THE 15TH RUSSIAN-CHINESE WORKSHOP ON SPACE WEATHER

September 9-13, 2024, Irkutsk, Russia

The Rayleigh–Taylor Instability as a Trigger of Solar Flares

A.V. Stepanov, *Pulkovo Observatory and Ioffe Institute, St. Petersburg, Russia*

V.V. Zaitsev, *Instutute of Applied Physics, Nizhny Novgorod, Russia*

C. de Jager: Flares are different

Flare models are also quite different («standard» CSHKP, current-interruption,...)

"Standard" model is realized in 20-30% flares

There are several flare triggers under discussion

- Thermal trigger (Syrovatskii 1976; Ledentsov 2021)
- Topological trigger (Somov 2009; Kusano et al 2012)
- Loop-loop interaction (Kumar et al 2010)
- Prominence trigger (Pustilnik 1973; Zaitsev & Stepanov 1992)

We suggest the R-T instability as a flare trigger

Two problems in flare physics

- How to heat plasma for10 s
- How to accelerate huge number of charged particles

Hoyng et al (1976): Long-standing 'number problem' in the solar flare physics

The impulsive solar flare produce ~ 10^{37} >20 keV ellectrons/s 10-100 s.
Total number of electrons *Ne* (> 20 keV) ≈ 10^{39} (Miller et al. JGR 1997).

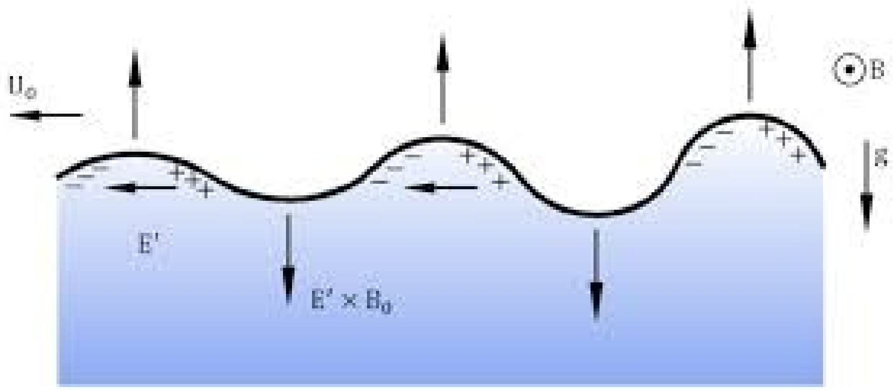
This exceeds the electron number stored in the coronal part of a magnetic loop : (1-5)×10^{37} (Emslie & Hénoux, 1995).

In 'giant flares' number of >20 keV electrons can be as high as 10^{41} (Kane et al. 1995).

Bulk loop plasma must be in acceleration regime?

Way out: Acceleration in the chromosphere?

Magnetic Rayleigh-Taylor Instability
(great role in astrophysics)



Kruskal & Schwarzschild (1954)
Chandrasekhar (1981)

$$\omega^2 = -gk\frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} + \frac{2B_0^2 k_x^2}{\mu(\rho_1 + \rho_2)}$$

Density Evolution of Returning Filament Blobs 7

CME matter
fell back to
the surface

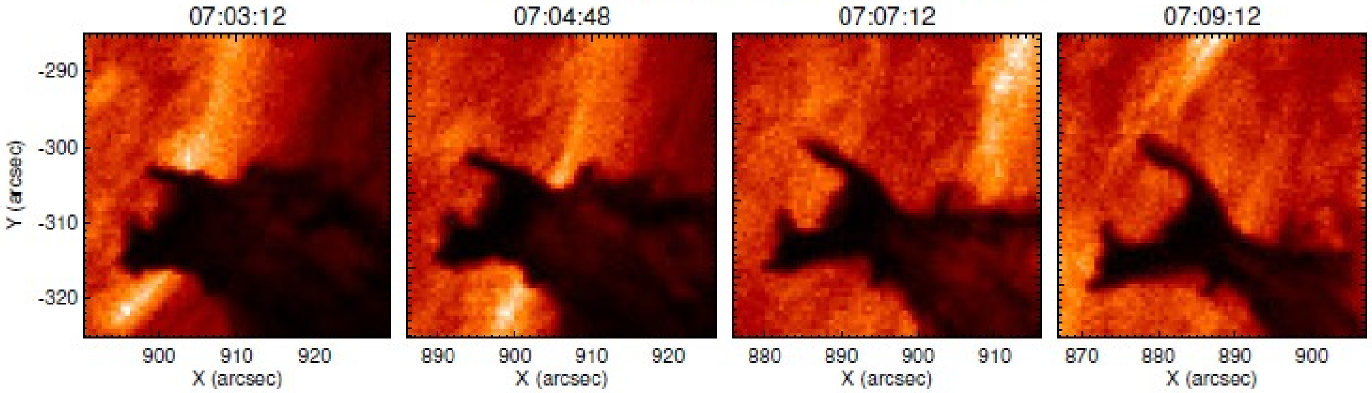
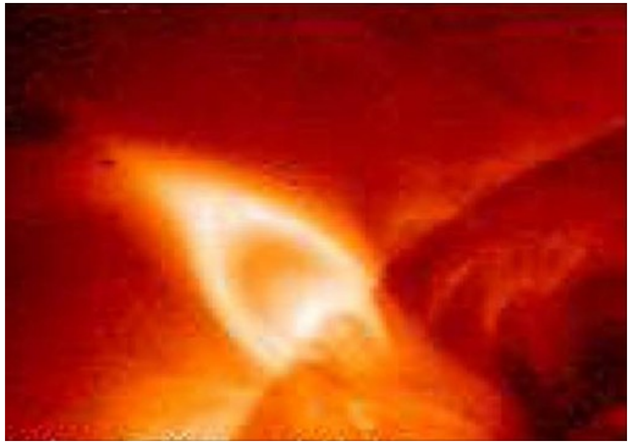


FIG. 10.— Evolution of blob morphology: 171 Å images of the first 4 images in Figure 9. Notice the back-end of the blob does not appear in the first N_H map; this is due to dark material lying in the background which leads to little or no difference in intensity between the blob/background images.

The Rayleigh-Taylor instability
(Ballooning mode)



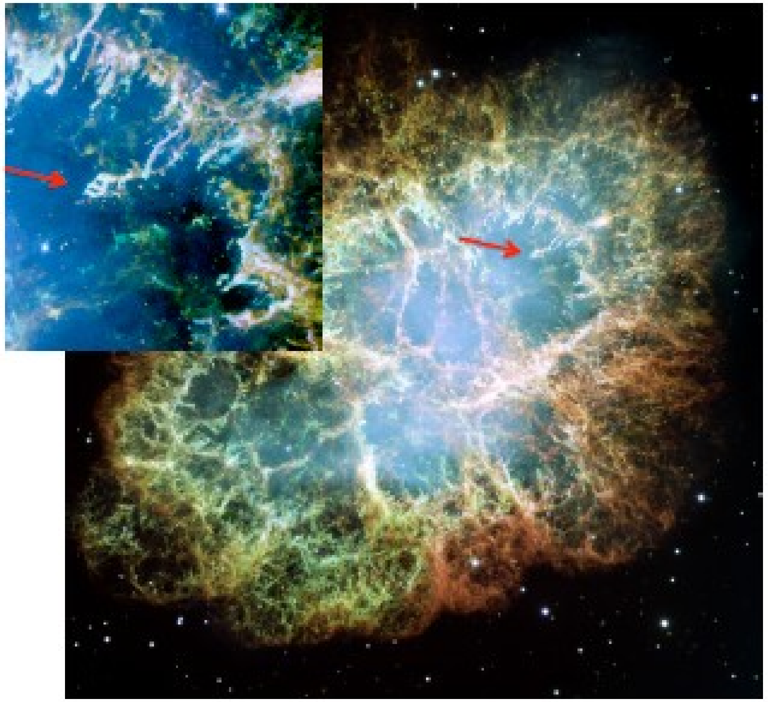


FIG. 2.— The Rayleigh-Taylor instability as observed in the Crab Nebula. Credit: NASA, ESA and Allison Loll/Jeff Hester (Arizona State University). Acknowledgement: Davide De Martin (ESA/Hubble)

We apply the RTI to the typical magnetic flare configuration – a flare loop.

Two cases will be considered

- RTI near loop foot points
- RTI at loop top induced by prominence

Consequences of RTI as a flare trigger:

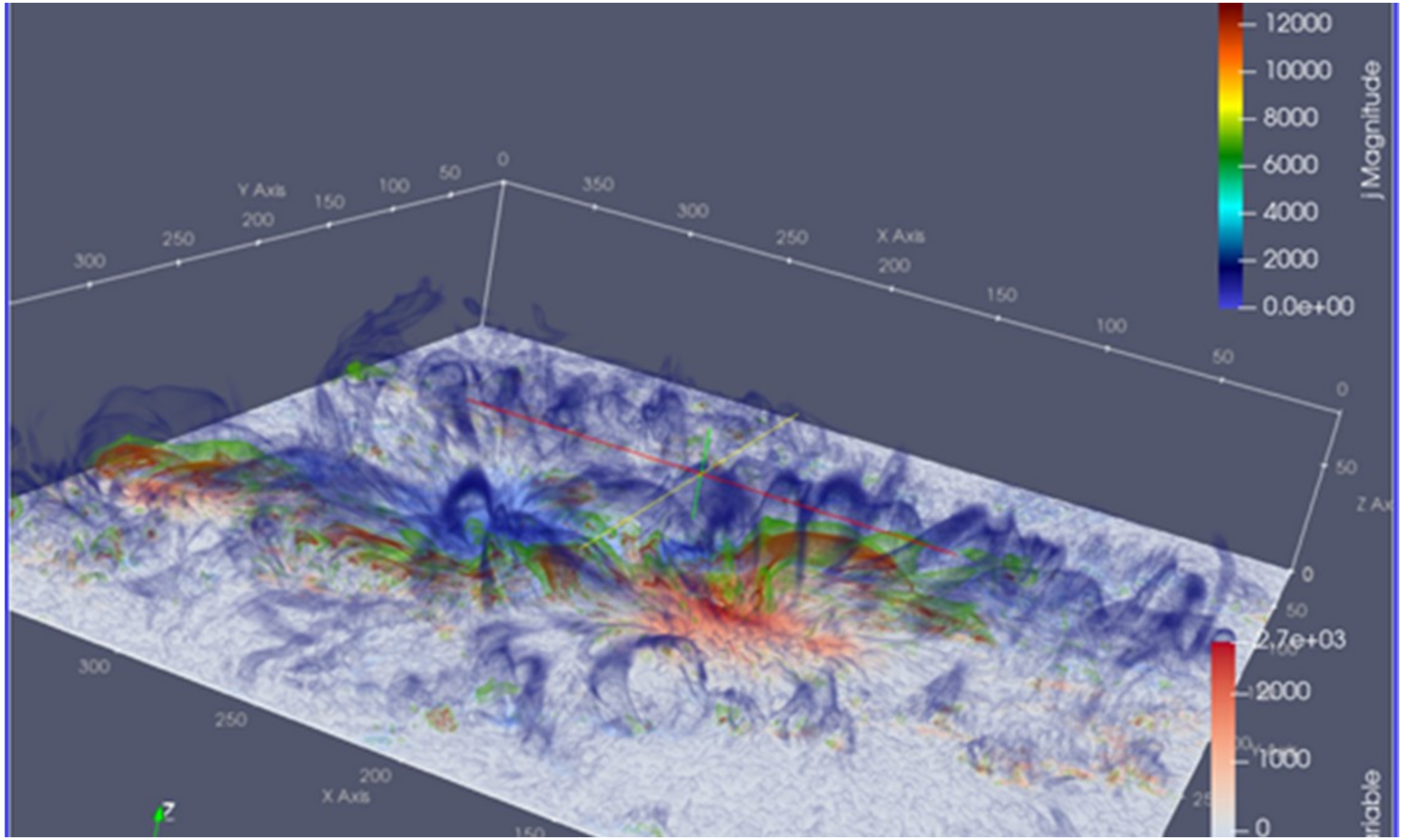
- plasma heating due to Joule dissipation

- charged particle acceleration

Melnikov et al (ApJ 2024)

Reconstruction of electric currents in active region using NLFFF approximation based on SDO/HMI data

$$\boldsymbol{j} = c/4\pi \cdot rot\ \boldsymbol{B}$$

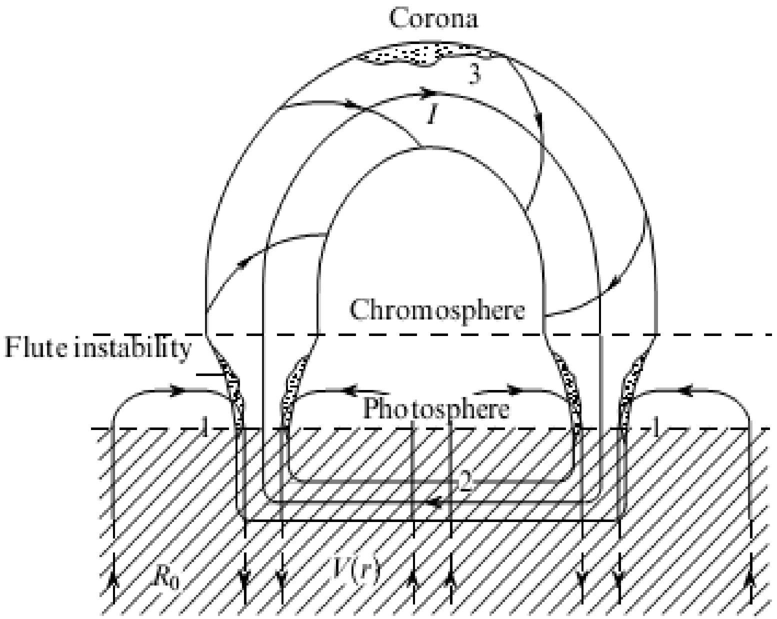


Great currents I = 10^{11}-10^{12} A in magnetic structures at h=2000-8000 km
Medium currents I = 10^{9}-10^{10} A in high loops (up to 30 000 km).

Current-carrying loops organized into arcades under which the flux ropes are located with quite strong electric currents

Loop formed by photosphere convection

Zaitsev & Stepanov (1992, 2000)



Loop footpoints – in nodes of supergranulation cells, Δ ≈ 30000 km.

Convection velocity $V_r \approx 0.1$ -0.5 km/s

Generation of current in region 1

$\omega_{ci} \ll \nu_{in}$, $\omega_{ce} \gg \boldsymbol{\nu}_{en}$ →

charge separation →

electric field E_r with B_z give Hall current j_φ, and as a result B_z is grow.

Magnetic field grows up to moment when field enhancement due to convection is equal to the magnetic field diffusion.

Max magnetic field is determined by energy×time of convective motion.

e.m.f. $$\Xi = \frac{l}{\pi c r^2}\int_0^r V_r\, B_\varphi\, 2\pi r dr \approx \frac{|\bar{V}_r| I l}{c^2 r}$$

$$\boxed{\frac{1}{c^2}\frac{d(LI)}{dt} + RI = \Xi}$$

Alfvén & Carlqvist, Solar Phys. 1967

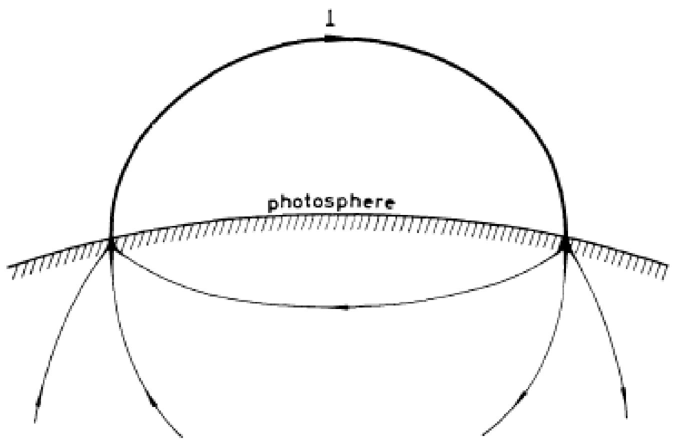
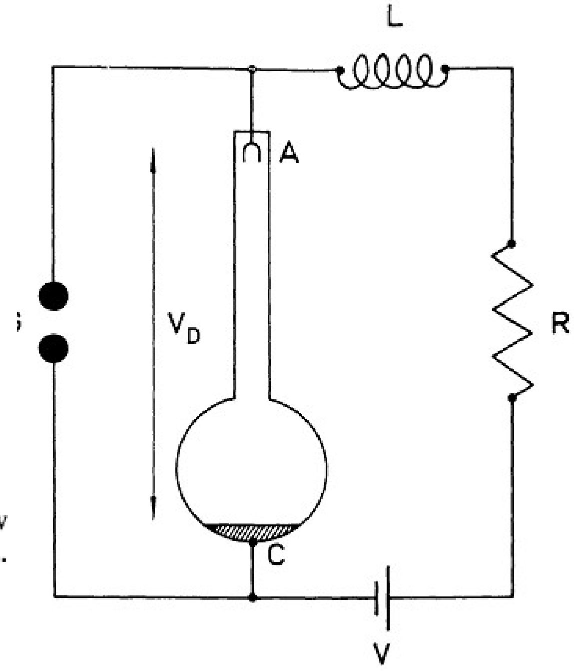


Fig. 4. General pattern of electric currents in the solar atmosphere. The current exists in narrow channels passing through the solar atmosphere and is closed in the photosphere or in deeper layers.

CURRENTS IN THE SOLAR ATMOSPHERE, AND SOLAR FLARES



current $I = 10^{11}$ amps

inductance $L = 10\ H$

time constant $\tau = 10^3$ sec

voltage drop over the interruption $V = L\, dI/dt \approx LI/\tau = 10^9$ volts

magnetic energy of the circuit $W = \frac{1}{2} LI^2 = 0.5 \cdot 10^{23}$ joules $= 0.5 \cdot 10^{30}$ ergs

Current-interruption model for solar flares

Stenflo (1969); Sen & White (1972); Spicer (1977); Kan, Akasofu, Lee (1982); Ionson (1982); Zaitsev & Stepanov (1991); Stepanov & Tsap (1993); Melrose (1995); Wheatland & Melrose (1995); Zaitsev, Urpo, Stepanov (2000)

Energy release in partially ionized plasma:
Important role of Cowling resistivity (Zaitsev, Urpo, Stepanov A&A 1988, 2000)

From generalized Ohm's law

$$\mathbf{E}^{*} = \frac{\boldsymbol{j}}{\sigma} + \frac{\boldsymbol{j}\times\boldsymbol{B}}{enc} - \frac{\nabla p_e}{en} + \frac{F}{cnm_i\nu_{ia}}\left[\left(n_a m_a \boldsymbol{g} - \nabla p_a\right)\times\boldsymbol{B}\right] - \frac{F^2}{cnm_i\nu_{ia}}\rho\frac{d\boldsymbol{V}}{dt}\times\boldsymbol{B}$$

Joule dissipation q = ***E*j***

$$q = \left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{V}\times\boldsymbol{B}\right)\boldsymbol{j} = \frac{j_z^2}{\sigma} + \frac{F^2}{(2-F)c^2 nm_i\nu_{ia}'}(\boldsymbol{j}\times\boldsymbol{B})^2$$

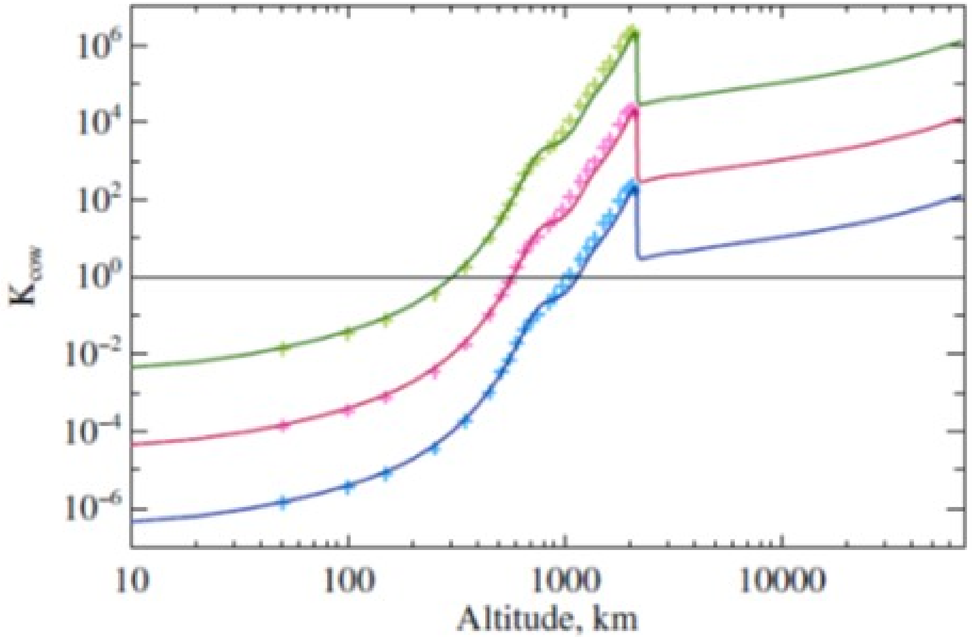
σ - Spitzer conductivity,
F – relative neutral density
j×**B** - Ampere force

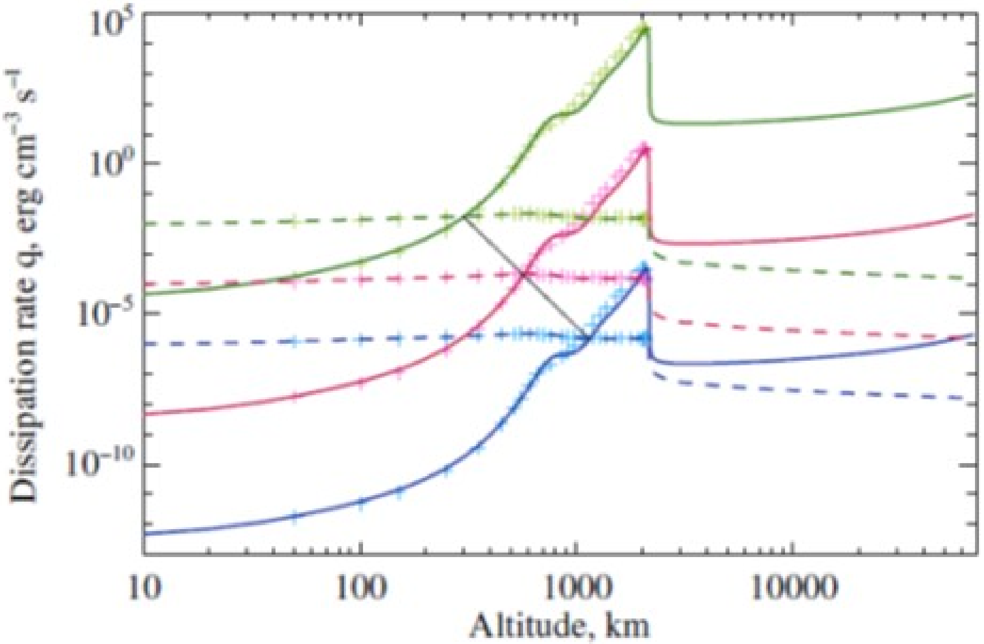
The energy release power

$$\frac{dW}{dt} = \left[\frac{m_e(\nu'_{ei}+\nu'_{ea})d}{e^2 nS} + \frac{2\pi F^2 I^2 d}{c^4 nm_i\nu'_{ia}S^2}\right]I^2 = \left[R_c + R_{nl}(I)\right]I^2$$

about 8-10 orders larger (due to Cowling resistance) compared to the Spitzer case.

Stepanov et al (2024): Joule dissipation in solar atmosphere (model by Avrett & Louser, 2008)





3×10^{11} A

3×10^{10} A

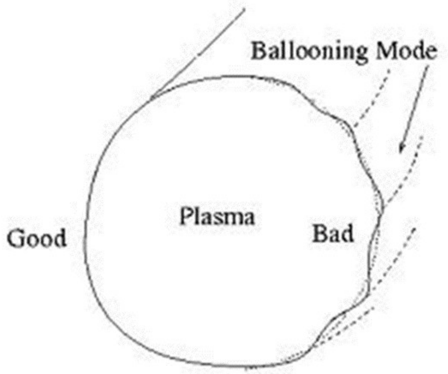
3×10^{9} A

On the left: K_{cow} *vs* altitude and current value. Cross-sign curves – model by Vernazza et al (1981).

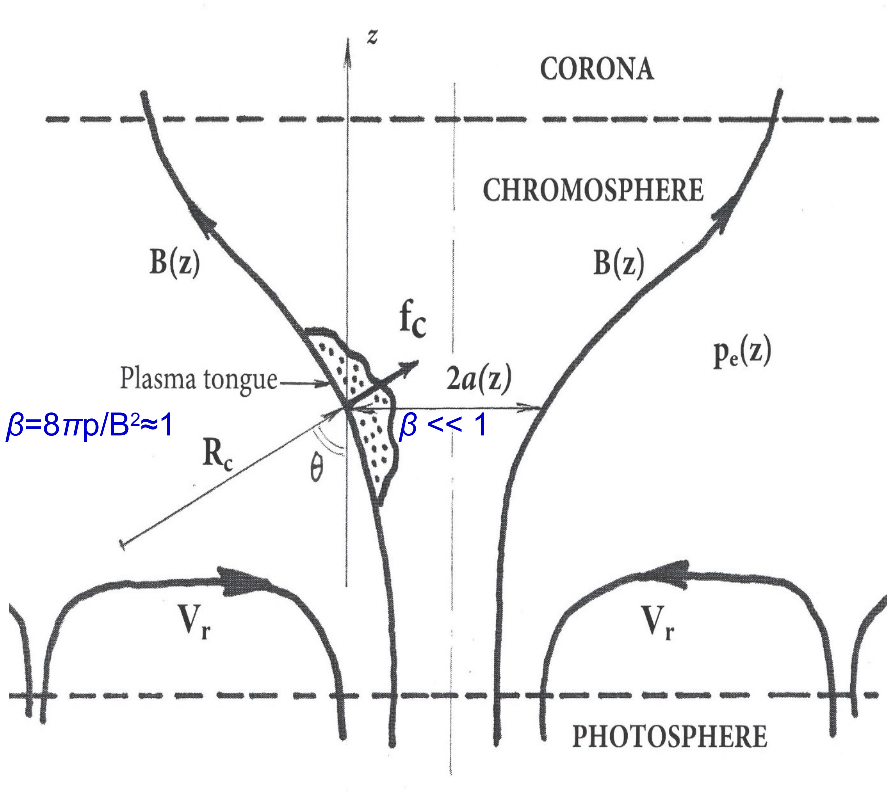
On the right: The Joule dissipation rates due to the Cowling (solid curves) and Spitzer (dashed curves) *vs* altitude and current value.

$$q = \frac{j_z^2}{\sigma}\left(1 + K_{cow}\right) \qquad K_{cow} = \frac{F^2}{(2-F)}\,\omega_e\tau_e\,\omega_i\tau_{ia} \qquad \omega_e = \frac{eB_\varphi}{cm_e},\ \omega_i = \frac{eB_\varphi}{cm_i},\ \tau_e = \frac{1}{\nu'_{ei}},\ \tau_{ia} = \frac{1}{\nu'_{ia}}.$$

The Rayleigh-Taylor instability at the foot-point of a current-carrying magnetic loops (ballooning mode)



Zaitsev & Stepanov (Solar Phys. 2015)



R-T instability condition:

$$\frac{nT}{2(n+n_a)T_e} + \frac{8\Lambda V_r^2(t)}{a^2 g} > 1$$

$$\vec{f}_c = \frac{2nk_B T}{R_c^2}\vec{R}_c \quad \Lambda = \frac{k_B T_e(z)}{m_i g}$$

$$B_z(r,t) \;,\quad \mathrm{B}_\varphi(r,t) \longrightarrow I_z(z,t)$$

Pre-heating of the R-T instability domain to $T \approx 10^4$ K by the electric current in a loop is needed.

Chromosphere pre-heating for ballooning instability

Modified Saha formula (Brown, 1973) :

$$\frac{(n+n_a)x^2}{1-x} = 7.2\times10^{18}T^{0.5}\exp\left(-6.583-\frac{1.185\times10^5}{T}\right)$$

$$x = n/(n+n_a)$$

Temperature to which the chromosphere should be heated for ballooning instability *($n > n_a$)*

.

<u>Chromosphere density</u>

$$n_{tot} = n+n_a = 10^{16},\ 10^{15},\ 10^{14}\ cm^{-3}$$

<u>Temperature should be as high as</u>

$$T \approx 2\times10^4 K,\ 1.5\times10^4 K,\ 1.2\times10^4 K$$

Current dissipation is provided by Cowling conductivity related to electron-atom collisions

$$q_J = \frac{n m_i \nu'_{ia} V_r^2 (1+x)}{(1-x)^2}$$

(Sen & White,1972)

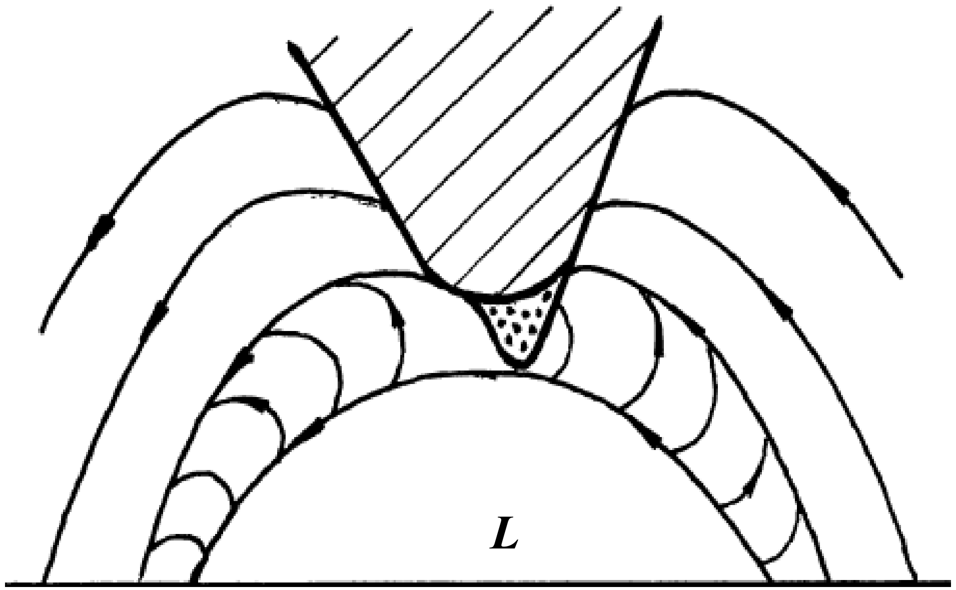
The radiation losses

$$q_r = (1.397\times10^{-8}T)^{6.15}(n+n_a)n$$

From $q_j > q_r$ we obtain the lower boundary for the rate of photosphere convection that provides pre-heating:

$$V_r \geq 3.5\times10^4 cm/s$$

Energy release in current-carrying coronal loop loaded by prominence



Pustyl'nik (1974)
Zaitsev & Stepanov (1992)

Instability condition:

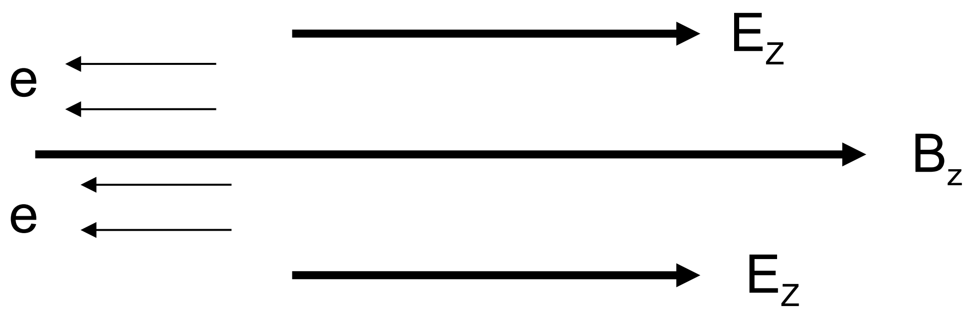
$$R < \frac{4\pi m_i n_p g L^2}{B^2}$$

Partially-ionized plasma penetrates in a current-carrying loop. Cowling resistance is important.

'Heavy liquid' of the prominence provokes a 'bad' curvature with the radius R.

Particle number supplied by a prominence into a loop for $\Delta t \approx 100$ s is $N_\mathrm{p} \approx 2\pi n_\mathrm{p} l_\mathrm{p} a V_\mathrm{Ti} \Delta t \approx 10^{36}$. 'Prominence above loop' approach can explain electron acceleration in moderate flares.

Electron acceleration in DC electric field is most effective



Acceleration rate (Knoepfel & Spong, 1979):

$$\dot{n}_s = 0.35 n \nu_{ei} V_a x^{3/8} \exp\left(-\sqrt{2x} - x/4\right)$$

$x = E_D / E_Z$ Dreicer field $E_D = 6\times10^{-8} (n_e / T)\ V/cm$

x < 1: bulk of electrons are in ‘run away’ mode

Induced electric field in a current-carrying loop

'Weak' current $p >> B_\varphi^2/8\pi$

Magnetic field disturbances are compensated by gas pressure disturbances, E_z = 0. This is the case of the linear Alfven wave propagating along B_{z0}.

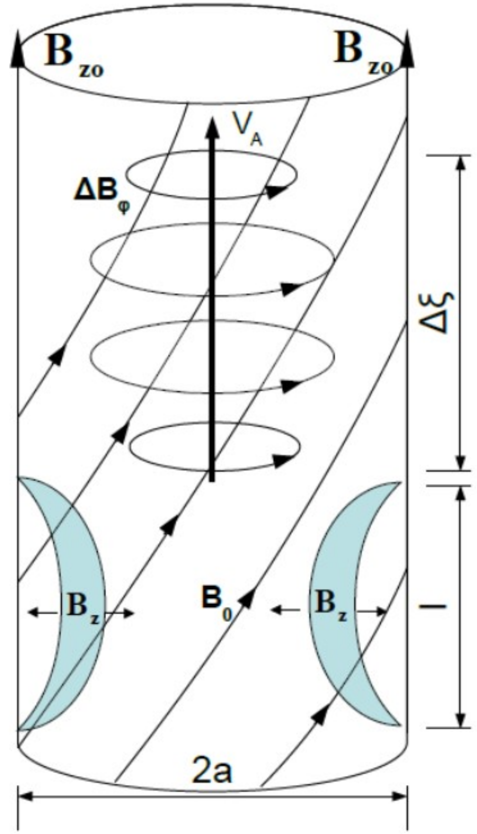
$$V_r = 0,\ V_z = 0, \qquad E_Z = 0$$

'Strong' currents $p << B_\varphi^2/8\pi$

$$\boxed{\frac{\partial^2 B_\varphi}{\partial t^2} - \frac{B_{0z}^2}{4\pi\rho}\frac{\partial^2 B_\varphi}{\partial z^2} = 0}$$

Magnetic field disturbances are not compensated by gas pressure disturbances

$$V_r \neq 0, \quad V_z \neq 0 \qquad \boxed{\frac{\partial E_z}{\partial r} = -\frac{1}{c}\frac{B_\varphi^2}{4\pi\rho V_A^2}\frac{\partial B_\varphi}{\partial t}} \qquad \overline{E}_z \approx \frac{I_0 V_A}{3c^2 l}$$



For $n_a \approx 10^{15}\, cm^{-3},\ B \approx 2\times 10^2\, G,\ l \approx (1 \div 5)\times 10^7\, cm,\ I_0 \approx 5\times 10^9\, A$

$E_{max} \approx 0.1$ V/cm and the electron energy $\varepsilon_s \approx 1$ MeV.

A pulse of magnetic field tension $B_\varphi^2/8\pi$ escapes from RTI region in form of non-linear Alfvén wave. Pulse of magnetic field pressure $B_z^2/8\pi$ remains in the RTI domain, and excites sausage oscillations.

Why super-Dreicer electric fields are needed?

$$\frac{E_Z}{E_D} = 2.2\times10^8 \frac{I_0^3(A)T}{a^2 B_{Z0}\Delta\xi n^{3/2}}$$

No enough particles in coronal part of a loop ~(1-5)×10^{37}

In chromospheric part of a loop ~ 5×10^{39} particles. It is sufficient to provide number of electrons into acceleration mode. This means that when the electrons are accelerated by electric fields the field values must be close to Dreicer field or even exceed it.

Induced electric fields must be close to ED or more to accelerate 10^{38}-10^{39} electrons. Super-Driecer fields can arise at the front of electric current pulse generated in the loop by RTI if the current value exceeds 10^{10} A.

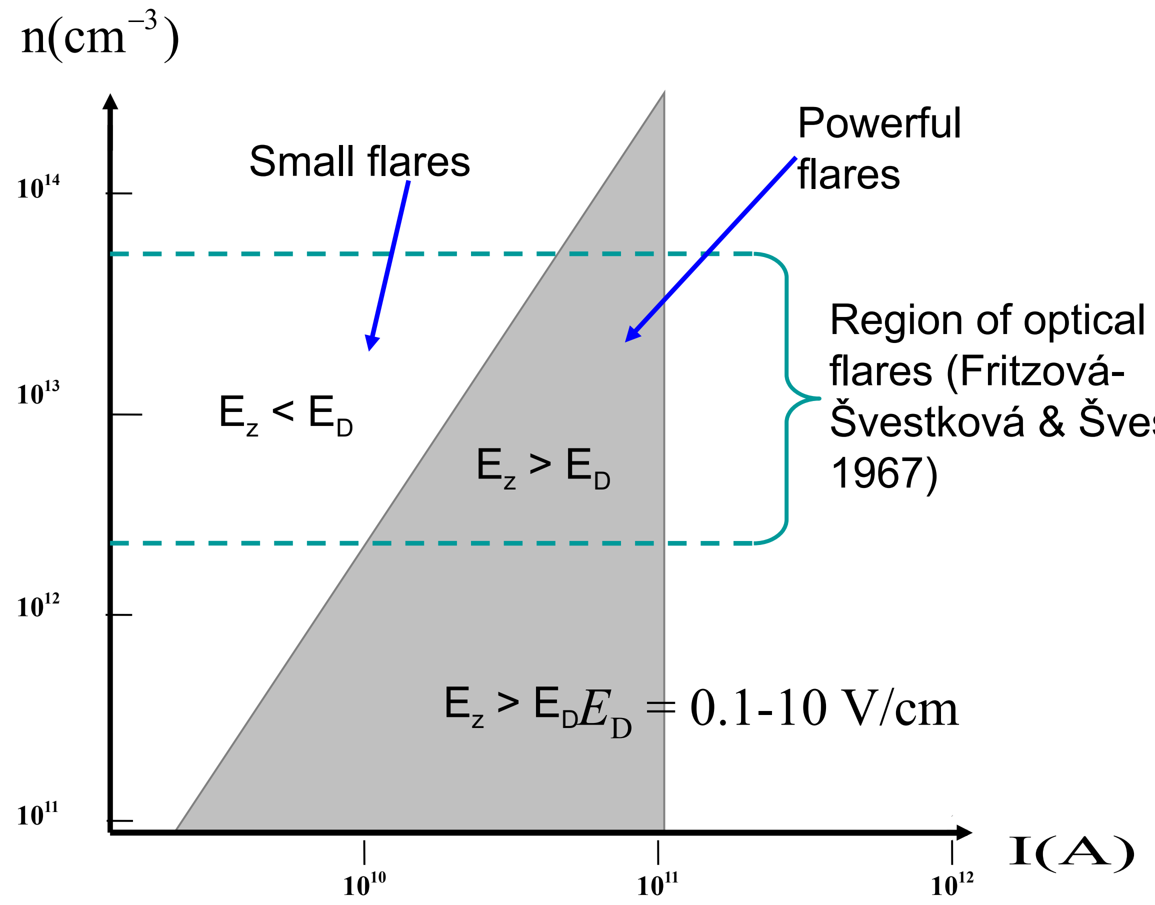
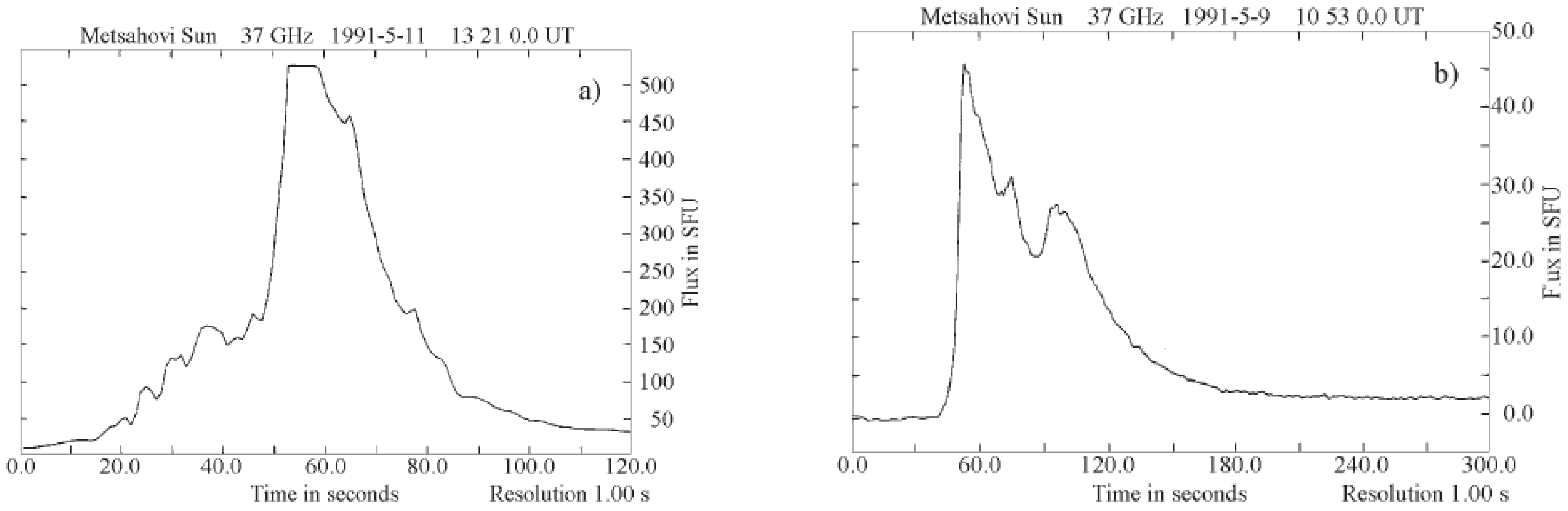


Diagram ‘plasma density vs electric current’ for a = 10^7 cm, B_{z0} = 2×10^3 G, T = 2×10^4 K, $\Delta\xi$ = 5×10^7 cm. The regions of super-Dreicer (in grey) electric fields at the leading edge of the current pulse propagating along magnetic loop away from the R-T instability domain are shown.

Dynamics of plasma tongue penetrating into a flux tube

$$\boxed{\frac{\partial^3 y}{\partial \tau^3} + \varepsilon_1 \frac{\partial^2 y}{\partial \tau^2} + \frac{\partial y}{\partial \tau} - 2\varepsilon\varepsilon_1 y \frac{\partial y}{\partial \tau} = \varepsilon y^2} \qquad y = -\frac{1}{r_0}\int\limits_0^t \left(V_0(t') + \frac{F^2 \rho}{n m_i \nu_{ia}} \frac{dV_0}{dt'} \right) dt'$$

$$t_c = 2(\gamma - 1)F^2 \frac{n + n_a}{n} \frac{1}{\nu_{ia}},\ t_A = \frac{r_0}{2V_A},\ \tau = \frac{t}{t_A} \qquad V_A = \frac{B_0}{\sqrt{4\pi\rho_0}},\ \varepsilon = \frac{t_c}{t_A},\ \varepsilon_1 = \frac{\varepsilon}{2(\gamma - 1)}$$



The examples of light curves from solar flares at 37 GHz observed with Metsähovi radio telescope (Zaitsev et al., 2000), which illustrate two regimes of penetration of the plasma tongue into a flux tube

Summary

From observations: 'Standard' flare model is not universal.
Substantial part of the magnetic energy is released directly in the low atmosphere.

Two ways out:

(i) Magnetic reconnection in partially-ionized plasma

- Ni Lei et al. (2007): Fast magnetic reconnection with Cowling's conductivity (Sweet–Parker's).
- Tsap et al. (2012): Ambipolar diffusion and magnetic reconnection ($\Delta \geq 100$ km).
- Sharykin et al. (2016): Magnetic reconnection triggered by two interacting magnetic flux tubes in the chromosphere.

(ii) The Rayleigh-Taylor instability

Key role in particle acceleration and heating of the lower solar atmosphere.
Heating and acceleration by electric field in the chromosphere *in situ*.
Coronal flares are also possible due to RTI of prominence at the loop top.

déjà vu: back to the "chromospheric flare"
(Giovanelli, 1946; Švestka,1976).

Thank you