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Heating of the ISM by Alfvén-wave damping

Felix Spanier

Institut für Theoretische Physik IV, Ruhr-Universität Bochum, Universitätsstr. 150, 44801 Bochum

Abstract. We calculate the heating rate from damping of Alfvén waves in the warm ionized medium. An anisotropic wave spectrum was used and the damping processes considered were collision Landau damping, Joule heating, viscous damping and ion-neutral collisions.

1 ISM scenario

We consider a scenario found in the **Warm Intercloud Medium** with the following parameters: temperature $T \approx 10^4$ K, particle density $n \approx 0.2$ cm^{-3} and a background magnetic field $B = 4\,\mu$G. Therefore we find an efficient cooling mechanism with the cooling rate

$$L_R = 5 \cdot 10^{-24}\, n_e^2 \text{ erg s}^{-1} \text{ cm}^{-3} \tag{1}$$

as proposed by Minter & Spangler (1997).

One finds a mixture of Alfvén and fast magnetosonic waves, we will **focus on Alfvén Waves**. As Spangler (1991) points out that these waves must wave numbers in the regime

$$k_{\text{min}} = \frac{2\pi}{10^{17}\text{cm}}\ ,\ k_{\text{max}} = \frac{2\pi}{10^{7}\text{cm}}$$

which is given by the ion inertia length on the one hand and on the distance between two clouds on the other hand.

2 Wave spectrum

We use an anisotropic power spectrum of electron density fluctuations from Spangler (1991)

$$P_{nn} = \frac{C_N^2}{(k_\parallel^2 + \Lambda k_\perp^2)^{\frac{2+s}{2}}} \tag{2}$$

To derive the magnetic fluctuation spectra a kinetic approach is needed (Schlickeiser & Lerche 2002)

$$\frac{P_{\text{yy}}^{\text{A}}(\vec{k})}{B_0^2} = \frac{\Omega_{\text{p}}^2 \sin^2\theta}{9V_{\text{A}}^2 k^2} \frac{P_{\text{nn}}^{\text{A}}(\vec{k})}{n_{\text{e}}^2} \tag{3}$$

whereas for fast magnetosonic waves the relation between both spectra is nearly linear.

The constant C_N is defined by normalisation over the total fluctuating power

$$\int d^3k\, P_{nn}(\vec{k}) \quad = \quad (\delta n_e)^2 \tag{4}$$

As the power is splitted into two parts for magnetosonic and Alfvén waves, we introduce two constants, C_A and C_M which determine the magnetic fluctuations.

$$(\delta B_A)^2 \quad = \quad \int d^3k P_{yy}^A(\vec{k}) \tag{5}$$

3 Damping Processes

For a given damping rate the energy dissipation rate is given by:

$$\epsilon_i = \int d^3k P^A_{yy} 2\gamma_i \tag{6}$$

Four different processes have been included in the calculation:

- Collisionless Landau damping
- Viscous damping
- Joule heating
- Ion-Neutral collisions

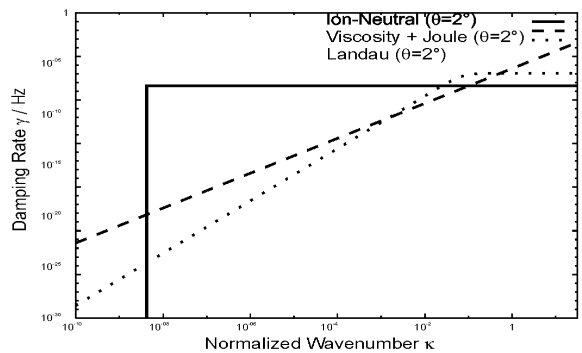

Fig. 1. Damping rates at $\theta = 2°$

3.1 Joule Heating

Joule heating is related to the resistivity of the plasma and the currents. We take the formula from Braginskii (1965)

$$\sigma_\perp = \frac{\omega_{pe}^2}{4\pi\nu_e}, \sigma_\parallel = 1.96\sigma_\perp \tag{7}$$

resulting in

$$\gamma_J(k) = \frac{\nu_e c^2 k^2}{2\omega_{pe}^2}\left(\cos^2\theta + 0.51\sin^2\theta\right) \tag{8}$$

Joule heating is **neglected in favor of viscosity**.

3.2 Viscosity

Viscosity was proposed by Hollweg (1985), the parameter η_0 cancels out due to the incompressibility of Alfvén waves

$$\gamma_V(k) = \frac{k^2}{2m_p n_e}\left((\eta_1^p + \eta_1^e)\sin^2\theta + (\eta_2^p + \eta_2^e)\cos^2\theta\right) \tag{9}$$

The electron contribution is small compared to the proton contribution

$$\gamma_V(k) \simeq 0.15\frac{k_B T_p}{m_p c^2}\frac{k^2 c^2 \tau_i}{(\Omega_p \tau_i)^2}\left(\sin^2\theta + 4\cos^2\theta\right) \tag{10}$$

Introducing

$$k_c = \frac{\Omega_p}{V_A} \ , \ \kappa = \frac{k}{k_c}$$

we find for Joule and viscous damping together

$$\gamma_{V+J} = 10^{-7}\kappa^2\left(\sin^2\theta + 4\cos^2\theta\right) \tag{11}$$

As Joule and viscous damping have the same k^2 dependence and similar angular depence we may sum them up. Integrating with 6 gives

$$\epsilon_{V+J} = 4\cdot 10^7 \frac{1+s}{3-s}(\delta B_A)^2 k_c^2 \frac{\kappa_{\rm max}^{3-s} - \kappa_{\rm min}^{3-s}}{\kappa_{\rm max}^{1+s} - \kappa_{\rm min}^{1+s}} H_{V+J}(\Lambda, s) \tag{12}$$

$$H_{V+J}(\Lambda, s) = \frac{3F\left(\frac{2+s}{2}, 1; 3; 1-\Lambda^{-1}\right)}{8F\left(\frac{2+s}{2}, \frac{1}{2}; \frac{5}{2}; 1-\Lambda^{-1}\right)} + \frac{3F(\frac{2+s}{2}, 2; 4; 1-\Lambda^{-1})}{8F(\frac{2+s}{2}, \frac{1}{2}; \frac{5}{2}; 1-\Lambda^{-1})} \tag{13}$$

resulting in

$$\epsilon_{V+J} = 10^{-39}\text{erg s}^{-1}\text{cm}^{-3}(\Lambda = 1) \tag{14}$$

This gives only a small contribution, so it has **no influence on ISM heating**.

3.3 Collisionless Landau

We are using the damping rate for obliquely propagating shear Alfvén waves (Ginzburg 1961, p.218, Eq. (14.56))

$$\begin{aligned} \gamma_L &= \left(\frac{\pi}{8}\right)^{1/2} \frac{\omega^3}{\Omega_\mathrm{p}^2} \frac{v_\mathrm{e}}{V_\mathrm{A}} \frac{\tan^2\theta}{\sin^2\theta + 3(\omega^2/\Omega_\mathrm{p}^2)\cos^2\theta} \\ &\quad \times \left(v_\mathrm{i}^2/v_\mathrm{e}^2 + (\sin^2\theta + 4\cos^2\theta)\exp[-V_\mathrm{A}^2/(2v_\mathrm{i}^2\cos^2\theta)]\right) \\ &\simeq \left(\frac{\pi}{8}\right)^{\frac{1}{2}} \frac{m_e}{m_p} v_e k_c \kappa^3 \frac{\cos\theta + \sin^2\theta}{\sin^2\theta + 3\kappa^2\cos^4\theta} \end{aligned} \tag{15}$$

Inserting into Eq. (6) yields

$$\epsilon_L = 1.1\cdot 10^{-5}\frac{1+s}{2-s} v_e k_c (\delta B_A)^2 \frac{\kappa_\mathrm{max}^{2-s} - \kappa_\mathrm{min}^{2-s}}{\kappa_\mathrm{max}^{1+s} - \kappa_\mathrm{min}^{1+s}} H_L(\Lambda, s) \tag{16}$$

$$H_L(\Lambda, s) = \frac{3F\left(\frac{2+s}{2}, 1; 3; 1-\Lambda^{-1}\right)}{8F\left(\frac{2+s}{2}, \frac{1}{2}; \frac{5}{2}; 1-\Lambda^{-1}\right)} \tag{17}$$

Approximations

$$H_L(\Lambda \gg 1) \simeq \mathit{const} \tag{18}$$

$$H_L(\Lambda \ll 1) \propto \Lambda^{1/2} \tag{19}$$

For given ISM parameters we find

$$\epsilon_L \simeq 3.8\cdot 10^{-42}\text{erg s}^{-1}\text{cm}^{-3}(\Lambda = 1) \tag{20}$$

Collisionless Landau damping can be ignored for any value of Λ.

Comparison to Fast Magnetosonic waves

Lerche & Schlickeiser (2001):

$$R(\Lambda = 1) = \frac{\epsilon_L^A(\Lambda = 1)}{\epsilon_L^M(\Lambda = 1)} \simeq 10^{-20}\frac{(\delta B_A)^2}{(\delta B_M)^2} \tag{21}$$

$$R(\Lambda \gg 1) \simeq 10^{-20}\Lambda^{s/2}\frac{(\delta B_A)^2}{(\delta B_M)^2} \tag{22}$$

$$R(\Lambda \ll 1) \simeq 10^{-20}\Lambda^{-s/2}\frac{(\delta B_A)^2}{(\delta B_M)^2} \tag{23}$$

3.4 Ion-Neutral

$$\gamma_\mathrm{N}(k) \simeq \nu_\mathrm{N}\cos^2\theta\ ,\ \kappa \geq \kappa_\mathrm{N}\cos\theta \tag{24}$$

$$\nu_\mathrm{N} = 4\cdot 10^{-9} n_\mathrm{H}\ \text{Hz} \tag{25}$$

$$\kappa_\mathrm{N} = \frac{\nu_N\ [\text{Hz}]}{B[\text{G}]} \tag{26}$$

γ_N holds for propagation angles $\mid \theta \mid \leq \frac{\pi}{2} - \omega_{\rm R}/43\Omega_{\rm p}$
Integrating considering the critical wave number

$$\epsilon_N = \frac{2}{\pi(2-s)(4-s)}\nu_N t_E^{\frac{s+1}{2}}(\delta B_A)^2 H_N(\Lambda, s) \quad (27)$$

$$H_N(\Lambda, s) = \frac{3F(\frac{2+s}{2}, 2; 3-\frac{s}{2}; 1-\Lambda)}{4F(\frac{2+s}{2}, \frac{1}{2}; \frac{5}{2}; 1-\Lambda)} \quad (28)$$

$$\epsilon_N = 1.74 \cdot 10^{-29} \text{erg s}^{-1}\text{cm}^{-3} \quad (29)$$

We have two approximations for H_N:

$$H_N(\Lambda \gg 1) \simeq 2^{s-3}(4-s)(2-s) \quad (30)$$

$$H_N(t_E < \Lambda \ll 1) \simeq \frac{s+1}{(4-s)(2-s)^2}\Lambda^{-s/2} \quad (31)$$

This is the **most important process**, though the heating rate is still too small to maintain the temperature balance.

4 Conclusion

- Ion-Neutral Damping is the dominant damping process in Alfvén waves
- Anisotropy can reduce damping for perpendicular waves
- Alfvén waves **cannot contribute significantly to the temperature balance of the ISM**

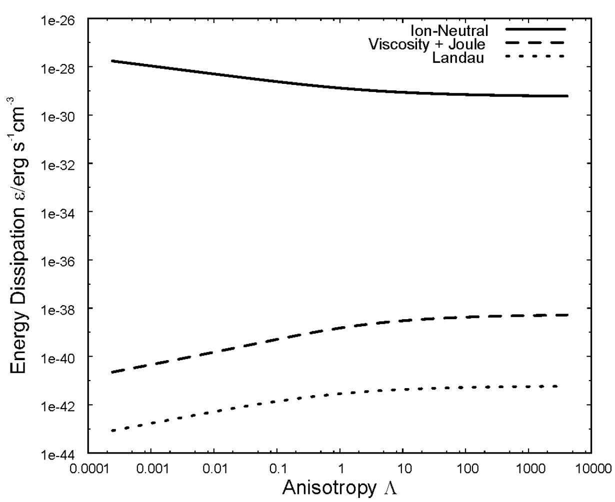

Fig. 2. Energy dissipation rate vs. anisotropy parameter Λ

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