Chapter 2

Evolution of nonlinear ion-acoustic solitary wave propagation in rotating plasma[1]

2.1 Introduction:

Over the last several decades, the study of nonlinear wave in various configurations of laboratory and space plasmas has received a tremendous boost in plasma dynamics. Washimi and Taniuti (1966) were probably the pioneers who, by the use of reductive perturbation technique, derived the well known nonlinear wave equation known as Korteweg-deVries (K-dV) equation for the study of soliton dynamics in plasmas. This equation has been found to be inadequate for the study of arbitrary amplitude solitary waves even though it could describe solitons quite effectively in plasmas as well as in other branches of physics. In the same decade, Sagdeev (1966) investigated the features of arbitrary amplitude nonlinear wave in plasma consisting of

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[1]This chapter is based on the paper published in Physics of Plasmas **13**, 082303 (2006).

isothermal electrons under the assumption $T_e >> T_i$, (where T_e and T_i are respectively the temperatures of electrons and ions) and cold ions. Both the nonlinear wave equations have set up a unique platform for the study of the soliton dynamics since the concept evolved in plasmas. These equations have been used to yield the solitons in plasma which, later on, showed a good agreement between theory and experiments (Ikezi *et al.*, 1970; Ikezi, 1973) as well as with the satellite observations in space (Gurnett, 1995; Wu *et al.*, 1996). In fact, interplanetary space and the Earth's magnetosphere encompass a rich variety of nonlinear plasma waves (Vok, 1975) that are confined to the compressive solitons with positive potential and density hump and does not support rarefactive solitons with density dip.

The formation of soliton in plasma-acoustic mode, analogous to what was first observed by Russell (1838) in water wave, has been due to the interaction of nonlinear effect with weak dispersive effect. Subsequently, many authors have studied the existences of solitons in various plasma models and were able to make good agreement between the theory and experimental findings and it also shows better compatibility with the scientific satellite observations in space. Initially, the investigations were made in simplified plasma model, while later on, the studies were extended to space, and that too, with the concept of multicomponent plasmas. Many authors (Su and Gardner, 1969; Lonngren, 1983; Torven, 1986; Raadu, 1989; Verheest, 1996) reviewed the observations to give comprehensive and informative observations about the different nature of solitons. Its yielding in multicomponent plasma with positive ionic species does not ensure any pioneer investigation; rather the result exhibits the schematic variations (Tran and Hirt, 1974). However, plasma, in presence of additional negative ions (Das, 1975;

Das, 1976) and multi-temperature electrons, yields new milestone in soliton dynamics and the observations were confirmed later in experiments as well as in space. The overall study on K-dV solitons in plasma depends on the nature of nonlinearity and dispersive effects. After Das (1975, 1976), nonlinear solitary wave has been furthered in exhibiting the compressive and rarefactive solitons (Das and Uberoi, 1972; Das *et al.*, 1997) Both the natures are found in space (Wu *et al.*, 1996) and laboratory plasmas (Watanabe, 1984; Aossey et *al.*, 1993) and it was concluded that plasma contaminated with an additional negative charge could exhibit such type of solitons. But fewer observations have been made about the role of dispersive effect showing the compressive and rarefactive solitons. Actual argument lies on the fact that the K-dV equation derived in fully ionized plasma does not ensure the variation of dispersive effect and thus could not sustain such behaviour in solitary waves. But the magnetized plasma shows the occurrences of compressive and rarefactive solitons (Kakutani *et al.*, 1968; Kawahara, 1972) which arises due to the dispersive effects caused by the embedded magnetic field.

From earlier knowledge (Chandrasekhar, 1953; Lehnert, 1954; Hide, 1966) it has been well pointed out that the force generated from rotation, however small in magnitude, has an effective dominant role in plasmas as well as in cosmic phenomena. Interest has then widened too in the theoretical and experimental investigations on rotating plasmas because of its great importance in problems encountered in rotating plasma devices in laboratory as well as in space plasmas. Further, it was shown that the Coriolis force has a tendency to produce an equivalent magnetic field effect as and when the ionized medium rotates (Uberoi and Das, 1970). As a result of this, the soliton propagation derived from the acoustic mode in plasma might be expected to give new features.

To investigate the interaction of small rotation in plasmas with a view to relating its existence in space and in atmosphere, plasma rotating with a uniform angular velocity about an axis making an angle θ with the direction of plasma-acoustic wave propagation has been considered. This attempt has been made in this chapter with the expectation of new findings based on its unique observation in linear wave (Uberoi and Das, 1970). Theoretical development expects a critical angle of rotation at which the dispersive effect vanishes and consequently soliton structure shows different nature in exhibiting the compressive and rarefactive soliton propagation. In order to study the evolution and propagation of soliton, a different approach has been employed. Further, in contrast to the steady state method, a new mathematical approach known as $\sec h$-method (or $\tan h$-method) has been used in obtaining the features of soliton propagation.

2.2 Basic Equations and Derivation of Nonlinear Wave Equation:

To study the solitary wave propagation, a plasma consisting of isothermal electrons (under the assumption $T_e >> T_i$) and singly charged positive cold ions has been considered. Here it is assumed that the plasma is rotating with a uniform angular velocity $\bar{\Omega}$ around an axis in xz-plane, making an angle θ with the direction of wave propagation along x-direction. The basic equations governing the plasma dynamics are the equations of continuity and motion. Other forces might have effective role in the dynamics but they have been neglected because of the aim of knowing the effect of Coriolis force in isolation. The basic equations, with respect to a rotating frame of reference (Uberoi and Das, 1970), can be written as:

$$\frac{\partial n_\alpha}{\partial t}+\vec{\nabla}.(n_\alpha \vec{v}_\alpha)=0 \tag{2.1}$$

$$\frac{\partial \vec{v}_\alpha}{\partial t}+(\vec{v}_\alpha.\vec{\nabla})\vec{v}_\alpha=\frac{q_\alpha}{m_\alpha}\vec{E}+\frac{q_\alpha}{cm_\alpha}(\vec{v}_\alpha \times \vec{\bar{H}}) \tag{2.2}$$

where the subscript $\alpha = i,e$ stands respectively for ions and electrons and $\vec{\bar{H}} = \vec{H} + 2\vec{\Omega}\left(\frac{cm_\alpha}{q_\alpha}\right) = \vec{H} + \vec{\bar{\bar{H}}}$ is the equivalent magnetic field as the combination of an applied uniform magnetic field and the generation of equivalent magnetic field $\vec{\bar{\bar{H}}}$ by the rotation. In the presence of Coriolis force, with respect to rotating frames of reference, the ions as well as electrons 'see' different equivalent magnetic field as $\vec{H} + 2\vec{\Omega}\left(\frac{cm_\alpha}{q_\alpha}\right)$. m_α is the mass of the α - charge moving with the velocity v_α and having density n_α and charge q_α. $\vec{E}$ is the electric field following the Maxwell equation $\vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$ but based on the assumption $\vec{\nabla}\times\vec{E}=0$, it follows $\vec{E} = -\vec{\nabla}\phi$; ϕ being the electrostatic potential field.

The isothermal electrons have been taken with an assumption that the phase velocity of the electrons is much smaller than electron thermal velocity, due to which, the isothermality of the plasma is expressed through electron density in the form of a Boltzmann relation as:

$$n_e = \exp(\Phi) \tag{2.3}$$

where n_e is the electron density normalized by n_0.

The density at equilibrium position derives charge neutrality condition, as $n_{i0} = n_{e0} = n_0$ and $\Phi = \frac{e\phi}{KT_e}$ is the normalized electrostatic potential. Further, the rotation taken is of small order, which allows the incorporation of the effect of Coriolis force in the dynamical system. Here the unidirectional propagation along x-direction has been considered. Thus the basic equations for the ions, under the fluid description, are written in the following normalized form as:

$$\frac{\partial}{\partial t}n + \frac{\partial}{\partial x}(nv_x) = 0 \tag{2.4}$$

$$\frac{\partial}{\partial t}v_x + v_x\frac{\partial}{\partial x}v_x = -\frac{\partial}{\partial x}\phi + \eta v_y \sin\theta \tag{2.5}$$

$$\frac{\partial}{\partial t}v_y + v_x\frac{\partial}{\partial x}v_y = \eta v_z \cos\theta - \eta v_x \sin\theta \tag{2.6}$$

$$\frac{\partial}{\partial t}v_z + v_x\frac{\partial}{\partial x}v_z = -\eta v_y \cos\theta \tag{2.7}$$

Here $\eta = 2\Omega$, and ϕ is linked to the mobility of the charges through Poisson equation as:

$$\frac{\lambda^2_D}{\rho^2}\frac{\partial^2}{\partial x^2}\phi = n_e - n \qquad (2.8)$$

where $\lambda_D = \sqrt{\left(\frac{KT_e}{4\pi e^2 n}\right)}$ is the Debye length, n is the number density of ions normalized by n_0. The velocity v has been normalized by the ion acoustic speed $c_s = \sqrt{\left(\frac{KT_e}{m_i}\right)}$. The space x and time t are respectively normalized by $\rho = \frac{c_s}{\omega_{ci}}$ and $(\omega_{ci})^{-1}$, where $\omega_{ci} = \frac{eH}{cm_i}$ is the ion-gyrofrequency.

In order to derive the desired nonlinear wave equation, the dependent variables are made to vary functionally on a variable $\xi = \beta(x - Mt)$, where M defines the Mach number and β^{-1} is the width of wave propagation. By employing the transformation, the basic Eqs.(2.4-2.8) have been reduced to the following set of ordinary differential equations. Because of the parallel effect of magnetic field along with equivalent magnetic field, the applied magnetic field has been neglected with a view to studying the nonlinear wave under the effect of Coriolis force in isolation.

$$-M\frac{d}{d\xi}n + \frac{d}{d\xi}(nv_x) = 0 \qquad (2.9)$$

$$-\beta M\frac{d}{d\xi}v_x + \beta v_x\frac{d}{d\xi}v_x = -\beta\frac{d}{d\xi}\phi + \eta v_y \sin\theta \qquad (2.10)$$

$$-\beta M \frac{d}{d\xi} v_y + \beta v_x \frac{d}{d\xi} v_y = \eta v_z \cos\theta - \eta v_x \sin\theta \tag{2.11}$$

$$-\beta M \frac{d}{d\xi} v_z + \beta v_x \frac{d}{d\xi} v_z = -\eta v_y \cos\theta \tag{2.12}$$

$$\beta^2 \frac{\lambda_D{}^2}{\rho^2} \frac{d^2}{d\xi^2} \phi = n_e - n \tag{2.13}$$

Now all the equations are integrated once along with the use of appropriate boundary conditions at $|\xi| \to \infty$, viz.

(i) $v_\alpha \to 0 (\alpha = x, y, z)$

(ii) $\phi \to 0$

(iii) $\frac{d}{d\xi}\phi \to 0$

(iv) $n \to 1$

Eq.(2.9) evaluates v_x as:

$$v_x = M\left(1-\frac{1}{n}\right) \tag{2.14}$$

Again, the use of v_x in Eqs. (2.10) and (2.11) derives the following equations:

$$v_y = \frac{\beta}{\eta\sin\theta}\left(1-\frac{M^2}{n^3}\frac{dn}{d\phi}\right)\frac{d}{d\xi}\phi \tag{2.15}$$

$$\frac{d}{d\xi}v_y = \frac{\eta(n-1)\sin\theta}{\beta} - \frac{\eta n v_z\cos\theta}{\beta M} \tag{2.16}$$

Similarly Eq. (2.12), after using Eq. (2.14) and (2.15), yields:

$$v_z = M\cot\theta\left(\frac{1}{n}-1\right)+\frac{\cot\theta}{M}\int_0^{\phi} n\,d\phi \tag{2.17}$$

Now, putting Eqs. (2.15) and (2.17) into Eq. (2.16), the desired modified Sagdeev potential equation has been derived in integral form as:

$$\beta^2\frac{d}{d\xi}\left(A\frac{d}{d\xi}\phi\right) = \eta^2(n-1) - \frac{\eta^2 n\cos^2\theta}{M^2}\int_0^{\phi} n\,d\phi \equiv -\frac{d}{d\phi}V \tag{2.18}$$

where V is defined as a classical Sagdeev potential, and the value of A evaluates as:

$$A = 1 - \frac{M^2}{n^3}\frac{dn}{d\phi} \tag{2.19}$$

Because of 'A' appearing under a differential operator $\frac{d}{d\xi}$, the standard form, as in the case of simple plasma as:

$$\frac{1}{2}\left(\frac{d\phi}{d\xi}\right)^2 + V(\phi, M) = 0 \tag{2.20}$$

cannot be derived here.

Equation (2.18) is the key nonlinear wave equation for acoustic mode and 'A' plays the main role in finding the soliton solution with new features. Generally this type of equation cannot be solved analytically completely. The variation of $V(\phi, M)$ could only give the information on the nature of soliton. However, in the present study, the right hand side expression cannot be formed explicitly as $V(\phi, M)$. Thus the potential variation, in rotating plasma, has the complexity because of 'A'. In order to obtain the nature of wave solution, Eq. (2.18) needs to modify further as:

$$\frac{1}{2}\frac{d}{d\phi}\left[\beta A \frac{d\phi}{d\xi}\right]^2 = A\left[1 - n - \frac{n\cos^2\theta}{M^2}\int_0^\phi n\,d\phi\right] \equiv -\frac{d}{d\phi}V \tag{2.21}$$

Now integration of Eq. (2.21) derives:

$$\beta^2 A^2 P = \phi - F(\phi) - \frac{BF^2(\phi)}{2} + M^2\left[\frac{1 - BF(\phi)}{F'(\phi)} - \frac{1}{2F(\phi)^2} - B\phi - \frac{1}{2}\right] \quad (2.22)$$

where the following expressions have been used $P = \left(\frac{d\phi}{d\xi}\right)^2$, $B = \frac{\cos^2\theta}{M^2}$ and

$F(\phi) = \int n d\phi$.

From the system of equations, P can be evaluated from Eq. (2.22) which leads to a nonlinear equation in F. But the analytical solution of the modified nonlinear equation would be difficult to obtain. Nevertheless, one can expand $F(\phi)$ in a power series in ϕ along with the similar expansion in P. This process is tedious and lengthy, and thus, an approximation has been made to the expression 'A', with a view to simplifying the algebraic analysis to derive the pseudopotential. Now, the small amplitude wave approximation along with the quasineutrality condition of plasma has been used. Again, the assumption that the electron Debye length is much smaller than the ion-gyroradius, enables the determination of the ion density from the relation:

$$n = n_e = \exp(\phi) \quad (2.23)$$

Under the broad assumption $\phi << 1$ for small amplitude nonlinear wave, Eq. (2.18) derives as:

$$\beta^2 A \frac{d^2}{d\xi^2}\phi = A_1\phi + A_2\phi^2 \quad (2.24)$$

where the co-efficients are

$$A_1 = 4\Omega^2\left(1-\frac{\cos^2\theta}{M^2}\right) \tag{2.25}$$

$$A_2 = 2\Omega^2\left(1-\frac{3\cos^2\theta}{M^2}\right) \tag{2.26}$$

and correspondingly, expression 'A' has been reduced to the following form:

$$A = 1-\frac{M^2}{n^3}\frac{dn}{d\phi} = 1-M^2\exp(-2\phi) = 1-M^2 \tag{2.27}$$

retaining the terms free from ϕ (Goswami and Bujarbarua, 1986; Das *et al.*, 2001). Simplification has been made based on the consideration of lowest order effect of 'A', and that too, has been done for the mathematical simplicity. However, consideration of $A = f(\phi)$ leads to complexity too (Das *et al.*, 2001; Baishya and Das, 2003). To avoid the mathematical complexity, 'A' has been approximated as the former expression. Further it is worth mentioning here that one can easily find the observation by taking the exact expression for 'A' and by transforming the nonlinear wave equation to a couple of differential equations which can be augmented to be solved by numerical procedure (Baishya and Das, 2003). However, the result does not get altered; rather it gives a schematic variation without affecting the scenario caused by the interaction of the Coriolis force in the dynamics. The above set of modified equations play the major role in the study of the small amplitude nonlinear wave in rotating plasma.

2.3 Derivation of soliton solution:

Inability of deriving the exact form of Sagdeev Potential equation leads to do some mathematical simplification into Eq. (2.24) to derive a solvable nonlinear wave equation for finding the features of soliton dynamics. In contrast to the steady state method, an alternate method called as $\sec h$-method has been used based on the knowledge of its soliton solution which could be in form of $\sec h(\xi)$ or any other hyperbolic function. It is true that the K-dV equation derived under the small amplitude approximation exhibits the soliton solution in the form of $\sec h(\xi)$ or $\tan h(\xi)$. For the need of present method, a transformation $\phi(\xi) = W(z)$ with $z = \sec h(\xi)$, has been introduced in Eq.(2.24), which, in fact, has wider application in complex plasma. Nevertheless, one can use some other procedure to get the nature of soliton solution in the present nonlinear wave equation. But, since the $\sec h$-method is comparatively of a wider range (Das and Sarma, 1998), it has been applied. Using this transformation, Eq. (2.24) has been reduced to a Fuchsian-like nonlinear ordinary differential equation as:

$$\beta^2 A z^2 \left(1 - z^2\right) \frac{d^2 W}{dz^2} + \beta^2 A z \left(1 - 2z^2\right) \frac{dW}{dz} - A_1 W - A_2 W^2 = 0 \qquad (2.28)$$

The regular singularity encourages the fundamental procedure of solving the hypergeometric differential equation by series solution technique and follows the most favourable straightforward technique to find the soliton solution. Now, the interest is to find the solution and thus to solve the Eq.(2.28), the Frobenius method known as the series solution method is used, and the solution for W(z) is assumed to be the form of a power series in z as:

$$W(z)=\sum_{r=0}^{\infty}a_r z^{(\rho+r)} \tag{2.29}$$

Using (2.29) into (2.28), the equation is deduced as an indicial equation in finding the coefficients a_r and ρ and is derivable in the form of the following recurrence relations:

$$\beta^2 Az^2\left(1-z^2\right)\sum_{r=0}^{\infty}(\rho+r)(\rho+r-1)a_r z^{(\rho+r-2)}+\beta^2 Az\left(1-2z^2\right)\times$$

$$\sum_{r=0}^{\infty}(\rho+r)a_r z^{(\rho+r-1)}-A_1\sum_{r=0}^{\infty}a_r z^{(\rho+r)}-A_2\left(\sum_{r=0}^{\infty}a_r z^{(\rho+r)}\right)^2=0 \tag{2.30}$$

The nature of roots from the indicial equation determines the nature of soliton solution of the differential equation and thus the modes of nonlinear wave propagation in plasma. The problem is then modified to find the values of a_r and ρ and to find it, the procedure is quite lengthy as well as tedious. To avoid such a laborious procedure, a catchy way (Das and Sarma, 1998) is adopted to find the series for W (z). The infinite series (2.29) is truncated into a finite one with (N+1) terms along with ρ=0. Then the actual number N of terms in series W (z) is determined by the leading order analysis in Eq. (2.28). Balancing the leading order of the nonlinear term with that of the linear term in the differential equation determines N = 2 and consequently the series for W(z) becomes a quadratic expression in z as:

$$W(z) = a_0 + a_1 z + a_2 z^2 \tag{2.31}$$

Series (2.31) has then been substituted into Eq. (2.28) and, with some algebra, the recurrence relation determines the following expressions:

$$-A_1 a_0 + A_2 a_0^2 = 0 \tag{2.32}$$

$$-\beta^2 A a_1 - A_1 a_1 + 2A_2 a_0 a_1 = 0 \tag{2.33}$$

$$4\beta^2 A a_2 - A_1 a_2 + A_2 a_1^2 + 2A_2 a_0 a_2 = 0 \tag{2.34}$$

$$-2\beta^2 A a_1 + 2A_2 a_1 a_2 = 0 \tag{2.35}$$

$$-6\beta^2 A a_2 + A_2 a_2^2 = 0 \tag{2.36}$$

From these recurrence relations, the coefficients are evaluated as

$a_0 = 0, a_1 = 0$, $a_2 = \dfrac{3A_1}{2A_2}$ along with $\beta = \sqrt{\dfrac{A_1}{4A}}$.

So the solution of the nonlinear wave equation finally derives as:

$$\phi(x,t) = \frac{3A_1}{2A_2}\sec h^2\left(\frac{x-Mt}{\delta}\right) \tag{2.37}$$

where

$$\delta = \sqrt{\frac{4A}{A_1}} \tag{2.38}$$

The solution represents a soliton profile in rotating plasma and shows the effective role of Coriolis force through the variation of A_1 and A_2.

2.4 Results and Discussions:

The present study describes the derivation of nonlinear wave equation in rotating plasmas. The results, obtainable by $\sec h$-method in Eq.(2.37), show a soliton profile which depends fully on the variations of A_1 and A_2 along with variation of θ and M . The Mach number, in the case of simplified plasma, could be derived from the optimal values of Sagdeev potential and it ranges from 1.1 - 1.6 (Sagdeev, 1966). But in different plasma configurations, it can have values lesser or greater than unity. Again, in the case of space plasmas, M can be even 5 and 50. Thus the variation of Mach number is restricted by the plasma configuration and, for some other complex configuration, the

Mach number could be less than one. However, without loss of generality, the Mach number greater than one has been considered for the numerical estimation.

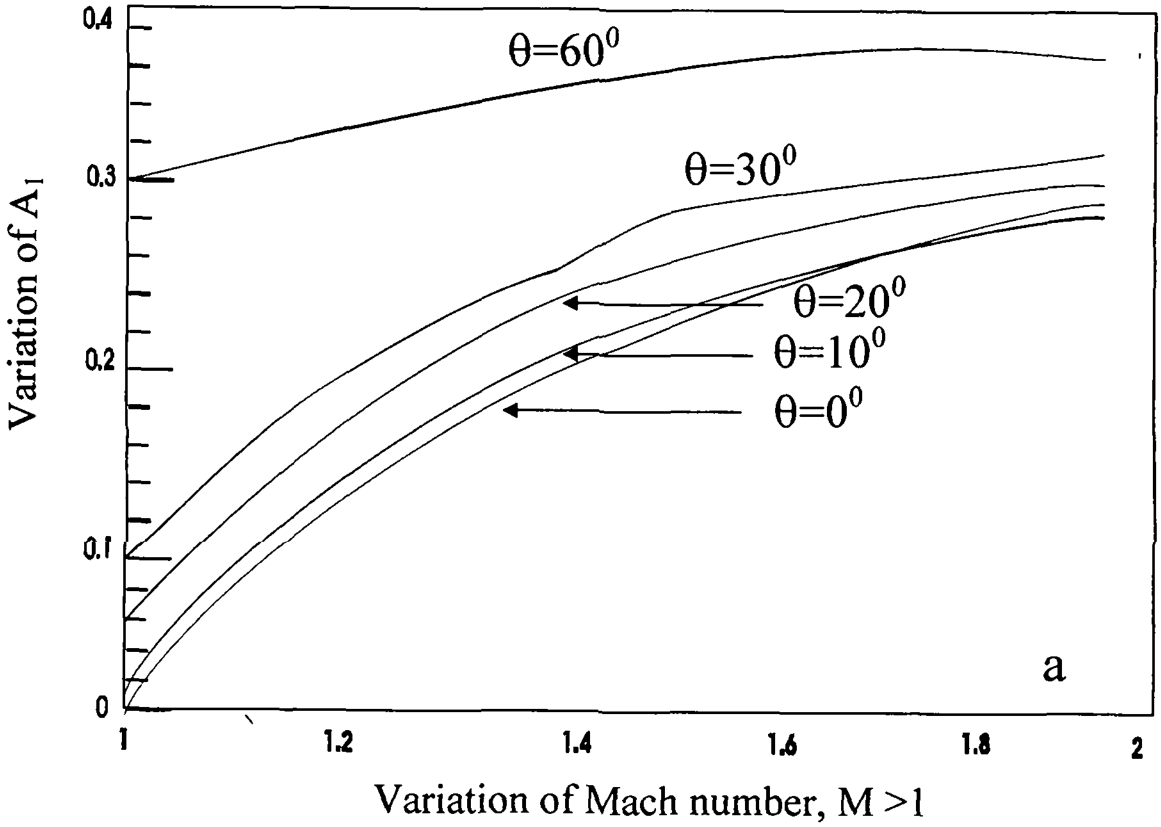
From the expressions of A_1 and A_2, it is clear that these values depend on M and θ. Thus, in Fig. 2.1, the variations of A_1 and A_2 with the Mach number M > 1 are plotted along with the variation on θ, i.e. for different magnitudes of rotation. For the typical values of plasma parameters under the consideration, A_1 is always positive while A_2 can be both positive as well as negative. The variation of A_1 and A_2 control the nature of soliton which will be of compressive nature in case of both having the same signs while it shows the rarefactive nature in the case of A_1 and A_2 having opposite signs. The point at which A_2 equals to zero bifurcates the entire region of propagation into two regions, showing the existence of compressive and rarefactive solitons. The region of rarefaction has been shown to decrease with the increase of θ reflecting the increase of region for compressive wave (Fig.2.2). Correspondingly, the width in the rarefactive region decreases with Mach number whereas it increases in the compressive region.

The case of M < 1 shows an entirely different nature of soliton propagation (Fig. 2.3). For very small and high values of Mach number, the soliton is of compressive nature. But in between, there exits a small region wherein rarefactive soliton can be observed. In the first region, both A_1 and A_2 are negative. In the second region, $A_1 > 0$, $A_2 < 0$; while in the third region (after the critical point), again $A_1 > 0$ and $A_2 > 0$. The increase of angular rotation decreases the width as seen from δ defined in Eq. (2.38) and correspondingly increases the amplitude i.e. the height of the soliton. As a whole, the Coriolis force for small rotation plays a crucial role in the formation of different nature of solitons. The functional variation on rotation and θ changes the sign of A_2 as a result of which compressive and rarefactive soliton could be observed. The positive magnitude of potential introduced in amplitude exhibits the compressive nature of soliton while the negative value of potential evaluates the region of rarefactive soliton propagation. But, at the critical point at which the variation changes, the non-existence of soliton in plasma-acoustic mode is shown. Thus the Coriolis force introduces a critical point at which A_2 disappears. Consequently, the formation of soliton will not be seen, and thus the Coriolis force shows a destabilizing effect on the formation of soliton in plasma.

In order to relate the present observations, we see, from Eq.(2.37), that as $A_2 \rightarrow 0$, the width of the solitary wave gets narrowed resulting in the amplitude being of large magnitude. Thus for maintaining the soliton nature, i.e. the relation between amplitude and width, the small magnitude of width causes a steepening of the solitary wave. Now, because of the narrow wave packet with large amplitude of solitary wave, there is a tendency for the wave to be collapsed or exploded, which is dependent on the conservation of energy within the wave profile. There is explosion of soliton at $A_2 \rightarrow 0$ when the amplitude of the plasma acoustic wave becomes infinitely large. It shows again that the possibility of explosion or collapse of soliton depends on the plasma parameters. The explosion has features similar to the collapse but actually differs by the fact that the explosion in the dynamical system does not conserve the energy and it goes parallel with the increase of amplitude. The collapse occurs as long as it maintains the property of soliton propagation and is expected as it progresses towards the critical angle θ. Near the critical angle θ, the nonlinear wave propagation exists within a narrow soliton wave packet with high electrostatic potential and thus high electric pressure. The property gives the relation of showing that the amplitude varies inversely with the width of the wave.

Thus, in the case of small width wave profile, soliton propagates with high amplitude as a result of which the solitary wave is prone to collapse leaving behind the formation of a narrow wave packet with the generation of high electric pressure. Consequently magnetic pressure as well grows in the region, and as a result, the narrow wave packet produces a depression in plasma density. Further increase in pressure leads ultimately to collapse in soliton with extremely small width lying within the wave packet. With all the inter related happenings, the soliton wave packet expects to be the source of radiation coined as soliton radiation (Karpman, 1993; Das and Sarma, 1998). The soliton, in the process, produces the radiation through the interaction of the nonlinearity in dispersive medium. Such phenomena could be analogous to the solitons and radiation in solar radio burst (Papadopoulos and Freund, 1978).

Emerging from the present observations, the rotation, however small in magnitude in plasma, has shown an effective role in exhibiting the radiative soliton even in simple plasma. Causes could not be found in simple plasma but similar observation could be expected in the case of higher order effect from the expansion of $\exp(\phi)$ or by the effect of complexity of plasma model as well as of magnetic field effect. Further it has been shown that the small rotation of plasma produces an equivalent magnetic field effect and changes the nature of soliton; causeway it exhibits the compressive and rarefactive solitons as well as radiation as similar to those in other plasma configurations as mentioned. Overall merit of the investigation lies in finding the nonlinear solitary wave solution by a modified method.



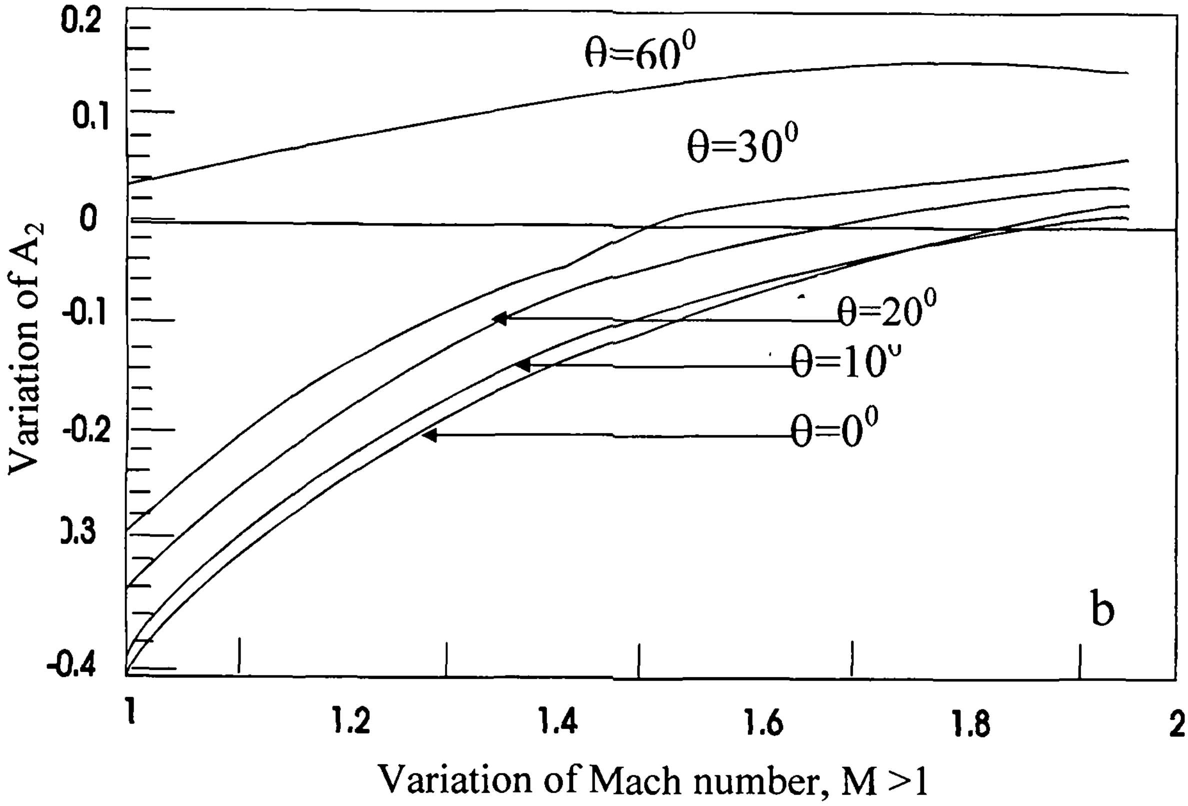


Fig. 2.1: Variation of A_1 and A_2 with Mach number

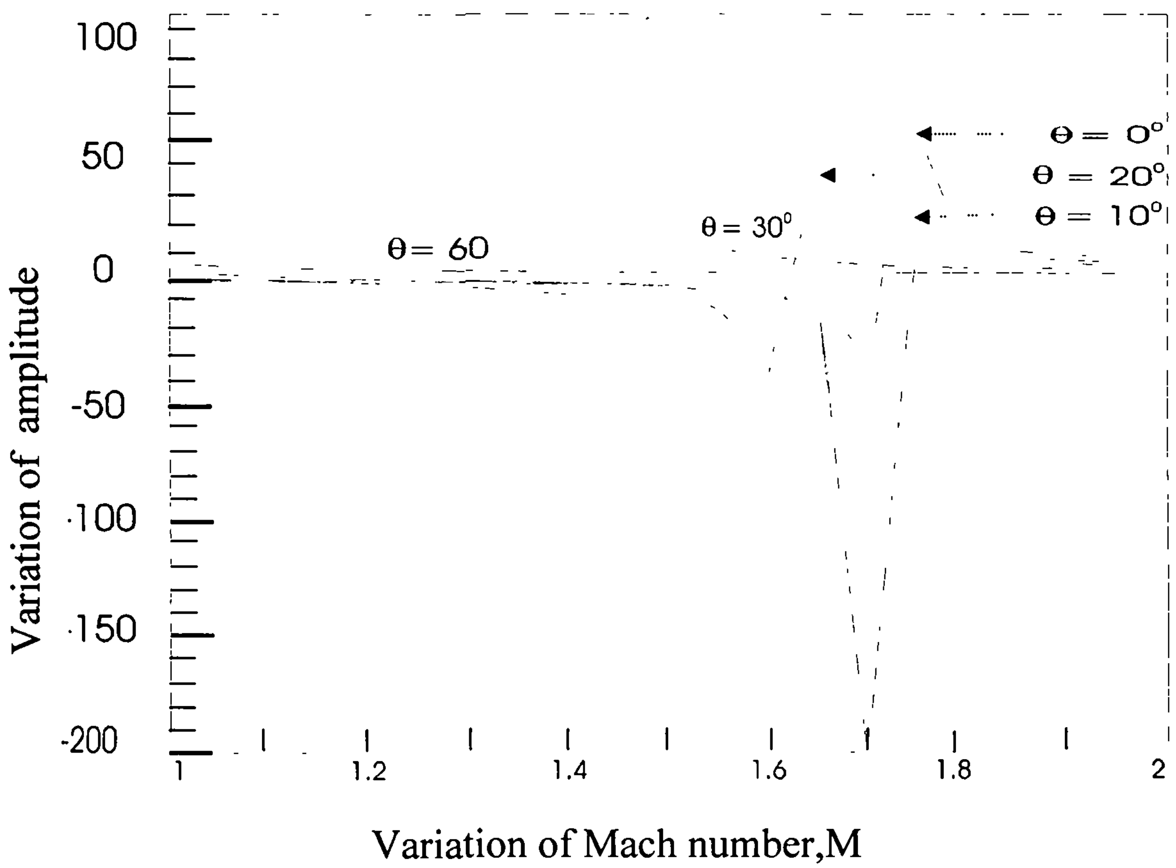


Fig. 2.2: Variation of amplitude with Mach number

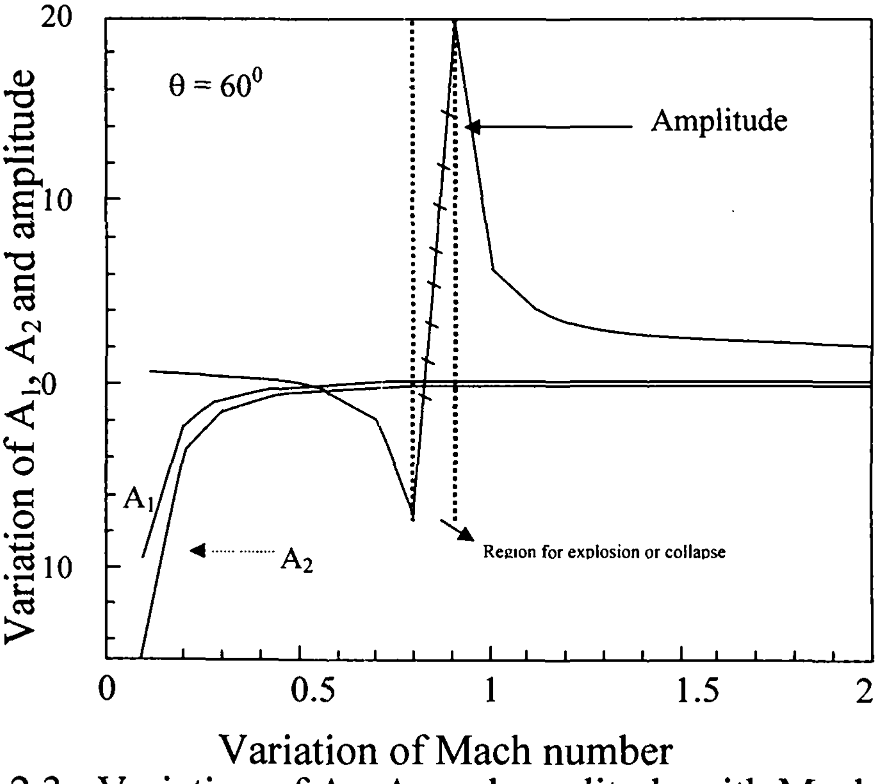


Fig. 2.3: Variation of A_1, A_2 and amplitude with Mach number