Binary Collision Contribution to the Relaxation of Dense, Non-ideal Two-Temperature Plasmas

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The first theoretical descriptions of temperature relaxation were given by Landau and Spitzer (LS approach) [1, 2]. Considering only small angle scattering (*straight line trajectories*), the temperature evolution is determined by: $dT_e/dt = \sum_\alpha (T_\alpha - T_e)/\tau^{\alpha e}$, where the electron-ion relaxation time is given by

$$\tau^{ei} = \frac{3 m_i m_e}{4\sqrt{2\pi} n_i Z_i^2 e^4 \lambda} \left(\frac{k_B T_e}{m_e} + \frac{k_B T_i}{m_i} \right)^{3/2} . \qquad (1)$$

Here, $\lambda = \ln(b_{max}/b_{min})$ is the Coulomb logarithm. We choose the electron Debye screening length for the maximum impact parameter ($b_{max} = \lambda_D^e$). b_{min} is given by an interpolation between the distance of closest approach and the deBroglie wavelength, i.e., $b_{min} = (\rho_\perp^2 + \lambda_{dB}^2)^{1/2}$. Obviously, the LS approach fails for $\lambda < 0$.

The failure of the LS approach (1) for strong coupling originates in the concept of straight line trajectories. Considering hyperbolic orbits (exact solution for Coulomb scattering), the resulting Coulomb logarithm has the form: $\lambda = 0.5 \times \ln\left(1 + (b_{max}^2/b_{ref}^2)\right)$. Note that b_{min} has been replaced now by a reference impact parameter which is not an *ad hoc* value but *defined* by the distance of closest approach. To incorporate quantum effects, the interpolation used for b_{min} can be applied for b_{ref}, too.

In recent experiments, much smaller relaxation rates than the LS approach predicts have been found for strongly coupled plasmas [3, 4, 5]. Similar theoretical predictions have been made by Dharma-warana & Perrot using a model which allows energy transfer through coupled modes [6]. However, the usual LS approach is ill-defined for strong coupling. Therefore, the data had to be compared with an *ad hoc* extension similar to the hyperbolic orbit approach.

We want to test if these discrepancies are due to limitations of the LS theory or the failure of the binary collision approach in general. Therefore, we apply a highly accurate approach to calculate the binary collision contribution to the energy relaxation rates. This theory is valid for strong electron-ion coupling, includes quantum effects, considers screened potentials and avoids any *ad hoc* cutoffs. We start from the definition of the average kinetic energy $\langle E_i \rangle = (2\pi\hbar)^{-3} \int d\boldsymbol{p}\, E_i(p)\, f_i(\boldsymbol{p}, t)$ and determine the change of the ion distribution function by the quantum Boltzmann equation. In the case $T_e \gg T_i$, the resulting equation for the energy transfer per ion reads [7]

$$\frac{\partial}{\partial t} E_i = \frac{1}{2\pi^2 \hbar^3} \frac{n_e \Lambda_e^3}{m_e m_i} \int_0^\infty dk\, k^5\, Q_{ei}^T(k) \exp\left(-\frac{k^2}{m_e k_B T_e} \right) . \qquad (2)$$

Here, $Q_{ei}^T = 2\pi \int d\theta (1 - \cos\theta)\, d\sigma_{ei}(k, \Omega)/d\Omega$ is the momentum transfer cross section of *e*-*i* scattering (θ denotes the scattering angle). We calculate the cross section by a numerical phase shift analysis using the Debye interaction potential $V_{ei}(r) = Z_i e^2 \exp(-r/\lambda_D^e)/r$ (T-matrix result).

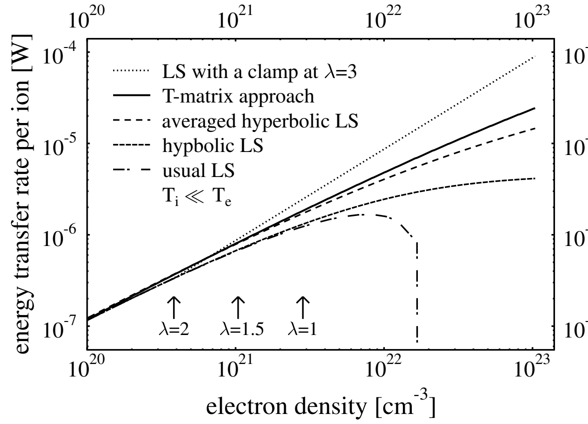

Figure 1: Temperature relaxation rates is different approximations. The system is an aluminum plasma with an electron temperature of $T_e = 5 \times 10^5$ K and an ion charge state of $\bar{Z} = 10$.

Fig. 1 shows the results for an aluminum plasma. Since the T-matrix approach considers all relevant effects (within the binary collision model), it can serve here as a benchmark. The usual LS theory shows the well-known break-down for small λ. Of course, this behaviour can be avoided with an *ad hoc* clamp ($\lambda' = 3$ if $\lambda < 3$), but too large rates follow in this model. Considering hyperbolic orbits, the break-down can be also avoided. However, the resulting rates are too small for strong coupling. The differences between the T-matrix and the hyperbolic LS approaches could result from i) the different averaging proceedure and ii) from the different potentials used (Debye pot. versus Coulomb cut-off pot.). To seperate these effects, we also calculated rates with a Coulomb cut-off cross section averaged over the distribution. In this case, the energy tranfer rates (dashed line) are much closer to the T-matrix results.

Finally, the T-matrix results are in general larger than the LS rates. Therefore, the descrepacies with the experimental and coupled mode results can only be explained by an invalidity of the binary collision approximation.

References

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