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Abstract

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ON THE GENERATION OF HIGH-ENERGY PARTICLES AND HARD RADIATION IN SOLAR FLARES

Cinematographic studies show that solar flares are an extremely nonstationary process of the explosion type. This is evidenced by the following facts: 1) the growth of the area of the luminous region occurs simultaneously with its intensity (or lags somewhat behind it); 2) the maximum intensity of a flare is the greater, the more rapid its rise; 3) sometimes bright fronts moving with supersonic velocities arise, whose behavior is similar to that of shock waves; moreover, on approaching spots, these fronts are decelerated, flare up, and spread as though along magnetic lines of force; 4) sometimes short-lived supergravitational accelerations of the solar plasma and bursts of radio emission arise at the same time ([1],[2]).

On the other hand, investigation of flare spectra with high resolving power and dispersion shows: 1) the concentration of all their continuous and line emission in very small ($0'', 5$—$2''$), short-lived (4^m—20^m) nuclei; 2) the appearance, in the phase of maximum development of strong flares (chiefly at hydrogen lines and occasionally at metals), of a special, very broad (up to 10—15 Å) line emission (“moustaches”), sometimes only on one side of the line (these moustaches also arise without flares, almost always near weak, growing spots; see below) ([3]).

The nonstationary continuous emission arises in optically thin nuclei located at different depths in the atmosphere of the Sun; its distribution over the spectrum (a noticeable increase of intensity toward the violet) and its small polarization indicate its nonthermal origin ([3]). The broadening of the line emission in the moustaches is not connected with the Stark effect or other analogous mechanisms, but is well explained, as we recently found ([4]), by a Doppler effect arising from macroscopic motions of streams of atoms with velocities from 100 to 1000 km/sec. The asymmetry of this emission also indicates the ejection of atoms from the “nucleus” of the flare in the form of concentrated jets, sometimes only in two opposite directions (along the magnetic field) ([3]). The emission in the nuclei and near wings of hydrogen lines in flares (arising in its peripheral, chromospheric layers) is broadened owing to the Stark effect (including the H_α line), and the best agreement between theoretical and observed contours is obtained for $p_e = 10$—50 bar, $n_e = 10^{13}$, $T_{\text{kin}} = 10^4$ °K, $n_H = 10^{13}$ (degree of ionization $x \simeq 1$) (5). Calculation of all the processes of excitation and ionization leading to the filling or emptying of various quantum levels shows that the electron gas in flares cools very rapidly (in fractions of a second), owing to cascade ionizations by electron impact, if there is no source maintaining its energy with a power of ~ 500 erg/cm$^3 \cdot$sec. The same estimate is obtained from the continuous optically thin emission of flares (3).

To the data listed should be added such facts as: 1) strengthening of the D_3 line in flares and moustaches, indicating the possibility of the formation

of neutrons there (6); 2) the occurrence in bursts of radio emission of particle streams with velocities $50—100 \cdot 10^3$ km/sec, as indicated by the radio spectra of bursts; 3) the occurrence in flares of cosmic rays with energies $\sim 10^9$ eV, and sometimes reaching 10^{11} eV (as in the case of 23 II 1956); 4) the reaction of the D-layer of the ionosphere (its lowering by 15 km during flares) indicates the occurrence not of L_α-radiation but of X-radiation, and direct rocket measurements indicate that it is concentrated in the region 0—5 Å and that its flux is $\sim 10^{-3}—10^{-2}$ erg/cm$^2 \cdot$ sec at the boundary of the terrestrial atmosphere (7).

The proposed explanation of flares as a kind of discharge (8) is untenable, since, owing to the frozen-in character of the magnetic field in the solar plasma, the currents necessary to explain the release of energy in a flare as a result of Joule losses cannot arise.

Recent photoelectric investigations of solar magnetic fields (in the interval from 10 to 1500 gauss), carried out by us with the aid of a solar magnetograph (9), have shown that: 1) flares arise at neutral points of the magnetic field when there is a considerable field gradient near such a point, and 2) the appearance of a flare leads to the destruction of the field near the neutral point. In addition, it was found that: 1) strong fields (up to 1000 gauss) also arise outside sunspots; 2) the magnetic fields in the solar plasma are not dipolar in character, but have a very fine structure (not less than 20 sq. sec.) and are similar to bundles of moving magnetic lines of force interlaced with one another. Considerable fields (up to 500 gauss) extend into the chromosphere. Neutral points (regions) are formed as a result of such tubes coming together along a surface (plane) when they are brought outward (10).

It can be shown (10) that, for a sufficiently large field gradient near the neutral point (greater than 10^{-6} gauss/cm), the plasma of a solar flare is unstable: the magnetic force compressing the plasma near the neutral point (plane) increases more rapidly during compression than the opposing gas pressure, so that the plasma can be compressed without limit (the pinch effect in a homogeneous current layer)*. The compression time is of the order of the time required for an Alfvén wave to traverse the characteristic size of the flare, and is comparable with the observed time of flare development (tens of seconds). However, already at a compression of ~ 0.1, hydromagnetic shock waves develop on both sides of the neutral plane, their fronts moving toward each other. At a compression of ~ 0.01, the reaction of the shock wave (the jump in total pressure) behind its front stops the compression of the plasma and causes its expansion—a phenomenon characteristic of the next phase of flare development. In this phase of development the temperature, pressure, density, and magnetic-field strength at the front are $T_2 = 30T_1$, $\rho_2 = 3\rho_1$, $p_2 = 100p_1$, $H_2 = 3H_1$, where the corresponding values ahead of the front are $T_1 = 2 \cdot 10^5$, $p_1 = 2 \cdot 10^4$, $\rho_1 = 10^{-9}$, $H_1 = 10^3$, and the velocities of the fronts are $\simeq 3 \cdot 10^7$ cm/sec. The collision of shock waves in the neutral plane leads to impulsive heating of the plasma to temperatures of $\sim$ 10 million degrees, causes powerful macroscopic motions of atoms with velocities exceeding 100 km/sec, manifested spectroscopically in the phenomenon of "whiskers." Such a process explains the concentration of the emission of flares and whiskers in small, short-lived "kernels," the appearance of high-velocity streams of atoms, the destruction of magnetic fields by flares, the subsequent expansion of flares, and a number of other observed features of flares (^{4}).

Before the collision of the shock waves, at a compression of ~ 0.01, a cavity arises between two parallel fronts approaching each other with a velocity $\simeq 10^8$ cm/sec, in which electrons can be accelerated. It is not difficult to see that

* With compression down to 10^{-4} of the initial characteristic size ($\sim 10^8$ cm), the frozen-in property of the field in the plasma is preserved; subsequently field diffusion and Ohmic losses begin to play a role. Radiative losses are insignificant for compression less than 10^{-2}; afterward deviations from adiabaticity set in; see the similar treatment in (^{11}).

both in this band and in the fronts, the cyclotron frequency ω considerably exceeds the frequency ν of proton–electron collisions (the plasma is hydrogen, ionization is practically complete), and the gyration radius r is smaller than l, the mean free path. This has as its consequence the constancy of the magnetic moment of the electron when it collides with the moving front, whose width is of the order of 5–10 l (^{12}). When electrons collide with the fronts, the latter act as "magnetic mirrors," and the energy of the electrons will increase as $1/a^2$, where a is the distance between the fronts (^{13}). However, electrons in the contracting band ("trap") will lose their energy owing to collisions, bremsstrahlung, radiation during rotation around the field lines, and the inverse Compton effect. Among these, the principal role in our case is played by ionization losses, which increase approximately as $1/a$. The other losses are considerably smaller than the gain and play no role. Therefore, when the fronts approach sufficiently closely, the energy gain will exceed the losses, and acceleration of the electrons will become possible. If the electron energy corresponds to the temperature 10^6, attained owing to the pinch effect (nonrelativistic case), this acceleration begins in a layer of $\sim 10^2$ cm (the width of the front is of the order of 1 cm). For particles with energy $\sim m_0c^2$, the width of this layer is comparable with the initial one ($\sim 10^6$ cm).

The electron streams must emerge chiefly along the neutral plane, producing strong bremsstrahlung, which will immediately escape outward in the form of hard X-rays and, possibly, γ-rays, as indicated by rocket measurements (thermal, hard radiation would emerge tens of minutes after the beginning of the flare). It is interesting to note that if the continuous emission of flares, observed in the visible part of the spectrum, is regarded as the long-wavelength tail of this bremsstrahlung, then in the X-ray region of the spectrum (0–5 Å) it proves to be of the same order as that measured by rockets (7), provided only that the energy contained in the electron stream lies within the range from $\sim m_0c^2$ to $100\,m_0c^2$. This indicates that processes similar to flares may be a source of the γ-radiation of the Sun and stars. A background of γ-radiation with intensity $\ll\sim 10^{-3}$ erg/cm$^2\cdot$sec., which may be suspected on the basis of rocket measurements, can be produced by 300 Sun-type stars within a radius of about 40 parsecs. Since the optical thickness of our Galaxy in γ-rays is negligible, measurement of galactic γ-radiation constitutes a means of studying processes in the most remote parts of the Universe (especially in regions where nonstationary formations predominate; on the occurrence of special emission in such formations, see (14)).

A study of the γ-radiation of the Sun and stars with the aid of artificial satellites is therefore of great interest.

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Note: Figure translations are in progress. See original paper for figures.

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