Effects of Suprathermal Particles in Space Plasmas

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Abstract. Velocity distribution functions of plasma particles measured by spacecraft in the solar wind and many other space plasmas show enhanced suprathermal tails. The presence of non-thermal populations in space plasmas has important consequences concerning particle acceleration and plasma heating. These effects are well described by the kinetic approach where the suprathermal tails can be represented by different velocity distribution functions such as a sum of two Maxwellians with different temperatures or, better, with a Kappa distribution decreasing as a power law of the velocity. In the present work, we show the consequences of the velocity filtration effect. Moreover, we establish the friction and diffusion coefficients of the Coulomb collision Fokker-Planck operator for background particles characterized by a Kappa distribution.

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INTRODUCTION: SUPRATHERMAL PARTICLES

Particle velocity distributions functions (VDF) with non-thermal populations are observed by spacecraft measurements in the solar wind and in many space plasmas such as the magnetosphere of the Earth and other planets ([1] for a review). In the solar wind for instance, electron velocity distributions are characterized by a thermal core and a halo suprathermal population [2]. Such distributions are well fitted by Kappa functions that have tails decreasing as a power law of the velocity. The fit determines three different parameters: the number density n, the temperature T and the kappa index characterizing the slope of the suprathermal tails. Electron VDF measured by Ulysses have been fitted with Kappa functions in [3]. Low values of the kappa index (between 2 and 7) are found, especially in the high speed solar wind, supporting the kinetic theoretical result that the suprathermal electrons influence the solar wind acceleration [4].

Kappa and Maxwellians

Instead of Kappa functions, another way often used to fit such distributions with enhanced suprathermal tails is a sum of two Maxwellians with different temperatures. Four parameters have then to be determined: n_1, T_1 and n_2, T_2 representing respectively the number density and temperatures of the two populations. An example

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of VDF obtained as a sum of two Maxwellians is presented on Figure 1 with typical values of n and T for the terrestrial ionosphere. Note that Kappa functions give in general better fits than a sum of two Maxwellians [5, 6] since the tails of the observed distributions do not decrease exponentially with the square velocity, but more as a power law. Using different functions as boundary conditions, it was clearly shown that important effects are produced by these suprathermal particles and are valid for any VDF with suprathermal tails. The Kappa distribution is a useful mathematical tool to represent such suprathermal distributions and it is appropriate even if the highest moments are not defined for the values of kappa <3/2.

The Evolution Equation

The effects of suprathermal particles are well evidenced by using the kinetic approach. In such models, the velocity distribution functions (VDF) f of the particles are determined by solving the evolution equation:

$$\frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} + \vec{a}.\frac{\partial f}{\partial \vec{v}} = \left(\frac{df}{dt}\right)_c \tag{1}$$

where the first term represents the time dependence of the VDF, the second term corresponds to the spatial diffusion ($\vec{r}$ is the position and $\vec{v}$ the velocity vector of the particles), the third term takes into account the effects of the external forces $\vec{F}$ ($\vec{a} = \vec{F}/m$ where $\vec{a}$ is the acceleration and m is the mass of the particles), and the term in the right hand side of the equation represents the effects of collisions and other interactions. The forces include the gravitational force (that is generally dominant at low radial distance, i.e. for instance in the solar corona [7]), the electric force (that is essential for the particle acceleration in the solar wind [4] and the planetary polar winds [8] for instance) and the Lorentz force due to the presence of the magnetic field (that causes the parallel alignment of the VDF to the magnetic field direction such as the strahl electrons in the solar wind [2], for instance). The results depend also on the boundary conditions, i.e., the VDF assumed at the reference level.

Different approximations can be used to solve the equation. In low-density plasmas such as the solar wind, the exospheric approximation is based on the assumption that all interactions between the particles can be neglected. Neglecting the right hand side in eq. [1] and the time dependent term to obtain steady state solutions, the Vlasov equation can be solved analytically using the Liouville theorem [9]. Such models have demonstrated the importance of the self-consistent electric field in the acceleration of the solar wind [8]. They also clearly demonstrate the velocity filtration effect [10, 11] that is able to explain the heating of the corona without depositing wave or magnetic field energy when suprathermal particles are assumed to be present at low altitudes in the solar atmosphere.

Velocity Filtration Effect

The velocity filtration effect has for consequence that the ratio of suprathermal particles over thermal ones increases as a function of altitude in an attraction field, as it is the case in stellar and planetary atmospheres in hydrostatic equilibrium [11].

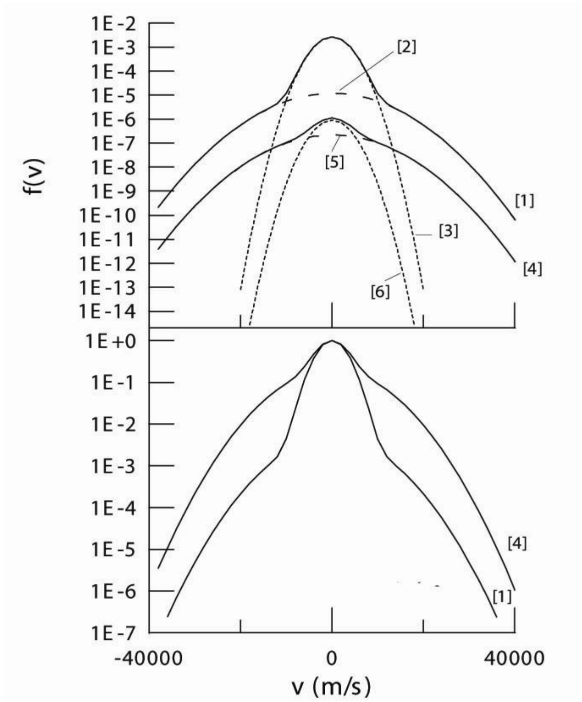

FIGURE 1. Velocity filtration effect illustrated for a VDF that is a sum of two Maxwellians with different temperatures. Top panel: The upper solid line [1] represent the sum of two Maxwellians with n_1= 100 cm^{-3}, T_1=8000 K (curve [2] and n_2=1000 cm^{-3}, T_2=1000 K (curve [3]). Curve [4] represents the distribution found at a higher altitude. Bottom panel: Normalized curves [1] and [4] illustrate the temperature increase.

This is clearly illustrated on Fig. 1 representing a VDF composed by a sum of two Maxwellians with different temperatures and its evolution with the altitude. In the top panel, the upper solid line [1] represents this sum of two Maxwellians at a reference altitude r_0 with respectively n_1= 100 cm^{-3}, T_1=8000 K and n_2=1000 cm^{-3}, T_2=1000 K.

At this altitude (1000 km), the temperature of the global VDF is given by

$$T(r_0) = \frac{n_1 T_1 + n_2 T_2}{n_1 + n_2} \tag{2}$$

Curve 4 represents the distribution found at a higher altitude in the attractive potential of the Earth. Considering a simple exospheric model [8] with two Maxwellians, the global temperature at this upper altitude is given by

$$T(r) = \frac{n_1 T_1 \exp\left(-\frac{mR(r)}{2kT_1}\right) + n_2 T_2 \exp\left(-\frac{mR(r)}{2kT_2}\right)}{n_1 \exp\left(-\frac{mR(r)}{2kT_1}\right) + n_2 \exp\left(-\frac{mR(r)}{2kT_2}\right)} \tag{3}$$

where R(r) is the total potential energy including the effects of the gravitational and electric potential. One can see that the thermal population (Maxwellian with T_2) tends to disappear to higher altitudes while the suprathermal population (Maxwellian with T_1) becomes dominant. This leads to a natural increase of the temperature (up to T_1 in the present example) directly related to the decrease of the number density appearing in the stellar and planetary atmospheres.

Effects of Particle-Particle and Wave-Particle Interactions

The velocity filtration effect remains effective even in regions where collisions are not fully negligible [12]. Indeed, more sophisticated kinetic models including the effects of Coulomb collisions have also been developed [13, 14]. They show that the suprathermal particles are less submitted to collisions than the thermal ones so that the velocity filtration effect may appear already in the very low corona where the collisions can not be neglected. Moreover, other effects than Coulomb collisions have been taken into account in the solar corona and the solar wind such as whistler wave turbulence [15], kinetic Alfvén waves [16] and cyclotron interactions [17]. The effects of these interactions can be included in the right hand side term of the evolution equation (1). Different diffusion coefficients are found depending on the spectra of the waves. The waves are found to play an important role in constraining the temperature anisotropies and generating velocity beams. The acceleration by resonant interaction with parallel electromagnetic waves can explain the existence of suprathermal electron distributions [18]. The choice of the wave-particle diffusion coefficient is crucial in the energization process.

Diffusion and friction coefficients for Coulomb collisions

In case of Coulomb collisions, the right hand term of eq.(1) can be written as Fokker-Planck operator [19, 20]: $\left(\frac{df}{dt}\right)_c = -\frac{\partial}{\partial\vec{v}}.\left[\vec{A}f - \frac{1}{2}\frac{\partial}{\partial\vec{v}}.(\vec{\vec{D}}f)\right]$ (4)

where the dynamic friction vector is

$$\vec{A} = -4\pi\sum_{\beta}\frac{Z_\alpha^2 Z_\beta^2 e^4 \ln\Lambda}{m_\alpha^2}\left(1+\frac{m_\alpha}{m_\beta}\right)\int d\vec{v}' f_\beta(\vec{v}')\frac{(\vec{v}-\vec{v}')}{\left|\vec{v}-\vec{v}'\right|^3} \tag{5}$$

and the velocity diffusion tensor is

$$\vec{\vec{D}} = 4\pi\sum_{\beta}\frac{Z_\alpha^2 Z_\beta^2 e^4 \ln\Lambda}{m_\alpha^2}\int d\vec{v}' f_\beta(\vec{v}')\left(\frac{\vec{\vec{I}}}{\left|\vec{v}-\vec{v}'\right|} - \frac{(\vec{v}-\vec{v}')(\vec{v}-\vec{v}')}{\left|\vec{v}-\vec{v}'\right|^3}\right) \tag{6}$$

$\vec{\vec{I}}$ is the unity matrix, the Coulomb logarithm ln Λ~15 in geophysical plasmas, *Ze* and *m* are respectively the charge and the mass of the particles, and the sum on the index β represents the effects of particles of β species on particles of α species.

In the present paper, we establish the expressions of ***A*** and ***D*** when the VDF of the background β particles is given by a Kappa function:

$$f_\beta(\vec{x}') = \frac{n_{0\beta}}{2\pi(\kappa w_\beta^2)^{3/2}} A_k \left(1+\frac{x'^2}{\kappa}\right)^{-(\kappa+1)} \tag{7}$$

where $x' = \sqrt{\frac{m_\beta}{2kT_\beta}} v' = \frac{v'}{w_\beta}$ and $A_k = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)}$ (Γ is the Gamma function).

Integrating on x', we find

$$\vec{A} = \frac{2c_0}{m_\alpha^2}\left(1+\frac{m_\alpha}{m_\beta}\right)\frac{m_\beta}{2kT_\beta} n_\beta \frac{\partial h}{\partial \vec{x}} \tag{8}$$

$$\vec{D} = \frac{2c_0}{m_\alpha^2}\sqrt{\frac{m_\beta}{2kT_\beta}} n_\beta \frac{\partial^2 g}{\partial \vec{x}\partial \vec{x}} \tag{9}$$

with $c_0 = 2\pi Z_\alpha^2 Z_\beta^2 e^4 \ln\Lambda$ (10)

$$h = \frac{1}{x}\left[1-\beta_2(b_2)\right] + \frac{A_k}{\kappa^{3/2}} b_2^\kappa \tag{11}$$

$$g = x\left[1-\beta_2(b_2)\right] + \frac{\kappa}{3x}\frac{A_k}{A'_k}\left[1-\beta_4(b_2)\right] + A_k\kappa^{1/2}\left(\frac{b_2^{\kappa-1}}{\kappa-1} - \frac{b_2^\kappa}{\kappa}\right) + \frac{A_k}{3\kappa^{3/2}} x^2 b_2^\kappa \tag{12}$$

$$\beta_2(b_2) = \int_0^{b_2} A_k t^{\kappa-3/2}(1-t)^{1/2}\,dt \quad \text{and} \quad \beta_4(b_2) = \int_0^{b_2} A_k t^{\kappa-5/2}(1-t)^{3/2}\,dt \tag{13}$$

$$b_2 = \left(1+\frac{x^2}{\kappa}\right)^{-1} \text{ and } A'_k = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-3/2)\Gamma(5/2)} \tag{14}$$

When $\kappa \to \infty$, these expressions tend to those obtained with an isotropic Maxwellian [20]. Nevertheless, for other values of κ, the Maxwellian is not the solution of the Fokker-Planck operator in case of Kappa functions.

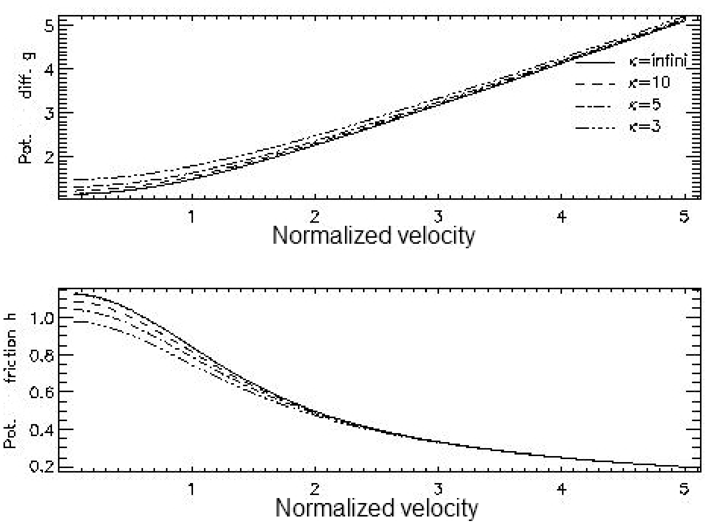

FIGURE 2. Diffusion and friction potential g and h for different values of the κ parameter.

Fig. 2 illustrates the diffusion *g* and friction potential *h* as a function of the normalized velocity for different values of the parameter κ. The solid line corresponds to the Maxwellian case when $\kappa \to \infty$. The results are clearly different when κ is small.

CONCLUSIONS

Different theories have been presented to explain the existence of suprathermal populations in space environments ([1] for a review). The presence of an enhanced population of high energy particles has important consequences concerning the velocity filtration, the temperature profiles as well as the acceleration of the particles. They have also consequences on the diffusion and friction coefficients of the Fokker-Planck operator that are established in the present paper. In case of collisions with non Maxwellian background particles, the Maxwellian is not the solution of the collision operator. The suprathermal particles can play an important role in the coronal heating and solar wind acceleration, as well as in stellar and planetary atmospheres and magnetospheres.

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REFERENCES

1. V. Pierrard and M. Lazar, *Solar Physics*, **287**, 153-174, doi: 10.1007/s11207-010-9640-2 (2010).
2. V. Pierrard, M. Maksimovic and J. Lemaire, *Astrophys. Space Sci.,* **277**, 2, 195-200 (2001).
3. M. Maksimovic, V. Pierrard and P. Riley, *Geophys. Res. Let.*, **24**, 9, 1151-1154 (1997).
4. M. Maksimovic, V. Pierrard and J. Lemaire, *Astron. Astrophys.*, **324**, 725-734 (1997).
5. I. Zouganelis, M. Maksimovic., N. Meyer-Vernet. H. Lamy and K. Issautier, *Astrophys. J.*, **606**, 542 (2004).
6. G. Le Chat, K. Issautier, N. Meyer-Vernet, I. Zouganelis, M. Maksimovic and M. Moncuquet, *Phys. Plasmas*, **16**, 102903 (2009).
7. V. Pierrard and H. Lamy, *Solar Physics*, **216**, 47-58 (2003).
8. J. Lemaire and V. Pierrard, *Astrophys. Space Sci.*, **277**, 2, 169-180 (2001).
9. V. Pierrard and J. Lemaire, *J. Geophys. Res.*, **101**, 7923-7934 (1996).
10. J. D. Scudder, *Astrophys. J.,* **398**, 299 (1992a).
11. J. D. Scudder, *Astrophys. J.*, **398**, 319 (1992b).
12. V. Pierrard, M. Maksimovic, and J. Lemaire, *J. Geophys. Res*., **104**, 17021-17032, (1999).
13.. V. Pierrard, M. Maksimovic, and J. Lemaire, *J. Geophys. Res*., **107**, A12, 29.305-29.312 (2001).
14. S. Landi, F. Pantellini, and L. Matteini, 12th International Solar Wind Conf., AIP Conf. Proc., **1216**, 218-222 (2010).
15. V. Pierrard, M. Lazar and R. Schlickeiser. *Solar Phys*. **269**, 2, 421-438, DOI 10.1007/s11207-010-9700-7 (2011).
16. V. Pierrard and Y. Voitenko, 12th International Solar Wind Conf., AIP Conf. Proc., **1216**, 102-105 (2010).
17. L. Matteini, S. Landi, M. Velli, and P. Hellinger, 12th International Solar Wind Conf., AIP Conf. Proc., **1216**, 223-226 (2010).
18. B. D. Shizgal, *Astrophys. Space Sci.,* **312**, 227-237 (2007)
19. M. N. Rosenbluth, W. M. McDonald, and D. L. Judd, *Phys. Rev.*, **107**, 1, 1957.
20. F. L. Hinton, in Basics plasma physics I and II, Galeev A.A. and R. N. Sudan Ed. 1983.