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Analysis of Jeans Instability of Partially-Ionized Molecular Cloud under Influence of Radiative Effect and Electron Inertia

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Abstract

The problem of Jeans instability of an infinite homogeneous self-gravitating of partially ionized gaseous plasma carrying a uniform magnetic field in presence of finite electron inertia, thermal conductivity and the arbitrary radiative heat-loss function has been studied. With the help of relevant linearized perturbation MHD equations of the problem using normal mode analysis, a general dispersion relation is obtained and the dispersion relation is discussed for longitudinal propagation and transverse propagation separately. We found that the effect of collision with neutrals and magnetic field have a stabilizing influence, while thermal conductivity has destabilizing influence on the Jeans instability. In addition, the classical Jeans result regarding the rise of initial break up has been considerably modified due to the arbitrary radiative heat-loss function.

Keywords: MHD (Magneto-Hydrodynamics), ISM (Inter-Stellar Medium) Thermal conductivity, Arbitrary radiative heat-loss functions, Partially-ionized plasma and Collision frequency, finite electron inertia

1. Introduction

In the past few decades, however, it has been realized that the problem of self-gravitational instability is a broad area of research in astrophysics, plasma physics and into many other crucial phenomena of the interstellar medium (ISM). It plays an important role in star formation in magnetic dusty clouds via the gravitational collapsing process. Jeans (1) in his famous theorem showed that an infinitely extending homogeneous static medium is unstable with respect to the gravitational sound wave with wave length $\boldsymbol{\lambda}$ greater than the critical Jeans wavelength $\lambda_j = c\,(\pi/G\rho)^{1/2}$, where the symbols have their usual meanings. A number of investigators have extended the problem under different conditions. Chandrashekhar (2) has given a comprehensive account of the effect of a magnetic field and rotation separately and simultaneously on the gravitational instability of an infinite homogeneous medium and it has been shown that Jeans criterion remains unaffected by the separate or simultaneous inclusion of the rotation and the magnetic field. In this connection, many investigators have discussed the Gravitational instability of a homogeneous plasma considering the effects of various parameters. [Herrneger (3), Chhajlani and Sanghavi (4), Elmegreen (5), Langer (6)' and Bondyopadhya (7)]. Recently, Lima et al. (8) have investigated the problem of Jeans gravitational instability and non-extensive kinetic theory. Pensia et al. (9) have studied the problem of magneto-thermal instability of self-gravitating, viscous, Hall plasma in the presence of suspended particles. Khan and Sheikh (10) have discussed the instability of thermally conducting self-gravitating system. All these investigations have been carried for fully ionized plasma.

Frequently plasmas are not fully ionized and instead may be partially ionized so that the interaction between the neutral gas and the ionized fluid becomes important. In cosmic physics such situations occur in the solar photosphere, chromospheres and in cool interstellar clouds. The importance of the influence of the neutral-ion collisions on the ionization rate in these regions has pointed by Alfven (11). In this direction many researchers have discussed the problem of gravitational instability of partially plasma considering the effects of various parameters [Lehnert (12), Kumar and Shrivastava (13), and Ali and Bhatia (14)].

In the past few years, it has been argued that thermal instability may be a reasonably good candidate, which can accelerate condensation, giving rise to localized structure which grow in density by losing heat, mainly through radiation. The first comprehensive analysis of thermal instability in a diffuse interstellar gas is first given by Field (15). Bora and Talwar (16) have studied the magneto-thermal instability with generalized ohm's law. Talwar and Bora (17) have analyzed the stability of self-gravitating composite system of optically thin radiating plasma and stars. More recently Prajapati et al. (18) have discussed the problem of self-gravitational instability of rotating viscous Hall plasma with arbitrary radiative heat-loss functions and electron inertia.

From the above studies, we find that the finite electron inertia, thermal conductivity, magnetic field, radiative het-loss functions and interaction between neutral gas and ionized fluid are the important parameters to discuss the gravitational instability of plasma. Thus, in the present problem we investigate the effects of arbitrary radiative heat-loss functions and finite electron inertia on the self-gravitational instability of partially ionized plasma.

2. Linearized Perturbation Equations

We assume that the two components of the partially ionized plasma (the ionized fluid and the neutral gas) behave like a continuum fluid and their state velocities are equal. The effects of the magnetic field, field of gravity and the pressure on the neutral components are neglected. Also it is assumed that the frictional force of the neutral gas on the ionized fluid is of the same order as the pressure gradient of the ionized fluid. Thus, we are considering only the mutual frictional effects between the neutral gas and the ionized fluid. It is assumed that the above medium is permeated with a uniform magnetic field $\vec{H}$ *(0, 0, H)*.

Thus the linearized perturbation equations governing the motion of hydromagnetic thermally conducting two components of the partially ionized plasma are given by

$$\rho\frac{\partial\vec{v}}{\partial t} = -\vec{\nabla}\delta p + \vec{\nabla}\delta\varphi + \frac{1}{4\pi}\left(\nabla\times\vec{h}\right)\times\vec{H} + \rho_d\nu_c(\vec{v_d} - \vec{v}), \quad (1)$$

$$\frac{\partial\vec{v}_d}{\partial t} = -\nu_c(\vec{v_d} - \vec{v}), \quad (2)$$

$$\frac{\partial\delta\rho}{\partial t} = -\rho\vec{\nabla}\vec{v}\,, \quad (3)$$

$$\nabla^2\delta\varphi = -4\pi G\delta\rho\,, \quad (4)$$

$$\frac{1}{(\gamma-1)}\frac{\partial\delta\rho}{\partial t} - \frac{\gamma}{(\gamma-1)}\frac{p}{\rho}\frac{\partial\delta\rho}{\partial t} + \rho\left(\mathcal{L}_\rho\delta\rho + \mathcal{L}_T\delta T\right) - \lambda\nabla^2\delta T = 0, \quad (5)$$

$$\frac{\delta p}{p} = \frac{\delta T}{T} + \frac{\delta\rho}{\rho}\,, \quad (6)$$

$$\frac{\partial\vec{h}}{\partial t} = \vec{\nabla}\times\left(\vec{v}\times\vec{H}\right) + \frac{c^2}{\omega_{pe}^2}\frac{\partial}{\partial t}\nabla^2\vec{h}\,, \quad (7)$$

$$\vec{\nabla}.\vec{h} = 0, \quad (8)$$

The parameters φ, G, λ, R, c, ρ, ρ_d, υ_c, γ, T, ω_{pe} and p denote the gravitational potential, gravitational constant, thermal conductivity, gas constant, velocity of light, density of ionized component, density of neutral components

$(\rho \gg \rho_d)$, collision frequency between two components, ratio of two specific heats, temperature, finite electron inertia and pressure, respectively.

The perturbations in fluid velocity, fluid pressure, fluid density, magnetic field, gravitational potential, temperature and the radiative heat-loss function are given as $\vec{v}(v_x, v_y, v_z)$, δp, $\delta\rho$, $h\,(h_x, h_y, h_z)$ $\delta\varphi$, δT, and $\delta\mathcal{L}$ respectively. In equation (5), $\mathcal{L}_{\sigma,T}$ are the partial derivatives of the density dependent $(\partial\mathcal{L}/\partial\rho)_T$ and temperature dependent $(\partial\mathcal{L}/\partial T)_\rho$ heat-loss functions respectively.

3. Dispersion relation

We assume that all the perturbed quantity vary as

$$\exp\{i(k_x x + k_z z + \omega t)\}.$$

where $\boldsymbol{\omega}$ is the frequency of harmonic disturbances, $k_{x,z}$ are wave numbers in x and z direction, respectively, such that $k_x^2 + k_z^2 = k^2$ combining equation (5) and (6), we obtain the expression for δp as

$$\delta p = \left(\frac{\alpha+\sigma c^2}{\sigma+\beta}\right)\delta\rho\,, \qquad \alpha = (\gamma-1)\left(\mathcal{L}_T T - \mathcal{L}_\rho \rho + \frac{\lambda k^2 T}{\rho}\right),$$

$$\beta = (\gamma-1)\left(\frac{\mathcal{L}_T T\rho}{p} + \frac{\lambda k^2 T}{p}\right) \tag{9}$$

where σ = iω, $c = (\gamma p/\rho)^{1/2}$ is the adiabatic velocity of sound in the medium.

$$f = \left(1 + \frac{c^2 k^2}{\omega_{pe}^2}\right),$$

Using equation (2) – (9) in equation (1), we obtain the following algebraic equations for the amplitude components

$$\left(\sigma^2 + k_z^2 V^2 + \frac{B\nu_c}{\sigma+\nu_c}\sigma^2\right)v_x + \frac{ik_x}{k^2}\sigma\Omega_T^2 s = 0, \tag{10}$$

$$\left(\sigma^2 + k^2 V^2 + \frac{B\nu_c}{\sigma+\nu_c}\sigma^2\right)v_y = 0, \tag{11}$$

$$\left(\sigma + \frac{B\nu_c}{\sigma+\nu_c}\sigma\right)v_z + \frac{ik_z}{k^2}\Omega_T^2 s = 0, \tag{12}$$

$$(ik_x k^2 V^2)v_x - \left(\sigma^3 + \frac{B\nu_c}{\sigma+\nu_c}\sigma^3 + \sigma\Omega_T^2\right)s = 0. \tag{13}$$

where $s = \delta\rho/\rho$ is the condensation of the medium, $V = H/(4\pi\rho)^{1/2}$ is the Alfven velocity, $c^2 = \gamma c'^2$ where c and c' are the adiabatic and isothermal velocities of sound. Also we have assumed the following substitutions

$$B = \frac{\rho_d}{\rho}, \qquad \Omega_T^2 = \frac{\sigma\Omega_j^2 + \Omega_I^2}{\sigma+\beta}, \qquad \Omega_I^2 = k^2\alpha - 4\pi G\rho, \qquad \Omega_j^2 = k^2c^2 - 4\pi G\rho,$$

$$R_1 = (1+B)\,\nu_c, \qquad a = \sigma + \frac{B\nu_c}{\sigma+\nu_c}\sigma, \qquad M = a\sigma^2 + \sigma\Omega_T^2,$$

$$M_1 = \sigma a + k_z^2 V^2, \qquad \Omega_k = \frac{\gamma\lambda k^2}{\rho c_p}, \qquad M_2 = \sigma a + k^2 V^2.$$

The non-trial solution of the determinant of the matrix obtained from equation (10) to (13) with v_x, v_y, v_z, S having various coefficients that should vanish is to give the following dispersion relation.

$$M_1 M_2 a M + M_1 a k_x^2 V^2\,\Omega_T^2 = 0. \tag{14}$$

The dispersion relation (14) shows the combined influence of thermal conductivity and arbitrary radiative heat-loss functions on the self-gravitational instability of a two components of the partially-ionized plasmas we find that in this dispersion relation the terms due to the arbitrary radiative heat-loss function with thermal conductivity have entered through the factor Ω_T^2 and the terms written by multiplying (c^2k^2/ω_{pe}^2) appeared due to our consideration of finite electron inertia parameter in the present problem.

4. Analysis of the dispersion relation

4.1. Longitudinal mode of propagation: -For this case we assume all the perturbations longitudinal to the direction of the magnetic field i.e. ($k_z = k,\ k_x = 0$). This is the dispersion relation reduces in the simple form to give

$$\left(\sigma + \frac{B\nu_c}{\sigma+\nu_c}\sigma\right)\left(\sigma^3 + \frac{B\nu_c\sigma^3}{\sigma+\nu_c} + \sigma\Omega_T^2\right)\left(\sigma^2 + \frac{B\nu_c\sigma^2}{\sigma+\nu_c} + k^2V^2\right) = 0. \quad (15)$$

We find that in the longitudinal mode of propagation the dispersion relation is modified due to the pressure of neutral particles, thermal conductivity, finite electron inertia and arbitrary radiative heat-loss functions. This dispersion relation has three independent factors, each represents the mode of propagation incorporating different parameters. The first factor of this dispersion relation equating to zero

$$\sigma + (1 + B)\nu_c = 0. \quad (16)$$

This represents stable mode due to collision frequency. The second factor of equation (15) equating to zero, we obtain following dispersion relation

$$\sigma^4 + \sigma^3(R_1 + \beta) + \sigma^2\left[(1 + B)\beta\nu_c + \Omega_j^2\right] + \sigma\left[\nu_c\Omega_j^2 + \Omega_I^2\right] + \nu_c\Omega_I^2 = 0. \quad (17)$$

This dispersion relation for self-gravitating fluid shows the combined effect of neutral particles, thermal conductivity and arbitrary radiative heat-loss function. It is evident from equation (17) that the condition of instability is independent of magnetic field. The dispersion relation (17) is a fourth degree equation which may be reduced to particular cases so that the effect of each parameter is analyzed separately.

For thermally non-conducting, non-radiating, fully ionized fluid we have $\alpha = \beta = \nu_c = 0$ the dispersion relation (17) reduces to

$$\sigma^2 + \Omega_j^2 = 0, \text{ and } k < k_j = \left(\frac{4\pi G\rho}{c^2}\right)^{1/2}. \quad (18)$$

The fluid is unstable for all Jeans wave number $k < k_j$. It is evident from equation (18) that Jeans criterion of instability remains unchanged in the presence of neutral particles.

For non-arbitrary radiative heat-loss function but thermally conducting and self-gravitating fluid having neutral particles, the dispersion relation (17) reduces to

$$\sigma^4 + \sigma^3(R_1 + \Omega_k) + \sigma^2\left[R_1\Omega_k + \Omega_{j1}^2\right] + \sigma\left\{\Omega_{j1}^2(\nu_c + \Omega_k)\right\} + \nu_c\Omega_k\Omega_{j1}^2 = 0. \quad (19)$$

From equation (19) we get

$$k < k_{j1} = \left(\frac{4\pi G\rho}{c'^2}\right)^{1/2}. \quad (20)$$

where k_{j1} is the modified Jeans wave number for thermally conducting system. It is clear from equation (20) that the Jeans length is reduced due to thermal conduction [as γ > 1], thus the system is destabilized. If we consider self-gravitating and thermally non-conducting plasma incorporated with neutral particles, arbitrary radiative heat-loss function then the condition of instability is given as

$$k < k_{j2} = k_j \left(\frac{\gamma \mathcal{L}_T}{\mathcal{L}_T - \rho \frac{\mathcal{L}_\rho}{T}} \right)^{1/2} . \quad (21)$$

where, k_{j2} is the modified critical wave number due to inclusion of arbitrary radiative heat-loss function. Comparing equation (18) and (21) we find that the critical wave number k_{j2} is very much different from the original Jeans wave number k_j and k_{j2} depends on derivatives of the arbitrary radiative heat-loss function with respect to local temperature $\mathcal{L}_T$ and local density $\mathcal{L}_\rho$ in the configuration. It is clear from equation (21) that when the arbitrary radiative heat-loss function is independent of density of the configuration (i.e. $\mathcal{L}_\rho$= 0), then $k_{j2} = k_j$ i.e. critical wave number remains unaffected and if the arbitrary radiative heat-loss function is independent of temperature ($\mathcal{L}_T$= 0), then k_{j2} vanishes.

The condition of instability of the system, when combined effect of all the parameters represented by the original dispersion relation (17) is given as

$$k_{j3} = \frac{1}{2^{1/2}} \left[\left\{ \frac{4\pi G\rho}{c'^2} + \frac{\rho^2 \mathcal{L}_\rho}{\lambda T} - \frac{\rho \mathcal{L}_T}{\lambda} \right\} \pm \left\{ \left(\frac{4\pi G\rho}{c'^2} + \frac{\rho^2 \mathcal{L}_\rho}{\lambda T} - \frac{\rho \mathcal{L}_T}{\lambda} \right)^2 + \frac{16\pi G \rho^2 \mathcal{L}_T}{\lambda c'^2} \right\}^{1/2} \right]^{1/2} . \quad (22)$$

Furthermore, if it is considered that the arbitrary radiative heat-loss function is purely density dependent ($\mathcal{L}_T$= 0) then the condition of instability is given as

$$k < k_{j4} = \left(\frac{4\pi G\rho}{c'^2} + \frac{\rho^2 \mathcal{L}_\rho}{\lambda T} \right)^{1/2} . \quad (23)$$

It is evident from inequality (22) that the critical wave number is increased or decreased, depending on whether the arbitrary radiative heat-loss function is an increasing or decreasing function of the density.

Now equating zero the third factor of equation (15) and after solving we obtain dispersion relation as

$$\sigma^6 + \sigma^5 A_1 + \sigma^4 A_2 + \sigma^3 A_3 + \sigma^2 A_4 + \sigma A_5 + A_6 = 0. \quad (24)$$

where $A_1 = 2R_1$, $A_2 = 2\frac{V^2k^2}{f} + R_2^2$, $A_3 = 2\frac{V^2k^2}{f}(R_2 + \nu_c)$

$A_4 = \frac{V^4k^4}{f^2} + R_2[\frac{4V^2k^2\nu_c}{f}]$, $A_5 = \frac{V^4k^4}{f^2}\nu_c$, $A_6 = \frac{V^4k^4}{f^2}\nu_c^2$, $R_2 = \nu_c(1+\beta)$.

This dispersion relation shows the combined influence of magnetic field, finite electron inertia and the effect of the neutral particles, but this mode is independent of thermal conductivity, finite electron inertia, arbitrary radiative heat-loss function and self-gravitation. This equation gives Alfven mode modified by the dispersion effect of the neutral particles and finite electron inertia.

4.2. Transverse propagation: - For this case we assume all the perturbations are propagating perpendicular to the direction of the magnetic field, for, our convenience, we take $k_x = k$, and $k_z = 0$, the general dispersion relation (16) reduces to

$$a^2[\ \sigma^2 a\ (\sigma a + k^2V^2) +\ \sigma a\Omega_T^2] = 0. \tag{25}$$

This is the general dispersion relation for transverse propagation shows the combined influence of magnetic field, self-gravitation, thermal conductivity presence of neutral particles and arbitrary radiative heat-loss function on the self-gravitational instability of a two components of the partially-ionized plasmas. Dispersion relation (25) has two distinct factors, each represents different mode of propagation when equated to zero, separately. The first mode is same as discussed in the dispersion relation (16). The second factor of equation (25) equating zero and substituting the values of a and Ω_T^2 we get

$$\sigma^5 +\ \sigma^4[2R_1 +\ \beta] + \sigma^3\left[\Omega_j^2 + \frac{k^2V^2}{f} +\ 2\beta R_1 + R_1^2\right] +\ \sigma^2\left[\Omega_I^2 + 2\nu_c R_1\Omega_j^2\ + \frac{k^2V^2}{f}(R_1 + \nu_c + \beta) + R_1\beta(R_1 + \nu_c)\right] +\ \sigma\ \left[\Omega_I^2(R_1 + \nu_c) + \nu_c R_1\Omega_j^2 + \frac{k^2V^2}{f}R_1\nu_c + \beta\frac{k^2V^2}{f}(R_1 + \nu_c)\ \right] + R_1\nu_c\left(\beta\frac{k^2V^2}{f} +\ \Omega_I^2\right)\ =\ 0. \tag{26}$$

This dispersion relation for transverse propagation represents the combined influence of thermal conductivity, arbitrary radiative heat-loss function on the self-gravitation instability of two components partially-ionized plasmas with the effect of neutral particles. The condition of instability is obtained from dispersion relation (26) as

$$\beta k^2V^2\ + f(\ k^2\alpha - 4\pi G\rho) < 0. \tag{27}$$

This is modified Jeans condition of instability due to magnetic field, finite electron inertia, thermal conductivity and arbitrary radiative heat-loss function. If the fluid expressed by equation (26) does not contain arbitrary radiative heat-loss function then the critical Jeans wave number below which the system is unstable is obtained from the constant terms of equation (26) and is given as

$$k_{j5}^2 = \frac{\gamma k_j^2}{1+\frac{\mathrm{v}^2}{fc^2}}\,. \tag{28}$$

If the arbitrary radiative heat-loss functions are included in a thermally non conducting medium, the corresponding value of critical wave number is given by

$$k_{j6}^2 =\ \gamma k_j^2\left[\frac{T\mathcal{L}_T}{T\mathcal{L}_T(1+\frac{\mathrm{v}^2}{fc^2}) - \mathcal{L}_\rho\rho}\right]. \tag{29}$$

The disturbances with a wave number $k < k_{j6}$ are unstable, where for $k > k_{j6}$, the disturbances are stable.

In the general case when both the arbitrary radiative heat-loss functions and thermally conductive effect are present simultaneously then it can be seen by a little simplification of equation (26) that the critical Jeans wave number is given by

$$2\left(1+\frac{v^2}{fc^2}\right)k_{j7}^2 = \left[\left\{\frac{4\pi G\rho}{c^2}+\frac{\rho^2\mathcal{L}_\rho}{\lambda T}-\frac{\rho\mathcal{L}_T}{\lambda}\left(1+\frac{v^2}{fc^2}\right)\right\} \pm\left\{\left(\frac{4\pi G\rho}{c^2}+\frac{\rho^2\mathcal{L}_\rho}{\lambda T}-\frac{\rho\mathcal{L}_T}{\lambda}\left(1+\frac{v^2}{fc^2}\right)\right)^2+\frac{16\pi G\rho^2\mathcal{L}_T}{\lambda c^2}\left(1+\frac{v^2}{fc^2}\right)\right\}^{\frac{1}{2}}\right]. \quad (30)$$

The medium is unstable for wave number $k < k_{j7}$. It may be noted here that the critical wave number involves, derivative of temperature dependent and density dependent arbitrary radiative heat-loss function, thermal conductivity of the medium and the magnetic field.

5. Conclusion

In the present paper, we have investigated the problem of Jeans instability of a infinite homogeneous, self-gravitating magnetized two component of partially-ionized gaseous plasma incorporating thermal conductivity and finite electron inertia with considering arbitrary radiative heat-loss functions. The general dispersion relation is obtained, which is modified due to the presence of these parameters. This dispersion relation is reduced for longitudinal and transverse modes of propagation. We find that the Jeans criterion remains valid but the expression of the critical Jeans wave number is modified. Thermal conductivity affects the sonic modes for making the process isothermal in place of adiabatic and shows the destabilizing effects on the system in both directions.

In the case of longitudinal propagation, we obtain a non-gravitating Alfven mode modified by the presence of finite electron inertia. The thermal mode is obtained separately having the effects of thermal conductivity and arbitrary radiative heat-loss functions. We find that the condition of instability is unaffected by the presence of finite electron inertia and magnetic field. It is also found that the density dependent heat-loss function has a destabilizing influence on the disturbances of the system. We also find that the value of critical Jeans wave number increases with increasing density and decreasing temperature of the neutral component. The basic destabilizing influence underlying the thermal instability is a heat-loss function which decreases with temperature and increases with density. In such a situation, a small temperature perturbation tends to grow naturally, for instance, lowering the temperature leads to higher radiative loss and further cooling. In the solar corona, the arbitrary radiative heat-loss functions $\mathcal{L}_{\sigma,T}$ depends on local density and temperature. Thus we conclude that radiative instability is opposed by the mechanism of thermal conduction which smoothes out any spatial temperature gradient.

In the transverse mode of propagation, we find that the critical Jean's wave number also depends on the magnetic field, finite electron inertia, thermal conductivity and arbitrary radiative heat-loss function. The Jeans wave number involves the magnetic field, and the electron inertia parameter *f* which shows that the second mechanism which counter-balances the radiative instability in addition to thermal conduction is a result of the frozen-in field restriction of the motion of the magnetized plasma. The fall in the local temperature and pressure results in a cool condensation and the plasma flow ensures toward the cool region which is, however checked by the frozen-in field condition, thus providing a stabilization.

Thus we may conclude from this investigation that the Jeans criterion determines not only the instability of the medium but also the stability of the medium. For all perturbations having wave number greater than Jeans the system will remain necessarily stable.

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