MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Peculiarities of Joule dissipation in the solar atmosphere

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Abstract. The peculiarities of the electric current dissipation in the magnetic flux rope throughout the solar atmosphere from the photosphere to the corona are considered. It has been shown that the dissipation depends on both the magnitude of the electric current and the altitude. The dissipation rate reaches its maximum near an altitude of 2100 km and has a rather complex behaviour. The regions of predominance of Cowling and Spitzer resistances are determined. The consequences of these peculiarities in current problems of solar physics are discussed.

Keywords: solar atmosphere; heating; flares; Couling resistivity; Joule dissipation

DOI: 10.26119/VAK2024.119

1 Introduction

The neutral component of plasma plays an important role in Joule dissipation in the solar atmosphere. For example, a study of the output of a magnetic flux through the partially ionized solar atmosphere by Leake & Arber (2006) led to the conclusion that there is a maximum of Cowling resistivity at an altitude of $h = 1900$ km, but below 1000 km and above 2100 km up to 2300 km the resistivity was assumed to be zero. Here we used the updated model of the solar atmosphere C7 by Avrett & Loeser (2008) extending to the corona and showed that there are some peculiarities of Joule dissipation in the solar atmosphere. We also discuss the consequences of these peculiarities for problems of coronal heating, pre-flare plasma heating, white light flares (WLFs), and the formation of the transition region (TR) and sunspot light bridges (SBs).

2 The problem statement

We consider the dissipation of longitudinal electric currents in magnetic flux tubes (flux ropes) of radius r with foot-points located in the photosphere. It is assumed that the current $I = I_z$ is directed along the flux tube axis z and along the magnetic field B_z. To determine the rate of Joule dissipation, we can use the generalized Ohm's law

$$\mathbf{E} + \frac{1}{c}\mathbf{V} \times \mathbf{B} = \frac{\mathbf{j}}{\sigma} + \frac{\mathbf{j} \times \mathbf{B}}{enc} - \frac{\nabla p_e}{en} + F\frac{\mathbf{f_a} \times \mathbf{B}}{cnm_i\nu'_{ia}} - \frac{F^2\rho}{cnm_i\nu'_{ia}}\left[\frac{d\mathbf{V}}{dt} \times \mathbf{B}\right]. \quad (1)$$

Here $\mathbf{V} = \left(\sum_k n_k m_k \mathbf{V}_k\right) / \left(\sum_k n_k m_k\right)$, $j = I/\pi r^2$, $\rho = n_a m_a + n_e m_e + n_i m_i$, $p = p_a + p_e + p_i$, $\sigma = ne^2 / \left[m_e(\nu'_{ei} + \nu'_{ea})\right]$ is the Spitzer conductivity, $\nu'_{kl} = \left[m_l/(m_k + m_l)\right]\nu_{kl}$ is the effective collision frequency, $F = \rho_a/\rho$, $n_i = n_e = n$, $\mathbf{f_a} = \nabla p_a$. According to (Zaitsev et al. 2023), the rate of Joule dissipation per unit volume of the flux tube is

$$q = \left(\mathbf{E} + \frac{1}{c}\mathbf{V} \times \mathbf{B}\right)\mathbf{j} = \frac{j_z^2}{\sigma} + \frac{F^2}{(2-F)c^2 n m_i \nu'_{ia}}(\mathbf{j} \times \mathbf{B})^2 = \frac{j_z^2}{\sigma}, \quad (2)$$

where $B_\varphi \approx 2I/cr$. To compare the dissipation rates due to the Spitzer and Cowling resistivities we represent eq. (2) as

$$q = \frac{j_z^2}{\sigma}\left(1 + K_{cow}\right), \quad K_{cow} = \frac{F^2}{1-F}\,\omega_e\tau_e\omega_i\tau_{ia}, \quad (3)$$

where $\omega_e = \frac{eB_\varphi}{cm_e}$, $\omega_i = \frac{eB_\varphi}{cm_i}$, $\tau_e = \frac{1}{\nu'_{ei}}$, $\tau_{ia} = \frac{1}{\nu'_{ia}}$.

3 Results

To obtain the altitude dependence of the rate of Joule dissipation $q(h)$ in a flux tube with $r = 10^8$ cm from the photosphere to corona, we used the C7 atmosphere model by Avrett & Loeser (2008). We showed that the Cowling resistivity as well as the curves of $q(h, I)$ are more complicate compared to the results obtained in Leake & Arber (2006). In particular, $q(h, I)$ exhibits a clear maximum at an altitude of $h = 2100$ km for currents $I = 3 \times 10^9$ A, 3×10^{10} A, and 3×10^{11} A corresponding to the TR (see Fig. 2 in Zaitsev et al. (2023)), such that at $h \leq 1000$ km, the Cowling resistance is smaller than that of Spitzer ($K_{cow} < 1$) for current $I < 10^{11}$ A. This is caused by the decrease in the Hall parameter $\omega_i \tau_{ia}$ in eq. (3). In other words, the Cowling resistance decreases due to the increasing role of interparticle collisions as the atmospheric density increases.

In the corona, the relative fraction of neutral atoms at a temperature of $T = 10^6$–5×10^6 K is extremely small, $F \approx 10^{-7}$ (Zaitsev et al. 2023). However, at high current values, the Joule dissipation is determined by the Cowling resistivity at a current of $I \geq 10^9$ A. This occurs because the Ampère force accelerates the ions to speeds significantly greater than the relative speed of the electrons and ions in the current. In this case, the accelerated ions give up their energy to the neutrals in one collision, while the "e-i" energy exchange occurs m_i/m_e times slower.

The threshold value of the electric current can be estimated when the Joule dissipation $q = K_{cow}\, j_z^2/\sigma \approx 2.2 \times 10^{-9} I^4/(n_e^2 r^6 T^{3/2})$ ergs cm^{-3} s^{-1} exceeds the radiation losses $q_r \approx 10^{-19} n_e^2 T^{-1/2}$ ergs cm^{-3} s^{-1}, $10^5 < T < 10^7$ K. Taking $T = 1.6 \times 10^6$ K, $n_e = 7.5 \times 10^7$ K at $h = 7 \times 10^4$ km we obtain that $q > q_r$ requires $I > 2.3 \times 10^9$ A.

4 Ring currents in the foot-points of flux tubes and white light flares

Ring or Hall currents j_φ at the foot points of magnetic flux tubes arise as a result of "gearing" of the vertical component of the magnetic field B_z and the radial component of the photospheric convection velocity V_r (Zaitsev & Stepanov 2021):

$$j_\varphi = \frac{\sigma V_r B_z}{c(1 + K'_{cow})}, \quad K'_{cow} = \frac{F^2}{2 - F}\, \omega_e \tau_e\, \omega_i \tau_{ia}. \tag{4}$$

Here instead of ω_e and ω_i in eq. (3) we use $\omega_e = \frac{eB_z}{cm_e}$, $\omega_i = \frac{eB_z}{cm_i}$, i.e., K'_{cow} does not depend on the magnitude of the ring current, but is determined by the magnitude of the longitudinal magnetic field B_z. Hence, the rate of Joule dissipation is determined as $q = \frac{j_z}{\sigma}(1 + K'_{cow})$.

To determine the value of K'_{cow} at $h = 300$ km, where the white light flares are located, we assume that $B_z \approx 2 \times 10^3$ G, $T = 15000$ K, $n_a \approx 10^{16}$ cm^{-1} (Zaitsev & Stepanov 2021) and estimate $n_e = 2 \times 10^{15}$ cm^{-3} using the modified Saha formula we found $K'_{cow} \approx 0.07$, i.e. the Spitzer resistivity plays a decisive role in the current dissipation. The threshold for generating WLFs emission is $q(t) \geq q_r = (n_a + n_e)n_e\chi(T)$, where the radiation-loss function is $\chi(T) = (1.397 \times 10^{-8}T)^{6.15}$ for $8 \times 10^3 < T < 2 \times 10^4$ K. The inequality $q(T) \geq q_r$ means that the heating can occur at $V_r B_z \geq 10^8$ cm s^{-1} G (De Pontieu et al. 2011). Assuming that $B_z = 10^3$ G in the sunspot penumbra, the heating can occur at $V_r \geq 10^5$ cm s^{-1}, which exceeds the typical convection velocity of 3×10^4 cm s^{-1}. This may be the reason why white light flares are so rare events.

5 Consequences of peculiarities in Joule dissipation

5.1 Maximum in Joule dissipation: Coronal heating and TR formation

Dissipation rate maximum at $h \approx 2100$ km leads to very important consequences. First of all, it is dealing with the heating of solar corona, which is one of the important unsolved problems in astrophysics. Solar corona loses 10^{28} ergs s $^{-1}$ due to radiation and thermal conductivity. Hot coronal loops are unlikely to be sources of heating due to the low electron thermal conductivity through the magnetic field. The most likely sources of heating are open magnetic flux tubes, such as type II spicules, extending into the corona (De Pontieu et al. 2011; Zaitsev et al. 2020). Heating of type II spicules in the TR, where the rate of Joule dissipation increases, may compensate for the rate of heat loss from the corona. Estimations by Zaitsev et al. (2020) have shown that this requires about 10^4 type II spicules i.e. about 1% spicules observed simultaneously on the Sun.

Type II spicules may also be responsible for TR formation. We showed in Zaitsev et al. (2023) that Joule scattering in type II spicules is very effective for the formation of the transition layer TR, and its thickness Δz depends on the magnitude of the electric current:

$$\Delta z \approx \sqrt{\frac{4k_e T_c^{7/2}}{7q_{max(I)}}}, \tag{5}$$

where $k_e \approx 0.9 \times 10^{-6}$ erg cm^{-1} K$^{-7/2}$, T_c is the coronal temperature. For example, at $I = (3-5) \times 10^{10}$ A, eq. 5 gives $\Delta z \approx 23$–230 km.

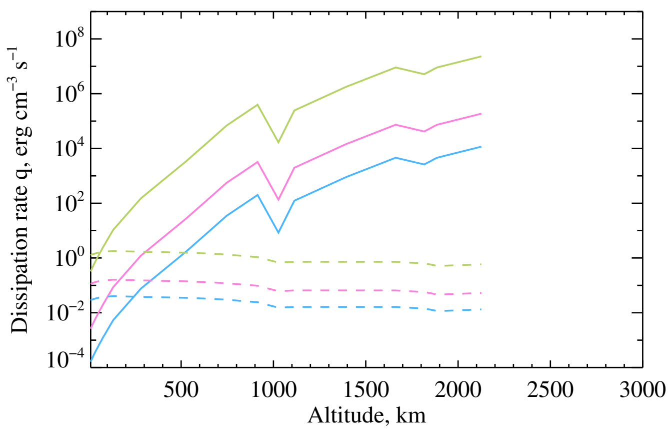

Fig. 1. Dissipation rates vs altitude for electric current magnitudes $I = 1.5 \times 10^{11}$ A (blue curves), 3×10^{11} A (magenta curves), and 10^{12} A (green curves) using the Maltby-M model with $r = 7 \times 10^7$ cm. The dots indicate dissipation rate under the Spitzer conductivity while the solid lines correspond to Cowling conducivity.

5.2 Formation of sunspot light bridges

Among the sunspots, a special place is occupied by light bridges (LBs), the sizes, shapes and brightness of which are very diverse. The formation of a LB begins usually at one edge of the umbra in the form of a bright thin (≤ 1 arcsec) rope which gradually grows and divides the umbra into small pieces.

In our model the LB has the form of a low-lying magnetic flux rope with the foot-points rooted in the penumbra. The electric current generated at the foot-points of the LB due to convective motions in the penumbra is closed by the surface return currents. We assume also that the plasma parameters in the LB correspond to the Maltby-M umbral core model by Maltby et al. (1986). The result of calculations is presented in Fig. 1. To estimate the Joule dissipation rate for LB heating, we used the observed LB parameters by Louis et al. (2021): the length is ≈ 14 arcsec $\approx 10^9$ cm, radius is $\approx$ 1arcsec $\approx 7 \times 10^7$ cm, height of the top is $h \approx 10^3$ km, $T \approx 6800$ K, $B_z \approx 1.3$ kG, and the average electric current density $j_z \approx 0.1$ A m^{-2} corresponding to the current $I_z \approx 1.5 \times 10^{11}$ A. The result $q \approx 3$ erg cm^{-3} s^{-1} is in agreement with the observed value. The formation of LBs can be caused by a weakening of the magnetic field in the sunspot and/or a decrease in magnetic flux but not by the emergence of a new magnetic flux (Louis et al. 2021).

5.3 Heating of pre-flare plasma

Another possible evidence in favor of Joule dissipation in low solar atmosphere follows from GOES, RHESSI, SDO/AIA, and Solar Orbiter/STIX observations. The "Hot onset" interval (10–17 MK) increases at the initial soft X-ray and before any detectable hard X-ray emission Hudson et al. (2021). From the emission measurements, the electron density was estimated to be 5×10^{11} cm^{-3}, and attention was drawn to the fact that the onset of soft X-ray emission occurs in the chromospheric foot-points of low-lying loops, and not in coronal structures. From the other side, the electric currents up to $I \approx 10^{12}$ A were measured in the flare precursor (Wang et al. 2017). Thus, "hot onset" phenomena can be a consequence of the Joule heating of the low solar atmosphere.

6 Summary

1. The dependence of the Cowling resistivity on the altitude and current value is not pulse-like (Leake & Arber 2006), but is much more complex.
2. Despite the low density of neutrals in the corona, $n_a/n_e \sim 10^{-7}$, the Cowling resistivity exceeds the Spitzer resistivity at a current of $I \geq 10^9$ A.
3. In the photosphere and lower chromosphere, the Spitzer resistivity dominates over the Cowling resistivity.
4. Joule scattering features can explain a wide variety of solar phenomena, such as coronal heating, hot starts of progenitors, white light flares, and the formation of the transition region and sunspot light bridges.

Funding

This study was supported by the Russian Science Foundation grant No. 22-12-00308.

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