ON THE ENERGY RELEASE BY MAGNETIC FIELD DISSIPATION IN THE SOLAR ATMOSPHERE

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Abstract. The energy release by Joule magnetic-field dissipation in the solar atmosphere is discussed. It is shown that the heating is unimportant in the case of granulation and intergranular space. In the case of spot features the additional temperatures ΔT_r with the accounting of the radiation losses are no more than 30° for small new spots, ≈ 1° for the large umbrae and 300° for bright points in large umbrae. This effect gives the possibility to suggest a hypothesis on the source of temperature inhomogeneity in the spot umbra and the nature of bright points. In the chromosphere the dissipation is negligible.

1. Introduction

In solar astrophysics the idea became established that Joule magnetic-field dissipation in the solar atmosphere did not exist and there was no need to pay attention to energy release by this process. Two facts were especially conducive to the wide spread of this idea.

(1) The calculations of the conductivity for the case of fully ionized gas gave very great values for all layers in the solar atmosphere.

(2) The widespread idea on the homogeneity of the structural elements of the solar atmosphere was used for the calculation of the time scale of dissipation, and this led in many cases to very large values of magnetic-field length scale l. Time scale t is proportional to l^2 and this led to very large values of t.

This situation is essentially changed now. The calculations for the partially ionized gas made by NAGASAWA (1955), KOPECKÝ (1957, 1958), STEPANOV and PETROVA (1959), VASILJEVA (1962), SCHRÖTER (1966), KIEPENHEUER (1966), KUKLIN (1966), KOPECKÝ and KUKLIN (1966), and OSTER (1968) have shown that in many layers of the solar atmosphere the conductivity is essentially lower than the value accepted by COWLING (1953).

On the other hand some recent investigations have shown the great importance of the fine structure in magnetic-field and other physical conditions in the solar atmosphere.

It seems useful under such circumstances to discuss once more the question of the probability of Joule dissipation and energy, released by this process, and to call attention to some cases where the suggestion on the absence of dissipation seems now not to be so unquestionable as before.

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2. Some Numerical Estimations

Two questions are especially important in this discussion:

(1) What is the time of dissipation for different features in the solar atmosphere? This question was discussed recently by Bumba *et al.* (1966). They accept $S = 10^{-14}\,\mathrm{cm}^2$ for their calculations. For our calculations we accept $S = 10^{-15}\ \mathrm{cm}^2$. Cowling's formula was accepted for calculation of the time scale of dissipation (Cowling, 1953),

$$t = \frac{4\pi\lambda_0 l^2}{c^2}. \tag{1}$$

For calculation of the conductivity in the photosphere we accept the formula of Kopecký (1957, 1958)

$$\lambda_0 = 0.26\,\frac{e^2}{(3km_e T)^{1/2} S}\cdot\frac{n_e}{n_n}; \tag{2}$$

in the chromosphere results of Stepanov and Petrova (1959) and Vasiljeva (1962) were used.

(2) What is the value of the energy released by magnetic-field dissipation, and how large is the heating of atmospheric layers by this process? The radiation is proportional to T^4, and because of that, this additional energy flux would be very soon swept out by the radiation losses. The dissipation is not an instantaneous process and usually is dragged on for a very long time, and energy release in the unit of time is not so large. Because of this small increase of effective radiation, the temperature is sufficient to compensate additional energy flux. Thus, for the estimation of the heating in the photosphere we have the formula

$$\frac{H^2}{8\pi}\,h = \frac{3}{2}Nk(T_2 - T_1)\,h + \sigma\,(T_2^4 - T_1^4)\,t. \tag{3}$$

Here h is dissipation layer thickness, σ is Stefan-Boltzmann's constant, T_1 and T_2 are initial and final temperatures respectively. The comparison of the first and the second terms in the right part of the Equation (3) shows that the increasing of the kinetic energy of the particles in the energy balance for photosphere may be neglected if $N \lesssim 10^{17}\ \mathrm{cm}^{-3}$, $h \leqslant 10^9$ cm, $t \geqslant 10^2$–10^3 sec, that is practically for all interesting cases. Bumba *et al.* (1966) took into account only the first term in (3) and this led to the unreally large heating.

If the increasing of effective temperature is small, we can use the simplified formula

$$\Delta T_r = \frac{\varepsilon}{4\sigma T^3}\,h, \tag{4}$$

where

$$\varepsilon = \frac{H^2}{8\pi}\frac{1}{t}\ \mathrm{erg/cm^3\ sec}.$$

TABLE I

	Accepted characteristic values							
	N	l	H	t_0	λ_0	t	ε	ΔT_r
	cm^{-3}	cm	gs	sec	CGSE	sec	erg/cm^3 sec	degree
Granulation	3×10^{16}–10^{17}	3×10^7–10^8	1	5×10^2–5×10^3	10^{11}	10^6–10^7	4×10^{-9}–4×10^{-8}	
Intergranular space	10^{16}–10^{17}	10^7	10	5×10^2–5×10^3	10^9–10^{10}	10^3–10^4	4×10^{-4}–4×10^{-3}	
Small new spot	10^{16}–10^{17}	3×10^7–10^8	10^3	10^3–10^5	10^9–10^{10}	10^4–10^6	4×10^{-2}–4	30
Umbra	10^{16}–10^{17}	5×10^8	3×10^3	10^5–5×10^6	10^9–10^{10}	5×10^6–5×10^7	10^{-2}–10^{-1}	1
Bright points in large umbra	10^{16}–10^{17}	10^7	10^3	2×10^3–10^4	10^9–10^{11}	10^3–10^5	0.4–40	300
Chromosphere								
(a) active								
$h = 3000$ km	10^{12}	3×10^8–10^9	500		10^{12}–10^{13}	10^9–10^{11}	10^{-7}–10^{-5}	
$h = 6000$ km	10^{10}		100		10^{14}	10^{11}–10^{12}	4×10^{-9}–4×10^{-10}	
(b) quiet								
$h = 3000$ km	10^{12}	3×10^8–10^9	10		10^{12}–10^{13}	10^9–10^{11}	4×10^{-9}–4×10^{-11}	
$h = 6000$ km	10^{10}		1		10^{14}	10^{11}–10^{12}	4×10^{-13}–4×10^{-14}	

Rough numerical estimations on the basis of Equations (1)–(4) for some solar features are given in Table I. The observed values of the lifetime for some features are given in the column t_0. For the estimation of the upper limit ΔT_r, the dissipation thickness $h = 10^8$ cm and minimal possible dissipation times t were taken.

Initial temperature T in all cases was taken as 4000°, dissipation in the chromosphere was estimated for active and quiet chromosphere on the heights 3000 km and 6000 km.

3. Discussion of the Numerical Estimations

From the examination of Table I it seems to follow that in the photosphere only for granules the lifetime is undoubtedly much smaller than the dissipation time. In the other photospheric cases (especially for intergranular space, small new spots and bright points in the large umbra) the conditions may occur (more or less real) for the effect of dissipation to be considerable. From the energetic point of view the magnetic-field dissipation in granules and intergranular space does not give any considerable heating. In the spots the heating computed without taking into account radiation losses leads us to the unreally large temperatures (Bumba *et al.*, 1966), but taking into account radiation, as we could expect, diminishes the heating considerably. Only for bright points in the large umbra ΔT_r reaches 300°. This effect gives us the possibility to suggest a hypothesis on the source of temperature inhomogeneity in the spot umbra and the nature of bright points. These bright points might be suggested as the tops of the magnetic tubes. In the upper layers of the spot, where the conductivity is relatively lower the dissipation leads to the considerable heating of the top parts of the tubes. After intensive radiation losses the temperature of these features diminishes and becomes equal to the temperature of nearly cold regions of the spot. The more precise quantitative evaluation of this hypothesis meets with great difficulties. Especially unknown is how to evaluate the dissipation of the field, consisting of the many separate structural elements, different in the field strength physical conditions and conductivity too. This difficulty has been indicated recently by Bumba *et al.* (1966). It is worth mentioning that if we take the formula of Chandrasekhar (1961) we should receive t on the order of value smaller and correspondingly larger values of ε. But the uncertainty in the accepted values of dimensions in different features seems to be more decisive than the differences in formulae of Cowling and Chandrasekhar.

It is seen from Table I, too, that dissipation in chromosphere is practically excluded if we take into account the longitudinal conductivity λ_0 only.

It is worth mentioning, however, that Stepanov and Petrova (1959) and Vasiljeva (1962) have shown that on the heights 3000–10000 km conductivity λ_3, which determines the dissipation of transversal currents, is diminished and reaches the values 3×10^6–10^7. This must lead to a more rapid dissipation of the transversal currents, the field should dissipate sooner and become force-free. The time scale of this process for $l \approx 3 \times 10^8$ cm is about 3×10^3–10^4 sec.

A similar process might exist in the spot, where the conductivity λ_3 in the upper layers ($t \leqslant 1$) of large umbra for $S = 10^{-15}$ cm^2 is probably 5–50 times smaller than

λ_0 (KOPECKÝ and KUKLIN, 1966), and this effect may lead to a sooner dissipation and increase the tendency to establishment of the quasi-force-free structure.

Our estimations seem to show the possibility of dissipation in different features in the solar atmosphere. But, of course, they do not prove that dissipation does exist. Really not only the low conductivity is needed for dissipation, but the existence of currents (curl $H \neq 0$) and a sufficiently high number of particles to support these currents, too. In practice in the solar atmosphere the potential fields (curl $H=0$) are possible, where the currents are absent and the dissipation in these layers equal to zero. On the other hand the direct measurements (SEVERNY, 1965; MOGILEVSKY, 1968) with solar vector magnetograph show that considerable currents exist in the photosphere near sunspots and the question of the field dissipation remains important.

References

BUMBA, V., KOPECKÝ, M., and KUKLIN, G. V.: 1966, *Bull. Astron. Inst. Czech.* **17**, 57.
CHANDRASEKHAR, S.: 1961, *Hydrodynamic and Hydromagnetic Stability*, Oxford University Press.
COWLING, T. G.: 1953, in *The Sun* (ed. by G. P. Kuiper), The University of Chicago Press, Chicago, p. 532.
KIEPENHEUER, K. O.: 1966, in *Atti del Convegno sulle Macchie Solari, Firenze*, Roma, p. 26.
KOPECKÝ, M.: 1957, *Bull. Astron. Inst. Czech.* **8**, 71.
KOPECKÝ, M.: 1958, in *Electromagnetic Phenomena in Cosmical Physics* (IAU Symposium No. 6), Cambridge, p. 513.
KOPECKÝ, M. and KUKLIN, G. V.: 1966, *Bull. Astron. Inst. Czech.* **17**, 45.
KUKLIN, G. V.: 1966, *Rezultaty nabljudenij i issledovanij v MGSS v Sibiri i na Dalnem Vostoke*, vyp. 1, ser. *Fizika Solnca i kosmičeskije luči*, p. 17.
MOGILEVSKY, E. I.: 1968, *Solnechnaja aktivnost*, N 3, Izd. Nauka, Moskwa.
NAGASAWA, S.: 1955, *Publ. Astron. Soc. Japan* **7**, 9.
OSTER, L.: 1968, *Solar Phys.* **3**, 543.
SCHRÖTER, E. H.: 1966, in *Convegno sulle Macchie Solari, Firenze*, Roma, p. 222.
SEVERNY, A. B.: 1965, *Izv. Krymsk. Astrofiz. Observ.* **33**, 34.
STEPANOV, V. E. and PETROVA, N. N.: 1959, *Izv. Krymsk. Astrofiz. Observ.* **21**, 352.
VASILJEVA, G. J.: 1962, *Izv. Pulkovo* **22**, n. 170, 22.