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Eigenfunctions for Vlasov Equation in Multi-species Plasmas

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Abstract

The normal mode expansion method for the Vlasov equation has been developed to multi-species plasmas in an infinite system. The perturbed charge density for the Vlasov-Poisson system in muti-species plasmas is found be the same form as the perturbed distribution function in a single species plasma. The eigenfunctions and adjoint eigenfunctions, and the orthogonality relations between them have been derived. The complete set of eigenfunctions for the charge density is constructed, which has been applied for the initial value problems. The continuum contribution consists of the ballistic mode and pure continuum contribution. Scalar potential and each species distribution function are also solved making use of the complete set of eigenfunctions.

Keywords: Vlasov equation, muti-species plasma, normal modes, adjoint equation, orthogonality, complete set of eigenfunctions, initial value problem, Van Kampen mode, ballistic mode.

1. Introduction

Van Kampen has developed the normal mode approach for the electron plasma oscillation described by the Vlasov equation. He proved the continuum contribution(Van Kampen mode), which is the contribution from the singular eigenfunction over the continuous eigenvalue spectrum induced from the wave-particle resonance condition, plays an essential role for the completeness of the Vlasov eigenfunctions.[1)] Case[2)] has developed this method for the same electron oscillation problem, introduced the orthogonality relations, and constructed the complete set of eigenfunctions for the case where the discrete set of eigenvalues exists in addition to the continuous eigenvalue spectrum. This normal mode expansion method has also been developed in the field of neutron transport theory by Case and Zweifel[3)], and applied to many problems.[4)5)] The essence of the normal mode approach is that the solution of transport equation like Vlasov equation consists of the discrete mode determined from the dispersion relation, and the continuum contribution. Depending on a parameter value, the discrete mode may vary and disappear, while the continuum contribution always exists, and never disappears.

In the linear plasma stability theory, the discrete eigenvalue evaluated from the dispersion relation is usually examined, because the discrete eigenvalue determines whether the system grows or decays in time, or the stability of the system. The continuum contribution which is independent of the dispersion relation does not grow in time. It represents the effect of wave-particle resonance, or the dynamics of particles trapped by potential wave in the linear theory.

The normal mode approach is applied, to the authors knowledge, only to the electron plasma oscillation where cold ions are introduced only to keep the zero-th order charge neutrality. Since ions and electrons equally contribute to the dielectric function and the dispersion relation if ion and electron temperatures are the same, it may be interesting and useful if the complete set of eigenfunctions is constructed for the cases including both electron and ion dynamics. The purpose of the present paper, therefore, is to construct the complete set of eigenfunctions for the Vlasov equation for muti-species plasmas in the electrostatic approximation.

2. Vlasov -Poisson system for multi-species plasmas

We consider the Vlasov equation for the j-th species charged particles perturbed distribution function f_j in the electrostatic approximation:

$$\frac{\partial f_j}{\partial t} + v.\nabla f_j + \left(\frac{e}{m}\right)_j E.\frac{\partial f_{0j}}{\partial v} = 0, \quad (1)$$

where E=- $\nabla\phi$ is the perturbed electric field with ϕ being the perturbed scalar potential, e_j and m_j are charge and mass, and f_{0j} is the unperturbed distribution for the j-th species particle. We must solve eq.(1) combining with the Poisson equation:

$$\nabla^2\phi = -4\pi\sum_j e_j\int d^3v f_j(r,v,t). \quad (2)$$

We assume for the perturbed quantities f_j and ϕ are proportional to the Fourier factor exp(ik . v). Combining with eq.(2), eq.(1) can be written in the form:

$$\frac{\partial f_j}{\partial t} + ik.vf_j = ik.\frac{\partial f_{0j}}{\partial v}\frac{4\pi}{k^2 m_j}\rho(v,t), \quad (3)$$

where the charge density ρ is defined by

$$\rho(v,t) = \sum_j e_j g_j(v), \quad (4)$$

and g_j is the integrated distribution function given by

$$g_j(v) = \int f_j(v,v_\perp)dv_\perp. \quad (5)$$

Integrating eq.(3) over $\mathbf{v}_\perp$, we have

$$\frac{\partial g_j}{\partial t} + ik.vg_j(v,t) = -ik\alpha_j(v)\int dv\rho(v,t), \quad (6)$$

where the quantity α_j is defined by

$$\alpha_j(v) = -\frac{4\pi e_j}{m_j k^2}\frac{\partial}{\partial v}\int f_{0j}(v,v_\perp)dv_\perp. \quad (7)$$

Multiplying e_j to both sides of eq.(6) and adding, we have an equation for ρ:

$$\frac{\partial\rho}{\partial t} + ikv\rho = -ik\alpha\int_{-\infty}^{\infty} dv\rho(v,t), \quad (8)$$

where

$$\alpha = \sum_j e_j\alpha_j. \quad (9)$$

When ρ is solved from eq.(8), the j-th distribution function g_j is obtained by solving eq(6) with respect to t.

3. Normal Modes

We here develop the normal modes given by Van Kampen and Case for multi-species plasmas. Since eq.(6) for the charge density ρ is the same form as the equation for the distribution function g treated by Case, we may apply the same method. We assume the solution of the form ρ ~ exp(-iωt), and introduce the parameter μ = ω/k. Then eq.(8) can be written by

$$(\mu - v)\rho = \alpha\int_{-\infty}^{\infty} dv\rho(v). \quad (10)$$

If we require the normalization condition to ρ:

$$\int_{-\infty}^{\infty} dv\rho(v) = 1, \quad (11)$$

then from eq.(19), ρ is given in the form

$$\rho(v) = \frac{\alpha(v)}{\mu - v}. \quad (12)$$

Since v varies between - ∞ to ∞, the solution (12) becomes singular when μ is on the real axis, i.e, μ ∈ Σ. When μ is not real, introducing eq.(12) into eq.(11), we have the discrete eigenvalue condition or dispersion relation:

$$\varepsilon(\mu) \equiv 1 - \int_{-\infty}^{\infty}\frac{\alpha(v)}{\mu - v}dv = 0. \quad (13)$$

The corresponding eigenfunction for i-th eigenvalue becomes

$$\rho_{\mu_i}(v) \equiv \rho_i(v) = \frac{\alpha(v)}{\mu_i - v}. \quad (14)$$

For μ ∈ Σ, we assume the singular solution in the form

$$\rho_\mu(v) = P\frac{\alpha(v)}{\mu - v} + \lambda(\mu)\delta(\mu - v), \qquad (15)$$

where P in eq.(15) means the Chaucy principal value integration. The coefficient λ is obtained by introducing eq.(15) into eq.(11):

$$\lambda(\mu) \equiv 1 - P\int_{-\infty}^{\infty}\frac{\alpha(v)}{\mu - v}dv. \qquad (16)$$

The second δ -function term in eq.(15) is the characteristics of the Van Kampen mode, which represents the trapped particle resonance with the potential wave ϕ in the linear theory. It is also a source of incoherent fluctuations.

Let us here introduce the adjoint equation

$$(\mu - v)\rho^* = \int_{-\infty}^{\infty} dv\alpha\rho^*(v). \qquad (17)$$

For the adjoint function ρ^*, we also require the normalization condition:

$$\int_{-\infty}^{\infty} dv\alpha\rho^*(v) = 1\ . \qquad (18)$$

From eqs.(17) and (18), we have the same dispersion relation as given by eq.(13). Then for the discrete eigenvalue μ_i, the adjoint eigenfunction becomes

$$\rho_i^*(v) = \frac{1}{\mu_i - v}. \qquad (19)$$

For $\mu \in \Sigma$, the singular adjoint eigenfunction can be written as

$$\rho^*(v) = P\frac{1}{\mu - v} + \lambda^*(\mu)\delta(\mu - v). \qquad (20)$$

Introducing eq.(20) into eq.(18) , the coefficient λ^* is obtained in the form

$$\lambda^*(\mu) = \frac{\lambda(\mu)}{\alpha(\mu)} \qquad (21)$$

Multiplying eq.(1) by $\rho_{\mu'}(v)$, eq.(17) by $\rho_\mu(v)$, subtracting one from the other, and integrating over all v yields for $\mu \neq \mu'$

$$(\mu - \mu')\int_{-\infty}^{\infty} dv\rho_\mu(v)\rho_{\mu'}^*(v) = 0. \qquad (22)$$

If we introduce the scalar product by

$$\langle\rho_\mu, \rho_{\mu'}^*\rangle \equiv \int_{-\infty}^{\infty} dv\rho_\mu(v)\rho_{\mu'}^*(v) \qquad (23)$$

then eq.(22) means the orthogonality relation:

$$\langle\rho_\mu, \rho_{\mu'}^*\rangle = 0 \quad \text{for} \quad \mu \neq \mu' \qquad (24)$$

For the discrete eigenvalues μ_i and μ_j, the scalar product of eigenfunctions ρ_i, ρ^*_j becomes

$$\langle\rho_i, \rho_j^*\rangle = C_i\delta_{ij}, \qquad (25)$$

where the coefficient C_i is given by

$$C_i = \int_{-\infty}^{\infty}\frac{\alpha(v)}{(\mu_i - v)^2}dv. \qquad (26)$$

From the definition of the dielectric function given by eq.(11), C_i is also written as

$$C_i = -\left.\frac{d\varepsilon(\mu)}{d\mu}\right|_{\mu=\mu_i}. \qquad (27)$$

For μ and $\mu' \in \Sigma$, the product of the singular eigenfunctions $\rho_\mu(v)$ and $\rho^*_{\mu'}(v)$ can be written by[4)5)]

$$\rho_\mu(v)\rho_{\mu'}^*(v) = \frac{1}{\mu' - \mu}\left\{\rho_\mu(v) - \alpha\rho_{\mu'}^*(v)\right\} + \frac{\lambda^2 + \pi^2\alpha^2}{\alpha}\delta(\mu - v)\delta(\mu' - v).$$

Integration of this equation over v yields the orthogonality relation for these singular eigenfunctions

$$\langle\rho_\mu, \rho_\mu^*\rangle = C_\mu\delta(\mu - \mu'), \qquad (28)$$

where the coefficient C_μ is given by

$$C_\mu = \frac{\lambda^2(\mu) + \pi^2\alpha^2(\mu)}{\alpha(\mu)}. \qquad (29)$$

This coefficient can also be written in terms of the dielectric function making use of the formula

$$\lim_{x\to 0}\varepsilon(\mu \pm ix) \equiv \varepsilon^\pm(\mu) = \lambda(\mu) \mp i\pi\alpha(\mu), \qquad (30)$$

in the form:

$$C_\mu = \frac{\varepsilon^+(\mu)\varepsilon^-(\mu)}{\alpha(\mu)}. \qquad (31)$$

Applying the orthogonality relations (25) and (28), the set of eigenfunctions $\{\rho_i(v), \rho_\mu(v)\}$ is complete will be proved in the Appendix.

Here we briefly examine the discrete eigenvalue for a Maxwellian plasma. If we assume the Maxwell distribution for the j-species unperturbed distribution function:

$$f_{0j} = n_0\left(\frac{\pi}{v_j^2}\right)^{\frac{3}{2}}\exp\left(-\frac{v^2}{v_j^2}\right), \qquad (32)$$

where v_j is j-th thermal velocity. In this case, α is reduced to

$$\alpha = -\sum_j \frac{1}{\sqrt{\pi}} \left(\frac{k_{Dj}}{k} \right)^2 \frac{v}{v_j} \exp\left(-\left(\frac{v}{v_j} \right)^2 \right), \quad (33)$$

where $k_{Dj}=(4\pi n_o e^2/T_j)^{1/2}$ with $T_j = m_j v_j^2/2$ and m_j being j-th species mass, is the Debye wave number. The dispersion function defined in eq.(13) becomes

$$\varepsilon(\mu) = 1 + \sum_j \left(\frac{k_{Dj}}{k} \right)^2 \left\{ 1 + \frac{\mu}{v_j} Z\left(\frac{\mu}{v_j} \right) \right\}, \quad (34)$$

where Z is the plasma dispersion function.

If we assume the cold ion limit with $\alpha_i=0$, and the large argument approximation for electrons, $Z(x)=-(1+1/2x^2)/x$ for $x>>1$ to the argument of the Z in eq.(34), we find the discrete eigenvalue determined by eq.(13), as $\mu_0 = v_e k_D / k\sqrt{2}$, which can be rewritten as $\omega_0=\omega_{pe}$ with $\omega_{pe} =(4\pi n_o e^2/m_e)^{1/2}$ being the electron plasma frequency. In the cold ion limit, we recover the electron plasma oscillation. By the same manner, for cold electron limit with $\alpha_e=0$, we can derive the ion plasma oscillation. In general the dispersion relation (13) yields a hybrid oscillation frequency.

4. Initial Value Problem

We here apply the orthogonality relations obtained in the previous section to the initial value problem. Let us expand the charge density at t=0 in terms of the eigenfunctions:

$$\rho(v,0) = \sum_j a_j \rho_j(v) + \int A(\mu) \rho_\mu(v) d\mu. \quad (35)$$

Applying the relation (25) to the discrete terms in eq.(35), the coefficients are determined by

$$a_j = \frac{1}{C_j} \int \frac{\rho(v,0)}{\mu_j - v} dv. \quad (36)$$

By the same manner for $\mu \in C$, applying eq.(28), the coefficient A is determined in the form

$$A(\mu) = \frac{1}{\varepsilon^{+}(\mu)\varepsilon^{-}(\mu)} \left\{ \alpha(\mu) P \int \frac{\rho(v,0)}{\mu - v} dv + \lambda(\mu)\rho(\mu,0) \right\}. \quad (37)$$

Making use of these coefficients, the time dependent solution is given in the form

$$\rho(v,t) = \sum_j a_j e^{-ik\mu_j t} \rho_j(v) + \int A(\mu) e^{-ik\mu t} \rho_\mu(v) d\mu. \quad (38)$$

Depending on the parameter values, the discrete eigenvalues μ_j may vary in the complex μ-plane. If $Im(\mu_j)<0$, we must seek the discrete eigenvalue in the lower half μ-plane by analytical continuation of the dispersion function ε like Landau did. In this case, the discrete mode damps as time goes on. When the discrete eigenvalue does not exist in the whole μ-plane, the first term disappears and the system is described by the continuum contribution alone.

If we take into account the space dependence, eq.(38) may be written for a fixed k in the form:

$$\rho(x,v,t) = \sum_j a_j e^{ik(x-\mu_j t)} \rho_j(v) + \int A(\mu) e^{ik(x-\mu t)} \rho_\mu(v) d\mu. \quad (39)$$

The velocity dependence of the charge density can be seen by substituting the eigenfunctions:

$$\rho(x,v,t) = \sum_j a_j e^{ik(x-\mu_j t)} \frac{\alpha(v)}{\mu_j - v} + \lambda(v) A(v) e^{ik(x-vt)}$$
$$+ P \int \frac{\alpha}{\mu - v} A(\mu) e^{ik(x-\mu t)} d\mu. \quad (40)$$

Equation (40) indicates that the discrete mode term may show singularity when the discrete eigenvalue is real and $\mu_j = v$. The second term is the ballistic mode which becomes steady on the orbit x=vt. The third singular integral term is the pure continuum contribution. As a function of velocity, each term varies in complicated manner depending on temperatures and forms of distribution functions particularly for muti-species plasmas.

When $\rho(x,v,t)$ is obtained, from eq.(2), the scalar potential is determined by

$$\phi(x,t) = \frac{4\pi}{k^2} \int \rho(x,v,t) dv. \quad (41)$$

Since the eigenfunctions are normalized by eq.(11), eq.(41) can be rewritten as

$$\phi(x,t) = \frac{4\pi}{k^2} \left\{ \sum_j a_j e^{ik(x-\mu_j t)} + \int A(\mu) e^{ik(x-\mu t)} d\mu \right\}. \quad (42)$$

Substitution of coefficients given by eqs.(36) and (37), and the initial charge density $\rho(v,0) = \rho_o \delta(v - v_o)$ for the sake of simplicity, into eq.(42), we have

$$\phi(x,t)=\frac{4\pi}{k^2}\rho_0\left\{\sum_j \frac{e^{ik(x-\mu_j t)}}{\varepsilon'(\mu_j)}\frac{\alpha(v_0)}{\mu_j-v_0}+\frac{\lambda(v_0)e^{ik(x-v_0 t)}}{\lambda^2(v_0)+\pi^2\alpha^2(v_0)}\right.$$
$$\left.+P\int\frac{e^{ik(x-\mu t)}}{\mu-v_0}\frac{\alpha(\mu)d\mu}{\lambda^2(\mu)+\pi^2\alpha^2(\mu)}\right\}. \quad (43)$$

Equation (43) also indicates that the first discrete mode becomes singular when the initial beam velocity v_0 coincides with the eigenvalue μ_0.

Let us apply the normal mode expansion method to solve each distribution function. Since arbitrary function can be expanded by the complete set of the eigenfunction $\{\rho_j(v),\rho_\mu(v)\}$, we may apply the complete set of eigenfunctions for the charge density ρ to solve the distribution function $g_j(v,t)$. If we expand $g_j(v,0)$ in the form

$$g_j(v,0)=\sum_i a_i^j\rho_j(v)+\int A^j(\mu)\rho_\mu(v)d\mu, \quad (44)$$

the expansion coefficients can be obtained making use of the orthogonality relations: multiplying both sides of eq.(44) by ρ_i^*, and integrating over v, we have from eq.(25)

$$a_i^j=\frac{1}{C_i}\int\frac{g_j(v,0)}{\mu_i-v}dv. \quad (45)$$

By the same manner, making use of eq.(28), we obtain

$$A^j(\mu)=\frac{1}{\varepsilon^*(\mu)\varepsilon(\mu)}\left\{\alpha(\mu)P\int\frac{g_j(v,0)}{\mu-v}dv+\lambda(\mu)g_j(\mu,0)\right\}. \quad (46)$$

Applying these coefficients, the time dependent distribution function is then given by

$$g_j(v,t)=\sum_i a_i^j e^{-ik\mu_i t}\rho_j(v)+\int A^j(\mu)e^{-ik\mu t}\rho_\mu(v)d\mu. \quad (47)$$

The solution (47) can recover eq.(38) if we multiply by e_j both sides of eq.(47) and add with respect to j. The distribution function of each species is also obtained by solving eq.(6) with respect to time t.

5. Summary

The normal mode expansion method for the Vlasov equation in an electron plasma has been developed to the case of multi-species plasmas in an infinite system. The equation of charge density for the Vlasov-Poisson system in the multi-species plasmas is found to be the same form as that of electron plasma treated by Van Kampen and Case. The eigenfunctions have been constructed, and the orthogonality relations have been derived by the same manner as Case. The completeness has also been proved by applying the orthogonality. The orthogonality relations of eigenfunctions has been applied for the initial value problem of the charge density. Once the charge density is solved, the scalar potential, and each species distribution function is easily derived. When the discrete eigenvalue is real (purely oscillatory), the discrete mode is found to show a singularity in the velocity space at the phase velocity of eigenfrequency. The continuum contribution is separated into the ballistic mode and pure continuum contribution (singular principal value integral over the continuum), which may be a source of incoherent fluctuations.

Appendix Completeness of Eigenfunction

The completeness of eigenfunctions has already been proved by Case. Here we show the completeness directly making use of the orthogonality relation,[4)5)] and compare with Case's result. First we show briefly Case's proof: if arbitrary function g(v) expanded as

$$g(v)=\sum a_i\rho_i(v)+\int A(\mu)\rho_\mu(v)d\mu, \quad (A.1)$$

then it is sufficient to show that it is always possible to solve eq.(A.1) with respect to A(v). If we introduce g' by

$$g'(v)=g(v)-\sum_i a_i\rho_i(v), \quad (A.2)$$

then, eq.(A.1) is rewritten as follow

$$g'(v)=\lambda(v)A(v)+\alpha(v)P\int\frac{A(\mu)}{\mu-v}d\mu. \quad (A.3)$$

In order to solve A(v), Case introduce three complex functions:

$$N(z)=\frac{1}{2\pi i}\int\frac{A(\mu)}{\mu-z}d\mu, \quad (A.4)$$

$$Q(z) = \frac{1}{2\pi i}\int \frac{\alpha(v)}{v-z}dv, \qquad \text{(A.5)}$$

$$M(z) = \frac{1}{2\pi i}\int \frac{g'(v)}{v-z}dv, \qquad \text{(A.6)}$$

which are analytic with cut along the real axis, and tend to zero at infinity. Each quantity in eq.(A.3) can be expressed by the limiting values of these functions for v $\in\Sigma$:

$$N^+(v) - N^-(v) = A(v), \qquad \text{(A.7)}$$

$$\pi i\{N^+(v)+N^-(v)\} = P\int \frac{A(\mu)}{\mu - v}d\mu, \qquad \text{(A.8)}$$

$$Q^+(v) - Q^-(v) = \alpha(v), \qquad \text{(A.9)}$$

$$\lambda(v) = 1 + \pi i\{Q^+(v)+Q^-(v)\}, \qquad \text{(A.10)}$$

$$M^+(v) - M^-(v) = g'(v). \qquad \text{(A.11)}$$

Substitution of these expressions into eq.(3) yields

$$N^+(v)\varepsilon^+(v) - M^+(v) = N^-(v)\varepsilon^-(v) - M^-(v)$$

where $\varepsilon(z)=1+2\pi iQ(z)$ is the dielectric function. This equation means that the complex function

$$J(z)=N(z)\varepsilon(z)-M(z)$$

is continuous across the real axis, i.e., analytic in the whole complex z-plane, and tends to zero at infinity. From the Louville theorem J(z)=0 in the whole complex plane, that is, the function N is determined by $N(z)=M(z)/\varepsilon(z)$. Since $M(\mu_i)=0$ at the discrete eigenvalue condition $\varepsilon(\mu_i)=0$, N is analytic at this point, and the gap condition of N from eq.(A.7) gives A, we have

$$A(v) = \frac{M^+(v)}{\varepsilon^+(v)} - \frac{M^-(v)}{\varepsilon^-(v)}. \qquad \text{(A.12)}$$

Let us apply the orthogonality relations to solve eq.(A.3). Multiplying both sides of eq.(A.3) by ρ^*_μ integrating over v, and applying eq.(28), we have

$$A(v) = \frac{1}{\varepsilon^+(v)\varepsilon^-(v)}\left\{\lambda(v)g'(v) - \alpha(v)P\int\frac{g'(\mu)}{\mu - v}d\mu\right\}. \text{(A.13)}$$

Introducing the relations $\varepsilon^+ + \varepsilon^- = 2\lambda(v)$, $\varepsilon^+ - \varepsilon^- = 2\pi i\alpha(v)$,

$$M^+(v) + M^-(v) = \frac{1}{\pi i}P\int\frac{g'(\mu)}{\mu - v}d\mu, \qquad \text{(A.14)}$$

and eq.(A.11) into eq.(A.13), we find

$$A(v) = \frac{1}{\varepsilon^+(v)\varepsilon^-(v)}\left\{M^+(v)\varepsilon^-(v) - M^-(v)\varepsilon^+(v)\right\}. \text{(A.15)}$$

which reduces to eq.(A.12), and the completeness is proved by applying the orthogonality relations.

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