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# A new approach to the problem of the coronal heating

Jovo Vranjes
*LMCC, Leuven*
*Belgium*

# A new approach to the problem of the coronal heating

J. Vranjes

Centrum voor Plasma-Astrofysica
Katholieke Universiteit Leuven
http://wis.kuleuven.be/cpa

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- Details in:

J. Vranjes and S. Poedts, A new pradigm for solar coronal heating, *Europhys. Lett.* **86**, 39001 (2009).

J. Vranjes and S. Poedts, The universally growing mode in the solar atmosphere: coronal heating by drift wave, *MNRAS* **xx**, xx (2009), doi:10.1111/j.1365-2966.2009.15180.x.

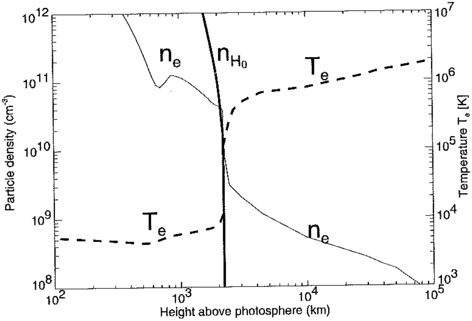
J. Vranjes and S. Poedts, Solar nanoflares and smaller energy release events as growing drift waves, *Phys. Plasmas*, to be published (2009).

J. Vranjes and S. Poedts, Electric field in solar magnetic structures due to gradient driven instabilities: heating and acceleration of particles, *MNRAS*, to be published (2009)?

# Outline

1. Background and history
2. Heating by drift wave
   - Kinetic model
   - Fluid model
3. Summary

# Outline




- Problem of "coronium"!?

- W. Grotrian, Naturwiessenschaften **27**, 214 (1939)
- B. Edlén, Z. Astrophys. **22**, 30 (1942) $\Rightarrow$ The temperature of the solar corona is over a million degrees!

- Van Speybroeck et al., Nature **227**, 818 (1970): brightest points above sunspots $\Rightarrow$ temperature-magnetic field relation established.

# (Some) Heating requirements

A self-consistent model must:

1) provide an energy source for the extremely high temperature in corona, including

2) a reliable and efficient mechanism for the energy transfer from the source to the plasma particles, and

3) this with a required heating rate.

4) explain the discrepancy between ion and electron temperatures (typically $T_i > T_e$),

5) explain the origin of the large temperature anisotropy ($T_\perp > T_\parallel$) with respect to the direction of the magnetic field, particularly for ions,

6) explain the observed stronger heating of heavier ions,

7) it should work everywhere in corona (with different heating requirements in different regions).

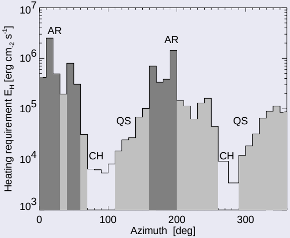



FIG. 1.—Composite soft X-ray image of the Sun observed on 1992 August 26 with *Yohkoh* (*top panel*). The histogram shows the heating rate requirement (*bottom panel*) in the 36 azimuthal sectors around the Sun. The labels indicate the locations of active regions (AR; *dark gray*), quiet-Sun regions (QS; *light gray*), and coronal holes (CH; *white*).

Aschwanden, ApJ **560**, 1035 (2001):

- active regions → 82.4% of the energy budget,
- quite Sun regions → 17.62%,
- coronal holes → 0.4%.

# Popular heating models (and associated problems)

- Heating by Alfvén waves (AW).
- Magnetic reconnection (nano-flares).

- although 'the details are not yet complete'.

- Problem of source: AW generated 'somewhere' below and propagates towards corona.
- How is the energy dissipated?
- Small flux of Alfvén waves.
- In case of reconnection: unfavorable distribution of magnetic 0-points (only 2 % in the corona, 54 % in the photosphere!)
- "Nano-flares remain the leading candidate... even though no one has definitely observed them" (C. Day, Phys. Today, May 2009).

$\Rightarrow$ Almost non of the heating criteria properly satisfied.

# Exotic: axions in action



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ARTICLE

**Some solar flares may be caused by dark matter**

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15:36 22 August 2008
NewScientist.com news service
Anil Ananthaswamy

Some solar flares may be caused by dark matter particles called axions spewing out from the centre of the Sun, new calculations suggest.

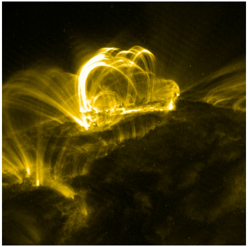
Solar flares are sudden changes in the Sun's brightness thought to be caused when twisted magnetic fields on the Sun snap and reconnect explosively.

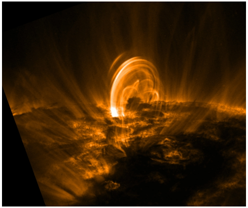
But they could also be caused by dark matter, the mysterious entity that makes up most of the universe's mass – if it is made up of theoretical particles called axions.

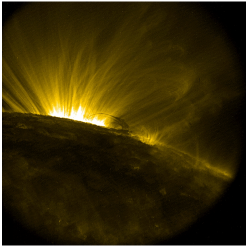
"I do not mean to deny that the evidence is in some ways very strong in favour of your theory, I only wish to point out that there are some other theories possible."

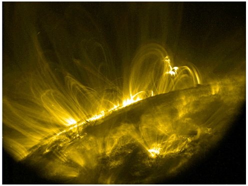
Sherlock Holmes, *Adventure of the Norwood Builder, A. C. Doyle*

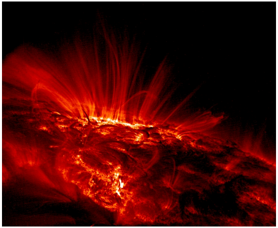
# Outline

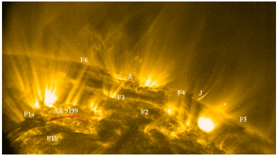








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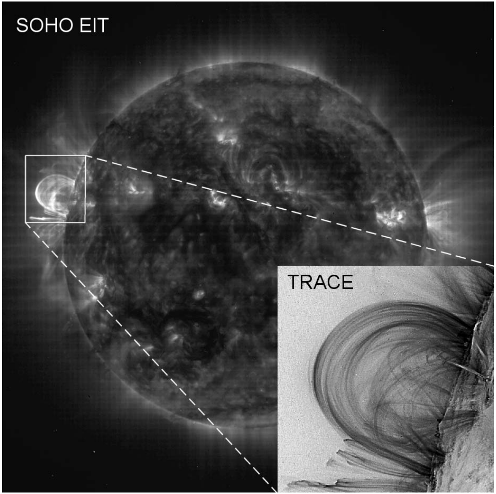


# Drift wave heating: advantages

**Universally unstable:**

- Collisional instability within fluid theory.
- Collision-less instability within kinetic theory.

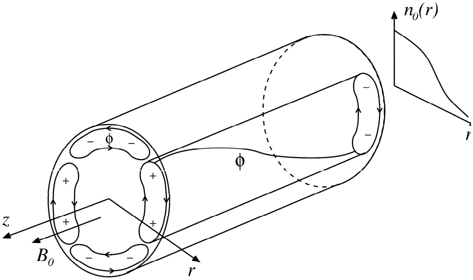
**The driving energy is already present in corona.**

- This energy naturally transmitted to plasma species by well known effects that are beyond the standardly used coronal models.

**Based on well established basic theory that is verified and confirmed by means of laboratory plasma experiments.**

- All needed for the heating mechanism to work is the presence of a density gradient perpendicular to the magnetic field.

# Typical geometry




- A drift wave in cylindric geometry with poloidal wave number $m = 2$.

# Drift wave heating: formulas

## Kinetic drift wave:

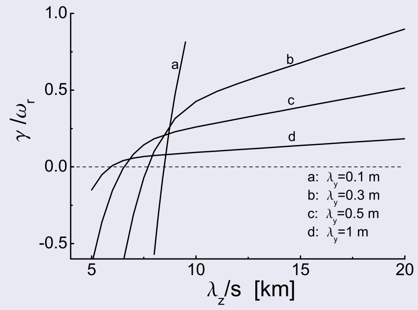
$$\omega_r = -\frac{\omega_{*i}\Lambda_0(b_i)}{1-\Lambda_0(b_i)+T_i/T_e+k_y^2\lambda_{di}^2}, \quad \omega_{*i} = k_y\frac{v_{Ti}^2}{\Omega_i}\frac{n_{i0}'}{n_{i0}}, \quad \nabla_\perp n_{i0} = -\vec{e}_x n_{i0}'$$

$$\gamma \simeq -\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega_r^2}{|\omega_{*i}|\Lambda_0(b_i)}\left[\frac{T_i}{T_e}\frac{\omega_r-\omega_{*e}}{|k_z|v_{Te}}\exp[-\omega_r^2/(k_z^2v_{Te}^2)] + \frac{\omega_r-\omega_{*i}}{|k_z|v_{Ti}}\exp[-\omega_r^2/(k_z^2v_{Ti}^2)]\right].$$

$$\Lambda_0(b_i)=I_0(b_i)\exp(-b_i), \; b_i = k_y^2\rho_i^2, \; \lambda_{di}=v_{Ti}/\omega_{pi}, \; \omega_{*e} = -k_y\frac{v_{Te}^2}{\Omega_e}\frac{n_{e0}'}{n_{e0}}.$$

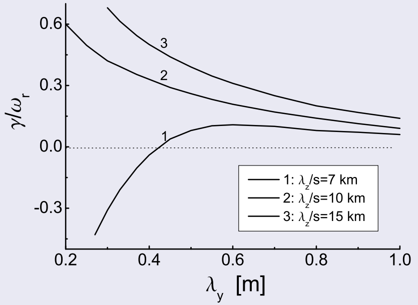
- the presence of the energy source seen already in the real part of the frequency $\omega_r \propto \nabla_\perp n_0$; compare with AW: $\omega = kc_a$.

# Drift wave: instability 1



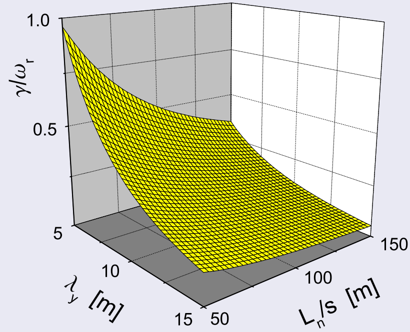

The growth rate in terms of the parallel wavelength, for several perpendicular wavelengths $\lambda_y$, and for the density scale-length $L_n = s \cdot 100$ m, $s \in (0.1, 10^3)$.

# Drift wave: instability 2




The growth rate normalized to $\omega_r$ in terms of the perpendicular wavelength, for several values of $\lambda_z$.

# Drift wave: instability 3




The growth rate normalized to the wave frequency $\omega_r$ in terms of the perpendicular wavelength $\lambda_y$ and the density scale-length $L_n$, for $\lambda_z = s \cdot 2 \cdot 10^4$ m, $s \in (0.1, 10^3)$.

# Drift wave: heating

- heating due to Landau damping on ions

$$\gamma = |\gamma_{el}| - |\gamma_{ion}|$$

- as long as the density gradient is present, there is a continuous precipitation of energy from the wave to the plasma.
- $|\gamma_{el}|$ produces a growth of the wave $\Rightarrow$ stochastic heating

- single particle interaction with the wave
- experimentally verified [Sanders, Bellan, Stern, PoP **5**, 716 (1998)]
- ion particle perpendicular trajectory in the wave field:

$$d\chi/d\tau = \Upsilon, \qquad \chi = k_y x, \quad \Upsilon = k_y y, \quad \tau = \Omega_i t$$

$$d^2\Upsilon/d\tau^2 = -\Upsilon + [m_i k^2 \phi/(eB_0^2)] \sin(\Upsilon - \tau\omega/\Omega_i).$$

- stochastic heating for a sufficiently large wave amplitude

$$a = k_y^2 \rho_i^2 \frac{e\phi}{\kappa T_i} \geq 1.$$

- the maximum achieved bulk ion velocity

$$v_{max} \simeq [k_y^2 \rho_i^2 e\phi/(\kappa T_i) + 1.9]\Omega_i/k_y.$$

- ideally, this requires

$$|\gamma_{el}| \geq |\gamma_{ion}|, \tag{1}$$

  so that the wave amplitude may grow and at some point both heating mechanisms may take place, simultaneously.
- 1.9 appears after making Poincaré plots of particle trajectories for different values of $a$. Slightly different values (1.5 and 2.3) reported in Drake & Lee, PF **24**, 1115 (1981), and McChesney *et al.*, PFB **3**, 3370 (1991).

- in the stochastic heating the ions move in the perpendicular direction to large distances (comparable to the perpendicular wavelength) and feel the time-varying field of the wave due to the polarization drift $\vec{v}_{pi} = (\vec{e}_z \times \partial \vec{v}_{i\perp}/\partial t)/\Omega_i$; $\vec{v}_{i\perp}$ is the leading order $\vec{E} \times \vec{B}$-drift $\Rightarrow$ $v_{pi} \sim a\omega/k_y$ $\Rightarrow$ the perpendicular displacement due to the polarization drift is $\delta = v_{pi}/\omega = a/k_y$ $\Rightarrow$ ions become stochastic.
- the polarization drift in the direction of the wave number vector $\Rightarrow$ the crucial electrostatic nature of the wave in the given process of heating.
- the stochastic heating is highly anisotropic, takes place mainly in the direction normal to the magnetic field $B_0$ (both the $x-$ and $y$-direction velocities are stochastic).
- in view of the mass difference predominantly acts on ions
- the stronger the magnetic filed the more localized heating.
- all these facts have been confirmed experimentally.

# Heating: numbers

- Small perturbations $e\phi/(\kappa T_i) = 0.01$; $\lambda = 0.5$ m, $L_n = 100$ m

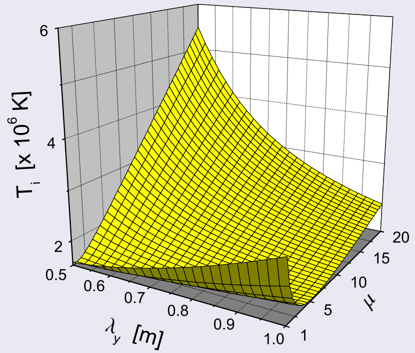
  $\Rightarrow \phi = 60$ V achieved within $\tau_g = 0.06$ s.
  $\Rightarrow$ The energy release rate $\Gamma_{max} = \Sigma_{max}/\tau_g \simeq 0.7$ J/(m$^3$ s); 4 orders of magnitude above the necessary value.

- For $L_n = 100$ km (i.e., setting $s = 1000$) [$\omega_i = 0.07$ Hz, $\omega_r = 0.25$ Hz],

  $\Rightarrow \tau_g = 64$ s
  $\Rightarrow \Gamma_{max} = 6.3 \cdot 10^{-4}$ J/(m$^3$ s), around 10 times the value presently accepted as necessary.

- Ion heating rate: $10^7 - 10^8$ K/s, similar to the one in the experiments.
- Moderate electric field magnitude, same order as in the experiments [electric field observed in flares $7 \cdot 10^4$ V/m - $1.3 \cdot 10^5$ V/m; Davies, Sol. Phys. **54**, 139 (1977); Zhang & Smartt, Sol. Phys. **105**, 355 (1986)].

| | $\phi = 60$ [V] | |
|---|---|---|
| $\lambda_y$ [m] | $v_{max}$ [m/s] | $T_{eff}$ [K] |
| 0.3 | $2.12 \cdot 10^5$ $(1.50 \cdot 10^5)$ | $1.82 \cdot 10^6$ $(3.50 \cdot 10^6)$ |
| 0.5 | $2.20 \cdot 10^5$ $(1.10 \cdot 10^5)$ | $1.96 \cdot 10^6$ $(2.01 \cdot 10^6)$ |
| 0.8 | $2.79 \cdot 10^5$ $(1.78 \cdot 10^5)$ | $3.14 \cdot 10^6$ $(1.78 \cdot 10^6)$ |
| | $\phi = 80$ [V] | |
| $\lambda_y$ [m] | $v_{max}$ [m/s] | $T_{eff}$ [K] |
| 0.3 | $2.54 \cdot 10^5$ $(1.89 \cdot 10^5)$ | $2.61 \cdot 10^6$ $(5.78 \cdot 10^7)$ |
| 0.5 | $2.45 \cdot 10^5$ $(1.37 \cdot 10^5)$ | $2.43 \cdot 10^6$ $(3.02 \cdot 10^6)$ |
| 0.8 | $2.95 \cdot 10^5$ $(1.21 \cdot 10^5)$ | $3.50 \cdot 10^6$ $(2.35 \cdot 10^6)$ |
| | $\phi = 100$ [V] | |
| $\lambda_y$ [m] | $v_{max}$ [m/s] | $T_{eff}$ [K] |
| 0.3 | $2.96 \cdot 10^5$ $(2.30 \cdot 10^5)$ | $3.54 \cdot 10^6$ $(8.62 \cdot 10^7)$ |
| 0.5 | $2.71 \cdot 10^5$ $(1.62 \cdot 10^5)$ | $2.95 \cdot 10^6$ $(4.23 \cdot 10^6)$ |
| 0.8 | $3.10 \cdot 10^5$ $(1.36 \cdot 10^5)$ | $3.88 \cdot 10^6$ $(3 \cdot 10^6)$ |

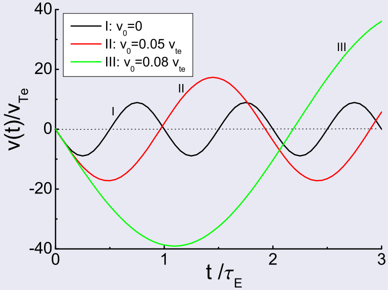



The stochastically increased ion temperature $T_{eff} = m_i v_{max}^2/(3\kappa)$ (in millions K) in terms of the perpendicular wave-length $\lambda_y$ and the ion mass.

## Electron acceleration

- Time-varying electric field; parallel component (normalized to the Dreicer runaway electric field) $|\nabla_z \phi|/E_d = |k_z \phi|/E_d = 3.1,\ 4.1$, for $\lambda_z = 10$ km and $\phi = 60, 80$ V/m, respectively. Here, we use $\lambda_y = 0.5$ m, $B_0 = 10^{-2}$ T, $n_0 = 10^{15}$ m$^{-3}$, $L_n = [(dn_0/dx)/n_0]^{-1} = 100$ m.
- The Dreicer electric field is $E_d = eL_{ei}/(4\pi\varepsilon_0\lambda_d^2)$. Here, $L_{ei} = \log(\lambda_d/b_0)$ is the Coulomb logarithm, $\lambda_d = \lambda_{de}\lambda_{di}/(\lambda_{de}^2 + \lambda_{di}^2)^{1/2}$ is the plasma Debye radius, and $b_0 = [e^2/[12\pi\varepsilon_0\kappa(T_e + T_i)]$ is the impact parameter for electron-ion collisions.
- For the temperature of one million K, $E_d = 0.012$ V/m.
- The parallel wave field exceeds the Dreicer field so that the bulk plasma species (primarily electrons) can be accelerated by the wave in the parallel direction.

## Velocity of electrons accelerated by the drift-wave electric field with $\phi = 80$ V, for three different starting velocities.




$$v(t) = v_0 - \frac{eE_z}{m_e(k_z v_0 - \omega_r)}$$

$$\times \{\sin[k_z z_0 + (k_z v_0 - \omega_r)t]$$

$$-\sin(k_z z_0)\} .$$

## Consequence?

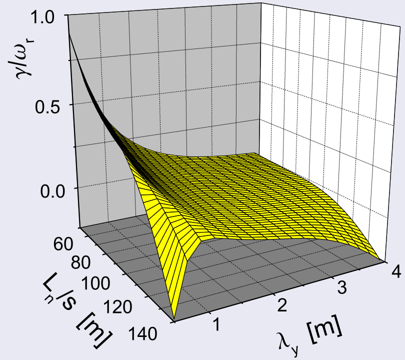
- Non-thermal (non-Maxwellian, kappa) distribution.

# Application to Rapid Energy Releases (RERs)

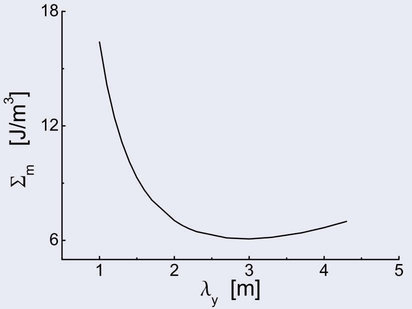
- Flares, micro-flares, nano-flares, ephemeral regions, explosive events, blinkers, X-ray bright points, transient brightening,...
  - strong heating, increase in temperature up to 20-40 MK for flares.
  - particle acceleration.
- Questions:
  - where the energy comes from?
  - by what mechanism is is released?
  - how is it transformed into (random and directed) particle energy?
- Answer(?):
  - reconnection ("although the details of the process remain a subject of study").
- Problem:
  - not all RERs are magnetic by nature! [Mayfield & Chapman, Sol. Phys. **70**, 351 (1981);

## Example

- $B_0 = 5 \cdot 10^{-3}$ T, $n_0 = 10^{16}$ m$^{-3}$, $T_0 = 7 \cdot 10^5$ K, and $\lambda_z = s \cdot 10^4$ m, $s \in (0.1 - 10^3)$.




The growth rate normalized to the wave frequency $\omega_r$ in terms of the perpendicular wavelength and the density scale-length $L_n$.




Volumetric energy $\Sigma_m = n_0 m_i v_m^2$ J/m$^3$ released during stochastic heating by the drift wave in terms of the perpendicular wavelength. Here, $\phi = 10^3$ V and we use the same parameters as before.

- The energy release rate $\Gamma_m = \Sigma_m/\tau_g$ , in J/(m$^3$s); $\tau_g = 1/\gamma$.

## Example

- Small initial perturbation $e\phi_0/(\kappa T_i) = 0.01$
- The growth time till it gets the value $\phi$ is $\tau_g = \log(\phi/\phi_0)/\gamma$.
- Taking $s = 1$ and $s = 10^3$, at the minimum $\lambda_y \Rightarrow \tau_g \simeq 0.2$ s, $\tau_g \simeq 3.3$ min, respectively.
- The total plasma volume involved in RER: $V_p = L_x L_y L_z$. Take $L_x = L_n$, for $L_z$ take one wavelength $\lambda_z$ only, for $L_y$ take a layer of around 10 km.
- At the minimum $\lambda_y$ and for $s = 10^3 \Rightarrow \Sigma_m V_p = 1.5 \cdot 10^{16}$ J (range of nano-flare).
- This value can easily become considerably larger (for a larger volume, for $\lambda_y$ not taken at minimum, increasing the density for one order of magnitude increases the energy for one order too).

# Fully inhomogeneous plasma

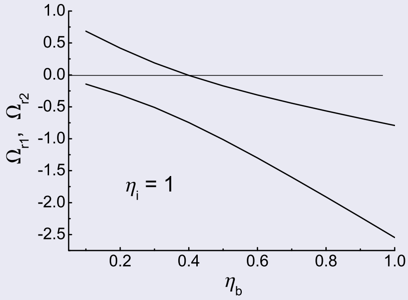
- Weiland's model.
- Inhomogeneous density, temperature, magnetic field

$$L_n = \left(\frac{1}{n_0}\frac{dn_0}{dx}\right)^{-1}, \quad L_T = \left(\frac{1}{T_0}\frac{dT_0}{dx}\right)^{-1}, \quad L_B = \left(\frac{1}{B_0}\frac{dB_0}{dx}\right)^{-1}.$$

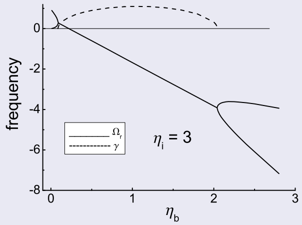
$$\Omega^2\left(1+k_y^2\rho_s^2\right) + \Omega\left[\frac{10\eta_b}{3\tau} + k_y^2\rho_s^2\frac{5\eta_b}{3\tau} - 1 + \eta_b + k_y^2\rho_s^2\frac{1+\eta_i}{\tau}\right]$$
$$+\frac{5\eta_b^2}{3\tau^2} + \left(\eta_i - \frac{7}{3} + \frac{5\eta_b}{3}\right)\frac{\eta_b}{\tau} + k_y^2\rho_s^2\frac{1+\eta_i}{\tau}\frac{5\eta_b}{3\tau} = 0. \qquad (2)$$

$$\Omega \equiv \frac{\omega}{\omega_{*e}}, \quad \rho_s = \frac{c_s}{\Omega_i}, \quad c_s^2 = \frac{\kappa T_{e0}}{m_i}, \quad \eta_b = \frac{\omega_{bi}}{\omega_{*i}} = \frac{L_n}{L_B}, \quad \omega_{be} = -\tau\omega_{bi}, \quad \eta_i = \frac{L_n}{L_T}, \quad \tau = \frac{T_{e0}}{T_{i0}}.$$

$$\omega_{bj} = \vec{k}_y\vec{v}_{bj}, \quad \vec{v}_{bi} \simeq \frac{2T_{i0}}{q_iB_0}\vec{e}_\parallel \times (\vec{e}_\parallel \cdot \nabla)\vec{e}_\parallel.$$



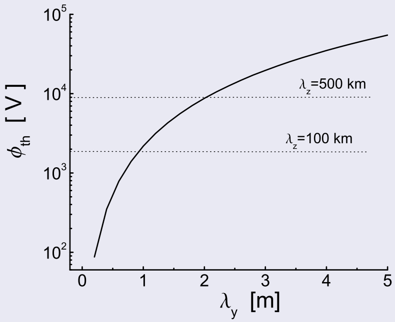

Two real solutions (normalized to $\omega_{*e}$) in the case $\eta_i = 1$ and $k_y \rho_s = 0.1$.




The solutions of Eq. (2) for $\eta_i = 3$ showing two real solutions for small $\eta_b$ and for $\eta_b > 2.04$. The dashed line is the growth-rate for the complex-conjugate solutions in between.

# Electric field

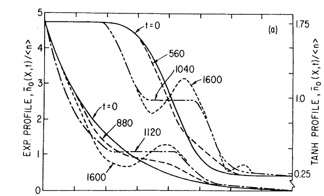
- Very strong electric fields reported: $7 \cdot 10^4 - 1.3 \cdot 10^5$ V/m. It is widely believed that these electric fields appear in the process of magnetic reconnection = change in magnetic field topology.
- Observations show that some strong energy release events appear without a measurable change of the magnetic energy and configuration and, hence, a different description/source needed.
- Assuming the parallel wave-length 100(500) km, the amplitude of the electrostatic potential $\phi$ necessary to achieve the Dreicer value is about 1.8(9) KV. However, in the perpendicular direction this same potential gives the electric field $k_y\phi$ that is around $E_\perp = 5.7(29)$ KV/m. For the parallel wave-length of about 1000 km we would have $\phi = 18$ KV and consequently $E_\perp = 57$ KV/m. These estimates are for the number density $n_0 = 10^{16}$ m$^{-3}$. Taking $n_0 = 10^{17}$ m$^{-3}$ yields 54, 270 kV/m, respectively.




The threshold value of the potential $\phi$ in terms of the perpendicular wave-length, above which the stochastic heating takes place. Above the dotted line the parallel electric field exceeds the Dreicer value, resulting in a simultaneous acceleration of particles.

# What is missing?

- Nonlinearity and collisions lead to the radial flattening of the density profile in the region occupied by the wave, resulting in the saturation of the growth.




- W. W. Lee and H. Okuda, Phys. Rev. Lett. **36**, 870 (1976)

- The energy diffusion (due to any reason) in the perpendicular direction may reduce the local effects of the demonstrated strong heating rate.

- The coupling with the Alfvén wave, proportional to $k_z k_y$
- Particle (electron) acceleration by the electric field.
- All these effects (the nonlinearity, collisions, particle acceleration by the electric field, diffusion, and coupling with the Alfvén wave) will more effectively act on short scales.
- All of them (except the particle acceleration?) will tend to reduce the mode amplitude.

# Outline

- All heating requirements may be satisfied.
- Rapid energy releases (e.g. nanoflares) could be explained.
- Possibility for explaining the presence of the $\kappa$-distribution.
- Possible explanation for the particle acceleration.
- Physical background for the observed extremely strong electric fields ($10^5$ V/m).

"Elementary, my dear Watson" the great detective said quietly, "Entirely elementary."

Sherlock Holmes, *The hound of the Baskervilles, A. C. Doyle*

Indeed! But is there anything better?

Numerics needed.