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Abstract

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ASTRONOMY

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ON A POSSIBLE MECHANISM OF THE LUMINESCENCE OF CHROMOSPHERIC FLARES

(Presented by Academician V. G. Fesenkov, 29 I 1963)

It is known that many chromospheric flares are accompanied by an increase in the intensity of cosmic rays on Earth. For rough preliminary calculations it is assumed that during a flare 10^{33} particles with energy 10^9 eV are produced, that the density in the flare is $5 \cdot 10^{12}$ atoms/cm^3, and that 1 cm^3 contains 10^7 hydrogen atoms on the second level and $2.3 \cdot 10^6$ atoms on the third level, that the area of the flare is $3 \cdot 10^{19}$ cm^2 and its depth 10^8 cm ($^{1-5}$). The ionization losses of fast particles were calculated by the formula

$$K = \frac{4Nz^2(Z/A)\,\pi r_e^2 m_e c^2}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2}{(1-\beta^2)I(z)} - \beta^2\right],$$

where K is the energy loss per 1 g/cm^2, N is Avogadro' s number, $\beta = v/c$ is the ratio of the particle velocity to the speed of light; the quantities z, Z, and A for fast protons moving in hydrogen are equal to unity. r_e is the classical electron radius; m_e is its mass; $I(Z)$ is the mean excitation and ionization potential, taken to be 13 eV. It turned out that the total energy release is 0.15 erg/cm^3 • sec. In 10^3 sec, over the whole volume of the flare this gives $4.5 \cdot 10^{29}$ erg, which corresponds to the total energy emitted by flares. The energy release in a column with a cross section equal to 1 cm^2 is $1.5 \cdot 10^7$ erg/cm^2 • sec. On the other hand, the radiation of a flare in H_α (^{6}) is 7—8 $\cdot\, 10^6$ erg/cm^2 • sec • steradian. For L_α, according to (^{7}), one can obtain about $4 \cdot 10^6$ erg/cm^2 • sec • steradian and, according to rocket observations, no more than 10^7 erg/cm^2 • sec • steradian. Apparently, L_α and H_α must together carry off almost all the energy that is released in flares, $1.5 \cdot 10^7$ erg/cm^2 • sec.

The calculation shows that the energy carried away by radiation arising directly during the passage of fast particles, because of excitations and ionizations with subsequent recombinations, is very small, and the excess of energy remaining in

Figure 1

Figure 1: Figure 1

the medium must cause a rise in temperature, continuing until the number of hydrogen atoms on the third level reaches $2—3\cdot 10^6$ cm^{-3}, and until the radiation can carry away all the energy released per unit volume, i.e., approximately 10^4 °K. For this it is necessary that ~ 24 erg be released in 1 cm^3. Thus, the time for ignition of the flare will be $24/0.15 = 150$ sec. The change in brightness (ignition) begins not immediately after the appearance of the additional radiation, but after a time close to the mean residence time of a quantum in the volume under consideration, which, according to ([8]), is estimated as $t = zt$, where $z = \tau_0^2/4$ is the mean number of scatterings, and t is the time between two successive moments of scattering of the quantum. In our case $t \sim 1/A_{ik}$, $\tau_0 = Zn_{iK_{ik}}$, where τ_0 is the optical thickness. Finally, for H_α we have $t = 6.7 \cdot 10^{-5}$ sec, and for L_α, $t = 1.3 \cdot 10^6$ sec. Taking into account the escape of quanta in the wings of the line at such a large optical thickness will change the estimate of the time elapsing from the moment of appearance of additional radiation to the increase in the surface brightness observed by us in L_α by not more than a factor of 1000. Then the residence time of a quantum in the medium will be of the order of 1000 sec. Some role in this delay will also be played by diffusion of quanta in the gas located above the flare. Hence it is clear that increases in radiation in L_α should be expected later than the flare begins in H_α.

The delay may reach several tens of minutes. This should be kept in mind when attempting to measure flare radiation in L_α with rockets and satellites. The delay also leads to smearing in time.

One can attempt to take into account the distribution of particles over energies and the dependence of the change in the release of energy in the volume under consideration on time. We shall restrict ourselves to particle energies above $E_0 = 5 \cdot 10^7$ eV and assume that the total energy of the particles is equal to the total energy adopted by us in the preliminary calculation: $10^{33} \cdot 10^9 \cdot 1.6 \cdot 10^{-12} = 10^{30}$ erg. For the particle spectrum over energies it is assumed that at the initial moment $N(E) = \dfrac{A\gamma}{E^\gamma}$, $\gamma = 3$ (9),

Fig. 1. Dependence of the release of energy in the medium on time. The dashed line shows the assumed course of the brightness of the flare in H_α up to the maximum

and since, as the particles move toward the Earth, one may expect the spectrum to change in the direction of an increase, the calculations are also made for $\gamma = 2$. For $\gamma = 3$ the total number of particles is $5 \cdot 10^{34}$; for $\gamma = 2$ we have 10^{34}. In the calculations it is assumed that a single short-time injection of particles into the volume of the flare takes place. For the ionization losses we have:

$$\frac{dQ}{dt} = \int_{5\cdot 10^7}^{\infty} N(E,t)\frac{dE}{dt}\,dE.$$

If the change of the spectrum with time is taken into account, then after a number of transformations and simplifications we obtain for $\gamma = 3$

$$\frac{dQ}{dt} = \frac{A_3 B}{(3/2)^{1/3}} \int_{x_0}^{\infty} \frac{dx}{x^3\left({}^2/_3 x^{2/3} - Bt\right)^{1/3}}$$

and for $\gamma = 2$

$$\frac{dQ}{dt} = \frac{A_2 B}{(3/2)^{1/3}} \int_{x_0}^{\infty} \frac{dx}{x^2\left({}^2/_3 x^{2/3} - Bt\right)^{1/3}},$$

where

$$x = \left(\frac{3}{2}\right)^{2/3}\left(Bt + {}^2/_3 E^{3/2}\right)^{2/3}$$

and x_0 corresponds to E_0; $B = 4.7\cdot 10^{-8}$, $A_3 = 1.6\cdot 10^{25}$, $A_2 = 8\cdot 10^{29}$.

For $t > t_1$, where t_1 is determined from the relation ${}^3/_2 B t_1 = x_1^{2/3}$, $E(t)$ for particles with initial values less than x_1 is equal to zero, so that the integral must be taken from x_1 to ∞. In practice we took it from $\left({}^3/_2 Bt\right)^{3/2}$ to ∞.

The results of the calculations are given in Table 1 (the values of dQ/dt are given for a calculation per 1 cm^3 of the flare in erg/cm$^3\cdot$s).

The dependence of energy release on time is presented in Fig. 1. It is also shown there how the development of the glow of flares in H_α can be represented. Similar dependences are encountered very often in photometry of flares (^{10}). A small change in the spectrum of the particles, and their repeated and brief injection, can explain all the variety of dependences of the course of flare radiation in H_α with time.

Table 1

	0	10	50	100	200	300	400	500
3	18.0	5.6	2.1	0.59	0.21	0.10	0.06	0.04
2	12.0	9.0	3.6	1.8	0.9	0.6	0.45	0.36

Up to now we have spoken of quantities characteristic of strong flares, but the glow of weak flares may also be a consequence of the ionization losses of fast particles, since in weak flares a sufficiently large number of particles of relatively low energies may be formed; these will not escape from the solar atmosphere and will not be observed on Earth.

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