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Suppression of Parallel Transport in Flaring Plasmas: Effects on Nonthermal and Thermal Aspects of Flares

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Background/Motivation

- Simoes & Kontar: ratio of intensities in coronal/chromospheric sources $\rightarrow$ more efficient trapping of electrons in corona compared to purely collisional process
- Jeffrey et al., Kontar et al. – variation of HXR source size with energy $\rightarrow$ consistent with mix of collisions and an effective turbulent mean free path $\lambda_T \sim 10^8$ cm
- Additional presence of turbulent scattering affects transport coefficients – in particular thermal/electrical conductivities κ, σ
- Implications for
  - Cooling time for 10^7 K flare coronal plasma
  - Return current losses suffered by accelerated electrons

Effective mean free path/scattering frequency

$$\nu(v) = \nu_C(v) + \nu_T(v)$$

Collisions

$$\nu_C(v) = \frac{4\pi n_e e^4 \ln\Lambda}{m_e^2}\frac{1}{v^3} \equiv \frac{v}{\lambda_{\mathrm{C}}(v)}$$

$$\lambda_{\mathrm{C}}(v) = \frac{m_e^2}{4\pi n_e e^4 \ln\Lambda} v^4 \equiv \lambda_{\mathrm{ei}}\left(\frac{v}{v_{\mathrm{te}}}\right)^4$$

Turbulent scattering

$$\lambda_T(v) = \lambda_0\left(\frac{v}{v_{\mathrm{te}}}\right)^\alpha$$

Overall

$$\nu(v) = \frac{v_{\mathrm{te}}}{\lambda_{\mathrm{ei}}}\frac{1 + R(v/v_{\mathrm{te}})^{4-\alpha}}{(v/v_{\mathrm{te}})^3}$$

$$R = \frac{\lambda_{\mathrm{ei}}}{\lambda_0}$$

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Relation between λ and Transport Coefficients

Thermal conductive flux

$$q_{\|} = -\kappa_{\|}\frac{dT_e}{dz}$$

$$\kappa_{\|} = \frac{2n_e k_B (2k_B T_e)^{1/2}}{m_e^{1/2}}\lambda$$

Current density (Ohm's Law)

$$j_{\|} = \sigma_{\|} E_{\|}$$

$$\sigma_{\|} = \frac{n_e e^2 \lambda}{m_e^{1/2}(2k_B T_e)^{1/2}}$$

Both κ and σ are proportional to λ

Decrease in λ due to collisionless scattering reduces both κ and σ

Formal expressions for κ and σ

Chapman-Enskog expansion:

$$f = f_0(z, v) + \epsilon f_1(z, \mu, v)$$

Isotropic Maxwellian — First order anisotropic term

$$f_1(z, v, \mu) = -\frac{\mu}{\nu}\left[v\frac{\partial f_0(z,v)}{\partial z} - \frac{eE_\parallel}{m_e}\frac{\partial f_0(z,v)}{\partial v}\right]$$

$$\nu = \frac{v_{\text{te}}}{\lambda_{\text{ei}}}\frac{Rx^{4-\alpha}+1}{x^3}$$

$$f_1 = -\mu\lambda_{\text{ei}}\frac{x^4}{Rx^{4-\alpha}+1}\left[\left(x^2 - \frac{5}{2}\right)\frac{1}{T_e}\frac{dT_e}{dz} + \frac{eE_\parallel}{k_B T_e}\right] f_0$$

Heat flux

$$q_{\|}(z) = 2\pi \int_0^\infty dv\, v^2 \int_{-1}^{1} d\mu\, \mu \left(\frac{m_e v^2}{2}\right) v\, f_1(z, v, \mu)$$

$$x = \frac{v}{v_{\text{te}}}$$

$$-\frac{4}{3\sqrt{\pi}} n_e\, k_B T_e\, v_{\text{te}}\, \lambda_{\text{ei}} \int_0^\infty dx\, \frac{x^9}{Rx^{4-\alpha}+1} \left[\left(x^2 - \frac{5}{2}\right)\frac{1}{T_e}\frac{dT_e}{dz} + \frac{eE_{\|}}{k_B T_e}\right] e^{-x^2}$$

$$q_{\|} = -\kappa_{\|}\frac{dT_e}{dz} - \alpha_{\|} E_{\|}$$

$$\kappa_{\|} = \frac{4}{3\sqrt{\pi}} n_e\, k_B\, v_{\text{te}}\, \lambda_{\text{ei}} \int_0^\infty \frac{x^9}{Rx^{4-\alpha}+1}\left(x^2 - \frac{5}{2}\right) e^{-x^2}\, dx$$

$$\alpha_{\|} = \frac{4}{3\sqrt{\pi}} n_e\, e\, v_{\text{te}}\, \lambda_{\text{ei}} \int_0^\infty \frac{x^9}{Rx^{4-\alpha}+1} e^{-x^2}\, dx$$

Current density

$$j_{\|}(z) = -2\pi e \int_0^\infty dv\, v^2 \int_{-1}^{1} d\mu\, \mu\, v\, f_1(z, v, \mu)$$

$$= \frac{4}{3\sqrt{\pi}} n_e\, e\, v_{\text{te}}\, \lambda_{\text{ei}} \int_0^\infty dx\, \frac{x^7}{R x^{4-\alpha} + 1} \left[\left(x^2 - \frac{5}{2} \right) \frac{1}{T_e} \frac{dT_e}{dz} + \frac{e E_{\|}}{k_B T_e} \right] e^{-x^2}$$

$$j_{\|} = \beta_{\|} \frac{dT_e}{dz} + \sigma_{\|} E_{\|}$$

$$\beta_{\|} = \frac{4}{3\sqrt{\pi}} \frac{n_e\, e\, v_{\text{te}}\, \lambda_{\text{ei}}}{T_e} \int_0^\infty \frac{x^7}{R x^{4-\alpha} + 1} \left(x^2 - \frac{5}{2} \right) e^{-x^2}\, dx$$

$$\sigma_{\|} = \frac{4}{3\sqrt{\pi}} \frac{n_e\, e^2\, v_{\text{te}}\, \lambda_{\text{ei}}}{k_B T_e} \int_0^\infty \frac{x^7}{R x^{4-\alpha} + 1} e^{-x^2}\, dx$$

Summary

$$\begin{pmatrix} q_{\|} \\ j_{\|} \end{pmatrix} = \begin{pmatrix} -\kappa_{\|} & -\alpha_{\|} \\ \beta_{\|} & \sigma_{\|} \end{pmatrix} \begin{pmatrix} dT_e/dz \\ E_{\|} \end{pmatrix}$$

$$\kappa_{\|} = \frac{4}{3\sqrt{\pi}} n_e \, k_B \, v_{\text{te}} \, \lambda_{\text{ei}} \int_0^\infty \frac{x^9}{Rx^{4-\alpha}+1} \left(x^2 - \frac{5}{2}\right) e^{-x^2} \, dx$$

$$\alpha_{\|} = \frac{4}{3\sqrt{\pi}} n_e \, e \, v_{\text{te}} \, \lambda_{\text{ei}} \int_0^\infty \frac{x^9}{Rx^{4-\alpha}+1} e^{-x^2} \, dx$$

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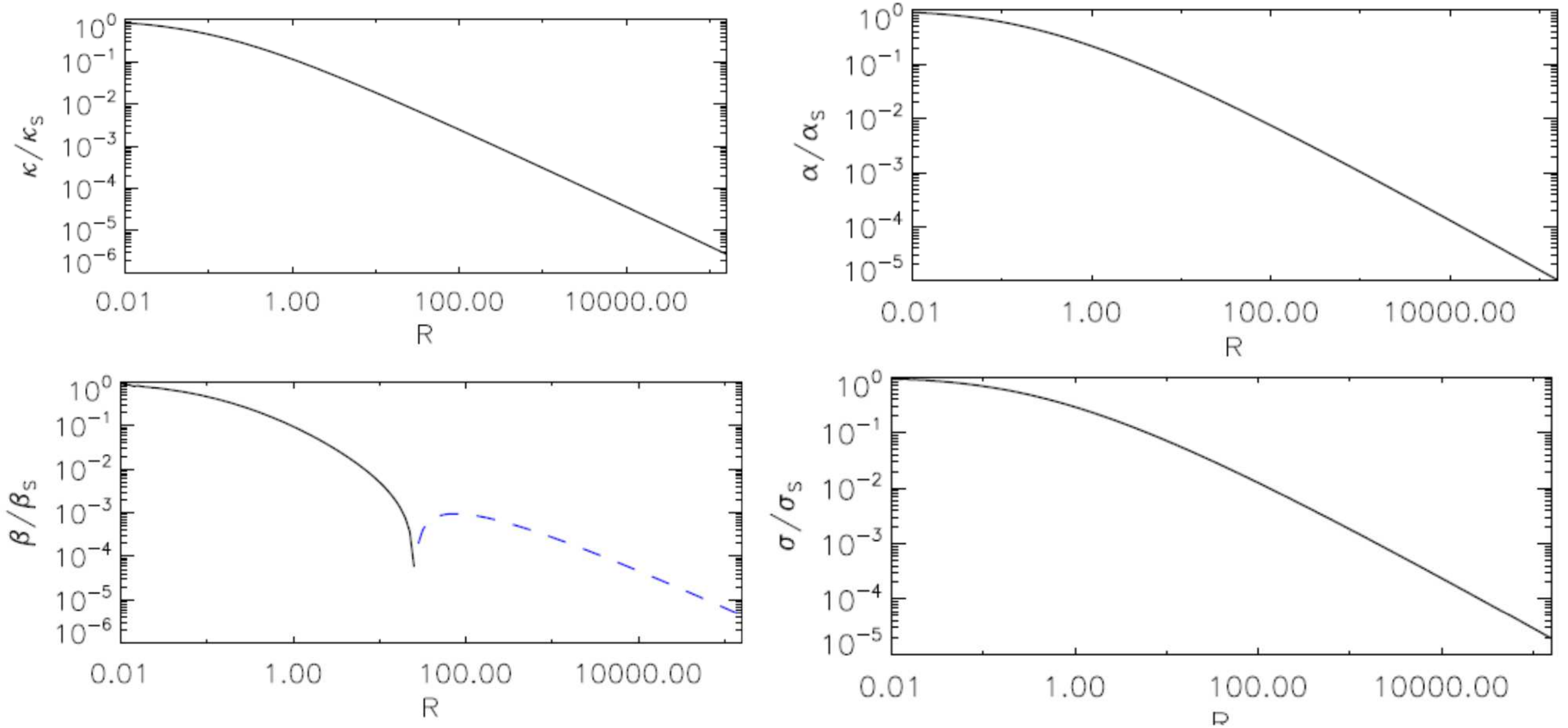
$$\sigma_{\|} = \frac{4}{3\sqrt{\pi}} \frac{n_e \, e^2 \, v_{\text{te}} \, \lambda_{\text{ei}}}{k_B T_e} \int_0^\infty \frac{x^7}{Rx^{4-\alpha}+1} e^{-x^2} \, dx$$

Variation with R



$$\begin{pmatrix} q_{\parallel} \\ j_{\parallel} \end{pmatrix} = \begin{pmatrix} -\kappa_{\parallel} & -\alpha_{\parallel} \\ \beta_{\parallel} & \sigma_{\parallel} \end{pmatrix} \begin{pmatrix} dT_e/dz \\ E_{\parallel} \end{pmatrix}$$

Implications for Flares

1. Cooling of 10^7 K plasma

2. Importance of Return Current Ohmic energy losses

Cooling of Flare Coronal Plasma

$$\frac{\partial(n_e k_B T_e)}{\partial t} = -\frac{\partial q_{\|}}{\partial z} + Q$$

$$q_{\|} = -\frac{2n_e k_B (2k_B T_e)^{1/2}}{m_e^{1/2}} \lambda \frac{dT_e}{dz}$$

$$2n_e k_B \left(\frac{2k_B T_e}{m_e}\right)^{1/2} \lambda \left(\frac{T_e}{L^2}\right) \simeq Q$$

Classical Conduction: $\lambda \sim T_e^2$; LHS $\sim T_e^{7/2}/L^2$

$$T_e \simeq \frac{m_e^{1/7}}{2k_B} \left(2\pi e^4 \ln \Lambda\right)^{2/7} Q^{2/7} L^{4/7} \simeq 50\, Q^{2/7} L^{4/7}$$

$$T_e \simeq 3 \times 10^7\,\mathrm{K}$$

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Cooling of Flare Coronal Plasma

$$2n_e k_B \left(\frac{2k_B T_e}{m_e}\right)^{1/2} \lambda \left(\frac{T_e}{L^2}\right) \simeq Q$$

Turbulent Conduction: λ ~ const = λ_T; LHS ~ $T_e^{3/2}/L^2$

$$T_e \simeq \frac{m_e^{1/3}}{2k_B}\left(\frac{QL^2}{n_e \lambda}\right)^{2/3}$$

$$\nu_T = |\mu| \left(\frac{\delta B_\perp}{B_0}\right)^2 \frac{v}{\lambda_B}$$

$$T_e \simeq \frac{m_e^{1/3}}{2k_B}\left(\frac{Q}{n_e}\right)^{2/3} L^{4/3} \lambda_B^{-2/3} \left(\frac{\delta B_\perp}{B_0}\right)^{4/3}$$

$$T_e \simeq 1 \times 10^8\,\mathrm{K}$$

Comparison

Classical Conduction: $\lambda \sim T_e^2$

$$T_e \simeq \frac{m_e^{1/7}}{2k_B}\left(2\pi e^4 \ln\Lambda\right)^{2/7} Q^{2/7} L^{4/7} \simeq 50\, Q^{2/7} L^{4/7}$$

$$T_e \simeq 3 \times 10^7\,\mathrm{K}$$

Turbulent Conduction: $\lambda \sim \text{const} = \lambda_T$

$$T_e \simeq \frac{m_e^{1/3}}{2k_B}\left(\frac{Q}{n_e}\right)^{2/3} L^{4/3} \lambda_B^{-2/3} \left(\frac{\delta B_\perp}{B_0}\right)^{4/3}$$

$$T_e \simeq 1 \times 10^8\,\mathrm{K}$$

$L^{4/7}$ and $L^{4/3}$, respectively

Implications

Suppression of thermal conductivity (reduced value of κ) $\rightarrow$

1. Increased coronal temperature
2. Longer cooling time (Moore et al. 1978)

Value of σ and Return Current Losses

$$|dE/dt| = e\,\mathcal{E}_{||}\,v = e\,v\,j_{||}/\sigma_{||}$$

Reduction in σ due to collisionless turbulent scattering $\longrightarrow$ higher value of dE/dt.

Impacts:

- Energy loss profile for electrons
- Hard X-ray efficiency/spectrum/height structure
- Atmospheric heating/chromospheric response

Conclusions

- Observations suggest that noncollisional scattering plays a significant role in energy/current transport processes in flare plasmas
- Both the thermal conductivity (κ) and electrical conductivity (σ) values are affected. This leads to

1. Increased coronal temperature
2. Longer cooling time for SXR plasma
3. Different loop scaling laws
4. Different cooling time profile (Bian et al., submitted)
5. Different energy loss profile for accelerated electrons
6. Changes in hard X-ray efficiency (ergs of electrons per erg of observed HXR emissivity)/spectrum/height structure
7. Changes in atmospheric heating depth profile and so chromospheric response to flare heating