CHAPTER VI

CONCLUSIONS AND DISCUSSIONS

The main purpose of the present work has been to carry out a study of the low frequency wave particle interactions and their possible consequences. Since the resonant interactions are the strongest wave particle interactions, and there too, the gyro-resonance and the Landau resonance are much more important than any other resonances, we restrict our attention to these two types of interactions only. Our approach to this study consists in first finding how the waves affect or modify the plasma particle distribution function and then seeing how this modified distribution affects the low amplitude perturbations existing in the system.

During the course of this study; special emphasis has been placed upon whether a particular type of interaction studied has some relevance with the generation mechanism of the VLF emissions or with their preferential triggering at half the equatorial electron gyrofrequency.

The study of these interactions has been made from different angles, e.g. the effect of two types of resonances, considered independently, the combined effect of both the resonances and the effect of one type of resonance over the other and each time, attempts have been made to critically examine whether a particular type of interaction is likely to contribute to the generation of very low frequency emissions, and if so, whether it favours emissions at some particular frequency or not.

6.1 A BRIEF SURVEY (SYNOPTIC VIEW) OF THE WORK DONE:

We start with the consideration of the Landau resonance of off angle whistler mode pulses propagating in a predominantly cold collisionless plasma having a high energy tail in the distribution. We find that $V_\perp$ of the particles is not affected considerably whereas the $V_\parallel$ of these particles is altered in such a way that the changes in $V_{\parallel}$ when plotted against the initial $V_{\parallel}$ exhibit some sort of quasiperiodicity along the $V_{\parallel}$ axis. The consequent evolution of the distribution function $f(v_{\parallel})$ is calculated and, as expected, it is found that the distribution develops a fine structure close to the central resonant velocity of the pulse. The time period for which the changes in $V_{\parallel}$ and the evolution of f have been calculated is small compared to the quasilinear relaxation time of the system. Therefore, the interaction does not lead to the formation of a ledge in the resonant range of the velocity space.

The fine structure developed by f contains alternate negative and positive gradients of f with $V_{\parallel}$. A pulse with a suitable frequency propagating through this modified distribution of particles will undergo growth at the frequencies in its side bands that resonate with the particles lying in the regions of positive gradients in the distribution function.

The results obtained from this study can be applied to the equatorial magnetosphere where the static magnetic field can be crudely considered as uniform and where the particle distribution has a high energy tail because of the high energy particles trapped in the radiation belts.

The time period over which our model calculations have been extended ~~are~~ is of the same order as the periods for which the waves and particles remain in the equatorial region while moving along a field line. If the distribution function gets modified by an initial off angle whistler mode pulse, it is easy to see that another pulse propagating in the same mode will be affected in such a way that its central frequencies get damped whereas its sidebands start growing.

Herein we have not included the effect of the nonequatorial regions of the earth's magnetic field and that of the nonuniformity of the field close to the equatorial magnetosphere. Therefore, it can not be assesed as to how much would be the contribution of this mechanism to VLF emissions, but, it seems that the mechanism might play an important role during the onset of these emissions.

The period during which the wavepacket traverses the equatorial region is the time which is the most significant period for the interaction and is much shorter than the quasilinear relaxation time of the system. Therefore, the process of ledge formation does not come into picture here.

Next, we consider the effect of the gyroresonance of a large amplitude whistler mode pulse. The interaction leads to the diffusion of resonant particles into the velocity space and to the consequent formation of a fine structure in the distribution which is smeared out after the wave packet has passed through. This smeared out distribution is unstable such that the perturbations at frequencies slightly higher and slightly lower than the central frequency of the wave packet grow whereas those close to the central frequency are damped. Similar results were earlier discovered by Das (1968) for interactions of plasma with low amplitude VLF pulses. The present work, however, brings out the following additional important, but subtle features associated with the interaction: As we increase the amplitude $\vec{E}(\omega)$ of the pulse and decrease its band width such that $\int |E(\omega)|^2 d\omega$ remains constant, then at a certain critical amplitude the growth rate γ suddenly increases almost by a factor of three above the background probably because of the sudden appearance of two regions in velocity space contributing to the growth at the same frequency. The value of the critical amplitude depends upon the loss cone angle and on the value of $\int |E(\omega)|^2 d\omega$. As long as we keep $\int |E(\omega)|^2 d\omega$ constant, an increase in the amplitude $\vec{E}(\omega)$ of the pulse means a decrease in its band width. Also, the inverse Fourier transform of the frequency spectrum of a pulse shows that a decrease in the band width of a pulse is equivalent to an increase in its duration T. This indicates that long duration pulses have large amplitude at their central frequency ω_f $\int |E(\omega)|^2 d\omega = \text{Const}$. Thus if the duration of a pulse is increased beyond a certain critical limit the growth rate suddenly increases to a rather high value. This type of interaction may account for the observational fact that the VLF emissions are frequently triggered by Morse Code dashes having a duration of 150 msec. and are rarely triggered by Morese Code dots having only a 50 msec. duration. It is evident that a short duration (large band width) pulse has to be more powerful in order to attain the critical amplitude. This indicates, that, provided they they are strong enough, dots are also capable of triggering VLF emissions.

Another important feature discovered during the course of the present work is that secondary peaks protrude in the growth rate curves on either side of the central resonant frequency. They are more prominent if the pulses under consideration have large amplitude as well as the large band width. This suggests that a strong whistler mode wave packet with a short duration is capable of producing observed multiple emissions.

After studying the effects of the Landau resonance and the gyroresonance separately we attempt to study the simultaneous effect of the two resonances on the particle distribution caused by a succession of whistler mode pulses. Ashour Abdalla has already shown that the gyroresonance of these pulses leads to the formation of a slot in the velocity distribution of the particles in presence of a loss cone. Here, through a parallel model for the Landau resonance interaction, we come to a similar conclusion that the Landau resonance would also cause the formation of a similar slot in the velocity distribution under similar conditions. However, the Landau resonant slot is weak because of the inherent weakness of the effects of the Landau resonance of whistlers as compared to that of their gyroresonance.

The weakness of the Landau resonance slot would not have allowed preferential growth at a frequency $\omega = \frac{1}{2}\Omega_{eq}$ for which both the Landau resonant speed and the gyroresonant speed of the particles are same but for the additional feature of the whistler mode propagation that comes into picture at this frequency. The group velocity of a whistler mode pulse is roughly equal to the phase velocity of the central wave of the pulse at $\omega = \frac{1}{2}\Omega$ for small angles of propagation. In this case the Landau resonance becomes quite strong as all the waves inside the wave packet simultaneously resonate with the same set of particles and thus give a highly pronounced effect. This leads to the formation of a strong Landau resonant slot. It turns out that, for $\omega = \frac{1}{2}\Omega$, both the Landau resonant and the gyroresonant slots are strong and at the same time they occur at the same $|v_{\parallel}|$. Therefore, the two slots overlap each other and form a much deeper slot capable of giving preferential triggering to VLF emissions at the corresponding frequency $\omega = \frac{1}{2}\Omega$.

Next we study how the particle distribution distorted by Landau resonance will affect the gyroresonant growth rate of the perturbations. The distribution f with respect to $V_{\perp}$ is not affected much by Landau resonance but with respect to $V_{\parallel}$, it gets distorted and develops a ledge over the range of resonant velocities. The gradient $\partial f/\partial v_{\parallel}$ at the boundaries of the ledge will assume highly negative values whereas in the central part of the ledge it will approach to zero. The highly negative values of $\partial f/\partial v_{\parallel}$ would impart growth to perturbations moving in a direction opposite to that of the Landau resonant waves and at the same time undergoing gyroresonanc with the particles whose representative points in velocity space lie at the edges of the ledge.

The whole study has been done under the assumption that the growth of the gyroresonant perturbations has not reached the level beyond which they will react back on the distribution of particles.

The expression for growth rate contains two terms. One contributes to the growth and the other to the damping of the waves. If ω is not negligible compared to Ω, the damping term dominates over the growth term in the beginning. However, with time the growth term increases and in due course exceeds the damping term, thus leading to the amplification of the waves. Because of this, there is a finite time lag between the onset of the resonant interaction and the starting of the growth of the waves.

This type of interaction is also capable of contributing to the preferential generation of VLF emissions at $\omega = \frac{1}{2}\Omega_{eq}$. This is because of the association of a special feature of the whistler mode dispersion relation with this frequency. The Landau resonant $V_{\parallel}$ has a maximum value at

$\omega = \frac{1}{2}\Omega$ and this divides the whole distribution into two regions: one, the disturbed region and the other undisturbed. A particle in the undisturbed region can not have Landau resonance with any whistler mode wave having whatever frequency. If a broad spectrum of whistlers is assumed to exist in the system, a ledge is likely to form over the entire disturbed region and a sharp negative gradient would be formed at the boundary of the two regions which corresponds to the gyroresonant frequency $\omega = \frac{1}{2}\Omega$. Therefore, the perturbation at this frequency will be naturally favoured for growth. This model for the VLF emissions also accounts for (or predicts) ~~as~~ initial time delay before the waves start growing.

6.2 CONCLUSIONS:

The different types of wave particle interactions that we have studied so far distort the distribution in such a way that it supports building up of waves at certain frequencies whereas it leads to the dissipation of waves at other frequencies. The sufficiently grown waves are likely to appear as emissions but at this stage it seems as if no mechanism is uniquely responsible for these emissions. On the contrary, it looks that several mechanisms contribute to these emissions. The Landau resonant and the gyroresonant, both types of interactions play significant roles in the generation of these emissions. As far as simple emissions are concerned, the gyroresonance plays a more important role than the Landau resonance in the emission mechanism which is obvious from the fact that the gyroresonance interaction is stronger than the Landau resonant interaction. However, the preference in emissions observed at the frequency $\omega = \frac{1}{2}\Omega$ is because of the reinforcement of the gyroresonant effects by the Landau resonant effects that occur especially at $\omega = \frac{1}{2}\Omega$ and not at any other value of ω, as we have seen in chapter IV and V. Thus VLF pulse at any frequency is capable of generating an emission but if it happens to be centred close to $\omega = \frac{1}{2}\Omega_{eq}$, its chances of stimulating the emissions increase highly, firstly because the Landau resonance of the background whistler mode noise makes the distribution unstable for perturbations close to this frequency and secondly because **a** pulse centred at this frequency undergoes the group Landau resonance with the particles which is much stronger than the ordinary Landau resonance occuring for pulses centred at other frequencies.

If the mechanism discussed in chapter III is operative in the system, it is evident that the long duration pulses such as Morse Code dashes stand much better chances to stimulate VLF emissions compared to small duration pulses like the Morse Code dots. This is in agreement with the observations.

In the last chapter, while discussing the preferential generation of $\frac{1}{2}\Omega_{eq}$ emissions because of the gyroresonant growth of a perturbation caused by the quasilinear Landau resonant relaxation of the distribution we find that the growth starts only after a certain time lag. The emissions observed also show that there is a difference in the time of observation of the triggering pulse and the triggered pulse. Almost all types of interactions discussed show that the onset frequency is different from the frequency of the triggering pulse. This is also the case with the observations. However, none of the interactions discussed above throws any light over the observed variation of the frequency of an emission with time. The theory needs a little modification in this respect.

6.3 SUGGESTED EXPERIMENTS; and SCOPE FOR FURTHERNWORK:

Although this work discusses some aspects of the various types of low frequency wave particle interactions and their possible contribution to the stimulation of VLF emissions, a rigorous mathematical treatment of the whole subject is desirable. While considering the slot development due to both the Landau and the gyroresonances, we have considered the effects of the two resonances separately and then superimposed the effect of one over the other to simplify the situation. An exact treatment of the whole problem in which the two effects are considered to be taking place side by side is also desirable.

A mathematical study applicable to the real physical situations regarding the effectiveness of the group Landau resonance over the ordinary Landau resonance and experimental verification thereof would be quite useful to assess how much contribution to the VLF emissions at $\omega = \frac{1}{2}\Omega_{eq}$ comes from this mechanism.

A study may be carried out as to how the Landau resonant growth rate for an electrostatic first order perturbation would behave in a system containing a spectrum of zero order whistler mode waves tending to make the pitch angle distribution of the system isotropic.

A comparative study of different Planetary Magnetospheres should also be carried out to get a general and broader understanding of the features common to all these magnetospheres. A study of VLF emissions from different planetary atmospheres using artificial satellites which penetrate the atmospheres of such planets may be carried out. It will give a better understanding of the whole phenomenon of whistlers and VLF emissions.

Finally, this type of wave particle interactions may be studied in the laboratory. The controlled laboratory conditions will allow us to change the various parameters of the system and study the phenomena occuring there for all possible aspects. This would give us a much better insight into the magnetospheric Physics in general, and into the phenomenon of VLF emissions, in particular.