Dust–ion-acoustic waves in nonthermal magnetized collisional dusty plasma

Presenter

Md. Rakib Hassan

Department of Physics
Jahangirnagar University

Collaborator

Dr. Sharmin Sultana

Professor
Department of Physics
Jahangirnagar University
Savar, Dhaka-1342

Overview

- Introduction
    - Acoustic modes in plasma
    - Linear and nonlinear theory
    - Nonlinear equations in presence of **collision**
    - Particle distribution
- Theoretical background
- Aim of my work
- Plasma model
- Theoretical Predictions
- Applications
- Conclusions and Future Works

Introduction

Plasma:

- Fully or partially ionized but macroscopically neutral gases
- Contain charged and neutral particles
- Exhibit collective behavior due to long ranged Coulomb potential [1]
- Introduced by Tonks and Langmuir in 1929

Different Types Plasma

- **Electron-ion (e-i) plasma**
- **Dusty plasma with negative dust**
- Dusty plasma with positive dust
- Opposite polarity dusty plasma (OPDP)
- Electron depleted plasma
- Electron-positron-ion (e-p-i) plasma etc.

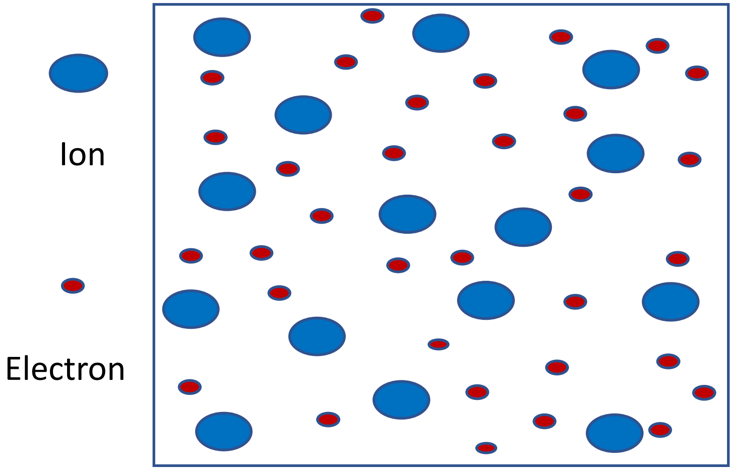


Figure-1: e-i plasma

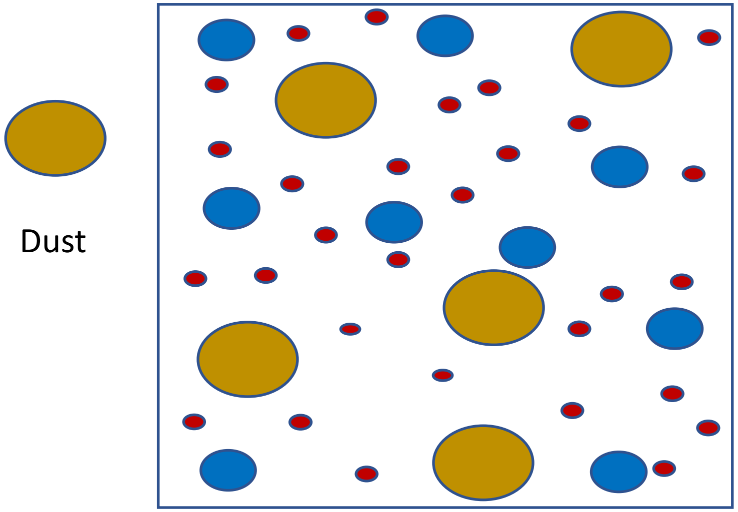
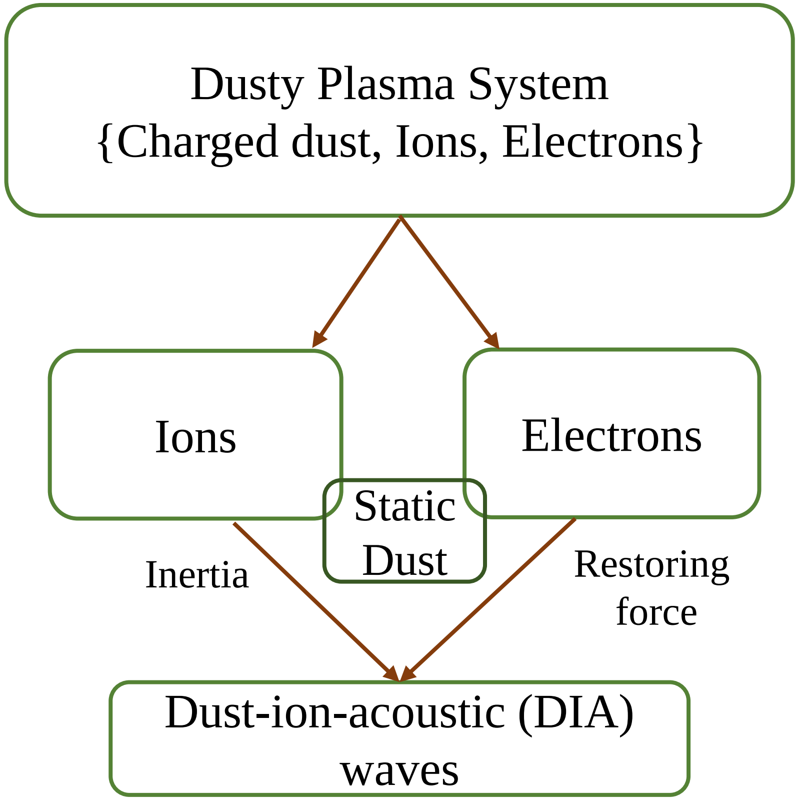


Figure-2: Dusty plasma

[1] P. K. Shukla and A. A. Mamun, Introduction to Dusty Plasma Physics (Institute of Physics Publishing Ltd., Bristol, 2002).

Acoustic Modes in Plasma

- ☐ Ion-acoustic waves (IAWs)
- ☐ Electron-acoustic waves (EAWs)
- ☐ Dust-acoustic waves (IAWs)
- ☐ **Dust-ion-acoustic waves (DIAWs)**


Dusty Plasma System
{Charged dust, Ions, Electrons}

Ions

Electrons

Static Dust

Inertia

Restoring force

Dust-ion-acoustic (DIA) waves

Chart-1: Generation of DIAWs in dusty plasma

Linear and Nonlinear Theory

Linear Theory

- Applicable when wave amplitude and perturbation are sufficiently small
- Supports superposition theory
- Predicts exponential growth of unstable waves

Nonlinear Theory

- Applicable when wave amplitude and perturbation are sufficiently large
- Does not support superposition theory
- Predicts that nonlinear effects cause saturation and limit the wave amplitude at a finite level

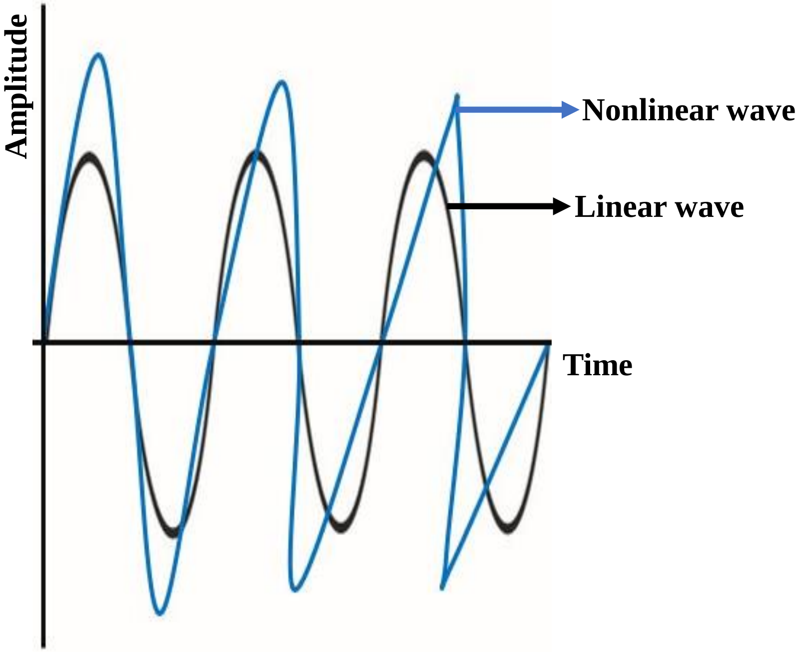


Figure-3: Linear and Nonlinear waves [2]

[2]. P. M. Jordan and B. Kaltenbacher, Evolution Equations & Control Theory **8**, 1 (2019).

Nonlinear equations in presence of Collision

- Korteweg de Vries (KdV) Equation
- Burgers Equation
- Korteweg de Vries Burgers (KdVB) Equation
- Nonlinear Schrodinger Equation (NLSE)
- Zakharov–Kuznetsov–Burgers (ZKB) equation

ZKB Equation

$$\frac{\partial \varphi}{\partial T} + \mathrm{A}\varphi \frac{\partial \varphi}{\partial Z} + B\frac{\partial^3 \varphi}{\partial \mathrm{Z}^3} + C\frac{\partial}{\partial Z}\left(\frac{\partial^2}{\partial \mathrm{X}^2} + \frac{\partial^2}{\partial \mathrm{Y}^2}\right)\varphi = E\nabla^2\varphi$$

Damped ZKB Equation

(With collision)

$$\frac{\partial \varphi}{\partial T} + \mathrm{A}\varphi \frac{\partial \varphi}{\partial Z} + B\frac{\partial^3 \varphi}{\partial \mathrm{Z}^3} + C\frac{\partial}{\partial Z}\left(\frac{\partial^2}{\partial \mathrm{X}^2} + \frac{\partial^2}{\partial \mathrm{Y}^2}\right)\varphi + \boldsymbol{D\varphi} = E\nabla^2\varphi$$

Particle Distribution

- κ = Nonthermal (superthermal) index and characterizes the plasma particles possessing excess energy [3]
- κ →3/2 represents superthermal distribution
- κ →∞ represents Maxwellian distribution

$$n_e = n_{e0}\left[1 - \frac{e\Phi}{k_B T_e(\kappa - 3/2)}\right]^{-\kappa+\frac{1}{2}}.$$

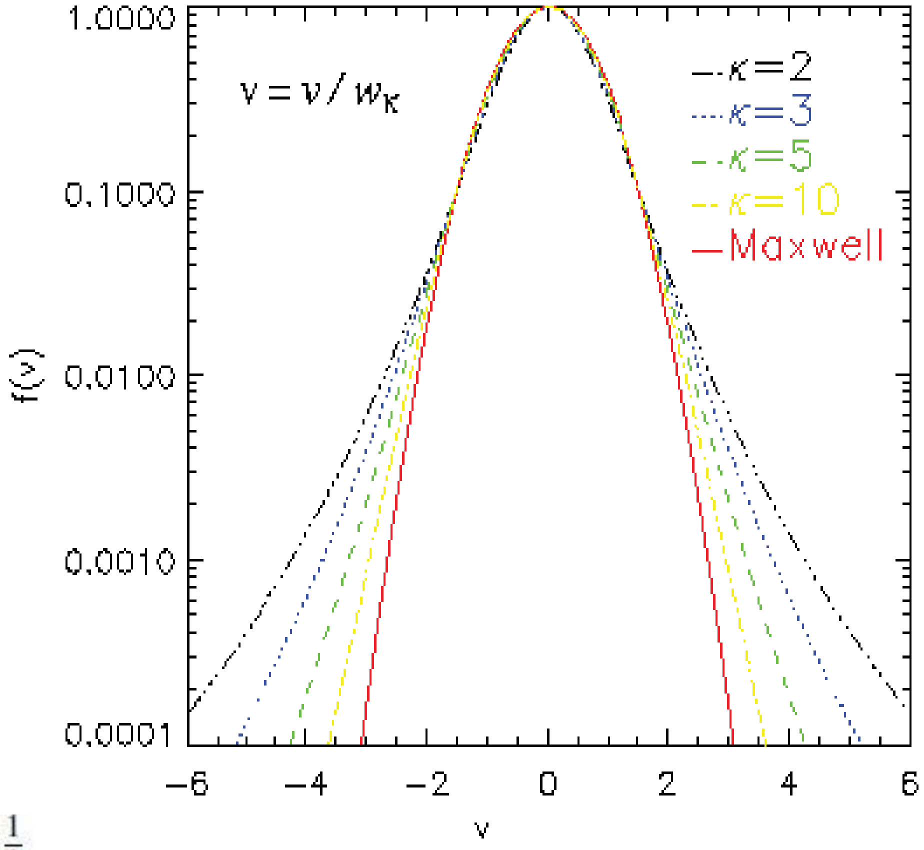


Figure-4: κ distribution function [3]

[3] M. Lazar, *et al.*, Superthermal Particle Populations in the Solar Wind and Corona; DOI: 10.5772/39281

Theoretical Background

Year	**Authors**	**Research Topic**	**Findings**
1992	A. A. Mamun [4]	IA waves	With ion temperature the amplitude of the solitary waves falls
2011	P. Chatterjee *et al.* [5]	IA waves	Only subsonic solitary waves can exist.
2012	K. Roy, *et al.* [6]	IA waves	With the ion temperature the amplitude of solitary wave falls.
2015	S. Sultana, & I. Kourakis [7]	Electron-acoustic (EA) waves	Spontaneous formation of multi-soliton configurations
2018	S. Sultana [8]	DIA solitary waves without ion temperature effect	Solitary pulse amplitude is seen to larger in a collisionless plasma.
2019	S. Sultana, *et al.* [9]	EA waves without considering collision effect	Only the positive EA solitary waves are found to exist.
2021	M. R. Hassan & S. Sultana. [10]	DIA solitary waves with temperature effect and collision (κ- distributed)	In presence of ion-neutral collision both positive and negative solitary waves get damped.

Continued…

[4] A. A. Mamun, Phys. Rev. E **36**, 2 (1997).

[5] P. Chatterjee *et al*. Phys. Plasmas **16**, 042311 (2009).

[6] K. Roy, *et al*. Phys. Plasmas **19**, 104502 (2012).

[7] S. Sultana, & I. Kourakis, Phys. Plasmas **22**, 102302 (2015).

[8] S. Sultana, Phys. Lett. A **382**, 1368 (2018).

[9] S. Sultana, A. Mannan, & R. Schlickeiser, Eur. Phys. J. D, **73,** 220 (2019).

[10] M. R. Hassan & S. Sultana, Contrib. Plasma Phys, **e202100065,** 61 (2021).

Aim of the Work

The principal aim of this work is to investigate the nonlinear dynamics of the electrostatic waves analytically and numerically in nonthermal (superthermal) magnetized collisional plasmas. In particular

- Investigation of the electrostatic shock and solitary wave dynamics in weakly dissipative and weakly nonlinear plasmas via the damped ZKB equation.

- Bifurcation analysis of the dust-ion-acoustic waves in our considered medium.

Plasma Systems

Components

- κ- distributed Electron
- Positive and Negative Dust
- Positive warm ion fluid

Basic Governing Equations

$$\frac{\partial n}{\partial t}+\frac{\partial (nu)}{\partial x}+\frac{\partial (nv)}{\partial y}+\frac{\partial (nw)}{\partial z}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\frac{\partial \Phi}{\partial x}-\ \Omega v+\frac{\sigma}{n}\frac{\partial n^{\gamma}}{\partial x}-\nu_i \mathrm{u}+\eta'\nabla^2 u \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\frac{\partial \Phi}{\partial y}+\ \Omega u+\frac{\sigma}{n}\frac{\partial n^{\gamma}}{\partial y}-\nu_i \mathrm{v}+\eta'\nabla^2 v \qquad (3)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\frac{\partial \Phi}{\partial z}+\frac{\sigma}{n}\frac{\partial n^{\gamma}}{\partial z}-\nu_i \mathrm{w}+\eta'\nabla^2 w \qquad (4)$$

$$\nabla^2\Phi=1+\alpha-n+p\Phi+q\Phi^2+r\Phi^3 \qquad (5)$$

Derivation and Solution of Nonlinear Equations

Stretching Coordinates and Variable Expansions

1. Independent variables

$$X = \varepsilon^{1/2}\, x, \qquad \eta' = \varepsilon^{1/2}\eta$$
$$Y = \varepsilon^{1/2}\, y, \qquad \nu_i = \varepsilon^{3/2}\nu,$$
$$Z = \varepsilon^{1/2}\, z, \qquad T = \varepsilon^{3/2} t$$

2. Dependent variables

$$n = 1 + \varepsilon n_1 + \varepsilon^2 n_2 + \cdots$$
$$u = \varepsilon^{3/2} u_1 + \varepsilon^2 u_2 + \cdots$$
$$v = \varepsilon^{3/2} v_1 + \varepsilon^2 v_2 + \cdots$$
$$w = \varepsilon w_1 + \varepsilon^2 w_2 + \cdots$$
$$\Phi = \varepsilon \varphi_1 + \varepsilon^{3/2} \varphi_2 + \cdots$$

Solution with zero collision (ν=0) [*]

$$\varphi_1(\xi, \tau) = \frac{3E^2}{25A(Bl^4{}_z + Cl^2{}_z(1 - l^2{}_z))} \left[4 - \left\{1 + \tanh\left[\frac{E}{10\left(Bl^4{}_z + Cl_z(1 - l^2{}_z)\right)}\,\xi\right]\right\}^2\right].$$

Solution with collision ($\nu \neq$0) [**]

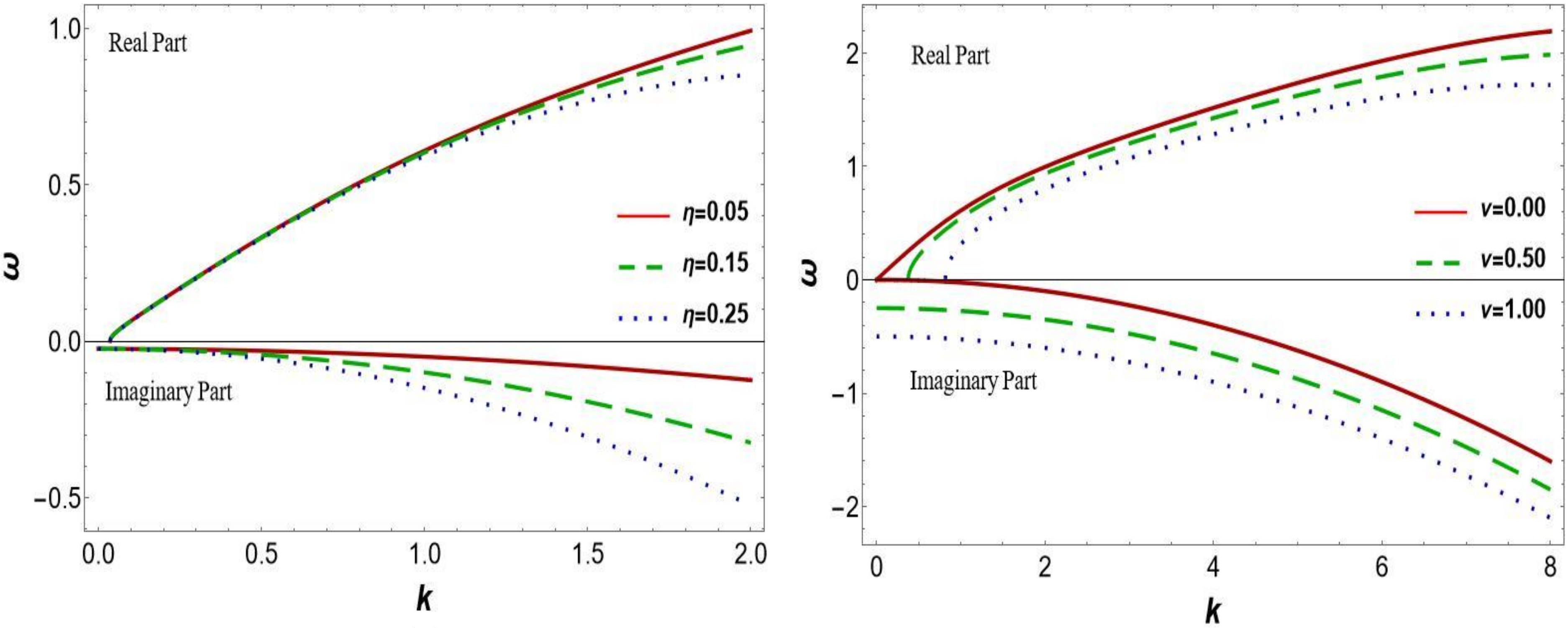
$$\varphi_1(\xi, \tau) = \frac{144EFl_z + 12EV + Fl_zD + 2VD}{3Al_z(4E - D)} - \frac{12E + 2D}{5Al_z}\tanh(\xi) - \frac{12F}{A}\, tanh^2(\xi).$$

Where $F = (Bl^2{}_z + C\,(1 - l^2{}_z))$.

[*] I. Kourakis, S. Sultana, & F. Verheest. *Astrophys Space Sci* **338,** 245–249 (2012).

[**] E. I. El-Awady & M. Djebli. *Astrophys Space Sci* **342,** 105–111 (2012).

Theoretical Predictions-1



(a)

(b)

Figure-5: Dispersion relation for the variation of (a) viscous coefficient and (b) ion-neutral condition

$$\omega = \sqrt{\left(\frac{k^2}{k^2+d_1}+\sigma\gamma k^2\right)-\frac{1}{4}(v_i+\eta k^2)^2}-\frac{1}{2}i(v_i+\eta k^2).$$

$$\Rightarrow \omega = \omega_r + i\omega_i,$$

Theoretical Predictions-2

$\alpha = \frac{Z_{dp} n_{dp0}}{Z_i n_{i0}}$ = positive dust-to-ion ratio

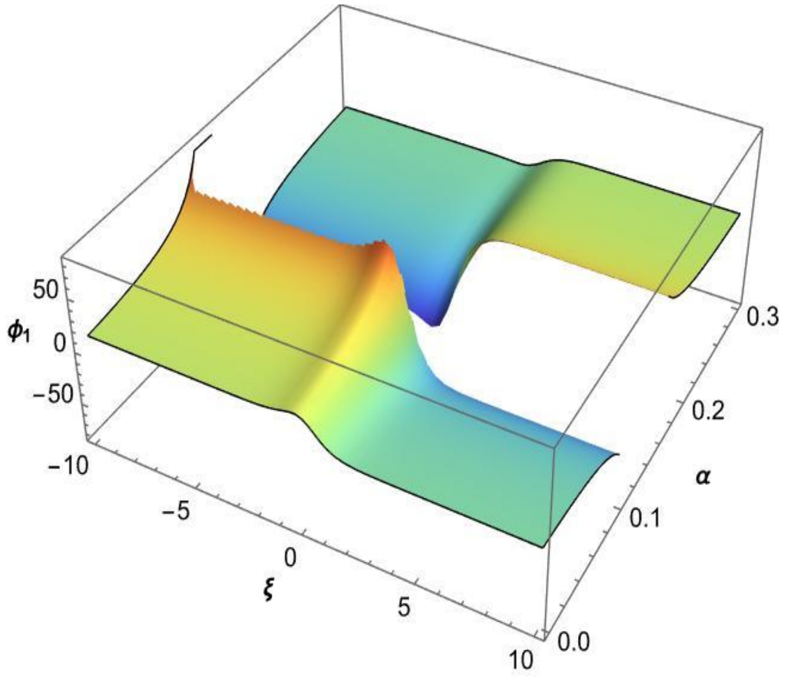


Figure-6: Variation of the shock structure in the adiabatic plasma with positive dust-to-ion ratio

$\mu = \frac{Z_{dn} n_{dn0}}{Z_i n_{i0}}$ = negative dust-to-ion ratio

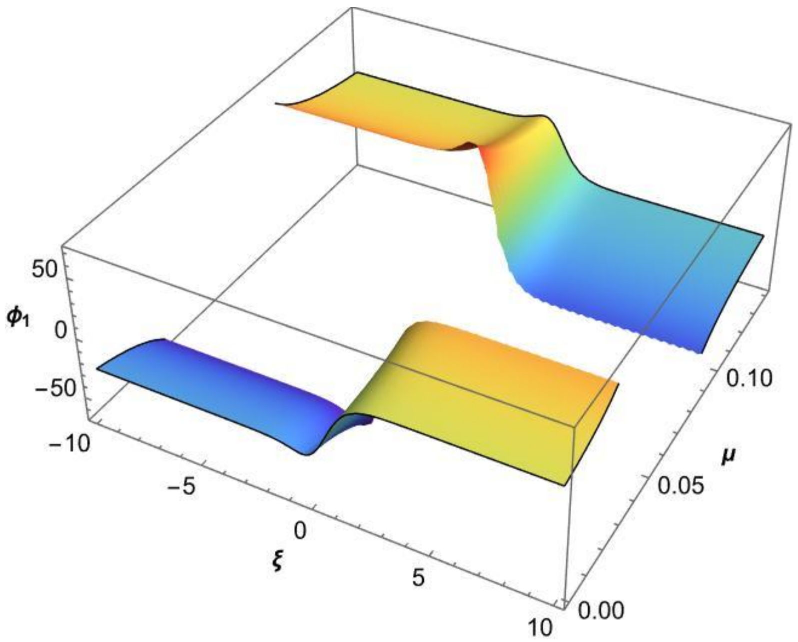


Figure-7: Variation of the shock structure in the adiabatic plasma with negative dust-to-ion ratio

Both the opposite polarity shock waves are found to exist.

Theoretical Predictions-3

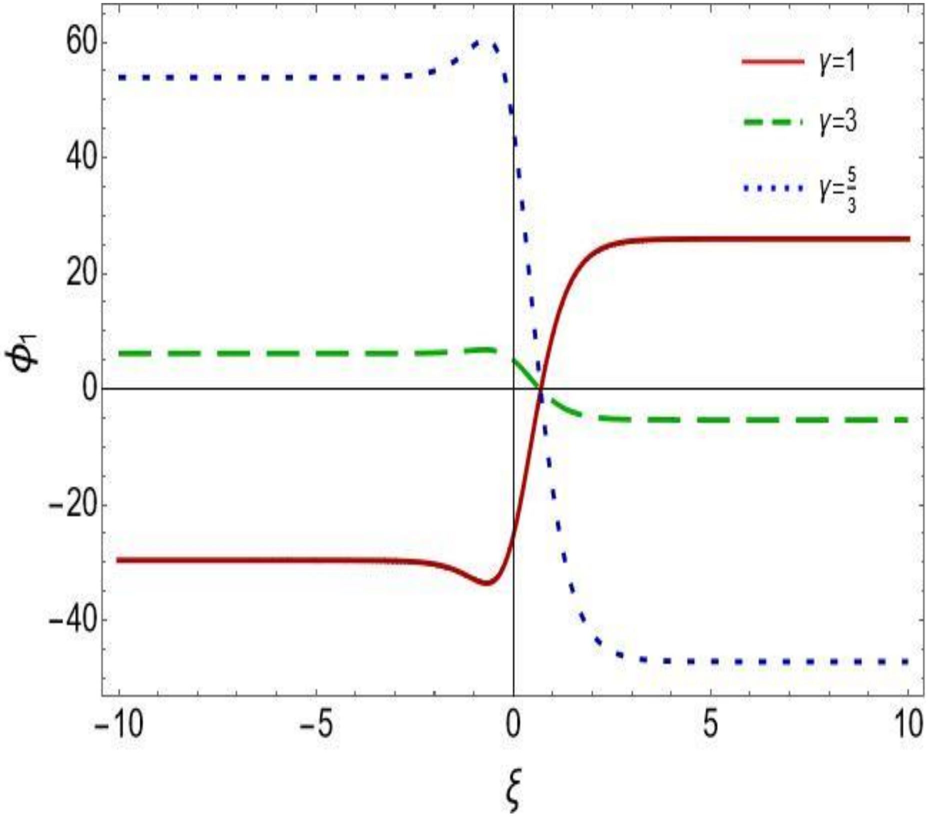


Figure-8: Variation of the shock structure with adiabaticity

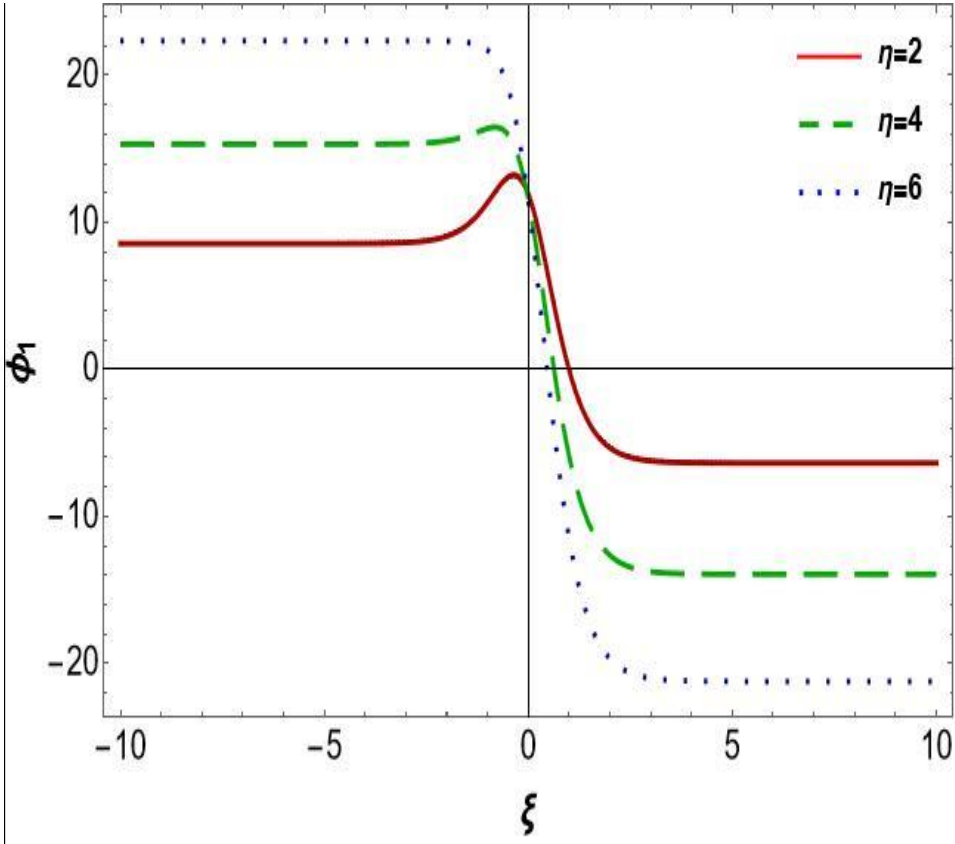


Figure-9: Variation of the shock structure with viscosity

- In isothermal (adiabatic) plasma shock structures are found to be negative (positive).

- The amplitude goes up with the rise of viscosity

Theoretical Predictions-4

$\sigma = \frac{T_i}{T_e} =$ ion-to-electron temperature ratio

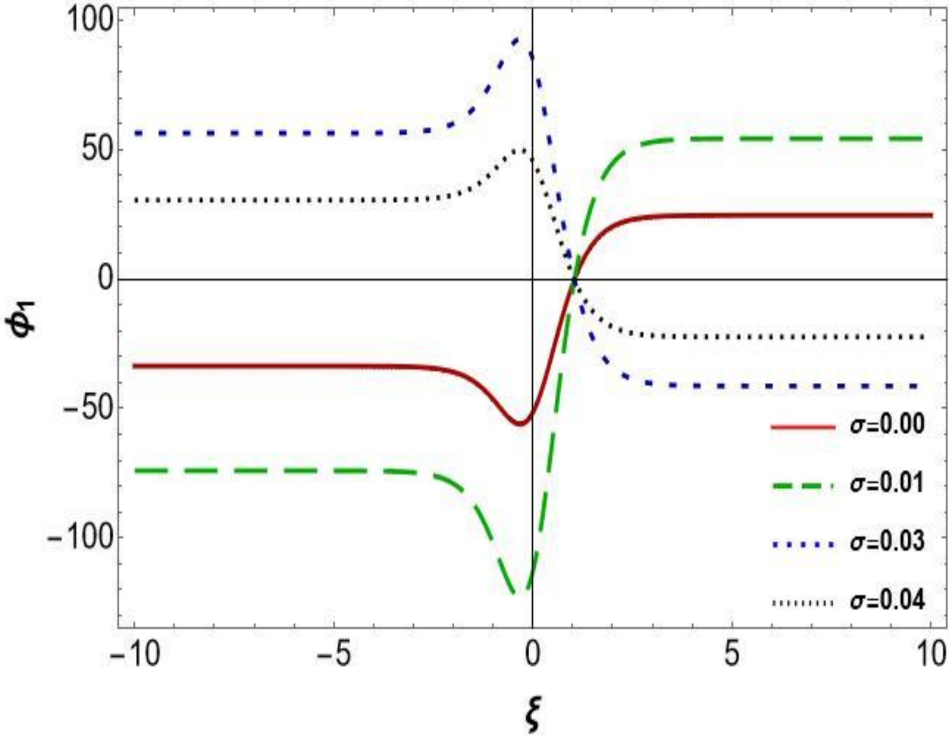


Figure-10: Variation of the shock structure with ion temperature effect

There is a critical ion temperature at which the shock amplitude becomes infinite.

$\Omega = \frac{eB}{m}/\omega_{pi}$= Normalized (by ion plasma frequency) ion cyclotron frequency

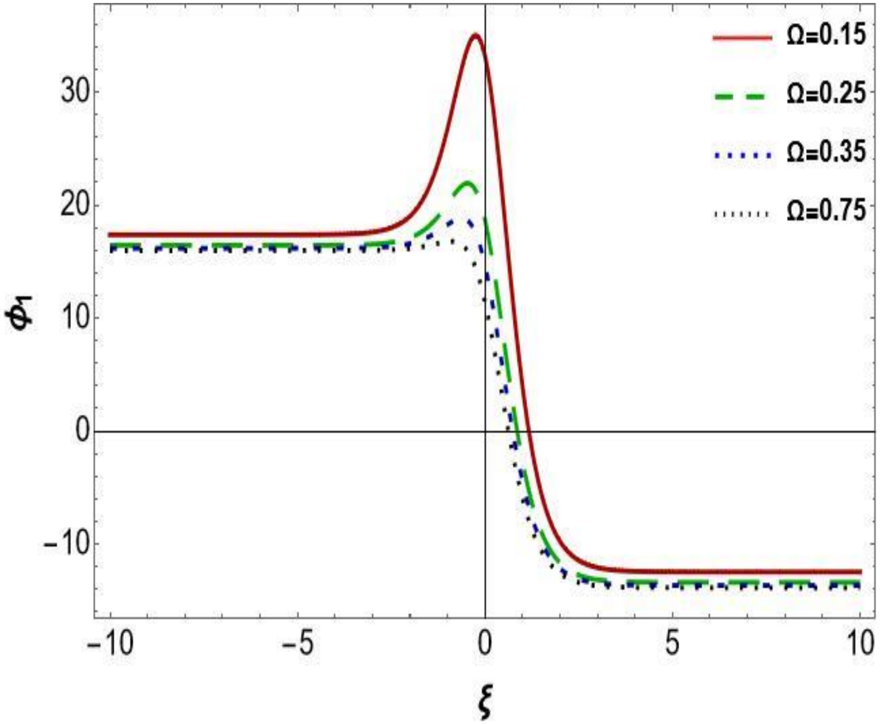


Figure-11: Variation of the shock with ion cyclotron frequency

Solitary shocks are seen to change into monotonic shocks with increasing magnetic field.

Theoretical Predictions-5

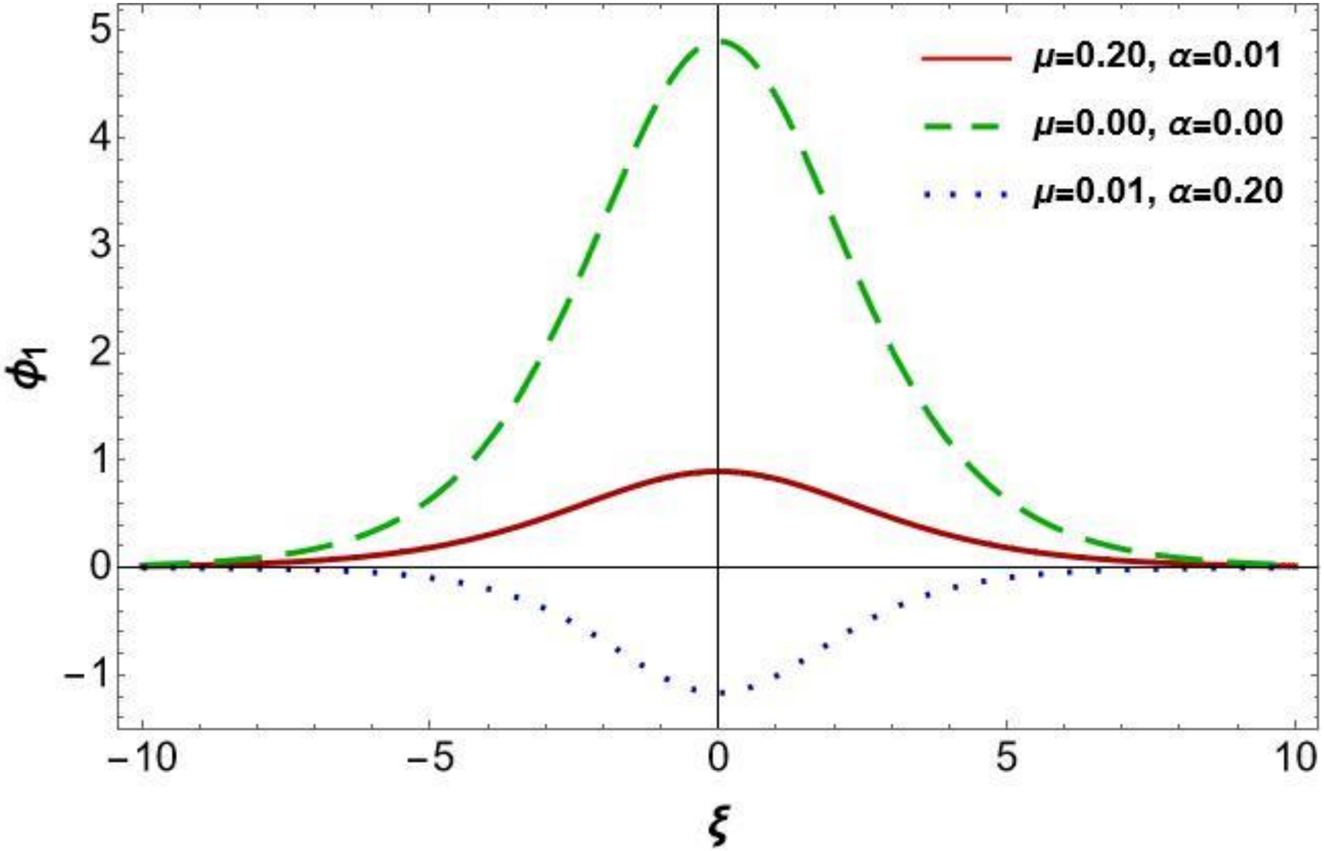
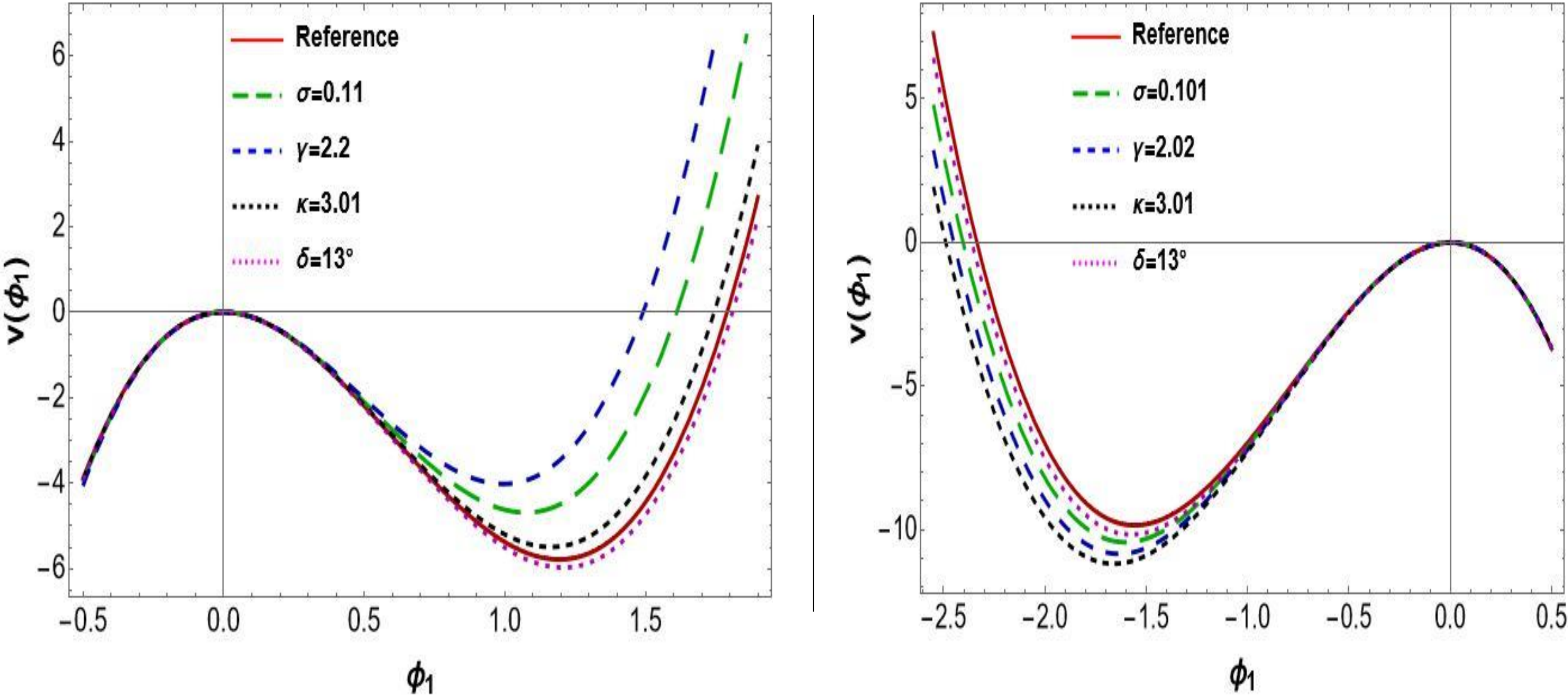


Figure-12: Variation of solitary waves with different opposite polarity dust grain composition

The amplitude and the width of the solitary pulse get dissipated with time due to electron-neutral collision

Theoretical Predictions-6



(a)

(b)

Figure-13: The influence of different plasma parameters on the Sagdeev potential *V*, for (a) negative dust dominant plasma, (b) positive dust dominant plasma.

Theoretical Predictions-7

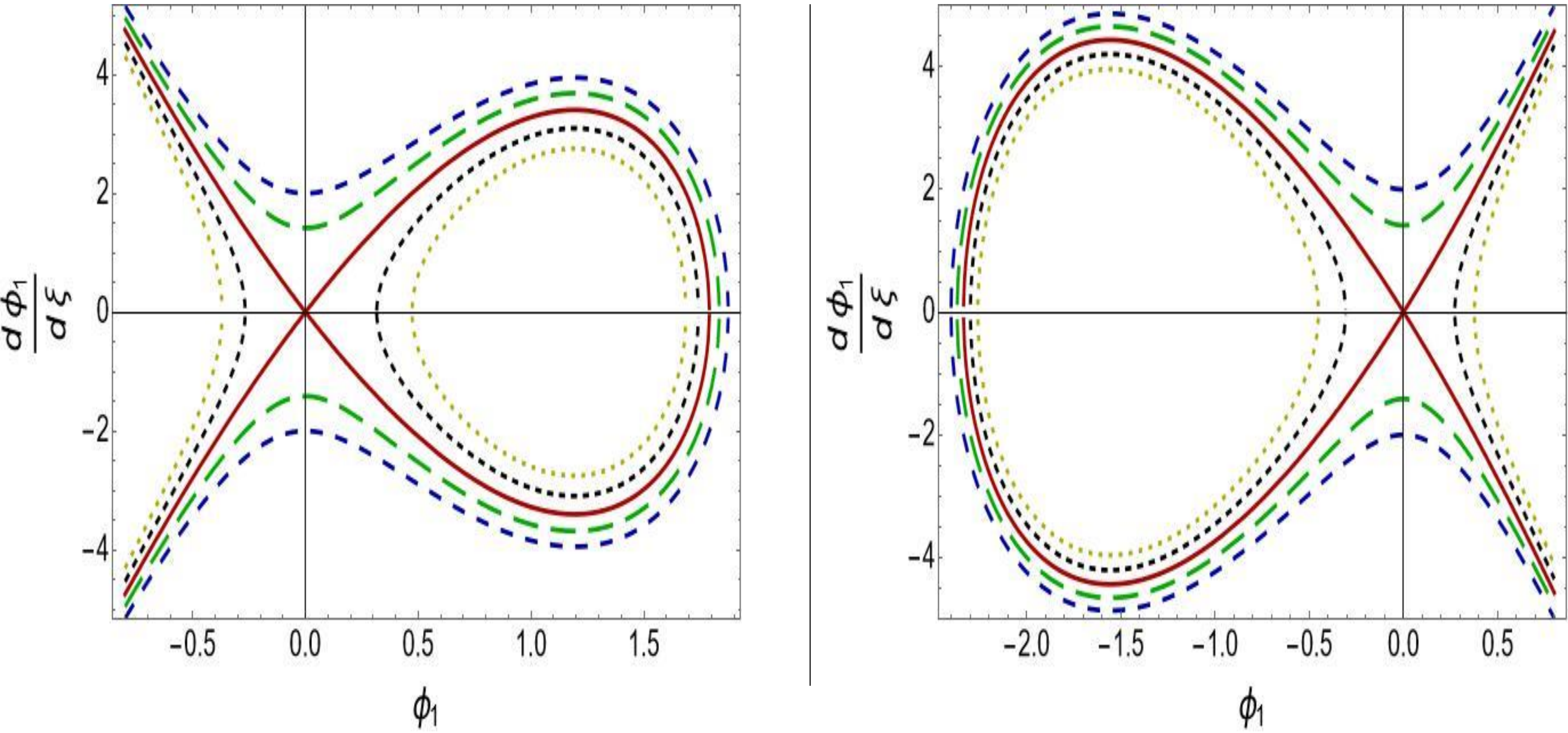


Figure 14: The variation of the phase portrait ($\frac{d\phi_1}{d\xi}$) against ϕ_1 showing the influence of different plasma parameters, where (a) negative dust dominant plasma, (b) positive dust dominant plasma. (H > 0-Green, Blue; H < 0-Black, Yellow; H=0-Red)

Applications

Space Applications

- In observing the waves behavior in Saturn’s F-ring and in Martian atmosphere [2, 3]
- In understanding the behaviors of EA and DIA solitary waves

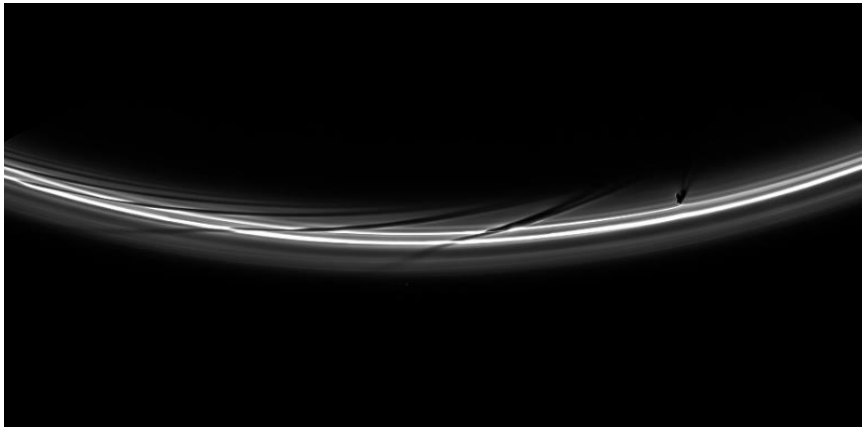


Figure-13: Processed using unfiltered images of Saturn’s F-ring taken by Cassini on January 14, 2009.

Laboratory Applications

- Laser-matter interaction [11]
- Q-machine [12]
- Fusion energy source [13]
- Plasma pyrolysis [14]

Figure-14: Q-machine schematic diagram [14]

[11] M. Shahmansouri and H. Alinejad, Phys. Plasmas **20**, 033704 (2013).
[12] H. L. Pécseli, Annales Geophysicae **33(7),** 875 (2015).
[13] D. E. Post, and R. Behrisch Physics of Plasma-Wall Interactions in Controlled Fusion (2013)
[14] https://www.power-technology.com/features/hotter-than-the-sun-iter-and-the-pursuit-of-nuclear-fusion/

Conclusions

This piece of investigative work will be handy to fathom more about the nonlinear structures and their properties in magnetized laboratory and space plasmas where:

- The ions have a significant temperature.
- Ion-neutral collision plays a significant role.
- The electrons follow the superthermal distribution.
- Both the positive and negative charged dust grains are existent.

Future Works

Deriving the nonlinear Schrodinger equation and thus analyze the rouge waves in the systems that we considered in my thesis.

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Thank You

Questions?