CHAPTER-I

INTRODUCTION

The plasma state is a characterization of matter where long range electromagnetic interactions dominate the short range interatomic or intermolecular forces among a large number of electrons and ions, moving with high speed corresponding to high temperature. Plasma is created either by heating, or by radiation or by electrical discharges etc. Progress in plasma physics is motivated by two very important applications: space exploration and thermonuclear fusion. This state is not naturally found on the earth whereas the space, outside the earth is filled with an active plasma of energetic charged particles, which exhibits many interesting physical phenomenon such as the interaction of the solar wind plasmas with the earth's magnetic field, particle acceleration, wave excitation and propagation etc..

1.1 Plasma Waves

Waves in a plasma, often act the carriers of energy and momentum, are excited by some kind of source. This can be either a fluctuation produced by some external means or a spontaneous fluctuation inside the plasma. There are various kinds of plasma wave phenomena that are observed in space but not in laboratory plasmas. The topside ionosphere is presently known to be a major source of hot plasma within the magneto-
sphere (Lundin 1989). Strongly enhanced plasma lines, upshifted and downshifted from the frequency of the monostatic incoherent scatter radar (430 MHz), including the ‘growing mode’, the ‘decay line’, the ‘broad line’ and the ‘image decay line’ are seen during incoherent radar measurements of a modified ionospheric region. These are indeed due to plasma oscillations and waves associated with the predicted instabilities in the modified ionosphere region. Space, is therefore the best laboratory for the study of plasma wave phenomena.

Due to the collective behaviour of charged particles, a plasma displays interesting electromagnetic and electrostatic characteristics. A variety of waves in various high and low-frequency ranges characteristic of electron and ion oscillations respectively, can exist in a plasma. The multiplicity of modes increases with the inclusion of external magnetic field (i.e. magnetized plasma). The frequencies which characterize various modes are (i) Electron plasma frequency ($\omega_{pe}$) (ii) electron cyclotron frequency ($\omega_{ce}= eB_0/m_e c$) where $B_0$ is the external magnetic field, (iii) ion plasma frequency $\omega_{pi} = (4\pi n_i e^2/m_i)^{1/2}$ where $m_i$ is the mass and $n_i$ is the density of ion, and (iv) ion cyclotron frequency ($\omega_{ci}$). In the following paragraphs a summary of various type of mode is given which can exist in a plasma and is studied by the author in multi-species plasma.

Lower hybrid wave (LHW) frequency ($\omega$) lies between the ion and electron gyrofrequencies (i.e. $\omega_{ci}<<\omega<<\omega_{ce}$). In the
limit $\omega \gg \omega_{ci}$; $k_{x}B_{i} > 1$, the ion response can be taken to be unmagnetized, where $B_{i}$ is the ion-gyro radius. For $k_{x}B_{e} < 1; \omega > k_{z}C_{e}$, LH can be written as

$$\omega^2 = \omega_{1h}^2 \left(1 + \frac{k_{x}^2}{k^2} \frac{m_{i}}{m_{e}}\right),$$

where $\omega_{1h}^2 = \frac{\omega_{pi}^2}{1 + \omega_{pe}^2/\omega_{ce}^2}$

$m_{i}$ ($m_{e}$) is the mass and $C_{i}$ ($C_{e}$) is the thermal velocity of ion (electron). This mode can energize ions normal to the interplanetary magnetic field (Marsch & Chang 1985), and the associated ion-heating may also be observed in a laboratory Q machine (Satyanarayan & Chaturvedi 1986).

In most of the heating experiments, the frequency regime of ion-Bernstein mode (IBW) is $\omega_{ci} < \omega < 2\omega_{ci}$ i.e. near the ion-cyclotron harmonic frequency. For long parallel wavelength $k_{z}C_{e} < \omega$; $\omega - \omega_{ci} > k_{z}C_{i}$ and $k_{x}B_{e} < 1$ one can obtain IBW, which propagates nearly perpendicular to the magnetic field. Due to the cyclotron subharmonic resonance it was observed (Yakase et al. 1987; Okada et al. 1987) that non-resonant ions could be directly accelerated by this mode.

In addition to the weakly damped, now well known Langmuir and ion-acoustic wave, a third weakly damped electron-acoustic wave can become important if the plasma electrons can be described in terms of two component one hot (denoted by h) and
the other relatively cold (subscript c). Observations in the earth's bow shock region (Marsch 1985) and in the auroral magnetosphere (Roth & Hudson 1986) have demonstrated that a relative drift between two electron components with different temperatures can yield growing waves at intermediate frequencies of \( \omega_{\text{pi}} < \omega < \omega_{\text{pe}} \), where \( \omega_{\text{pi}}(\omega_{\text{pe}}) \) is the ion (electron) plasma frequency and \( \omega \) is the wave frequency. This wave may contribute significantly to electron heating (Sharma et al 1984; Gary & Tokar 1985).

We have studied two normal waves which appear to propagate in a two-ion species plasma whereas such waves are not possible in single ion species plasma. One of which can exist in a cold, magnetized plasma and have ion-ion hybrid resonance (IIHR) frequency

\[
\omega_{\text{IIHR}} = \frac{\omega^2_{\text{pL}} \omega^2_{\text{cH}} + \omega^2_{\text{pH}} \omega^2_{\text{cL}}}{\omega^2_{\text{pL}} + \omega^2_{\text{pH}}}
\]

where \( L \) and \( H \) stands for light and heavy ions. For the parameters in a laboratory discharge device, its frequency becomes \( \omega_{\text{IIHR}} = 3.2\omega_{\text{cH}} \). This mode plays an important role in the magnetospheric plasma (Dash et al 1984) and also in the RF heating of fusion plasmas (Dash et al 1984; Bharuthram & Hellberg 1986).

In a plasma system consisting of hot electron and two-ion species having different temperatures, number densities and charge multiplicities, an acoustic-like mode exist such
that \( C_e \gg C_{ih} \gg v_p \gg C_{ic} \), where \( (C_e, C_{ih}, C_{ic}) \) are thermal velocities and \( v_p \) is the phase velocity. Here electron temperature is higher than hot ion temperature, so that the perturbed electron density and velocity can be neglected. In that case electron debye length becomes larger than that of hot and cold ions and hence electrons tend to provide a dynamic neutralizing negative background. Under such assumption, even for the shorter wavelength case \( (k^2 p^2_e \gg 1) \), this mode appears to propagate as a normal mode (Dwivedi et al 1989). Such a plasma system arises where preferential heating of ion-species take place.

Whistlers, the dispersed impulses of low-frequency electromagnetic energy are generated in lightening flashes and ionospheric discharges. The whistler mode wave excited by auroral electrons in the frequency range between the lower-hybrid frequency (1 to 2 kHz) and the electron plasma frequency (50 to 150 kHz). For \( \omega \ll \omega_{ce} \) the dispersion relation of obliquely propagating whistler wave can be written as

\[
k^2 = \frac{\omega^2}{c^2} \frac{\omega}{\omega_{ce} \cos \alpha}.
\]

This wave can be used to establish a low-frequency communication link, as may be the case in the ionosphere (Stubbe et al 1981; Shoucri et al 1982; Okada & Iwai 1988).

In the altitude range of 3000 to 10,000 km. on the nightside auroral field lines, the upper hybrid (UH) frequency is
about 100-600 kHz. If one neglects ion motion and takes \( k_z \ll n_0 \). Taking \( k_z c \ll c \), recover upper-hybrid wave

\[
1 - \frac{\omega_{pe}^2}{k^2 \omega_{ce}^2} - \frac{\omega_{pe}^2}{k^2 \omega_e^2} - \frac{k^2 \omega_e^2}{k^2} = 0
\]

The large amplitude electrostatic oscillations near the UH mode conversion layer is capable of giving rise to a variety of nonlinear effects, e.g., in laser produced plasmas near the critical layer where the self-generated magnetic field exists, in ionospheric plasmas stimulated by intense radio waves, as well as in laboratory plasmas in which an electron beam generates electrostatic waves. In a dense plasma \( (\omega_{pe}^2 \gg \omega_{ce}^2) \) such as the 2XIIB mirror machine (Sharma & Shukla 1983), the decay of an UH pump wave into a daughter wave and an electron-acoustic wave constitutes an important nonlinear process.

1.2 Instabilities in plasma

A wave moving with velocity \( (\omega/k) \hat{k} \) sees more particles moving slightly faster than the wave that it sees moving slightly slower than the wave. Consequently, the wave obtains more energy from the particles than the particles from the wave, and therefore, wave grows. A wave growing spatially/or temporally is termed as instability, the propagation characteristics of which can be studied by solving the dispersion relation which relates the frequency and the wave number of the instability as a function of parameter of the system. The collective interactions in a collisionless plasma may be
classified as wave-particle and wave-wave coupling. The time evolution of the system is greatly influenced by wave-particle interactions for particles travelling near the phase velocity of the wave, i.e. when the condition \( \omega_k \mathbf{k} \cdot \mathbf{v} = 0 \) is satisfied, where \( \omega_k \) is the wave oscillation frequency, \( \mathbf{k} \) is the wave vector and \( \mathbf{v} \) is the particle velocity. If more than one wave is present, then nonlinear wave-particle interaction in which particles resonate with the beat frequency of two waves

\[
\omega_k - \omega_{k'} - (\mathbf{k} - \mathbf{k'}) \cdot \mathbf{v} = 0
\]

may also play a significant role in the time evolution of the wave amplitude as well as the distribution of particles in velocity space. In many problems of interest, however the waves are weakly coupled to the particles in the sense that linear instability (or damping) is absent or sufficiently weak, and resonant wave-particle interactions of the forms described above do not play an important role. In this case, the evolution of the wave amplitudes is dominated by interaction with other waves, i.e. wave-wave coupling becomes dominant nonlinear process in a plasma.

The nonlinear effect we consider is the class of parametric instabilities. These may be defined as an amplification of an oscillation due to a periodic modulation of a parameter that characterizes the oscillation. The following properties characterize the parametric excitation phenomena:
1. **Matching condition:** The modulation and the excited oscillation should satisfy a phase-matching condition.

2. **Threshold:** Amplification occurs only when the modulation amplitude exceeds a certain critical value.

3. **Frequency Locking:** The frequencies of the amplified oscillations are determined by the modulation frequency rather than by the natural frequency.

Physically parametric excitation can be looked upon as a nonlinear instability of two waves (an idler and a signal) by a modulating wave (a pump) due to a mode coupling interaction. In the presence of a high amplitude wave \((\omega_o, \mathbf{k}_o)\), the electron of plasma acquire an oscillatory velocity \(\mathbf{v}_0\). Let there be a density perturbation \(n_{\omega, \mathbf{k}}\). This produces a nonlinear current \(-n_{\omega, \mathbf{k}} \mathbf{e} \mathbf{v}_0\) driving the high frequency side bands \((\omega \pm \omega_o, \mathbf{k} \pm \mathbf{k}_o)\). The pump and the side band exert a low frequency ponderomotive force on the electrons driving the original density perturbation.

If the pump wave is weakly damped in the plasma, it can transfer its energy in nonlinear interaction to another wave, (i.e. in the decay process). When damping of this wave is overcome by the above mentioned strong positive feedback mechanism, then instability results and both the low-frequency and side-band waves grow at the expense of pump wave energy. Such a mechanism bringing about anomalous absorption of a pump
wave in a plasma is important for the heating of high tempera-
ture plasma, when the collisional absorption mechanism becomes
ineffective. For an isotropic plasma in a sufficiently strong
electromagnetic field, there can be different three-wave and
four-wave decay processes which satisfy the following frequen-
cy and phase matching conditions

$$\omega_{1,2} = \omega + \omega_0, \quad \vec{k}_{1,2} = \vec{k} \pm \vec{k}_0$$

In the thesis we consider following parametric instabili-
ties in a multi-component plasma:

(a) Parametric decay instability.
(b) Stimulated Brillouin Scattering.
(c) Two-Plasmon decay instability.
(d) Filamentation instability.
(e) Oscillating two stream instability.

The importance lies in the fact that the scattering
phenomena provides a good tool for the diagnostic purpose.
Scattering processes are also of considerable interest to
plasma heating experiments by lasers because the scattered
radiation can freely leave the plasma and thus constitute a
potential source of energy loss. Absorptive (decay) instabili-
ties are also very important because they can be used in
determining how the plasma is heated and how it can modify the
current drive applications and plasma transport. Such decay
processes have larger growth rates than other parametric
processes in a plasma.
Non-uniformities in a plasma often provide a free energy source for plasma instabilities. We consider a plasma which is spatially non-uniform in the density, in a direction perpendicular to a static magnetic field ($\vec{B}$). We get a net drift of plasma along the $\vec{V}_{\text{m}} \times \vec{B}$ direction. Since the electrons and the ions gyrate in opposite directions, the ion drift and the electron drift also occur in opposite directions and a diamagnetic current is produced. This current driven instability was assumed to be responsible for the heating and transverse acceleration of the ions in the near-earth space plasmas.

When an intense charged particle beam is injected into a dense plasma, various instabilities are produced, depending on the frequency and parameter ranges of interest. Such unstable oscillations are usually subdivided into two classes: large-scale (macroscopic), with characteristic scale lengths of the order of the beam radius or larger, and small-scale (microscopic) for perturbations of length scale smaller than the beam radius. Microscopic instabilities can lead to plasma heating and particle diffusion, and can effectively limit the amount of beam energy which can be transported through a system. In the beam reference frame, the wave electric field can couple strongly to the beam particles causing beam bunching. As the bunches are decelerated by the wave, the wave extracts energy from it. This feedback mechanism results in exponential growth of the wave amplitude. Electrostatic mode waves ($\vec{E} = -\vec{\nabla}\phi$) can be excited by beam plasma interactions.
The source of the free energy required to drive the instabilities is the differential stream velocities of the beam and plasma components. Such a situation can arise in the case of a non-Maxwellian distribution of particles in the plasma.

1.3 Multi-species plasmas

Plasmas consisting of two distinct groups of charged particle species are encountered in many geophysical as well as in laboratory systems. A multi-ion component plasma exhibits some phenomena which do not occur in a singly ion plasma and may depend on the temperature ratios and the mass ratios of the ions. The topside ionosphere within the day side magnetospheric cleft is a strong source of plasma during magnetically quiet periods (Chappell et al 1987). This plasma may reach the plasma sheet, become further heated and eventually contribute significantly to the magnetospheric hot plasma. Recent data from the day side cleft by Viking display similar characteristics of more energetic escaping ionospheric plasma (Markland 1988; Lundin 1989). Strong fluctuations of the electric field are mainly observed within regions of upward flowing ions and low thermal plasma densities. Below the prime acceleration region, where accelerated electrons may be observed but where ionospheric ion beams and conics are absent, the electric field is quieter. Observations of a heated cold ion component below the main acceleration region (Lundin 1989) indicate that some turbulent heating may also take place there. Hence in order to study the phenomena which are related
to waves in the ionosphere, it is important to understand the nature of waves in multi-component plasma.

For a plasma in a magnetic field, it is sometimes possible to define two temperatures for the particles of a given species, associated with the parallel and perpendicular degrees of freedom with respect to the magnetic field. This is due to the anisotropic velocity distributions. Even in field free plasma the presence of directional features, e.g. particle streaming, two dimensional shock structures, unusual plasma production methods etc. may provide a plasma state with an enhanced temperature in some direction. The dynamics of the ions play a more important part than that of the electrons. For an acoustic like mode hotter ions produce restoring electrostatic force proportional to their temperature and the colder ions provide inertia for its propagation. Moreover, this mode propagates when the hotter ions form majority otherwise the phase velocity of this new mode becomes of the order of thermal velocity of the hotter ions and Landau damping can be expected to be dominant so as to damp the mode.

At an altitude of 1400 Km. in the plasmasphere, proton is the dominant ion species, with 2-5% of helium and oxygen ions (Hoffman et al 1974). These ions are in the 1-12KeV energy range, whereas the electron energy is of the order of 100eV. In the ring current around 7Re, O^{++} and He^{+} form less than 10% and He^{2+} forms less than 3% of the total ion population, H^{+} being the bulk ion component (Johnson 1979). These ions and elec-
trons have energies of the order of 40 KeV and 1-4 KeV respectively. In the 2 x IIB mirror machine, the deuteron ions together with 2-5% of impurities like proton and carbon are at energies around 14 KeV, while the electron energy is of the order of 100 eV (Coensgen et al 1976).

Magnetic mirror, laser plasmas, magnetosphere, solar wind and strongly interacting beam-plasma system are good examples for the existence of two-electron temperature plasmas. RF heating of magnetically confined plasmas (e.g. in magnetic mirrors), in the range of electron-cyclotron frequency is at present the primary technique of creating a hot electron population, which forms the thermal barrier in magnetic mirror.

The distribution of electrons heated by resonant absorption of intense laser light can be approximated well by two Maxwellian velocity distribution, which can be represented as the superposition of a hot Maxwellian velocity distribution with a colder Maxwellian velocity distribution and is well characterized by two electron temperature. A typical example of charged particles with anisotropic temperature is electrons and protons trapped in the radiation belt or the van Allen belt of the magnetosphere, whereas a typical example of charged particles with non-Maxwellian energy spectrum is auroral electrons which excite auroral curtains or arcs in the polar region.
Various authors (Ashour-Abdalla 1975; Gary & Tokar 1985; Guest & Miller 1988; Drake et al 1989) used two-electron temperature model to explain magnetospheric electrostatic emissions, laser-plasma interactions and electron rings in EBT devices, etc. Plasmas having electrons with two distinct velocity distribution are common in the solar wind near 1 AU (Fledman et al 1975). The hot 'halo' component having electrons with energies above 50 to 100 ev threshold, is mildly anisotropic and the cool 'core' component are nearly isotropic.

Strongly interacting beam-plasmas can also result in such electron distributions. In this thesis study of some linear as well as nonlinear instabilities have been made in a multi-species plasma. Threshold fields in such a plasma can be lower than in a single species plasma. Effect of second charged particle species is discussed.

1.4 Studies made in this thesis

In the present thesis problems associated with the stability of large amplitude waves propagating in plasmas, such as parametric decay at the beat frequency of two pump modes, stimulated Brillouin scattering, Oscillating two-stream instability, filamentation instability and parametric excitation at the electrostatic mode conversion layer have been investigated for extensive range of parameters of the magnetosphere, ionosphere and fusion plasmas. Hydrodynamical model of the plasma
is used and multi-species plasma system has been considered everywhere. Plasmas can be non-uniform in various waves, but not all cases lead to instability. In many cases an instability is generated by the combined effect of a non-uniformity and the existence of a current or a plasma flow. We have incorporated the problem describing current driven instability of an acoustic-like mode in a magnetized two-ion species plasma.

Chapter-2 deals with the problem of parametric decay of a whistler wave at the difference frequency of two electromagnetic waves in plasma. It is shown to decay parametrically into a lower-hybrid wave (LHW) and a low-frequency ion-Bernstein wave (IBW) in a collisionless, magnetized multi-ion species plasma. A nonlinear dispersion relation describing this parametric interaction process is derived. The low-frequency ponderomotive force along the direction of the external magnetic field leads to the dominant coupling. This decay instability is expected to play an important role in the saturation of the parametrically excited whistlers at the beat frequencies of pumps. For the typical ionospheric plasma parameters the growth rate is calculated numerically. It is found that the growth rate can be controlled by varying density ratio \( n_{OA}/n_{OB} \) and magnetic field \( B_0 \). The wave is thus expected to modify the dynamics of space plasmas and the observed ion-heating may be explained by the ion-Bernstein wave excitation.
Chapter-3 is divided into two parts. First part contains the problem of stimulated Brillouin scattering (SBS) in multi-ion species plasma. Using a hydrodynamical model, analytical investigation of the SBS of an electromagnetic wave by an acoustic-like mode has been done. The non-linear dispersion relation and the growth rate of the excited mode is derived. The non-linearity arises through the motion of ions which is introduced through ponderomotive force. We have seen that for any finite pump wave intensity, the instability grows. Increasing the charge multiplicity ratio ($Z_h/Z_c$) of ions the growth rate of the instability decreases and may thus lead to stabilization of the system.

Part-B discussed a current driven instability of acoustic-like mode in an inhomogeneous two-ion species magnetoplasma, with density gradients perpendicular to the magnetic field and the direction of wave propagation. The growth rate is found to depend on several parameters of two-ion species. This instability is assumed to be responsible for the heating of ions in near-earth space plasmas.

In chapter-4 it is shown that in a two-electron temperature plasma, a left-handed circularly polarized (LHCP) electromagnetic wave and an electrostatic electron-acoustic wave can grow at the electrostatic upper-hybrid mode conversion layer. The electromagnetic oscillating two-stream instability is also discussed in the same system for a positive group
dispersive upper-hybrid wave. The growth rates are found to be greater than the single electron plasma system. The addition of hot electrons will reduce the parametric decay and lead to saturation mechanism. These processes are found to be helpful in experiments on electron cyclotron heating of plasma confined in magnetic mirrors.

An analytical investigation of filamentation instability has been done in chapter-5. It is shown that slightly above the local lower-hybrid wave frequency, a filamentation instability can be obtained in a two-electron temperature plasma system due to the presence of electron-acoustic density perturbation. Hydrodynamical model of the plasma is used. Nonlinear coupling relation and growth rate is obtained. The role of second electron component is discussed with application in laboratory plasma.

Beam driven instability has been studied in chapter-6. An electrostatic instability for the cross field ion-ion hybrid mode excited by an energetic ion beam injected across the magnetic field in a collisionless homogeneous plasma is studied. Dispersion relation and growth rate for the wave propagating in such a system is derived. Unstable wave exist with maximum growth rate around \( \omega_0 \approx k_x v_{ob} \pm \omega_{cb} \), where \( \omega_{cb} \) is the cyclotron frequency of beam ions. Propagation characteristic of ion-ion-hybrid wave shows that an increase in the number density and a decrease in the mass of second ion species increases the wave frequency. Application of this process in
fusion plasma are discussed in connection with the important problem of the plasma stability during the injection of fast atomic beams into tokamks.

The work presented in this thesis has resulted in the following publications:

(01) "Parametric decay of a whistler wave at the difference frequency of two electromagnetic waves in a plasma"
By S. Guha and Ruby Sarkar

(02) "Stimulated Brillouin Scattering of an electromagnetic wave by an acoustic-like mode in multi-ion species plasma"
By S. Guha and Ruby Sarkar

(03) "Generation of electromagnetic wave in two-electron temperature plasmas"
By S. Guha and Ruby Sarkar

(04) "Modulational and Filamentation instabilities in ELMO-bumpy torus"
By S. Guha, Ruby Sarkar and M. Asthana
(05) "Excitation of ion-ion hybrid mode by beam-plasma interaction"

By S. Guha and Ruby Sarkar


(06) "Filamentation instability near the lower-hybrid wave frequency in a two-electron temperature magnetoplasma".

By Ruby Sarkar and K.P. Maheshwari


(07) "Current driven instability of an Acoustic-like mode in a magnetized two-ion plasma".

By S. Guha and Ruby Sarkar

REFERENCES


