Wave damping and wave energy dissipation in the interstellar medium: Shear Alfvén waves

Marian Lazar[1], Felix Spanier[2], Reinhard Schlickeiser[2]
[1] Universitatea "Alexandru Ioan Cuza", Facultatea de Fizica, Bd. Carol I Nr. 11, 6600 Iasi, Romania
[2] Institut für Theoretische Physik, Lehrstuhl IV: Weltraum- und Astrophysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Abstract

We are investigating different wave damping processes of Alfvén waves in the interstellar medium. As a result we find the damping rates and the total energy loss rate.

Introduction

ISM consists of three distinct phases in pressure equilibrium:

- **cold clouds,**
- **warm intercloud medium**
- **hot coronal gas generated by supernova explosions.**

Warm medium has a temperature between 6000 and 10^4 K and a HI-density of about 0.8 cm^{-3}, atomic and metallic **radiative transitions efficiently cool the gas** an efficient heating mechanism is required in order to **maintain the gas temperature.** Various heating processes of the ISM have been suggested,

- ***background ultraviolet and X-ray heating (e.g. Cheng & Bruhweiler 1990)***
- ***cosmic ray heating (e.g. Lerche & Schlickeiser 1982)***
- ***photoelectric emission from grains***

Lerche & Schlickeiser (2001) investigated the heating by **collisionless damping of fast magnetosonic** waves. It was demonstrated that the wave energy loss rates agrees with the cooling rates for the diffuse ISM when the anisotropy in the wave power spectrum is properly accounted for. Equilibrium temperature is determined by the balance of heating and cooling rates

$$\epsilon(\rho, T) = \lambda(\rho, T)$$

We will investigate the heating of the ISM by collisionless damping of shear Alfvén waves. We adopt a power spectrum of electron density fluctuation in the form

$$P_{nn}(\boldsymbol{k}) = C_N^2\,[k_{||}^2 + \Lambda k_\perp^2]^{-(2+s)/2}$$

is representing an **anisotropy factor** (>>1 represents a spectrum as suggested by Goldreich & Sridhar (1995)). The given wave spectrum operates between $L_{max}=10^{17}$ cm an $l_{min}=10^7$ cm, as estimated by Spangler (1991) by the physical size of warm intercloud medium and Whistler resonance.

Magnetic Field Fluctuations

Interstellar turbulence is a **mixture of fast magnetosonic waves and shear Alfvén** waves because the plasma = 0.22 is much smaller than unity.

We will need the power spectrum of the magnetic field fluctuations, but from observations we do have the power spectrum of interstellar electron density fluctuations. We have to discuss the relation of electron density and magnetic field fluctuations for plasma waves.

In classical MHD theory (Sturrock - 1961, Ch. 14.1) shear Alfvén waves are incompressible (n_e = 0). However, because the plasma parameter g = $_{ee}$/ $_{p,e}$ 10^{-10} of the diffuse intercloud gas is much less than unity, a full kinetic description rather than the MHD description of the plasma turbulence at turbulence spatial scales $l < l_{MHD}$ 0.003 pc is necessary. Schlickeiser & Lerche (2002) calculated the relation between the magnetic field fluctuation and electron density fluctuation power spectra for shear Alfvén waves and fast magnetosonic waves using linear kinetic theory.

If a wave propagates at an angle with respect to the uniform background magnetic field $\mathbf{B}_0=B_0\,\mathbf{e}_z$ They obtained for shear Alfv$_{én}$

$$\frac{P_{yy}^A(\boldsymbol{k})}{B_0^2} = \frac{\Omega_p^2 \sin^2\theta}{9V_A^2 k^2}\frac{P_{nn}^A(\boldsymbol{k})}{n_e^2}$$

$$\frac{P_{zz}^M(\boldsymbol{k})}{B_0^2} = \tan^2\theta\frac{P_{xx}^M(\boldsymbol{k})}{B_0^2} = \frac{1}{9[1+\beta\sin^2\theta]^2}\frac{P_{nn}^M(\boldsymbol{k})}{n_e^2} \simeq \frac{P_{nn}^M(\boldsymbol{k})}{9n_e^2} \qquad \theta \le 86 \quad \beta << 1$$

We immediately deduce the corresponding magnetic field power spectra of shear Alfvén waves as

$$P_{yy}^A(\boldsymbol{k}) = C_A^2\,\frac{k_\perp^2 k_c^2}{k^4[k_{||}^2+\Lambda k_\perp^2]^{(2+s)/2}}, \qquad k_c = \Omega_p/V_A = \omega_{p,i}/c$$

$$P_{zz}^M(\boldsymbol{k}) = C_M^2\,[k_{||}^2+\Lambda k_\perp^2]^{-(2+s)/2} \qquad C_A^2 + C_M^2 = (\frac{B_0}{3n_e})^2 C_N^2$$

C_A and C_M determine the values of the total fluctuation energy density in the wave. Minter & Spangler (1997) give the value B = 0.9 G. For given electron fluctuation spectrum the magnetic field fluctuation spectrum is much steeper.

Damping Rates

We will discuss the following damping processes in turn

- Collisionless Landau damping $_A$
- Joule dissipation $_J$
- Ion viscosity $_V$ (Braginskii 1965)
- Ion-neutral friction $_N$ (Kulsrud & Pearce 1969)

Energy Loss Rates

With given damping rates and power spectra it is easy to calculate the energy loss rates for the Alfvén waves

$$\epsilon_0 = \frac{1}{4\pi}\int d^3k\, P_{yy}^A(\boldsymbol{k}) 2\gamma_0(\boldsymbol{k}).$$

$$\epsilon_i = C_A^2 k_c^{1-s}\int_{\kappa_{min}}^{\kappa_{max}} d\kappa\kappa^{-s-2}\int_{-1}^{1} d\mu\frac{1-\mu^2}{[\mu^2+\Lambda(1-\mu^2)]^{\frac{2+s}{2}}}\gamma_i(\kappa,\mu) \qquad \mu=\cos\theta,\quad \kappa_{min}=k_{min}/k_c,\quad \kappa_{max}=k_{max}/k_c$$

Damping rates and energy loss rates for different processes

Landau-, Joule-, Viscous-damping and Ion-Neutral-Collisions

Collisionless Landau Damping

For an obliquely propagating wave the damping rate is given by Ginzburg

$$\gamma = (\frac{\pi}{8})^{1/2}\frac{\omega^3}{\Omega_p^2}\frac{v_e}{v_A}\frac{\tan^2\theta}{\sin^2\theta + 3(\omega^2/\Omega_p^2)\cos^2\theta}\times[v_i^2/v_e^2 + (\sin^2\theta+4\cos^2\theta)\exp[-V_A^2/(2v_i^2\cos^2\theta)]],$$

v_e and v_i are the electron- and ion-thermal velocity which are supposed to be Maxwellian distributed. The approximation for the damping rate is valid only for

$$v_e|\cos\theta| >> V_a|\cos\theta| >> v_i|\cos\theta|.$$

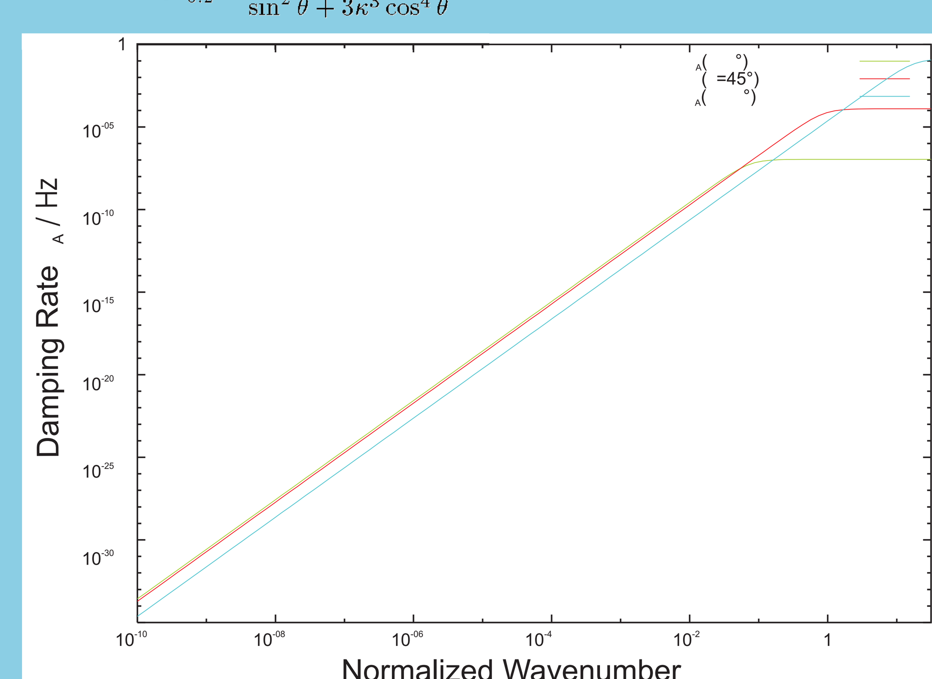
The exponential term is exceedingly small for all angles , so that we can write using the normalized wavenumber $_c$ the damping rate reads

$$\gamma_A(k) \simeq (\frac{\pi}{8})^{1/2}\frac{m_e v_e k_c}{m_p}\kappa^3\frac{\cos\theta\sin^2\theta}{\sin^2\theta+3\kappa^3\cos^4\theta}$$

We now use the typical parameters for the intercloud medium

- $n_e = 0.2\, n_{0.2}\, cm^{-3}$
- $T_e = 10^4\, T_4$ K
- $B_0 = 4\, b_4$ G
- $_c = 2\; 10^{-8}\, n_{0.2}^{1/2} cm^{-1}$

$$\gamma_A(\kappa) = 2.7\cdot 10^{-4} T_4 n_{0.2}^{1/2}\kappa^3\frac{\cos\theta\sin^2\theta}{\sin^2\theta+3\kappa^3\cos^4\theta}\ \mathrm{Hz}$$



With the damping rate, the energy loss rate can be easily calculated using formula

$$\epsilon_A \simeq 3.4\cdot 10^{-4} v_e C_A^2 k_c^{2-s}\Lambda^{-\frac{2+s}{2}}\Big[\int_{\kappa_{min}}^{1} d\kappa\kappa^{1-s}J_1(s,\Lambda) + \frac{k_c^2}{3}\int_1^{\kappa_{max}} d\kappa\kappa^{-1-s}J_2(s,\Lambda,k,k_c)\Big]$$

$$\epsilon_A \le 1.1\cdot 10^{-5}\frac{s+1}{2-s}v_e k_c(\delta B_A)^2\kappa_{\max}^{2-s}\kappa_{\min}^{s+1}\frac{1-(\frac{\kappa_{min}}{\kappa_{max}})^{2-s}}{1-(\frac{\kappa_{min}}{\kappa_{max}})^{1+s}}H_A(\Lambda,s) \quad \kappa_{\min} << 1 < \kappa_{\max}$$

$$H_A(\Lambda,s) = \frac{J_1(\Lambda,s)}{J(\Lambda,s)} = \frac{3}{8}\frac{F(1+\frac{s}{2},1;3;1-\ \Lambda^{-1})}{F(1+\frac{s}{2},\frac{1}{2};\frac{5}{2};1-\ \Lambda^{-1})} = \frac{3}{8}\frac{F(1+\frac{s}{2},2;3;1-\Lambda)}{F(1+\frac{s}{2},2;\frac{5}{2};1-\Lambda)}$$

It can be easily shown that the anisotropy function H_A is independent of for large values of L and varies with $^{1/2}$ for small values. In the isotropic case we obtain H_A=3/8. For the given parameters of the ISM

$$\epsilon_A(\Lambda) \simeq 3.8\cdot 10^{-42} T_4^{1/2} n_{0.2}^{-1} l_7^{-1/2} L_{pc}^{-8/3}(\delta B_A/0.9\mu G)^2 H_A(\Lambda,5/3)\ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

The result for **Alfvén** waves shows, that the energy loss rate is by **20 orders of magnitude smaller than for magnetosonic waves**

Joule and Viscosity dissipation

From Braginskii (1965) we find for the Joule dissipation that

$$\gamma_J(k) = \frac{c^2k^2}{8\pi}(\frac{\sin^2\theta}{\sigma_{||}} + \frac{\cos^2\theta}{\sigma_\perp}) = \frac{\nu_e c^2 k^2}{2\omega_{p,e}^2}[\cos^2\theta + 0.51\sin^2\theta]$$

Also from Braginskii (1965) the viscosity dissipation can be written as

$$\gamma_V(k) \simeq 0.15\frac{k_B T_p}{m_p c^2}\frac{k^2c^2\tau_i}{(\Omega_{p,0}\tau_i)^2}[\sin^2\theta + 4\cos^2\theta]$$

Both damping rates have similar angular dependence, but Joule dissipation is less efficient in ISM and can be neglected, so we have

$$\gamma_{V+J}(\kappa) \simeq \gamma_V(\kappa) = 10^{-7} n_{0.2}^2 T_4^{-3/2} b_4^{-4}\kappa^2[\sin^2\theta + 4\cos^2\theta]$$

With a similar technique as before we can derive the energy dissipation rate

$$\epsilon_{V+J} = 1\cdot 10^{-39} n_{0.2} T_4^{-3/2} b_4^{-4} L_{pc}^{-2}(\delta B_A/0.9\mu G)^2 H_{V+J}(\Lambda,s)\ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

The anisotropy term consists of two parts $H_{V+J}=H_A+h_{V+J}$

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

For values >>1 the anisotropy is independent of . For values of <<1 H varies with $^{-1/2}$

Ion-Neutral Friction

Instead of the well-known result of Kulsrud & Pearce (1969) we found for the damping rate for ion-neutral friction

$$\gamma_N(k) \simeq \nu_N\cos^2\theta$$

This damping rate is valid for values of with < $_D$

$$\theta_D = \frac{\pi}{2} - \frac{\omega_R}{43\Omega_p} = \frac{\pi}{2} - \frac{\kappa\cos\theta}{43} \ge \frac{\pi}{2} - \frac{\kappa}{43}$$

which we derived from the dispersion relation and the inclusion of the ion-neutral collision frequency in the Stix parameter.
We end up with the following energy dissipation rate

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

again we have an anisotropy function

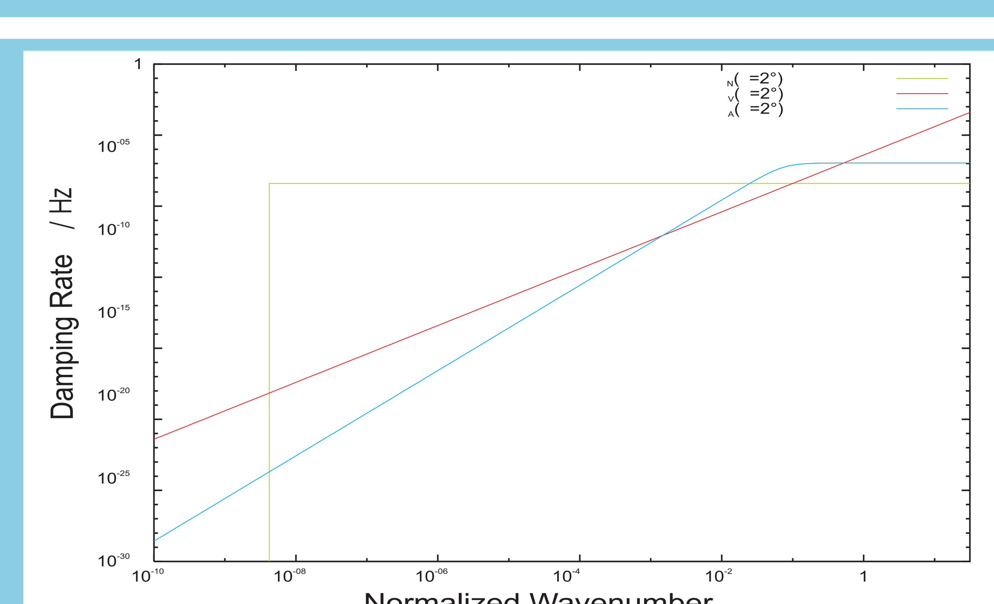
$$H_N(\Lambda,s) = \frac{F(1+\frac{s}{2},1-\frac{s}{2};3-\frac{s}{2};1-\ \Lambda^{-1})}{\Lambda^{\frac{2+s}{2}}J(\Lambda,s)} = \frac{3F(1+\frac{s}{2},2;3-\frac{s}{2};1-\Lambda)}{4F(1+\frac{s}{2},\frac{1}{2};\frac{5}{2};1-\Lambda)}$$

For small H varies with $^{-s/2}$, while we have

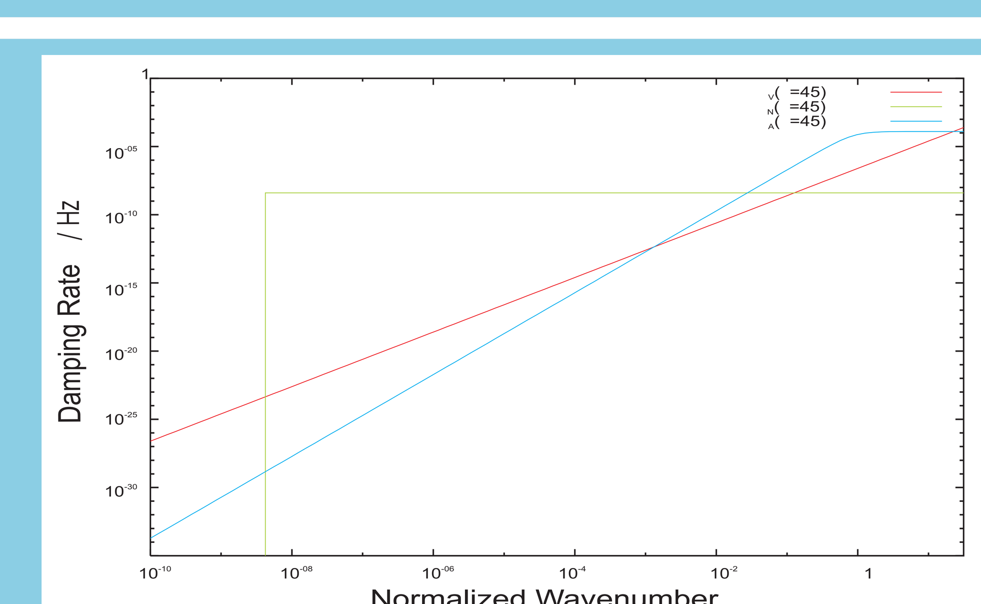
$$H_N(t_E < \Lambda << 1) \simeq \frac{(s+1)}{(4-s)(2-s)^2}\Lambda^{-s/2}$$

and the numerical value for the ISM

$$\epsilon_N \simeq 1.74\cdot 10^{-29} n_H^{-5/3} b_4^{8/3} L_{pc}^{-8/3} n_{0.2}^{-4/3}\mathrm{erg\ cm^{-3}\ s^{-1}}$$



Damping Rates at =2°



Damping Rates at =45°

Bibliography

1972 Abramowitz, M., Stegun, I. A., 1972, Handbook of Mathematical Functions, National Bureau of Standards, Washington
1965 Braginskii, S. I., 1965, Rev. Plasma Phys. 1, 205
1990 Cheng, K.-P., Bruhweiler, F. C., 1990, ApJ 364, 573
1995 Gary, S. P., 1986, J. Plasma Phys. 35, 431
1961 Ginzburg, V. I., 1961, Propagation of Electromagnetic Waves in Plasma, Pergamon Press, New York
1995 Goldreich, P., Sridhar, S., 1995, ApJ 438, 763
1985 Hollweg, J. V., 1985, J. Geophys. Res. 90, 7620
1969 Kulsrud, R. M., Pearce, W. P., 1969, ApJ 156, 445
2001 Lerche, I., Schlickeiser, R., 2001, A& A 366, 1008 (paper I)
1982 Lerche, I., Schlickeiser, R., 1982, MNRAS 201, 1041
1997 Minter, A. H., Spangler, S. R., 1997, ApJ 485, 182
2002 Schlickeiser, R., Lerche, I., 2002, J. Plasma Phys. 68, 191
2002 Schlickeiser, R., 2002, Cosmic Ray Astrophysics, Springer, Berlin
1991 Spangler, S. R., 1991, ApJ 376, 540
1961 Sturrock, P. A., 1994, Plasma Physics, Cambridge University Press

Conclusions and Outlook

- Ion-neutral collisions are the major damping process for the ISM
- Energy loss rate of Alfvén waves is by 3 orders of magnitude too small to explain the temperature of warm intercloud medium
- Fast magnetosonic waves have a higher loss rate for collisionless Landau damping

Acknowledgment

M.L. gratefully acknowledges support as young researcher of the PLATON network (EC contract HPRN-CT-2000-00153). F. S. and R.S. acknowledge partial support by the Deutsche Forschungsgemeinschaft through Sonderforschungsbereich 591

Please leave your address if you are interested in preprints