On the Role of Type-II Spicules in Heating and Replenishing the Solar Corona with Hot Plasma

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Solar corona losses: radiation ≈ 5×10^{27} erg/s; thermal conductivity ≈ 10^{28} erg/s
mass loss ≈ 10^{9}-10^{10} kg/s How to replenish?

Existing heating models:

Corona as a whole:

Acoustic, by sound waves, P=3-5 min (Kuperus et al. ARAA 1981)

Dissipation of MHD waves from highly turbulent chromosphere (Chashei, Shishov, Astr. Rep. 1989)

Magnetic reconnection in chromosphere (Litvinenko, ApJ 1999) But: 2-3 orders of magnitude less than required

Micro- and nano-flares (Parker, ApJ 1988; Schmelz at al. ApJ 2009)

a few hundred papers

Local: Coronal magnetic loops

Anomalous current dissipation *in situ* (Rosner et al. ApJ 1978); Nonlinear taring-mode reconnection (Galeev et al. ApJ 1981)

Field aligned DC Joule dissipation (Spicer, Int. Conf. Heidelberg, 1991; Zaitsev & Shibasaki, Astr. Rep. 2005)

MHD waves (Ionson, ApJ 1982, Hollweg, Int. Conf. Heidelberg, 1991; Ofman et al. ApJ 1995, Hood, LNPh 2010)

Parametric resonance (Zaitsev & Kislyakova, Astr. Rep. 2010).

thousands papers

Observations with High-resolution Coronal Imager (Hi-C) and Interface Region Imaging Spectrograph (IRIS)

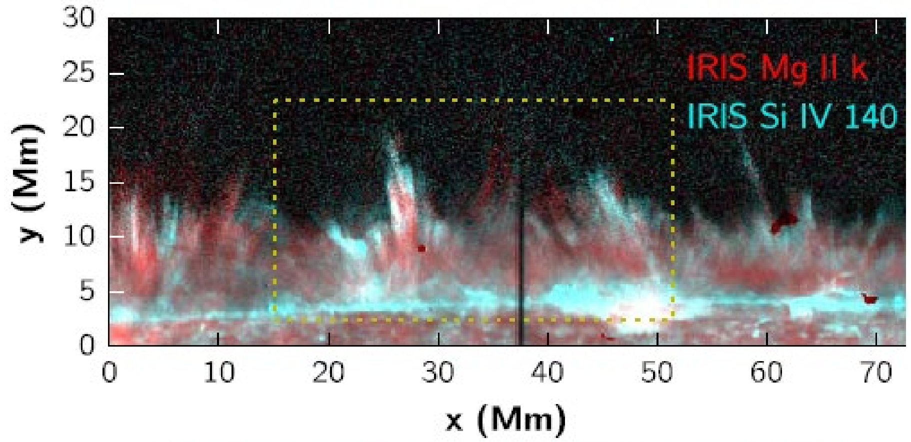
Peter et al. A&A 2013, Pereira et al. ApJ 2014:

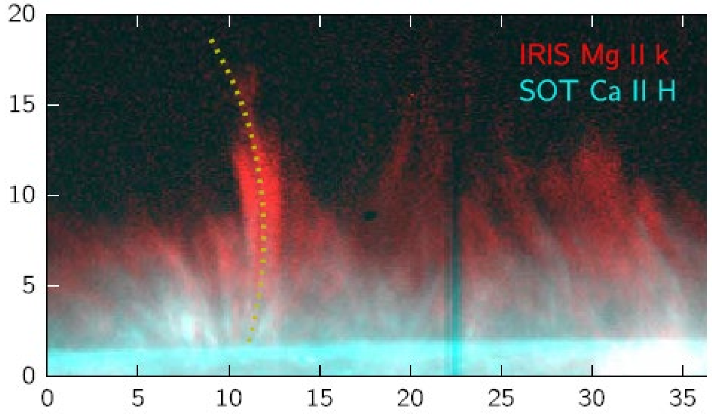
The solar corona up to heights of 10–20 thousand km is densely filled with magnetic loops and a “bush” of open magnetic flux tubes associated with spicules.

Type I spicules usually in active regions.

Type II spicules far from active regions: in coronal holes and in periods of quiet Sun.

Type II spicules are more dynamic: lifetime 10–150 s and heat up to ~2×10^6 K, sending material through the chromosphere at a speed of 50–150 km/s.





De Pontieu et al. Science 2011:

Type II spicules - a probable source of corona heating

but what is the mechanism for heating spicules?

Zaitsev, Stepanov, Kronshtadtov (Solar Phys. 2020): Main limitation for heat transfer from the magnetic loops to corona is a huge, by 10-12 orders of magnitude, decrease in heat transfer ⊥ B as compared to ∥ B.

Most favorable conditions: 10^22 erg/s is transferred from single loop to the corona. To heat the corona, a million permanently working loops are needed.

Magnetic loops can heat only local coronal areas.

And what about spicules?

Braginskii (Rev. Plasma Phys. 1, 1965):

$$q_T = -\kappa_{\|}^{i} \nabla_{\|} T - \kappa_{\perp}^{i} \nabla_{\perp} T + \frac{5}{2}\frac{nT}{m_i \omega_i}[\mathbf{b}\, \nabla T]$$

$$\omega_i \tau_i \gg 1, \quad \omega_i = 9.6\times 10^3 B \quad \tau_i = 0.9 T^{3/2}/n$$

$$\frac{\kappa_{\|}^{i}}{\kappa_{\perp}^{i}} \approx (\omega_i \tau_i)^2 \qquad (\omega_i \tau_i)^2 \approx 10^{12}$$

We show that convection of the photosphere plays a decisive role in coronal heating and generation of electric currents in spicules (Zaitsev et al. Solar Phys. 2020; Geomag & Aeron 2021)

emf due to convection at the foot-point of spicule

$$\Xi = \frac{l_1}{\pi c r_1^2}\int_0^{r_1} V_r B_\varphi 2\pi r\, dr \approx \frac{|\overline{V}_r| I l_1}{c^2 r_1}$$

Slow current changes are described by the equation

$$\frac{1}{c^2}\frac{d(LI)}{dt} + RI = \Xi \qquad R(I) = \frac{3\xi l_1 F^2 I^2}{\pi r_1^4 (2-F) c^4 n m_i \nu'_{ia}}$$

Established electric current flowing along the spicule:

$$I = \left[\frac{|V_r| \pi r^3 c^2 n m_i (2-F) l_1 \nu'_{ia}}{1{,}5 F^2 l}\right]^{1/2}$$

At the spicule foot-point $n = 10^{11}$-10^{13} cm^{-3}, $n_a = 10^{15}$-10^{17} cm^{-3}, $T = 10^4$ K,

$V_r = 10^4$-10^5 cm/s, $r = 10^7$ cm. Current in the magnetic flux tube $I \approx 3\times10^9$-3×10^{12} A.

Type II spicules as open magnetic structures

We choose spicule model as a plasma cylinder (Roberts 1979; Hollweg 1982).

Current dissipation due to Cowling resistance heats up the spicule not only in the chromosphere, but also in the corona ($T \geq 10^6$ K)

$$q = \frac{j_z^2}{\sigma} + \frac{F^2 B_\varphi^2 j_z^2}{(2-F)c^2 n m_i \nu_{ia}} \qquad F(T) \approx 0.15/T$$

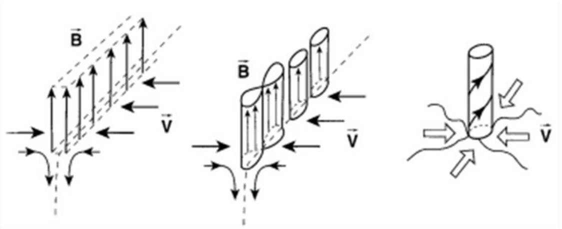
• (Verner & Ferland, ApJS 1996)

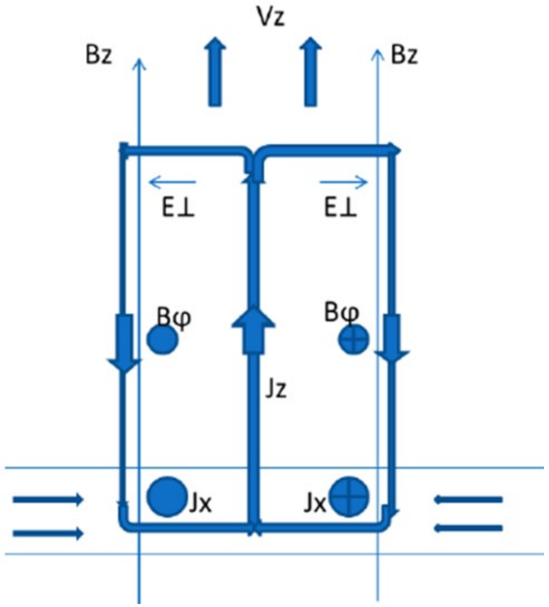
$$q = q_{Spit} + q_{Cow} = \frac{I_z^2}{\pi^2\, r_0^4\, \sigma} + 10^{-9} \frac{I_z^4}{n^2\, r_0^6\, T^{3/2}} \qquad j_z = \frac{I_z}{\pi r_0^2}$$

$$\frac{q_{Cow}}{q_{Spit}} \approx 10^{-1} \frac{I_z^2}{n^2\, r_0^2} \approx 10^4 - 10^6$$

for $I_z = (10^9 - 10^{10})A, \quad r_0 = 10^7 cm, \qquad n = 10^9 cm^{-3}$

$q_{Cow} = q_{Spit}$ at $I = 10^7 A$





Spicule electric circuit diagram: J_z - tube current, generated emf, J_X - Hall current, due to charge separation field in the flow V_r of photospheric plasma, $E_\perp = -(1/c)V_z B_\varphi$ - component of the electric field, forming a surface current, closing the circuit.

Spicule heating by electric currents

Heating rate: $q = \frac{j_z^2}{\sigma} + \frac{F^2 B_\varphi^2 j_z^2}{(2-F)c^2 n m_i \nu_{ia}'} \approx 2\cdot 10^{-9} \frac{I^4}{n^2 r_0^6 T^{3/2}}$ erg/s cm^3

Radiation losses at $10^5 K < T \le 2\cdot 10^7 K : q_r \approx \chi_0 n_e^2 T^{-1/2}, \quad \chi_0 = 10^{-19}$

From $q \geq q_r$ → current heats only the tip of spicule with $n \le 3{,}8 \cdot 10^2 \frac{I}{r_0^{1{,}5} T^{0{,}25}}$ см$^{-3}$

For $I = (10^{10} - 10^{12})\text{A}$, $r_0 = 2{,}5 \times 10^7$ cm the spicule tip heats up to $T = 5 \times 10^6 K$

Heat flux from spicule to the corona $Q_{Tsp} = \kappa_{\parallel}^e \frac{\Delta T}{\Delta z} \pi r_0^2 \approx \frac{0.9\times 10^{-6} T^{\frac{7}{2}}}{\Delta z} \pi r_0^2 \text{ erg s}^{-1}$

For $T = 5 \times 10^6 K, r_0 = 3 \times 10^7$ cm, $\Delta z = 5 \times 10^8$ cm ⟹ $Q_{Tsp} \approx 10^{24}$ erg/s

To compensate for coronal losses ($Q_{Tsp} \approx 10^{28}$ erg/s) ~10^4 hot Type-II spicules are required

i.e. ~ 1 % of the number of spicules simultaneously observed on solar disk.

Plasma flows from Type II spicules

Zaitsev, Stepanov, Kronshtadtov (Sol. Ph. 2020): Heating of the spicule foot-point due to the dissipation of the ring (Hall) current gives a pressure jump and plasma flow from the spicule.

Sporadic increase in pressure is by additional heating of the foot-points of the spicules by Hall currents due to increase in the velocity of convection driven by 5-min oscillations or the Rayleigh-Taylor instability.

Mass flux from the spicule is $\rho V_z^{max} \approx (5\text{-}20)\times 10^{-9}$ g/cm^{2}s. At S = 3.6x10^{17} cm^2 and 10^4 spicules, replenishing rate is (2-7)x10^{11} g/s. This coincides with the solar wind mass flux (5-10) x10^{11}g/s through a sphere of radius 1 a.u. at n = 5-10 cm^{-3} and V = 300-400 km/s near the Earth's orbit.

To estimate the flow rate we use a model of a cylindrical flux tube with a constant flow rate and ρ = const. The equation for the outflow velocity (Landau & Lifshitz, Fluid Mechanics):

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right) = \frac{1}{\eta}\frac{\partial p}{\partial z} + \frac{\rho g}{\eta}$$

For p и ρ = const over the cross section of the flux tube

$$V_z = \frac{1}{4\eta}\left(\left|\frac{\partial p}{\partial z}\right| - \rho g\right)(2R^2 - r^2)$$

$|\partial p/\partial z| = \xi\rho g$ (ξ= 2-5), $T = 3\times 10^6 K$, $n = 10^{11}\mathrm{cm}^{-3}$,

$R = 6\times 10^7$ cm gives $V_z^{max} \approx 25 - 100$ km/s

Energy contribution of a spicule in 100 s ≈ 2×10^{25} - 10^{28} erg

Conclusions

The main source of heating for the corona is photospheric convection.

Photospheric flows concentrate the magnetic field at the boundaries of supergranules up to B ~ kGs and interacting with this field generate electric currents of 10^{10} - 10^{12} A in spicules.

Current dissipation increases significantly due to incomplete ionization of the plasma and the associated Cowling conductivity. This has two important effects:

- Plasma heating in Type II spicules up to T ≈ (2-6) MK
- The appearance of jets of hot plasma from the spicules into the corona

To compensate for radiation and thermal conduction losses and replenishing the solar corona with hot plasma ≈ 10^4 hot spicules are required.

Magnetic loops are capable of heating the solar corona only locally.