concentrated mostly in short-lived small grains or nuclei of some hundred kms in size [1].

The most peculiar is the appearance of very narrow brilliant wings (the so-called 'moustaches') at the sides of undisturbed dark Fraunhofer lines spreading sometimes up to 15 Å from the center of the lines.

These moustaches appear always on the background of the continuous emission. But the most important feature of these phenomena is that the blue wing of these moustaches is *brighter* and *broader* than the red one; sometimes only *one* wing is observed at the blue side of the line. Example of these phenomena are given in Plates I and II.

The dark lines of the solar spectrum are shifted to the violet at the very laces where these grains of continuous and linear emission are observed.

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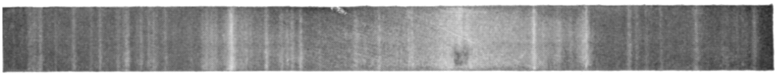

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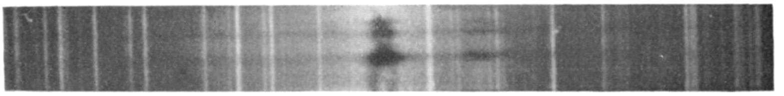

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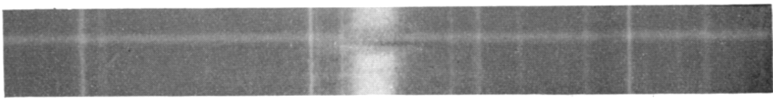

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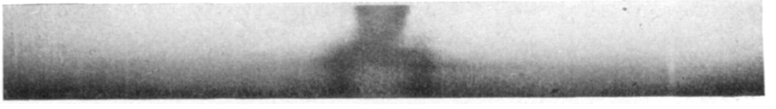

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Plate I. Examples of fine structure of emission of active regions. (*a*) The continuous emission near H-line; (*b*) the 'moustaches' in H-line; (*c*) the typical 'moustaches' in Hα-line; (*d*) the 'moustaches' in Hα above the limb.

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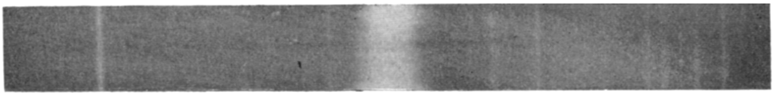

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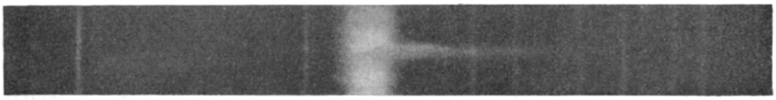

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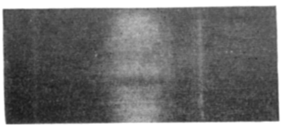

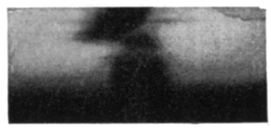

(c) (d)

Plate II. The examples of 'moustaches': (a) in Hα with one blue wing; (b) in Hα in absorption; (c) in Hα cutting the line; (d) at the bottom of eruptive prominence.

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Sometimes the Fraunhofer lines are slightly filled up with this emission. These nuclei of emission were observed in several cases above the limb. This shows that the grains of emission are emerging out of the deep layer and emitted at different levels in the solar atmosphere. The velocity of the ascending motions does not exceed 5 km/sec.

Photometric investigation showed that the continuous emission originates in a semi-transparent mass and possesses an energy distribution which looks like that of A0–B5-type stars (Fig. 1). The rate of energy generation in these nuclei does not exceed 20 % of the solar flux of radiation. Owing to the small size of these nuclei the temporary liberation of radiative energy appears to be very large and of the order of the

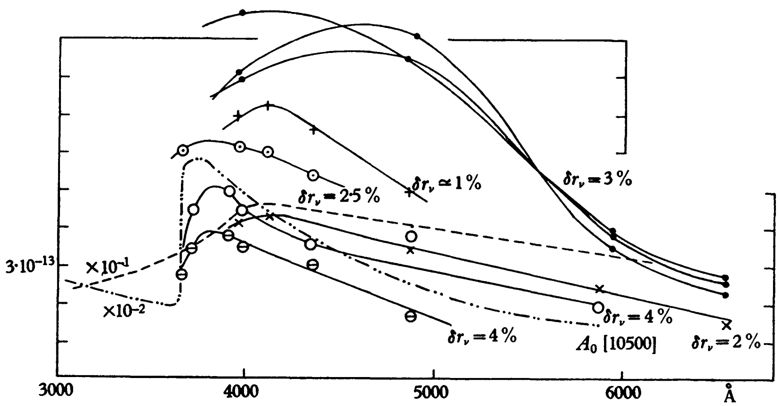

Fig. 1. The distributions of intensity in the grains of continuous emission (full lines); the dotted curve represents the same in undisturbed regions of the sun reduced by 10^{-1}; the dotted-point line the same in a A0-type star reduced by 10^{-2}, and δr_ν is the mean value of filling up of Fraunhofer lines with the continuous emission.

energy liberated in the deep interior of the sun owing to thermonuclear reactions.

The nature of this continuous emission is not clear as yet. It can be definitely said that this emission is not connected with the recombinations in the optically thin mass of hydrogen, as in this later case it should increase with the wave-length. It should not be produced by the process of scattering by free electrons, as this process could not secure the observed distribution of intensity along the spectrum. This emission is possibly connected with the relativistic electrons, although the effect of collisions makes the injection of these electrons somewhat improbable. Fig. 2 shows that the mean observed distribution of intensity of continuous emission might be explained by the emission of relativistic electrons possessing a differential spectrum of energy $dN(E) \propto E^{-1}$.

The preliminary results of measurements of polarization showed that this continuous emission is slightly polarized by 10 % in the plane perpendicular to the line of sight for grains near the limb of the sun. This fact also favours the hypothesis of relativistic electrons.

The results of spectrophotometric investigations of moustaches, as shown on Fig. 3 reveal clearly that the blue wing is brighter and broader than the red one in almost every case, which serves as an evidence of the

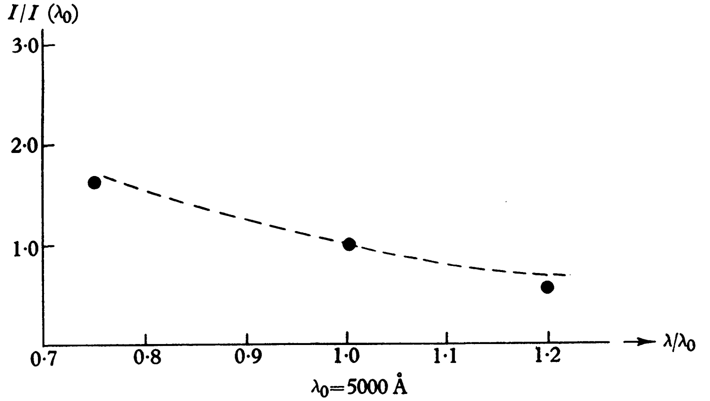

Fig. 2. The mean intensity distributions in grains (dots) compared with the theory for relativistic electrons with $dN(E) \propto E^{-1}$ (dashed line).

process of ejection of atoms out of the grain. The asymmetry of position indicates the velocity of emitting atoms up to 1000 km/sec. This effect of asymmetry *does not depend* on the position on the disk, showing that the process of corpuscular ejection is similar to a process of rapid symmetrical expansion or explosion of previously small mass but not to the process of pure radial ejection. (Particles moving from the observer are always going into the layers of larger optical depth and decelerating more rapidly than the approaching ones.)

Practically the same width of hydrogen and metallic moustaches shows that neither the Stark effect nor the natural damping are responsible for the broadening. The macroscopic motions (similar to turbulence) are most probably the cause of this broadening, which is insensitive to molecular weight. There is some evidence that collisions with neutral hydrogen also play an important role in the process of broadening going on in these moustaches.

Furthermore, the moving picture records show that the growth of line intensity emission is accompanied by the growth of area, that also evidences a process similar to explosion (Fig. 4). The duration of this growth of

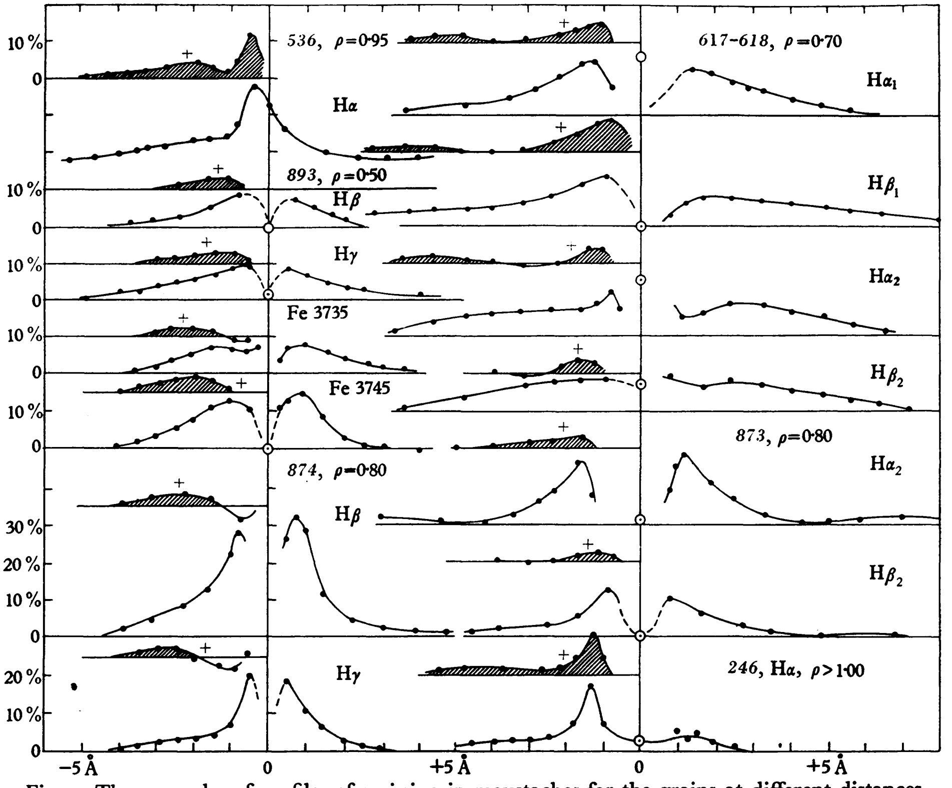

Fig. 3. The examples of profiles of emission in moustaches for the grains at different distances from the center of the sun's disc (ρ). The dashed areas are the asymmetry of these profiles showing the excess of emission in the blue wings. (All intensities in units of continuous spectrum of sun.)

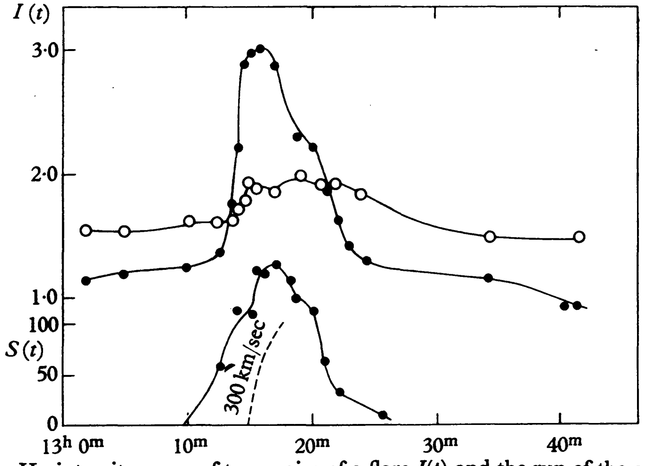

Fig. 4. The Hα-intensity curve of two grains of a flare $I(t)$ and the run of the area of this grain $S(t)$. (The dotted curve is the run of linear dimension of the brightest grain.)

intensity and expansion in flares and in knots of eruptive prominences is several minutes. The velocity of expansion of area or, probably, of the front of a shock-wave is of the order of several tens of km/sec. The process is highly dissipative: the lifetime increases with the area. The appearance of surges moving with supersonic velocities and subjected to extra-gravitational accelerations cannot be connected with any process, except an explosion-like process commencing with a shock-wave. These surges are accompanied by bursts of radio emission, i.e. by the process of non-linear oscillations of plasma. When falling at a right-angle on the system of magnetic lines of force of the nearest spot the shock-wave is reflected, as if it were reflected from a flexible wall. This can explain the observed appearance of a bright patch at the very border of spots' umbrae and the following lifting up of gases (the outburst of filament) along the curved path—the magnetic line of force of the spot's field. In several moving films we measured the explosive motions directly. The appearance of moustaches at the bottom of eruptive prominences should also be mentioned.

All these data lead to the conclusion that some unstable formations of small dimensions are lifted up on the surface of the sun. These formations are disintegrating. The process of decay, or instability of these formations manifests itself: (1) in the liberation of continuous emission in amounts comparable with the thermonuclear generation of energy in the interiors of the sun, (2) in the explosional ejection of particles with velocities up to 1000 km/sec, (3) in the formation of a shock-wave and macroscopic (or turbulent) motions, and (4) in the collisional excitation and ionization of atoms.

The probable source of these phenomena might be a sort of nuclear processes. Some general evidences concerning anomalous abundances of some elements, and especially the investigation of deuterium on the sun recently completed by us, lead to this conclusion. The spectrophoto-electric investigation by means of instruments of very high resolving power (600,000) showed that the depression between two water vapour lines λ 6561,105 and λ 6560,570, eventually connected with D_α increases from the center to the limb for 1·5–1·7 times (Fig. 5). The marked change of the contour λ 6561,105 (as a result of blending of the water vapour line with one of the D_α fine structure components) is also observed when passing from the center to the limb. The measured width and contour of this depression ($W = 1{\cdot}8$ mÅ) leads to the relative abundance of D/H from 3 to 5×10^{-5} [1].

The most striking is that this depression is markedly increasing in moustaches. It was recorded in several cases. Burbidge, Burbidge and

Fowler[2] have recently proposed a mechanism similar to bethatron, explaining the abundance of Li, Be, D, providing the existence of magnetic fields up to 10^5 gauss. This process secures $D/H > 10^{-5}$ in a hot spot, the energy of particles being $kT \approx 0{\cdot}5$ MeV. It is interesting that the amount of energy found above is of the same order of magnitude, when being related to the uppermost layers of photosphere. However, further investigations are highly desirable, especially regarding the magnetic properties of these fine-structure formations.

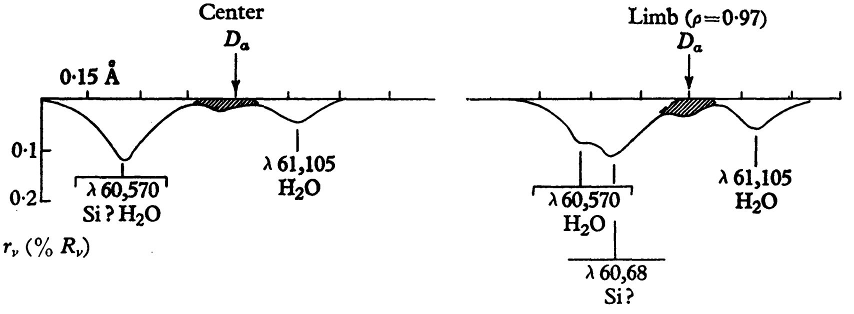

Fig. 5. The profiles of depression presumably connected with the D_α-line at the center and at the limb of the disc (50 photo-electric records).

2. ON THE ROLE OF ELECTROMAGNETICS IN ACTIVE REGIONS

The role of magnetic fields is more or less definite, when we are dealing with the space limitations of motions of solar plasma in the vicinity of a spot. The predominant motions along the magnetic lines of force in the case of electromagnetic prominences and filaments can be established from a comparison of curved paths of their knots and streams with the probable topography of the magnetic field of neighboring spots. The measured uniform motions along these curved paths can not be explained by means of field of forces of radiation pressure and gravity. The marked accelerations appear, as a rule, at the beginning and at the end of the path. The knots and streams do not penetrate, as a rule, into the umbrae of a spot. Its magnetic field prevents this process. Moreover the magnetic field of a spot restricts the possibilities of turbulent motions in the nearest prominences.

At the upper parts of the corona the curvature of the paths is less than in the lower ones and the knots of eruptive prominences are moving along spirals with radially increasing step as if it were a motion of an isolated charge in the field of a single magnetic pole[3].

The difference between the free paths of ions and electrons (and consequently the difference of retardation) in a knot moving rapidly through the corona may induce a current in the direction of motion and load to spiralling of the knot (Pikelner, [4]). The Evershed effect, the comparatively low temperature of a spot, the lowering of chromosphere above a spot—all these data show, that predominantly horizontal pressure gradients may appear in the vicinity of a spot. These gradients, as well as the above mentioned explosional processes, might be the cause of motions of solar plasma along the lines of force. Theoretical magneto-hydrodynamics of plasma, taking the gravity and compressibility into account, shows that small motions of the plasma should be accomplished along the lines of force even if the excess of pressure is of the order of several per cent of the equilibrium value (the theoretical accelerations were found to be of the order of the observed ones [5]). But supersonic motions and extra-gravitational accelerations (eruptions and surges) require a more powerful agent—similar to that described above. Moustaches, the large radial velocities and splashes of brightness in the bottom of eruptive prominences are further evidences of explosional processes of such a kind.

The sunspot's magnetic field, as well as a general magnetic field, can, of course, disturb the almost symmetrical outburst of particles from the grain of emission. But the ejection of particles can disturb somewhat, in its turn, the topography of the general magnetic field of the sun. In the case of the simple dipole field and the pure radial ejection of particles the Hall current and the induced magnetic field connected with it can appear in the stream of corpuscules. According to Ponomareff the topography of the resulting magnetic field should be very similar to the observed coronal forms. The stability of these forms evidences the possibility of such a magnetic field in the corona, which excludes the transfer of matter across the lines of force.

Far enough from the active regions and the sunspot's field well pronounced turbulent motions are observed (quiescent prominences). Here we have metamorphoses, which are similar to that observed in the earth's clouds and smokes. Trajectories of knots are similar to that of Brown's particles, the distribution of knots according to velocities being different from the simple law of random values. The Reynolds numbers are large ($\geqslant 10^5$). The observed correlative function between the difference in the brightness of knots and their distances agrees fairly good with the theoretical one for the case of local isotropic turbulence (Dubov [6]). This permits us to consider the knots as turbulent pulsations of density in the continuous plasma of prominences (the mean characteristic dimension $\approx 2 \times 10^9$, the characteristic time is 2×10^3 sec, the mean turbulent velocities are ≈ 10 km/sec). Owing to the process of entangling of the lines of force the turbulence should lead to an increase of the magnetic field up to a certain limiting value (about 1 gauss). It means that all motions in such a prominence should be transmitted by the hydromagnetic waves along the lines of force from one part of the mass to another. This process favours the development of the isotropic turbulence.

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Discussion

Burbidge: What are the average energies of the relativistic electrons which you suggest may be responsible for continuous emission in the grains?

Severny: This has not been computed. All we know is the total photometric energy which is about 10^5 erg/cm^3.

Burbidge: What is the magnetic field to account for the energy? I think that a very high electron density, some 10^8 relativistic electrons, might be needed if $H \approx 1$ gauss.

Severny: It is shown by Gordon that not many electrons are needed—it depends on their individual energies and, of course, on the magnetic field.

Spitzer: What is the angular diameter and the linear size of these bright grains?

Severny: Perhaps 2 sec of arc. But only in perfect weather can this be observed, the limitation being set by the circle of scattering. One calculates perhaps 300 km as the linear extent.

Spitzer: How frequent are the grains? How many are present on the solar disk at one time?

Severny: Sometimes three to five at a time; they occur especially in growing spots. They are very short-lived (10–15 min.) and often disappear while preparing for observation.

Alfvén: Are these phenomena associated with the emission of magnetic storms producing beams?

Severny: I do not know, but one could measure the depression in the wings of the spectral line emission (H and K or Hα). In this way one can try to predict magnetic storms with 80 % certainty.

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Alfvén: The displacement corresponds to a velocity of 300 to 1000 km/sec. Is there a possibility that this velocity continues outwards so that there is a radial emission?

Severny: In the case of pure radial ejection out of these grains the asymmetry of the moustaches should disappear near the limb, but the effect of asymmetry is even more pronounced near the border of the disk.

Alfvén: Can you estimate the total mass of gas which moves here?

Severny: There should be about 10^4 particles/cm^3 above the surface to secure the observed extra emission in the wings of H- and K-moustaches.

Alfvén: But what is the total mass integrated over the whole phenomenon?

Severny: The linear extent is 300 km squared so that one can estimate the total number.

Biermann: Did you want to suggest a relative abundance of deuterium of several times 10^{-5}, or else did you want to indicate an upper limit?

Severny: There was a change of the depression in the region of the D_α-line by a factor 1·5 when going from the center to the border of the sun. Comparing theoretical results with my observations, the abundance comes out to be $3\text{–}5 \times 10^{-5}$.

Öhman: Is the mean life time of these 2 min. elements as long as 40 min.?

Severny: Moustaches have 1–10 min. life time. On the other hand, there is sometimes continuous emission from half an hour to one hour.

Tuominen: Could the 'moustaches' represent the continuous spectrum of the prominence superimposed on the solar spectrum?

Severny: No, in the case of scattering by an electron condensation we should not observe the dependence of intensity on the wave-length.

Alfvén: The density 10^4/cm^3 is less than mean density in the corona. How did you get such a value?

Severny: The density was measured from the widths of additional depression in the wings of the H and K-lines.

Alfvén: But this density is much lower than in the photosphere.

Spitzer: Is this perhaps the number of excited atoms?

Severny: The value I have given for the density refers to the particle density of the additional flux which is able to produce an additional excitation of the chromosphere by means of collisions.

Alfvén: Yes, but I mean what total density in the moving piece of matter do you expect?

Severny: I am not able to answer that question. I want to keep to the observations as much as possible.

Cowling: The density 10^4/cm^3 must correspond to an appropriate height.

Severny: Yes, this height will not be more than that of the chromosphere, i.e. 10^3 km to 10^4 km.