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Oblique Solitary Waves in a Five Component Plasma with Pair Ions

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Research Article

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ABSTRACT

We investigate the influence of ions of different masses on oblique solitary waves in five component plasma consisting of positively and negatively charged heavier ions (dust), hydrogen ions and hotter and colder electrons. Of these, the heavier ions and colder photo-electrons are of commentary origin while the other two are of solar origin; the electrons being described by kappa distributions. The K-dV equation is derived and different attributes of the soliton such as amplitude and width are plotted for parameters relevant to that of comet Halley. We find that heavier ions strongly influence the amplitude and width of the solitary waves.

Multi-ion plasma is found in many regions of space like the earth's ionosphere, mesosphere, solar atmosphere, commentary environments, etc. Of this commentary plasma is of particular interest among researchers due to the presence of a wide variety of many species of ions: besides electrons and protons of solar origin, photoionization causes the production of H^+ and O^+ from water molecules present in the commentary atmosphere in addition to the associated photo-electrons [1]. Also, several positively charged hot lighter and heavier ions have been observed at comet Halley [2-5]. Further, the observation of negatively charged ions by spacecraft Giotto with energies between 0.03 to 3.0 keV and mass peaks in the range 7-19, 22-65 and 85-110 amu in comet Halley gave a new dimension to the investigations on plasma where negatively charged ion species act as an ion pair [6]. Later, many investigations were done where both positively and negatively charged dust particles coexist in the same plasma environment [7] in which former would be smaller and latter would be larger in size [8].

In recent decade, there were extensive studies on different nonlinear propagations of waves in different plasma environments [9-14]. This includes plasmas with cold dust and electrons and/or ions described by kappa distribution functions [15] and cold dust, adiabatic fluid ions and kappa described electrons [16].

Photo-ionization in commentary plasma environments causes the production of photo-electrons which in turn act as a major second electron component, apart from the typical solar hot electrons. For example, Zwickl et al. [17], observed such photo-electrons from photo-ionization of commentary neutrals at comet Giacobini-Zinner by the electron spectrometer on the spacecraft ICE. Also, Bhardwaj observed the production of energetic photo-electrons in a study related to the gas production rates in comets [18].

It is a fact that the presence of high energetic particles in plasma deviate from typical Maxwellian to a non Maxwellian type "kappa distribution". Such a kind of distribution was first predicted by Vasyliunas using energetic solar wind data [19]; this distribution has since been used to model a number of space and astrophysical environments.

We, therefore study the characteristics of dust ion-acoustic solitary waves in this five component plasma, in which the electrons are modeled by kappa distributions. We find that different heavier ions significantly affect the amplitude and width of the solitary waves.

BASIC EQUATIONS

We are interested in solitary waves in five component plasma. The heavier ions (dust) and lighter (hydrogen) ion components are treated as cold, while both the electrons are described by a Boltzmann-like distribution given by

$$n_s = n_{s0}\left[1+\frac{e_s\psi}{k_B T_s(\kappa_s-3/2)}\right]^{-\kappa_s+1/2} \tag{1}$$

Where s=se or ce.

In (1) s indicates the species (s=se for solar electrons and s=ce for commentary photo-electrons). n denotes the density (the subscript 0 denotes the equilibrium value), e_s the charge, T_s the temperature and K_s the spectral index for the species 's'. k_B is the Boltzmann's constant and ψ, the potential.

The normalized form of the equations of continuity and motion for the hydrogen ions and the dust pair particles, along with the Poisson's equation, are given by

$$\frac{\partial n_1}{\partial t}+\nabla.(\mathrm{n_1 u_1})=0 \tag{2}$$

$$\frac{\partial n_1}{\partial t}+\nabla.(\mathrm{n_1 u_1})=0 \tag{3}$$

$$\frac{\partial n_2}{\partial t}+\nabla.(\mathrm{n_2 u_2})=0 \tag{4}$$

$$\frac{\partial u_i}{\partial t}+(\mathrm{u}_i.\nabla)\mathrm{u}_i=-\alpha_i\beta_i\nabla\psi+\Omega_i(\mathrm{u}_{iz}\hat{\mathrm{y}}-\mathrm{u}_{iy}\,\hat{z}) \tag{5}$$

$$\frac{\partial u_1}{\partial t}+(\mathrm{u}_1.\nabla)\mathrm{u}_1=\nabla\psi-\Omega_1(\mathrm{u}_{1z}\hat{\mathrm{y}}-\mathrm{u}_{1y}\,\hat{z}) \tag{6}$$

$$\frac{\partial u_2}{\partial t}+(\mathrm{u}_2.\nabla)\mathrm{u}_2=-\alpha_2\beta_2\nabla\psi+\Omega_2(\mathrm{u}_{2z}\hat{\mathrm{y}}-\mathrm{u}_{2y}\,\hat{z}) \tag{7}$$

$$\begin{aligned}\nabla^2\psi &= n_1-(1-z_i\mu_i+\mu_{ce}+\mu_{se})\mathrm{n}_2 \quad -(1-z_2\mu_2+\mu_{ce}+\mu_{se})\mathrm{n}_i \\ &+\mu_{ce}\left(1-\frac{\psi}{\sigma_{ce}(\kappa_{ce}-3/2)}\right)^{-\kappa_{ce}+1/2} \quad +\mu_{se}\left(1-\frac{\psi}{\sigma_{se}(\kappa_{se}-3/2)}\right)^{-\kappa_{se}+1/2}\end{aligned} \tag{8}$$

In (2) to (8) n_i, n_1 and n_2 are the hydrogen ion, negative and positive dust number densities, normalized by their equilibrium values n_{i0}, n_{10} and n_{20} respectively. u_i, u_1 and u_2 are again, the corresponding fluid speeds all normalized by $\left(\frac{z_1 k_B T_1}{m_1}\right)^{1/2}$. ψ, which is now the dimensionless electric potential, is normalized by $\frac{k_B T_1}{e}$. The space and time variables are respectively normalized by the Debye length $\lambda_{D1}=\left(\frac{z_1 k_B T_1}{4\pi z_1^2 e^2 n_{10}}\right)^{1/2}$ and the inverse of the plasma frequency $\omega_{p1}^{-1}=\left(\frac{m_1}{4\pi z_1^2 e^2 n_{10}}\right)^{1/2}$. Also $\alpha_i=\frac{z_i}{z_1}$, $\alpha_2=\frac{z_2}{z_1}$, $\beta_i=\frac{m_1}{m_i}$, $\beta_2=\frac{m_1}{m_2}$, $\mu_s=\frac{n_{s0}}{z_1 n_{10}}$ and $\sigma_s=\frac{T_s}{T_1}$, where n_{s0} is the equilibrium density for species s. T_s and T_1 are the temperatures of species s and negative dust respectively. m_i, m_1 and m_2 are, respectively, the masses of hydrogen ions, negatively and positively charged dust particles while Zi (=1), Z_1 and Z_2 are the corresponding charge numbers.

To investigate nonlinear waves of small amplitude, we derive the K-dV equation with new variables ξ and τ as: $\xi=\varepsilon^{1/2}(\sum l_j j-Mt)$ where l_j denote the direction cosines with j=x, y or z; satisfying the relation $l_x^2+l_y^2+l_z^2=1$, M is the Mach number and $n_k=1+\varepsilon n_k^{(1)}+\varepsilon^2 n_k^{(2)}+\ldots\ldots\ldots$.

The physical quantities in the above equations can be expressed asymptotically as a power series in ε about equilibrium values as:

$$n_k=1+\varepsilon n_k^{(1)}+\varepsilon^2 n_k^{(2)}+\ldots\ldots\ldots \tag{9}$$

$$u_{xk}=\varepsilon u_{xk}^{(1)}+\varepsilon^2 u_{xk}^{(2)}+\ldots\ldots\ldots \tag{10}$$

$$u_{yk}=\varepsilon^{3/2}u_{yk}^{(1)}+\varepsilon^2 u_{yk}^{(2)}+\ldots\ldots\ldots \tag{11}$$

$$u_{zk}=\varepsilon^{3/2}u_{zk}^{(1)}+\varepsilon^2 u_{zk}^{(2)}+\ldots\ldots\ldots \tag{12}$$

$$\psi=\varepsilon\psi^{(1)}+\varepsilon^2\psi^{(2)}+\ldots\ldots\ldots \tag{13}$$

Where k=i (ions), 1 (negatively charged heavier ions/dust) or 2 (positively charged heavier ions/dust)

Using ((9)-(13)) in ((2)-(8)) and equating different powers of ε, we can derive the K-dV equation from (8) as [20]

$$\frac{\partial\psi^{(1)}}{\partial\tau}+A\psi^{(1)}\frac{\partial\psi^{(1)}}{\partial\xi}+B\frac{\partial^3\psi^{(1)}}{\partial\xi^3}=0 \tag{14}$$

Where

$$A=\frac{3l_x^4\left(-1+(1-z_i\mu_i+\mu_{ce}+\mu_{se})\alpha_2^2\beta_2^2+(1-z_2\mu_2+\mu_{ce}+\mu_{se})\alpha_i^2\beta_i^2\right)-M^4\left(\frac{\mu_{ce}(\kappa_{ce}-1/2)(\kappa_{ce}+1/2)}{\sigma_{ce}^2(\kappa_{ce}-3/2)^2}+\frac{\mu_{se}(\kappa_{se}-1/2)(\kappa_{se}+1/2)}{\sigma_{se}^2(\kappa_{se}-3/2)^2}\right)}{2Ml_x^2\left(1+(1-z_i\mu_i+\mu_{ce}+\mu_{se})\alpha_2\beta_2+(1-z_2\mu_2+\mu_{ce}+\mu_{se})\alpha_i\beta_i\right)}$$

and

$$B=\frac{M^3\left(1+\left(\frac{1-l_x^2}{\Omega_1^2}\right)+(1-z_i\mu_i+\mu_{ce}+\mu_{se})\left(\frac{(1-l_x^2)\alpha_2\beta_2}{\Omega_2^2}\right)+(1-z_2\mu_2+\mu_{ce}+\mu_{se})\left(\frac{(1-l_x^2)\alpha_i\beta_i}{\Omega_i^2}\right)\right)}{2l_x^2\left(1+(1-z_i\mu_i+\mu_{ce}+\mu_{se})\alpha_2\beta_2+(1-z_2\mu_2+\mu_{ce}+\mu_{se})\alpha_i\beta_i\right)}$$

Solution of the K-dv Equation

For the solution of the K-dV equation (14), we use the transformation $\psi=f(\xi-M_0\tau)=f(\chi)$ followed by Kolebage and Oyewande [21]. The solution of K-dV equation then is

$$\psi=\psi_m\,Sech^2\left(\frac{\xi-M_0\tau}{W}\right) \tag{15}$$

where $W=2\sqrt{\frac{B}{M_0}}$ and $W=2\sqrt{\frac{B}{M_0}}$ are, respectively, the amplitude and width of the soliton.

RESULTS AND DISCUSSION

Our equations are valid for arbitrary values of the charge numbers Z_1 and Z_2 on the heavier/dust particles. However we use, here, parameters observed at comet Halley: the density of hydrogen ions $n_{i0}=4.95\ cm^{-3}$ the temperature of these ions $Ti=8\times10^4 K$ and the solar electron temperature $T_{se}=2\times10^5 K$ [1]. The temperature of the secondary photo-electrons was set at $T_{ce}=2\times10^4 K$. The negatively charged heavier ions were detected at energy of the order of 1 eV with densities $\leq 1\ cm^{-3}$ in the 7-19 amu peaks with negatively charged oxygen ions being unambiguously identified [6].

Figure 1 is a plot of the solitary wave amplitude ψ_m versus the direction cosine l_x as a function of μ_i (the normalized hydrogen density). The lower, middle and upper surfaces represent He, C and O ions respectively. The other parameters for the figure are: $l_y=0.2$, $K_{ce}=7/2$, $K_{se}=13/2$, $z_1=1$, $z_2=2$, $n_{10}=0.1\ cm^{-3}$, $n_{20}=1\ cm^{-3}$, $T_{se}=2\times10^5 K$, $T_{ce}=2\times10^4 K$, $T_{He}=1.8\times10^4 K$, $T_c=1.5\times10^4 K$ and $T_O=1.16\times10^4 K$. It is clear from the plots that while the amplitude of the soliton increases with increasing obliqueness of propagation; it is almost independent of μ_i (for higher mass of the heavier particles). Also, the amplitude of the soliton decreases with increase in mass of the heavier species of ions.

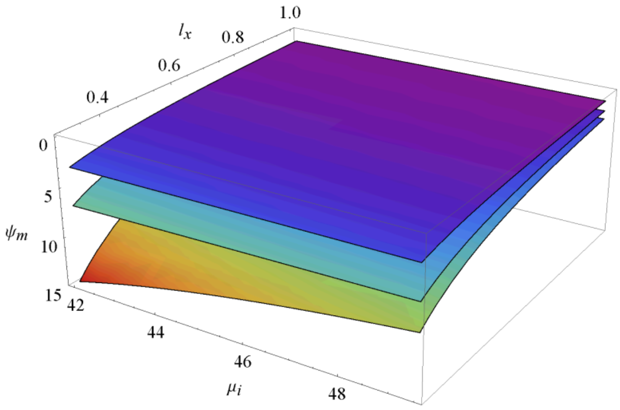

Figure 1: Amplitude ψ_m of the solitary wave vs. direction cosine l_x as a function of normalized hydrogen density μ_i for different heavier pair ions.

Figure 2 is a plot of the solitary wave amplitude ψ_m versus μ_{se} (the normalized solar electron densities) as a function of μ_i (the normalized hydrogen density). The lower, middle and upper surfaces represent He, C and O ions respectively. The other param

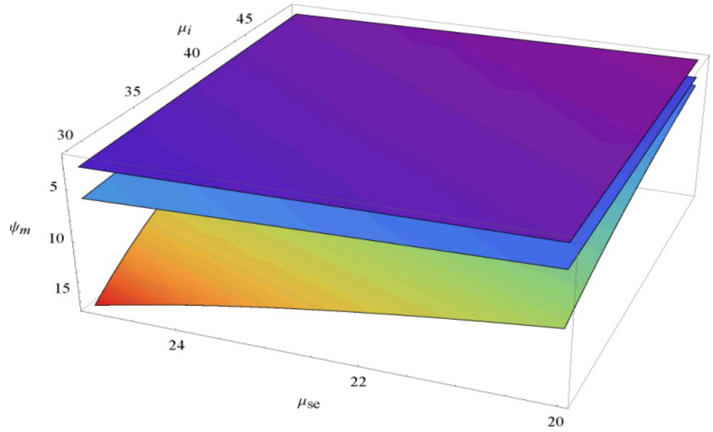

Figure 2: Amplitude ψ_m of the solitary wave vs. normalized solar electrons μ_{se} as a function of normalized hydrogen density μ_i for different heavier pair ions.

eters for the figure are: $l_x=l_y=0.2$, $K_{ce}=7/2$, $K_{se}=13/2$, $z_1=1$, $z_2=2$, $n_{10}=0.1\ cm^{-3}$, $n_{20}=1\ cm^{-3}$, $T_{se}=2\times10^5\ K$, $T_{ce}=2\times10^4\ K$, $T_{He}=1.8\times10^4\ K$, $T_c=1.5\times10^4\ K$ and $T_O=1.16\times10^4\ K$. Here also, the amplitude of the soliton decreases with increase in mass of the dust particles. We find that the soliton amplitude is sensitively dependent on the solar electrons, especially for lighter mass of the pair ions.

Next, in **Figure 3**, we investigate the dependence of the width W of the solitary waves on the normalized solar electron temperatures as a function of the direction cosine l_x. The upper, middle and lower surfaces are for He, C and O ions respectively. The other parameters for the figure are: $l_x=0.2$, $K_{ce}=7/2$, $K_{se}=13/2$, $z_1=1$, $z_2=2$, $n_{10}=0.1\ cm^3$, $n_{20}=1\ cm^{-3}$, $n_{i0}=4.95\ cm^{=3}$, $T_{ce}=2\times10^4\ K$, $T_{He}=1.8\times10^4\ K$, $T_c=1.5\times10^4\ K$ and $T_O=1.16\times10^4\ K$. The figure shows that the width W is almost independent of σ_{se}. However, in all the cases the width is a minimum for parallel and perpendicular directions [22].

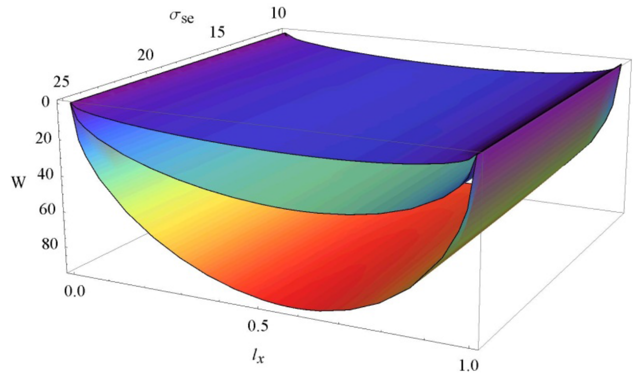

Figure 3: Width W of the solitary wave vs. direction cosine l_x as a function of normalized solar electron temperature σ_{se} for different heavier pair ions.

Finally, **Figure 4** depicts the variation of the width W of the soliton versus kappa indices of solar electrons K_{se} as a function of kappa indices of commentary electrons K_{ce} for different heavier ions. The lower, middle and upper surfaces is for O, C and He ions respectively. The other parameters for the figure are: $l_x=l_y=0.2$, $z_1=1$, $z_2=2$, $n_{10}=0.1\ cm^3$, $n_{20}=1\ cm^{-3}$, $n_{i0}=4.95\ cm^{-3}$, $T_{ce}=2\times10^4\ K$, $T_{He}=1.8\times10^4\ K$, $T_c=1.5\times10^4\ K$ and $T_O=1.16\times10^4\ K$. From the plots it is seen that the width of the solitary wave increases as mass of the pair ion increase. Also, the kappa indices of commentary electrons have a stronger influence on the width of the solitary waves as compared to solar electrons.

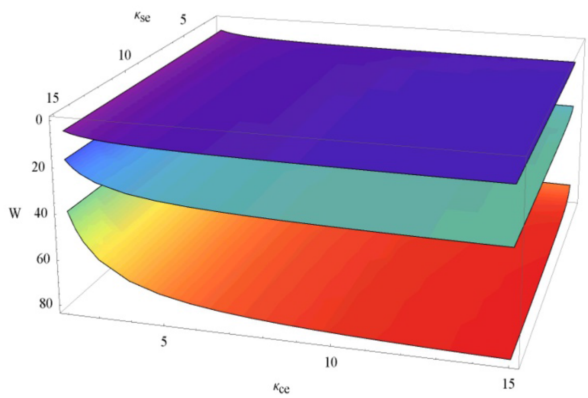

Figure 4: Width W of the solitary wave vs. kappa indices of solar electrons K_{se} as a function of kappa indices of commentary electrons K_{ce} for different heavier ions.

CONCLUSIONS

We have, in this paper, investigated the influence of ions of different masses on obliquely propagating solitary waves in five component plasma. The five components are hydrogen ions and hot electrons of solar origin; a pair of oppositely charged heavier ions (dust) and colder, photo-electrons of commentary origin. We find that the different pairs of heavier ions strongly influence the amplitude and width of the solitary waves. Our relations can be applicable to a number of space plasma environments [23-27].

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