Energy Transfer from Ions to Electrons and the Coulomb Logarithm

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ENERGY TRANSFER FROM IONS TO ELECTRONS AND THE COULOMB LOGARITHM*

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ABSTRACT

Application of Chandrasekhar's stellar approach to plasmas reveals the importance of nondominant terms in both the energy transfer from ions to electrons and the form of the Coulomb logarithm. Curves illustrate the role of dominant and nondominant terms in the neighborhood of $v_e \sim v_i$.

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ENERGY TRANSFER FROM IONS TO ELECTRONS AND THE COULOMB LOGARITHM

The role of the Coulomb logarithm in the energy transfer from a test ion to field electrons is discussed in the framework of Chandrasekhar's approach to the star problem. The inclusion of non-dominant terms permits test ions to lose energy to somewhat faster electrons (e.g., up to about $v_e \sim 10-20 v_i$), although at a very greatly reduced rate per electron compared to the dominant terms used for $v_e < v_i$; however, the two sets of energy losses are comparable for a Maxwellian sea of electrons. The effects of magnetic and electric fields on the energy loss terms are discussed briefly.

Chandrasekhar has evaluated the coefficient of dynamical friction $\Sigma \Delta v_{||}$ [1] and the energy dispersion [2] for a test star interacting with field stars. The energy loss rate is $m_i v_i \Sigma \Delta v_{||} / \Delta t$. His approach has been applied to the plasma physics case by numerous individuals [3].

By averaging Chandrasekhar's collision energy transfer term [2] ΔE (instead of ΔE^2 , which leads to energy dispersion) over the collision frequency for the plasma case, one can obtain the net energy transfer rate, i.e., power gain-power loss. This has important ramifications in the plasma case involving a test ion and field electrons since the nondominant contribution becomes quite significant compared with the dominant contribution because of the large differences in masses and velocities of ions and electrons.

Chandrasekhar's binary collision energy transfer term [2] expressed in plasma notation for a test ion in field electrons is

$$\Delta E_i = - \frac{2m_e m_i}{m_e + m_i} V V_G \cos(\phi - \psi) \cos \psi \cos i,$$

where V is the relative velocity, V_G is the velocity of the center of mass, ϕ is the angle which $\vec{V}$ makes with the projection of $\vec{V}_G$ on the orbital plane, i is the angle between the projection of $\vec{V}_G$ on the orbital plane and $\vec{V}_G$, and ψ is related to the impact parameter b by

$$\cos \psi = \frac{1}{\sqrt{\frac{b^2 m_e^2 m_i^2 V^4}{Z^2 e^4 (m_e + m_i)^2} + 1}}.$$

The expression for power transfer to Maxwellian electrons is then

$$\frac{dE_i}{dt} = \int \Delta E_i 2\pi b db N_e(v_e) \frac{\sin \theta d\theta d\phi}{4\pi} V dv_e \frac{d\theta}{2\pi},$$

assuming spherical symmetry for the electron velocities. This leads to

$$\frac{dE_i}{dt} = - \frac{\pi (m_e + m_i) Z^2 e^4}{2 m_e m_i v_i} \int_0^\infty \frac{N_e(v_e) J'}{v_e} dv_e,$$

where

$$N_e(v_e) = \frac{\sqrt{2} m_e^{3/2} n_e v_e^2}{\sqrt{\pi} (kT_e)^{3/2}} e^{-m_e v_e^2 / 2kT_e}$$

for a Maxwellian. J' for the net power transfer case differs slightly but importantly from Chandrasekhar's J for the power loss case [1]. In other words,

$$J' = \int_{|v_i - v_e|}^{v_i + v_e} \left(\frac{m_i - m_e}{m_i + m_e} + \frac{v_i^2 - v_e^2}{v^2} \right) \ln(1 + q^2 v^4) dv$$

and

$$J = \int_{|v_i - v_e|}^{v_i + v_e} \left(1 + \frac{v_i^2 - v_e^2}{v^2} \right) \ln(1 + q^2 v^4) dv ,$$

where $q = \lambda_D m_e m_i / Ze^2 (m_e + m_i)$. Gryziński [4] gives an equivalent expression for J' .

Under most conditions of practical interest in plasma physics, the $q^2 v^4$ term is large compared with unity except for v_e very close to v_i . (Pellet fusion and other partially or fully degenerate plasmas have very small $q^2 v^4$ terms for $v_e \leq v_i$, and both $q^2 v^4$ and 1 are important. Thus, Gryziński [4] obtains an energy loss rate four times larger than that of Fermi and Teller [5] as a result of using all the degenerate electrons.) Except for the narrow range of v_e very close to v_i (which does not exhibit any blowup), one can obtain approximately for the dynamical friction coefficient (see [1]) expressed in terms of J :

$$J_{<} \approx 8v_e \ln q(v_i^2 - v_e^2) \quad \text{for } v_e < v_i ,$$

$$J_{=} = 4v_i \ln(4qv_i^2) - 8v_i \quad \text{for } v_e = v_i ,$$

and

$$J_{>} \approx 8v_e \ln \frac{v_c + v_i}{v_c - v_i} - 16 v_i \quad \text{for } v_e > v_i .$$

Similarly, for the energy transfer coefficient one obtains for J'

$$J'_{<} \approx \frac{1}{m_e + m_i} \left\{ 8m_i v_e \ln q(v_i^2 - v_e^2) - 8m_e v_i \ln \frac{v_i + v_e}{v_i - v_e} + 16m_e v_e \right\} ,$$

$$J'_{=} = \frac{(m_i - m_e)v_i}{m_e + m_i} [4 \ln(qv_i^2) - 8] ,$$

and

$$J_{>} \approx \frac{1}{m_e + m_i} \left\{ 8m_i v_e \ln \frac{v_e + v_i}{v_e - v_i} - 4m_e v_i \ln q (v_e^2 - v_i^2) - 16m_i v_i \right\}.$$

Chandrasekhar states that in the dominant term approximation $J_{>} \rightarrow 0$ for $v_e > v_i$, and he concludes that one finds "the remarkable result that to a sufficient accuracy only stars with velocities less than the one under consideration contribute" to the dynamical friction [1].

This argument is not valid in the plasma test ion field electron case, because a fairly significant ion energy loss arises from the many electrons somewhat faster than the test ion because $N(v_e) \propto v_e^{-2}$ for $v_e^2 < 0.1 v_e^2$. Less than $\sqrt{\frac{16}{\pi}} \left[\frac{m_e E_i}{m_i k T_e} \right]^{3/2}$ of the electrons have $v_e \leq v_i$

for $E_i < 0.1 \left[\frac{m_i}{m_e} \right] k T_e$.

As an example, the case $q = \lambda_D m_e / Ze^2 = 3 \times 10^{-11}$, $T_e = 10$ keV, and $v_i = 2 \times 10^8$ cm/sec ($E_p \approx 21$ keV, $E_d \approx 42$ keV, or $E_t \approx 63$ keV) leads to the results shown in Fig. 1, which includes the nondominant as well as the dominant terms in J given earlier. The total area under the curve represents the energy loss rate of a test ion to a Maxwellian sea of electrons at $T_e \sim 10$ keV. Note that the area for $v_e \geq v_i$ is almost equal to the area below $v_e = v_i$, whereas with dominant terms only, J is taken to be zero for $v_e > v_i$. Thus, nondominant terms are important in the plasma case.

Consider now the velocity "breakpoint" (v_{eBP}) in energy transfer: for $v_e > v_{eBP}$ the test ion gains energy from the electrons, whereas below $v_e < v_{eBP}$ the ion loses energy to the electrons. To evaluate this, one sets $J_{>} = 0$ because only the fast electrons can heat the ions faster

than they cool. On expanding the first term of $J'_>$ one has

$$0 = m_i v_e \left[\frac{v_i}{v_e} - \frac{v_i^2}{2v_e^2} + \frac{v_i^3}{3v_e^3} + \dots - \left(-\frac{v_i}{v_e} - \frac{v_i^2}{2v_e^2} - \frac{v_i^3}{3v_e^3} - \dots \right) \right] \\ - \frac{1}{2} m_e v_i \ln(qv_e^2) - 2m_i v_i ,$$

and one obtains

$$0 = \frac{2}{3} m_i v_i \frac{v_i^2}{v_e^2} - \frac{1}{2} m_e v_i \ln(qv_e^2) .$$

This gives

$$v_{eBP}/v_i = \sqrt{\frac{4m_i}{3m_e \ln qv_e^2}}$$

$$\approx \sqrt{\frac{m_i}{15m_e}} = \begin{cases} 11.1 & \text{for protons} \\ 15.7 & \text{for deuterons} \\ 19.2 & \text{for tritons} \end{cases} \quad \text{for } \ln(qv_e^2) = 20.$$

It should be noted that the energy loss per electron at $v_e = 10v_i$ is $\sim 1/100$ as large as shown on Fig. 1 as compared with electrons at $v_e \leq v_i$, since $N(v_e) \propto v_e^2$ for v_e^2 well below the value $2kT_e/m_e$. Figure 2 gives the average energy loss rates per electron from a test ion to an electron of velocity v_e , thus showing the relative importance of the dominant terms compared to the nondominant terms.

Since most of the energy loss by the test ion occurs in the neighborhood of $v_e \sim v_i$, the energy loss is dominated by V in this region of velocity space and the Coulomb logarithm term is more nearly $\ln \Lambda_{ei} \sim \ln(qv_i^2)$; however, for electrons heating the test ion one has $\ln \Lambda_{ei} \sim$

$\ln(qv_e^2)$. Making the small v_e approximation $\left[J_{<}^* \approx \frac{8m_i v_e}{m_i + m_e} \ln(qv_i^2) \right]$ for

$$N(v_e) = n_e \frac{\sqrt{2} m_e^{3/2} v_e^2}{\sqrt{\pi} (kT_e)^{3/2}} e^{-m_e v_e^2 / 2kT_e},$$

and integrating from $v_e = 0$ to $v_e = v_i$ (the exponential is near unity for $T_i \sim T_e$), one obtains in the dominant approximation the energy loss

$$\frac{dE_i}{dt} \approx - \frac{8\sqrt{2}\pi n_e Z^2 e^4 \sqrt{m_e} E_i}{3m_i (kT_e)^{3/2}} \ln\left(\frac{\lambda_D m_e v_i^2}{Ze^2}\right).$$

This agrees with the classical loss expression [6] except for $\Lambda_{ie} = \lambda_D m_e v_i^2 / Ze^2$ instead of $\Lambda_{ei} = \lambda_D 3kT_e / Ze^2$. Similarly, for large values of v_e one has

$$J_{>}^* \approx - \frac{8m_e v_i}{m_e + m_i} \ln(qv_e^2),$$

leading to approximately (taking $v_e^2 \sim \overline{v_e^2} = 3kT_e/m_e$)

$$\frac{dE_i}{dt} \approx + \frac{8\sqrt{2}\pi n_e Z^2 e^4 \sqrt{m_e} E_e}{3m_i (kT_e)^{3/2}} \ln \frac{\lambda_D 3kT_e}{Ze^2},$$

which agrees with the classical heating expression in Ref. [6].

When evaluating numerically the exact integrals for $\frac{dE}{dt}$, one finds essentially numerical agreement (because of the contribution from the nondominant terms near $v_e \geq v_i$) with the classical form:

$$\frac{dE_i}{dt} \approx \frac{\frac{3}{2} kT_e \ln \Lambda_{ei} - KE_i \ln \Lambda_{ie}}{(kT_e)^{3/2}} \quad \text{(numerically)}$$

$$\propto \frac{(\frac{3}{2} kT_e - E_i) \ln \Lambda_{ei}}{(kT_e)^{3/2}}, \quad (\text{Ref. [6]})$$

where capital K is a numerical factor and $K \ln \Lambda_{ie} \sim \ln \Lambda_{ei}$ in the numerical cases studied. Thus, in the absence of energy source and radiation loss terms, $T_i \rightarrow T_e$ at equilibrium.

The qualitative effect of magnetic field cutoffs of the maximum impact parameter has been previously considered [7]; if $v_e/\omega_{ce} < \lambda_D$, the Coulomb logarithm is reduced for the ion energy loss. Thus, to correct quantitatively for magnetic field effects on the Coulomb logarithm, the exact expression for the energy transfer rate given in this note must be evaluated with the Debye length $\lambda_D = \lambda_D$ or $\sim v_e/\omega_{ce}$, whichever is smaller. This selectively reduces the ion energy loss term (small v_e case) compared with the ion energy gain case (large v_e), and at equilibrium $T_i > T_e$ for a Maxwellian electron distribution even in the absence of other energy gain or loss terms. What this means in a physical sense is that the ions gain a slight amount of energy at the expense of the electrons in the case of a strong magnetic field. There is no net transfer of energy from the magnetic field. The work of Montgomery et al. [9] treats the effect of the magnetic field on the Coulomb logarithm only for the electron-electron case. This leads to a much smaller correction due to the higher electron velocities compared to the test ion plasma electron case ($v_e/\omega_{ce} < \lambda_D$).

Some years ago the author considered several other ways of depleting the cold electron portion of the Maxwellian electron distribution, i.e., in the region of $v_e \leq v_i$. Among these prospects was the effect of electric and magnetic fields in a plasma and especially in a plasma

such as the Ion-Layer [8] where B is reduced from B_0 . All electrons (as well as ions) pick up a mean drift energy $m_e v_d^2 = m_e c^2 \epsilon_\perp^2 / B^2$ which may promote a significant number of the electrons out of the cold tail corresponding to $v_e \lesssim v_i$ and into the region $v_e > v_i$, where their individual stopping power is greatly reduced. Figure 2 illustrates the gross reduction of the energy loss if an electron is promoted from $v_e < v_i$ to $v_e > v_i$. This depletion effect is currently being investigated independently elsewhere [10]; whether an ion velocity increase will wash out any significant effect merits careful study.

Futch et al. [11] observed an approximately 5% depletion of cold electrons via ordinary Coulomb collision processes evaluated on the basis of Fokker-Planck analysis; however, they used $\ln \Lambda$ as a constant (as do Trubnikov [12] and Fowler and Rankin [13]) and extracted it from the velocity integral.

Sivukhin [14] recognized the relative velocity dependence of the Coulomb logarithm but treated it as a constant depending on the average velocity of the special classes he considered. This is a reasonably valid approximation when $v_{\text{test}} \gg v_{\text{field}}$ but not in the particular case we treat here, since for test ions losing energy to that class of electrons having $v_e \lesssim v_i$ the Coulomb logarithm is significantly different from the case of the much faster electrons in the plasma heating the test ions ($v_e \gg v_i$). Sivukhin's basic equation (3.9) agrees essentially with our analysis of Chandrasekhar since for a test ion of charge Z interacting with electrons

$$\left(\frac{dE}{dt}\right)_S = - \frac{4\pi Z^2 e^4}{\mu} \int \frac{L}{v^3} (\vec{V}_G \cdot \vec{V}) f(v_e) dv_e,$$

where L is the Coulomb logarithm. This is to be compared with the Chandrasekhar form

$$\begin{aligned} \left(\frac{dE}{dt}\right)_{Ch} &= - \frac{\pi Z^2 e^4}{2\mu v_i} \int \frac{f_e(v_e) J^2 dv_e}{v_e} \\ &= - \frac{\pi Z^2 e^4}{\mu v_i} \iint \left(\frac{m_i - m_e}{m_i + m_e} + \frac{v_i^2 - v_e^2}{v^2} \right) \ln(1 + q^2 V^4)^{\frac{1}{2}} dV \frac{f_e(v_e) dv_e}{v_e} \end{aligned}$$

and taking $L \sim \ln(1 + q^2 V^4)^{\frac{1}{2}}$ and following Chandrasekhar [2]

$$\left(\frac{dE}{dt}\right)_{Ch} = - \frac{\pi Z^2 e^4}{\mu v_i} \iint \frac{2L}{v_e v^2} (\vec{V}_G \cdot \vec{V}) dV f_e(v_e) dv_e.$$

Again, from Ref. [2]

$$\left(\frac{dE}{dt}\right)_{Ch} = - \frac{\pi Z^2 e^4}{\mu v_i} \iint \frac{L}{v_e v^3} (\vec{V}_G \cdot \vec{V}) 2v_i \cdot v_e \sin \theta d\theta f_e(v_e) dv_e$$

or

$$\left(\frac{dE}{dt}\right)_{Ch} = - \frac{4\pi Z^2 e^4}{\mu} \int \frac{L(\vec{V}_G \cdot \vec{V})}{v^3} f(v_e) dv_e,$$

which agrees with the Sivukhin formula.

The presence of nuclear energy reaction products heating the ions preferentially (via nuclear elastic collisions if T_e is ≥ 100 keV) and radiation losses cooling the electrons would lead to a still larger discrepancy between T_i and T_e , especially if the cold electron tail is depleted.

A detailed Fokker-Planck analysis appears appropriate to evaluate the effect of both magnetic and electric fields on equilibrium and on possible perturbations of the ion and electron distributions. Should the

stopping power of the cold electrons be significantly reduced, the cleaner advanced fusion fuels may be found to be even more technologically feasible [15].

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Figure Captions

- Fig. 1. Relative energy loss rate of a test ion to electrons of various v_e in a Maxwellian distribution at $T_e = 10$ keV, $v_i = 2 \times 10^8$ cm/sec, $n_e = 10^{14}$ e/cm³, and $q = 3 \times 10^{-11}$ sec²/cm².
- Fig. 2. Electron velocity dependence of the test ion energy loss rate per electron in a plasma at $n_e = 10^{14}$ e/cm³, $T_e = 10$ keV, $q = 3 \times 10^{-11}$ sec²/cm², and test ion velocity $v_i = 2 \times 10^8$ cm/sec.

Figure 1

Figure 2

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