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The problem of coronal heating

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The International Advanced Workshop on the Frontiers of Plasma Physics, AS-ICTP, Trieste, July 2010

- Useful review papers on coronal heating:

J. A. Klimtchuk, On solving the coronal heating problem, *Solar Phys* **234**, 41 (2006).

U. Narain, P. Ulmschneider, Chromospheric and coronal ceating mechanisms, *Space Sci. Rev.* **54**, 377 (1990).

Outline

1. Background and history
2. New paradigm: heating by drift waves
   - Stochastic heating
   - Electromagnetic effect
3. Summary

Outline

AS-ICTP 2009:

Drift wave in the corona:

- kinetic instability of the electrostatic drift wave,
- reactive (η_i-)instability within the two-fluid model,
- current driven instability,
- stochastic heating.

- 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.

Most popular heating models

- MHD model of heating by Alfvén waves:
  - Energy source below the surface; transferred into corona by the AW that are excited by foot points motions of the magnetic lines.
  - Problem of energy transport and dissipation: wave flux too small, dissipation too slow or sporadic; actual heating at scales much below MHD; heating requirements beyond the single-fluid model.
- Flares, micro-flares, nano-flares, ephemeral regions, explosive events, blinkers, X-ray bright points, transient brightening,...
  - rapid increase in temperature (up to 20-40 MK for flares).
- 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").

- Problems:
  - not all flares are magnetic by nature. [Mayfield & Chapman, Sol. Phys. **70**, 351 (1981); Jansens, *ibid.* **27**, 149 (1972):
    - Out of 6 observed events, 5 showed no measurable magnetic energy change and 1 result 'was questionable'.
  - Unfavorable distribution of magnetic 0-points [Régnier *et al.*, AA **484**, L47 (2008)]
    - 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).

Present status

Aschwanden *et al.* ApJ **659**, 1673 (2007): "The coronal heating problem has been with us over 60 years, and hundreds of theoretical models have been proposed without an obvious solution in sight."

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Outline

Reminder: 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)

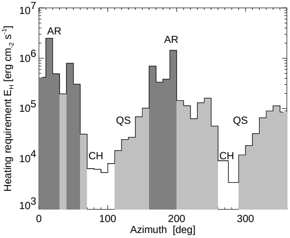
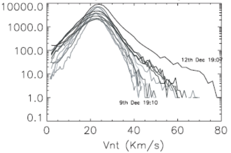


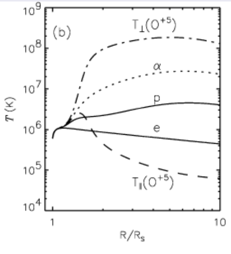
FIG. 1.—Composite soft X-ray image of the Sun observed on 1992 August 26 with *Yohkoh* (*top panel*). The histogram shows the heating rate requirement (*bottom panel*) in the 36 azimuthal sectors around the Sun. The labels indicate the locations of active regions (AR; *dark gray*), quiet-Sun regions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

Some observations





- Harra *et al.*, ApJL **691**, 99 (2009).

  Histograms of the nonthermal velocity. The y-axes show the number of pixels in the raster at each measurement. The time evolution: the earliest nonthermal velocity histogram shown as lighter gray and the later ones as darker. The nonthermal velocity is increasing close to the X-class flare on December 13.

- Li *et al.*, ApJL **501**, 133 (1998).

  Temperature of species.

Some observations

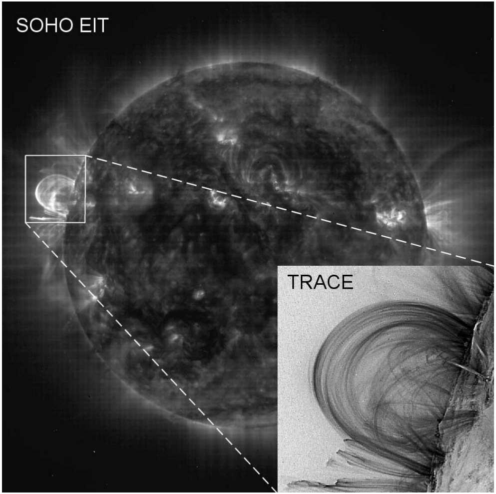
Flare	Electron density N_e (cm^{-3})	Electron temperature T_e (K)	Total electric field (kV cm^{-1})
16 July, 1970	3.5×10^{12}	10^4	0.5
4 June, 1982	1.7×10^{13}	10^4	1.6

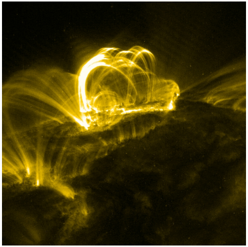
Time (UT)	Electric field (kV cm^{-1})	Electron temperature T_e(K)	Ion temperature T_i(K)
14:08:08	----	----	----
	0.7	----	----
14:08:55	0.8	----	----
	0.4	----	2.5×10^5
14:10:00	0	4.6×10^4	----
	0.5	4.1×10^4	1.0×10^5
14:10:53	----	3.0×10^4	----
	0.5	2.1×10^4	----
14:13:54	----	2.0×10^4	----
	0.0	3.5×10^4	----

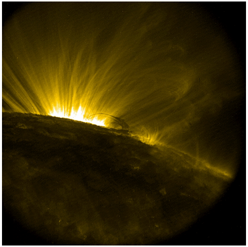
- Zhang and Smartt, Solar Phys. **105**, 355 (1986). Measured electric field in flares.

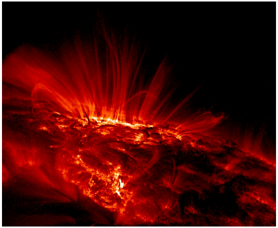
- Davis, Solar Phys. **54**, 139 (1977). Measured plasma parameters.

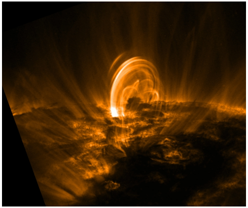
SOHO-TRACE difference

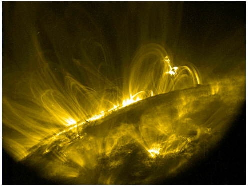


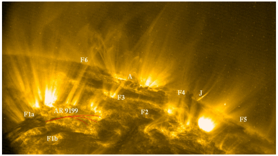











F6
A
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F1a
AR 9199
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F5
F1b

Drift wave in the corona

- Collisional and collision-less (reactive) instability within fluid theory.
- Collision-less instability within kinetic theory.
- Properties:
  - the driving energy is already present in corona,
  - strongly growing,
  - ions heated directly by the wave.

Kinetic drift wave:

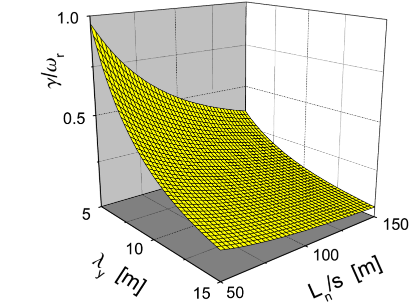
$$\omega_r = -\frac{\omega_{*i}\Lambda_0(b_i)}{1-\Lambda_0(b_i)+T_i/T_e+k_y^2\lambda_{di}^2},$$

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

$$\left.+\frac{\omega_r-\omega_{*i}}{|k_z|v_{Ti}}\exp[-\omega_r^2/(k_z^2v_{Ti}^2)]\right].$$

$$\Lambda_0(b_i)=I_0(b_i)\exp(-b_i),\;\; b_i=k_y^2\rho_i^2,\;\; \lambda_{di}=v_{Ti}/\omega_{pi},\;\; \omega_{*e}=-k_y\frac{v_{Te}^2}{\Omega_e}\frac{n_{e0}'}{n_{e0}}\quad \omega_{*i}=k_y\frac{v_{Ti}^2}{\Omega_i}\frac{n_{i0}'}{n_{i0}}.$$

Instability



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

- References on stochastic heating:

- G. R. Smith, A. N. Kaufman, Phys. Rev. Lett. **34**, 1613 (1975).
- C. F. F. Karney, A. Bears, Phys. Rev. Lett. **39**, 550 (1977).
- J. M. McChesney, R. A. Stern, P. M. Bellan, Phys. Rev. Lett. **59**, 1436 (1987).
- J. M. McChesney, P. M. Bellan, R. A. Stern, Phys. Fluids B **3**, 3363 (1991).
- A. D. Bailey, R. A. Stern, P. M. Bellan, Phys. Rev. Lett. **71**, 3123 (1993).
- A. D. Bailey, P. M. Bellan, R. A. Stern, Phys. Plasmas **2**, 2963 (1995).
- S. J. Sanders, P. M. Bellan, R. A. Stern, Phys. Plasmas **5**, 716 (1998).
- L. Chen, A. Lin, R. White, Phys. Plasmas **8**, 4713 (2001).
- R. White, L. Chen, A. Lin, Phys. Plasmas **9**, 1890 (2002).
- Z. M. Sheng, L. Yu, G. Hao, R. White, Phys. Plasmas **16**, 072106 (2009).

Polarization drift effects

$$v_{i\perp} = \frac{1}{B_0}\vec{e}_z \times \nabla_\perp \phi + \frac{v_{Ti}^2}{\Omega_i}\vec{e}_z \times \frac{\nabla_\perp n_i}{n_i} + \vec{e}_z \times \frac{\nabla_\perp \cdot \pi_i}{m_i n_i \Omega_i}$$
$$+\frac{1}{\Omega_i}\frac{d}{dt}\vec{e}_z \times \vec{v}_{i\perp}, \qquad \frac{d}{dt} \equiv \frac{\partial}{\partial t} + \vec{v}\cdot\nabla. \qquad (1)$$

$$\vec{v}_{pi} = -\vec{e}_y \frac{\omega_r k_y \phi_1(t)}{B_0 \Omega_i}\left[\left(1 - \frac{k_z}{\omega_r}\frac{dz}{dt}\right)\cos\varphi - \frac{\gamma}{\omega_r}\sin\varphi\right] \times$$
$$\times 1 / \left(1 - \frac{k_y^2 \phi_1(t)}{B_0 \Omega_i}\cos\varphi\right), \qquad \varphi = k_y y + k_z z - \omega_r t. \qquad (2)$$

- 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

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

- the polarization drift in the direction of the perpendicular 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.
- predominantly acts on ions
- confirmed experimentally.

Individual particle dynamics

$$y''(t) + y(t) - a(t)\sin\left[y(t) + \frac{k_z}{k_y}z(t) - bt\right] = 0, \tag{3}$$

$$z''(t) - a(t)\frac{k_z}{k_y}\sin\left[y(t) + \frac{k_z}{k_y}z(t) - bt\right] = 0, \tag{4}$$

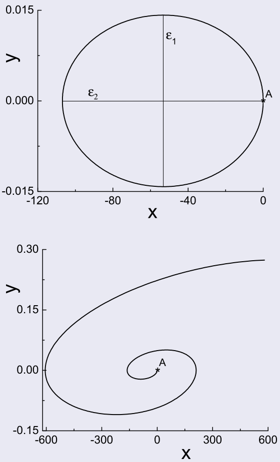
$$x'(t) - y(t) = 0. \tag{5}$$

- Normalization: $x, y, z \to k_y x, k_y y, k_y z, \; t \to \Omega_i t, \; b = \omega_r/\Omega_i$.
- Eq. (3): the Mathieu equation with a source term; neglecting the z-terms and introducing $\tau = bt/2$, for the small argument φ:

$$d^2y/d\tau^2 + [\alpha - 2q(t)\cos 2\tau]y(\tau) = c(\tau)\sin 2\tau, \tag{6}$$

where $\alpha = 4/b^2$, $q(\tau) = 2a(\tau)/b^2$, and $c(\tau) = -4a(\tau)/b^2$.

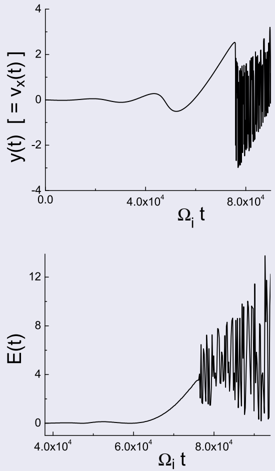
Small wave amplitude



- Particle positions in the x, y-plane within a wave period, after it starts from the point A with $(x, y, z) = (0, 0, 0)$, for a small and constant wave amplitude $\phi_1 = 0.86$ V.
- Time and space scales corresponding to the discussed drift wave in the corona.
- For electrons ϵ_2 the same; ϵ_1 reduced by a factor m_e/m_i.

- Growing electric field potential $\phi_1(t) = \widehat{\phi}\exp(\gamma t/\Omega_i)$, and $\widehat{\phi} = 0.86$ V.
- Maximum time 0.04 s; maximum potential $\phi = 17$ V.

Stochastic heating in action

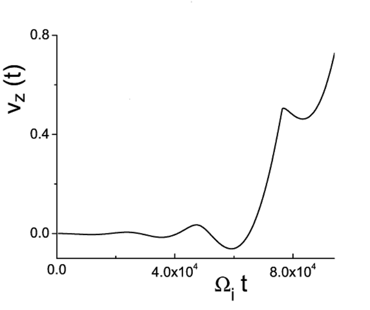


- Normalized displacement in the direction of the polarization drift $y(t)$, and the normalized perpendicular velocity component $y(t) \equiv v_x(t)$ ($v_y(t)$ of the same order and stochastic too!) .
- Stochastic effects after 0.078 s, for $\phi = 150$ V (2.5 times larger compared to the value obtained from the parameter a).

- Change in time of the normalized kinetic energy of a particle with a unit mass $E = (v_x^2 + v_y^2 + v_z^2)/2$.

- Plasma can support multiple waves in the same time.
- Consequence: the instability threshold can be considerably reduced [Sheng *et al.*, Phys. Plasmas **16**, 072106 (2009)]
  $\Rightarrow$ the ion heating by the given mechanism will be even more efficient .

Particle acceleration



- Normalized perturbed velocity in the direction parallel to the magnetic field.
- No stochastic effects; pure acceleration (solar wind?).

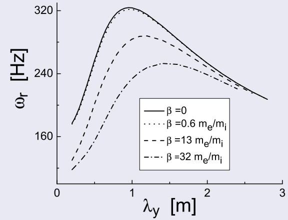
Dispersion equation

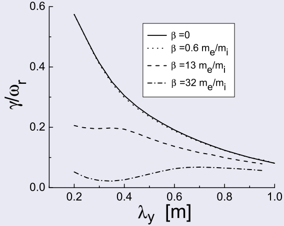
$$
-\frac{T_e}{T_i}\left[1-\frac{\omega-\omega_1}{\omega_2}\Lambda_0(b_i)\left(1+\alpha-i\Upsilon_i\right)\right.
$$
$$
\left.+\delta\left(\frac{s_1+f_1}{s_2+f_2}-1\right)\frac{\omega-\omega_1}{\omega}\Lambda_0(b_i)\left(i\Upsilon_i-\alpha\right)\right]
$$
$$
=1+i\Upsilon_*+\delta\left(\frac{s_1+f_1}{s_2+f_2}-1\right)\left(1-\frac{\omega_{*e}}{\omega}\right)\left(1+i\Upsilon_e\right). \tag{7}
$$

$$
\Upsilon_*=\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega-\omega_{*e}}{|k_z|v_{Te}}\exp\left(-\frac{\omega^2}{2k_z^2v_{Te}^2}\right),\quad \Upsilon_i=\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega_2}{|k_z|v_{Ti}}\exp\left(-\frac{\omega_2^2}{2k_z^2v_{Ti}^2}\right),\quad \omega_g=\frac{k_y g}{\Omega_i},\quad \delta=0,1,
$$

$$
\Upsilon_e=\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega}{|k_z|v_{Te}}\exp\left(-\frac{\omega^2}{2k_z^2v_{Te}^2}\right),\quad \omega_1=\omega_{*i}-k_y g/\Omega_i,\quad s_1=k_y^2\rho_s^2k_z^2c_a^2,\quad s_2=s_1+\omega(\omega_{*e}-\omega)\left(1+i\Upsilon_e\right),
$$

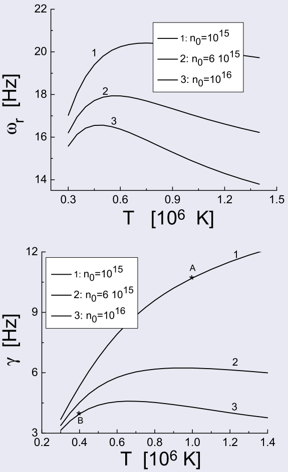
$$
f_1=\frac{T_e}{T_i}\Lambda_0(b_i)\omega_g(\omega-\omega_1)\left(\alpha-i\Upsilon_i\right),\quad f_2=f_1\frac{\omega_2}{\omega_g},\quad \alpha=\frac{k_z^2v_{Ti}^2}{\omega_2^2}\left(1+\frac{k_z^2v_{Ti}^2}{\omega_2^2}\right),\quad \omega_2=\omega+k_y g/\Omega_i.
$$





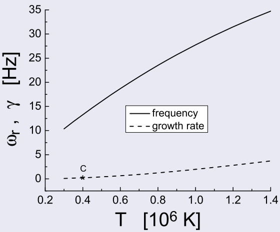
- The drift wave frequency for several different values of plasma β (i.e. plasma density) in terms of the perpendicular wave-length. The shape due to $\omega_r \sim k_y/(1+k_y^2\rho_s^2)$.
- Parameters:
  $n_0 = (10^{15}, 2\cdot 10^{16}, 5\cdot 10^{16})$ m^{-3},
  $B_0 = 10^{-2}$ T, $T_e = T_i = 10^6$ K,
  $L_n \equiv [(dn_0/dx)/n_0]^{-1} = s\cdot 10^2$ m,
  $\lambda_z = s\cdot 10^4$ m, $s \in 1 - 10^3$.

- The corresponding normalized growth rates: reduced due to electromagnetic effects.
- Drift-Alfvén coupling proportional to: $k_z^2 c_a^2 k_y^2 \rho_s^2(\omega - \omega_{*i})$.



- The drift wave frequency in terms of the plasma temperature. Number density per cubic meter.
- Parameters: $\lambda_y = 0.5$ m, $\lambda_z = 200$ km, $B_0 = 10^{-2}$ T, $L_n = 1$ km.
- At $T = 1.4 \cdot 10^6$ K the frequency reduced by 1.4.

- The corresponding growth rate.
- At $T = 1.4 \cdot 10^6$ K the growth rate reduced by 3.2
- Point A: $\beta = 0.64 m_e/m_i$, point B: $\beta = 2.5 m_e/m_i$.



- The drift wave frequency and the growth rate for $B_0 = 3 \cdot 10^{-2}$ T; other parameters as in line 3 before.
- Point C: $\beta = 0.3 m_e / m_i$.
- The growth rate at the point C, 50 times lower than in the point B.
- The points A, B, C:
  - the same magnetic loop,
  - different loops.

Example

Point A ($\beta = 0.64 m_e/m_i$):

- $a = 1 \Rightarrow \phi_1 = 61$ V, $v_{max} = 221$ km/s, $T_{max} = 1.97 \cdot 10^6$ K.
- The growth time [starting from $e\hat{\phi}/(\kappa T_i) = 0.01$, i.e., $\hat{\phi} = 0.86$] $\tau_g = \log(\phi/\hat{\phi})/\gamma = 0.4$ s.
- Note also that here $e\phi_1/(\kappa T_i) \simeq 0.7$.
- The total released energy density is $E_{max} = n_0 m_i v_{max}^2/2 = 0.04$ J/m^3; the energy release rate $\Gamma_{max} = E_{max}/t_g = 0.1$ J/(m^{3}s). Hence, Γ_{max} is about 1700 times the required value for the coronal active regions [that amounts to $\simeq 6 \cdot 10^{-5}$ J/(m^{3}s)].

Point B ($\beta = 2.5 m_e/m_i$): $E_{max} = 0.4$ J/m^3, $t_g = 1.3$ s, and $\Gamma_{max} = 0.3$ J/(m^{3}s), $T_{max} = 1.97 \cdot 10^6$ K.

Example

Point C ($\beta = 0.3 m_e/m_i$):

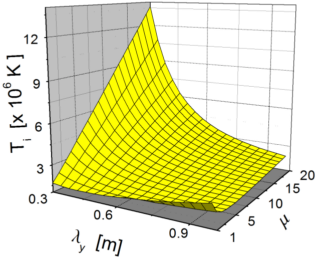
- $a = 1 \Rightarrow \phi_1 = 546$ V, $v_{max} = 663$ km/s, $T_{max} = 1.8 \cdot 10^7$ K.
- The growth time [starting from $\hat{\phi} = 0.34$] $\tau_g = \log(\phi/\hat{\phi})/\gamma = 33$ s (about 80 times longer than in the point A).
- About 90 times larger energy density $E_{max} = n_0 m_i v_{max}^2/2 = 3.67$ J/m^3; the energy release rate $\Gamma_{max} = E_{max}/t_g = 0.11$ J/(m^{3}s) (almost the same as in the point A).
- The areas with stronger background magnetic fields are subject to stronger stochastic heating.
- It can be shown that for $s = 10^3 \Rightarrow \Sigma_m V = 1.5 \cdot 10^{16}$ J (range of nano-flare); V-volume.

Some consequences:

- The potentials at the points A and C, 61 V and 546 V yield the perpendicular electric field $k_y\phi_1$ 0.77 kV/m and 6.9 kV/m , respectively.
- To have the threshold $a = 1$, $\phi_1 \sim \lambda_y B_0^2$; a slight increase in these two parameters will yield even stronger electric fields.
- Example: $\lambda_y = 2$ m, $B_0 = 4 \cdot 10^{-2}$ (instead of $\lambda_y = 0.5$ m, $B_0 = 3 \cdot 10^{-2}$ as in the point C) $\Rightarrow E_y \simeq 27$ kV/m.
- The three obtained values for the electric field yield the $\vec{E} \times \vec{B}$-drift: 77, 230, and 675 km/s, respectively.

- Hence, i) exceptionally strong perpendicular electric fields are expected during the proposed stochastic heating, and this particularly within stronger magnetic structures, and, ii) the perpendicular stochastic heating is accompanied with collective plasma drifts.

Stronger heating of heavier ions



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

Outline

Summary

- All heating requirements may be satisfied.

- Rapid energy releases (e.g. nano-flares) could be explained.

- Possibility for explaining the high energy tail in the κ-distribution.
  - Explanation for the particle acceleration.

- Observed extremely strong electric fields (10^5 V/m) can be explained.

- Details in:

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

J. Vranjes and S. Poedts, Solar nanoflares and smaller energy release events as growing drift waves,
Phys. Plasmas **16**, 092902 (2009).

J. Vranjes and S. Poedts, The universally growing mode in the solar atmosphere: coronal heating by drift wave,
MNRAS **398**, 918 (2009).

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