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Enhancement of Modulational instability of a lower hybrid wave due to dust charge fluctuations

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ABSTRACT

Highly charged dust grains immersed in plasma exhibit charge fluctuations. The impact of these charge fluctuations is investigated on modulational instability of a lower hybrid wave in complex plasma. It is shown that these effects enhance the frequency and growth rate of unstable mode. The growth rate of the unstable mode is also found proportional to pump amplitude.

Keywords: Dust grains, modulational instability, lower hybrid wave & growth rate.

I. INTRODUCTION

The study of parametric instabilities of large amplitude electrostatic [1-5] and electromagnetic [6-7] waves in a plasma have been an active field of research for the last few decades for their relevance to radio frequency current drive, heating of fusion plasmas [1,8,9] laser driven fusion [10], small scale laboratory experiments [11-13] and ionospheric modification experiments.

In recent years, considerable interest has been given in studying electrostatic waves in dusty plasmas[14-18]. Barkan *et al*.[16] have found experimentally that the presence of negatively charged dust grains enhanced the growth rate of current driven electrostatic ion-cyclotron (EIC) wave in a dusty plasma. Chow *et al*.[17-18] have studied the effect of dust charged fluctuations on the collisionless EIC instability using Vlasov theory. They have found that in presence of negatively charged dust grains as the ratio of positive ion density to electron density increased, the critical electron drift velocity (v_{de}) for the excitation of wave decreased showing that the mode was more easily destabilized in plasma containing negatively charged dust grains.

The dust has been noted to influence a three-wave parametric process in unmagnetized [19-21] and magnetized plasmas[22]. Liu and Tripathi[8] considered MI of lower hybrid waves in infinite plasma. Konar *et al*.[23] have studied MI of a lower hybrid wave in a plasma slab without dust grains. In this paper, we examine the influence of dust charge fluctuations and dust dynamics on the MI of lower hybrid waves in a plasma slab.

In section II, we carry out the instability analysis using fluid treatment. We obtain growth rate of the instability using first order perturbation theory. We incorporate a model of dust charge fluctuations by following Whipple *et al*.[14], Jana *et al*.[15] Results and discussions are given in section III. Conclusion part is given in Sec. IV.

IJARSE
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II. INSTABILITY ANALYSIS

Consider a plasma slab filled with homogeneous dusty plasma that is infinite in Z-direction and bounded b/w x=0 and x=a_0. It is immersed in a static uniform magnetic field $\vec{B}_s = B_s \hat{k}$. In equilibrium, the densities, charge, mass and temperature of the three species electrons, ions and dust grains in the plasma slab are denoted by (n_{e0}, -e, m_e, T_e), (n_{i0}, e, m_i, T_i) and (n_{d0},-Q_{d0}, m_d,T_d) respectively. We assume the potentials of the four waves of the form

$$\phi_0 = \phi_0(x)\exp\left[-i\left(\omega_0 t - k_{0z} z\right)\right] ,$$

$$\phi_1 = \phi_1(x)\exp\left[-i\left(\omega_1 t - k_{1z} z\right)\right],$$

$$\phi_2 = \phi_2(x)\exp\left[-i\left(\omega_2 t - k_{2z} z\right)\right],$$

$$\phi = \phi(x)\exp\left[-i\left(\omega t - k_z z\right)\right].$$

The mode structure equation for the lower hybrid pump wave can be obtained from the linear dispersion relation

$$\frac{\partial^2 \phi_0}{\partial x^2} + K_0^2 \phi_0 = 0 , \qquad (1)$$

where

$$K_0^2 = \frac{\omega_{LH}^2 m_i}{\omega_0^2 m_e} k_{0z}^2 - k_{0z}^2,$$

$\omega_{LH}^2 = \dfrac{\omega_{pi}^2}{1+\dfrac{\omega_{pe}^2}{\omega_{ce}^2}}$, $\omega_{pe}\left(=\sqrt{\dfrac{4\pi n_{e0} e^2}{m_e}}\right)$, $\omega_{pi}\left(=\sqrt{\dfrac{4\pi n_{i0} e^2}{m_i}}\right)$, and $\omega_{ce}\left(=\dfrac{eB_s}{m_e c}\right)$ are lower hybrid, electron plasma , ion plasma and electron cyclotron frequency respectively.

The parallel component of the ponderomotive force (F_{pz}) exerted by lower hybrid pump wave and the sidebands ($\phi_{1,2}$) on the electrons is given by

$$F_{pz} = -iek_z\phi_p \tag{2}$$

where

$$\phi_p = \frac{-ek_{0z}^2}{2m_e\omega_0^2}\left[\phi_0\phi_1 + \phi_0^*\phi_2\right] \tag{3}$$

Electron response to ϕ_p and self-consistent potential ϕ turns out to be

$$n_{e1} = \frac{-n_{e0}ek^2\left(\phi+\phi_p\right)}{m_e\omega^2} \tag{4}$$

where n_{e1} is the perturbed density of electrons.

The ion density perturbation at (ω, k) can be written as

$$n_{i1} = \frac{n_{i0}ek^2\phi}{m_i\omega^2}. \tag{5}$$

Similarly the dust density perturbation is given by

$$n_{d1} = -\frac{n_{d0}Q_{d0}k^2\phi}{m_d\omega^2}. \tag{6}$$

The dust charge fluctuation is given by,

$$Q_{d1} = \frac{|I_{e0}|}{i(\omega+i\eta)}\left(\frac{n_{i1}}{n_{i0}} - \frac{n_{e1}}{n_{e0}}\right). \tag{7}$$

where $\eta = 0.79a\left(\frac{\omega_{pi}}{\lambda_{Di}}\right)\left(\frac{1}{\delta}\right)\left(\frac{m_i}{m_e}\frac{T_i}{T_e}\right)^{\frac{1}{2}} \sim 10^{-2}\omega_{pe}\left(\frac{a}{\lambda_{De}}\right)\frac{1}{\delta}$.

In Eq. (7), we assume that the wave period $\left(\omega^{-1}\right)$ is nearly equal to the dust charging time $\left(\eta^{-1}\right)$.

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Substituting the value of n_{e1} and n_{i1} from Eqs. (4) and (5) in Eq. (7), we obtain

$$Q_{d1} = \frac{|I_{e0}| e k^2}{i(\omega + i\eta)\omega^2}\left[\frac{\phi}{m_i} + \frac{(\phi + \phi_p)}{m_e}\right] \tag{8}$$

In equilibrium, there is overall charge neutrality, i.e., $-en_{i0} + en_{e0} + Q_{d0} n_{d0} = 0$

$$\frac{n_{i0}}{n_{e0}} = 1 + \frac{n_{d0}}{n_{e0}}\frac{Q_{d0}}{e} \quad \text{or}$$

$$\frac{n_{d0}}{n_{e0}} = (\delta - 1)\frac{e}{Q_{d0}}$$, where $\delta = n_{i0}/n_{e0}$.

Using Eqs. (4), (5), (6) and (8) in the Poisson's equation,

$\nabla^2 \phi = 4\pi[n_{e1}e - n_{i1}e + n_{d0}Q_{d1} + Q_{d0}n_{d1}]$, we get

$$\phi = \frac{-\chi_e\left[1 + \frac{i\beta}{(\omega + i\eta)}\right]\phi_p}{\varepsilon_d}, \tag{9}$$

where

$$\varepsilon_d = 1 + \chi_e\left[1 + \frac{i\beta}{(\omega + i\eta)}\right] + \chi_i\left[1 + \frac{i\beta}{(\omega + i\eta)\delta}\right] + \chi_d ,$$

$\chi_e = \frac{-\omega_{pe}^2}{\omega^2}$, $\chi_i = \frac{-\omega_{pi}^2}{\omega^2}$, $\chi_d = \frac{-\omega_{pd}^2}{\omega^2}$, $\omega_{pd}\left(= \sqrt{\frac{4\pi n_{d0} Q_{d0}^2}{m_d}}\right)$ and

$\beta = \frac{|I_{e0}| n_{d0}}{e n_{e0}} = 0.397\left(1 - \frac{1}{\delta}\right)\left(\frac{a}{v_{te}}\right)\omega_{pi}^2\left(\frac{m_i}{m_e}\right)$, is the coupling parameter. χ_e, χ_i, χ_d are electron, ion and dust susceptibility respectively while ω_{pd} is the dust plasma frequency.

Nonlinear lower and upper sideband electron density perturbation is given by

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$$n_1^{nl} = \frac{\nabla.\left(n_{e1}V_0^*\right)}{2i\omega_1} \approx -\frac{ek_{0z}^2\phi_0^* n_{e1}}{2m_e\omega_0^2} \qquad (10)$$

and

$$n_2^{nl} = \frac{\nabla.\left(n_{e1}V_0\right)}{2i\omega_2} \approx -\frac{ek_{0z}^2\phi_0 n_{e1}}{2m_e\omega_0^2}, \qquad (11)$$

where $\omega_1 \approx -\omega_0$ and $\omega_2 \approx \omega_0$.

Using equations (10) and (11) in the Poisson's equation, we get the following nonlinear mode-structure equations for lower and upper sidebands:

$$\frac{\partial^2\phi_1}{\partial x^2} + K_{1d}^2\phi_1 = \frac{e^2k_{0z}^4k^2\phi_0^*\chi_e}{4m_e^2\omega_0^2\varepsilon_d M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]\left\{1+\chi_i\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]+\chi_d\right\}\left[\phi_0\phi_1+\phi_0^*\phi_2\right] \qquad (12)$$

and

$$\frac{\partial^2\phi_2}{\partial x^2} + K_{2d}^2\phi_2 = \frac{e^2k_{0z}^4k^2\phi_0\chi_e}{4m_e^2\omega_0^2\varepsilon_d M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]\left\{1+\chi_i\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]+\chi_d\right\}\left[\phi_0\phi_1 \cdot \phi_0^*\phi_2\right] \qquad (13)$$

where
$$K_{1d}^2 = \frac{\frac{\omega_{pi}^2}{\omega_1^2}\frac{m_i}{m_e}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]k_{1z}^2 - k_{1z}^2}{1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]-\frac{\omega_{pi}^2}{\omega_1^2}\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]-\frac{\omega_{pd}^2}{\omega_1^2}}, \qquad (14)$$

$$K_{2d}^2 = \frac{\frac{\omega_{pi}^2}{\omega_2^2}\frac{m_i}{m_e}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]k_{2z}^2 - k_{2z}^2}{1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]-\frac{\omega_{pi}^2}{\omega_2^2}\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]-\frac{\omega_{pd}^2}{\omega_2^2}} \quad \text{and} \qquad (15)$$

$$M = 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\left[1 + \frac{i\beta}{(\omega + i\eta)}\right] - \frac{\omega_{pi}^2}{\omega_0^2}\left[1 + \frac{i\beta}{(\omega + i\eta)\delta}\right] - \frac{\omega_{pd}^2}{\omega_0^2}.$$

If the R.H.S of Eqs.(12) and (13) are zero, then these equations represents

the linear response at $(\omega_{1,2}, k_{1,2})$ and solutions are represented by ϕ_{1n_1} and ϕ_{1n_2} respectively.

Expanding the solutions of Eqs.(12) and (13) i.e., ϕ_1 and ϕ_2 in terms of a complete set

of orthonormal functions ϕ_{1n_1} and ϕ_{1n_2} , we get

$$\phi_1 = \sum_{n_1} A_{n_1}^{(1)} \phi_{1n_1} \quad \text{and} \tag{16}$$

$$\phi_2 = \sum_{n_2} A_{n2}^{(2)} \phi_{2n_2} \quad . \tag{17}$$

In the absence of the pump wave, Eq. (12) becomes

$$\frac{\partial^2 \phi_1}{\partial x^2} + K_{1dn_1}^2 \phi_1 = 0 \tag{18}$$

Now subtracting Eq. (18) from Eq. (12), we

$$\left[K_{1d}^2 - K_{1dn_1}^2\right]\phi_1 = \frac{e^2 k_{0z}^4 k^2 \phi_0^* \chi_e}{4 m_e^2 \omega_0^2 \varepsilon_d M}\left[1 + \frac{i\beta}{(\omega + i\eta)}\right]\left\{1 + \chi_i\left[1 + \frac{i\beta}{(\omega + i\eta)\delta}\right] + \chi_d\right\}\left[\phi_0\phi_1 + \phi_0^*\phi_2\right]$$

Substituting the values of ϕ_1 and ϕ_2 from Eqs. (16) and (17), we get

$$\left[K_{1d}^2 - K_{1dn_1}^2\right]\sum_{n_1} A_{n_1}^{(1)}\phi_{1n_1} = \frac{e^2k_{0z}^4k^2\phi_0^*\chi_e}{4m_e^2\omega_0^2\varepsilon_d M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]\left\{1+\chi_i\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]+\chi_d\right\}\times$$
$$\left[\phi_0\phi_0^*\sum_{n_1} A_{n_1}^{(1)}\phi_{1n_1} + \phi_0^*\phi_0^*\sum_{n_2} A_{n_2}^{(2)}\phi_{2n_2}\right]$$

Multiplying both sides by $\phi_{1m_1}^*$ and integrating over 'x', we get

$$\int\left[K_{1d}^2 - K_{1dn_1}^2\right]\sum_{n_1} A_{n_1}^{(1)}\phi_{1n_1}\phi_{1m_1}^*\,dx = \int\eta_1\phi_{1m_1}^*\left[\phi_0\phi_0^*\sum_{n_1} A_{n_1}^{(1)}\phi_{1n_1} + \phi_0^*\phi_0^*\sum_{n_2} A_{n_2}^{(2)}\phi_{2n_2}\right]dx$$

(19)

where

$$\eta_1 = \frac{e^2k_{0z}^4k^2\chi_e}{4m_e^2\omega_0^2\varepsilon_d M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]\left\{1+\chi_i\left[1+\frac{i\beta}{(\omega+i\eta)\delta}\right]+\chi_d\right\}$$

Taking only one value n_1=m_1 , we get

$$\left[K_{1d}^2 - K_{1dn_1}^2 - \eta_1\int\phi_0\phi_0^*\phi_{1n_1}^*\phi_{1n_1}\,dx\right]A_{n_1}^{(1)} = \eta_1\sum_{n_2} A_{n_2}^{(2)}\int\phi_0^*\phi_0^*\phi_{2n_2}\phi_{1n_1}^*\,dx \qquad (20)$$

Similarly we will get

$$\left[K_{2d}^2 - K_{2dn_2}^2 - \eta_1\int\phi_0^*\phi_0\phi_{2n_2}\phi_{2n_2}^*\,dx\right]A_{n_2}^{(2)} = \eta_1\sum_{n_1} A_{n_1}^{(1)}\int\phi_0\phi_0\phi_{1n_1}\phi_{2n_2}^*\,dx \qquad (21)$$

Multiplying Eqs.(20) and (21) and taking n_1=n_2=n i.e., the mode number for lower and upper side bands to be same, non-linear dispersion relation for four coupled waves becomes

$$\left[K_{1d}^2 - K_{1dn}^2 - \eta_1\int|\phi_0|^2|\phi_{1n}|^2\,dx\right]A_{n_1}^{(1)}\left[K_{2d}^2 - K_{2dn}^2 - \eta_1\int|\phi_0|^2|\phi_{2n}|^2\,dx\right]A_{n_2}^{(2)} =$$
$$\eta_1^2 A_{n_2}^{(2)}A_{n_1}^{(1)}\int\phi_0^*\phi_0^*\phi_{2n}\phi_{1n}^*dx\int\phi_0\phi_0\phi_{1n}\phi_{2n}^*dx$$

or

$$\left[K_{1d}^2 - K_{1dn}^2 - \delta_1\right]\left[K_{2d}^2 - K_{2dn}^2 - \delta_2\right] = \mu \quad (22)$$

where $\delta_1 = \eta_1 \int |\phi_0|^2 |\phi_{1n}|^2 \, dx$, $\delta_2 = \eta_1 \int |\phi_0|^2 |\phi_{2n}|^2 \, dx$ and $\mu = \eta_1^2 \int \phi_0^* \phi_0^* \phi_{2n} \phi_{1n}^* dx \int \phi_0 \phi_0 \phi_{1n} \phi_{2n}^* dx$

As we know for modulational instability $k_z << k_{0z}$, $\omega << \omega_0$, we can expand K_{1d}^2 , K_{2d}^2 using Taylor's series for a function of two variable as

$$K_{1d}^2 = K_{1d}^2(-\omega_0, -k_0) + \omega \left.\frac{\partial K_{1d}^2}{\partial \omega_1}\right|_{-\omega_0} + k_z \left.\frac{\partial K_{1d}^2}{\partial k_{1z}}\right|_{-k_{0z}} + \frac{\omega^2}{2} \left.\frac{\partial^2 K_{1d}^2}{\partial \omega_1^2}\right|_{-\omega_0} + \frac{k_z^2}{2} \left.\frac{\partial^2 K_{1d}^2}{\partial k_{1z}^2}\right|_{-k_{0z}} \quad (23)$$

$$K_{2d}^2 = K_{2d}^2(\omega_0, k_0) + \omega \left.\frac{\partial K_{2d}^2}{\partial \omega_2}\right|_{\omega_0} + k_z \left.\frac{\partial K_{2d}^2}{\partial k_{2z}}\right|_{k_{0z}} + \frac{\omega^2}{2} \left.\frac{\partial^2 K_{2d}^2}{\partial \omega_2^2}\right|_{\omega_0} + \frac{k_z^2}{2} \left.\frac{\partial^2 K_{2d}^2}{\partial k_{2z}^2}\right|_{k_{0z}} \quad (24)$$

Now assuming $\omega = \omega_r + i\gamma$ and using the condition for modulational instability i.e., $\frac{\omega_r}{k_z} \approx \frac{\partial \omega_0}{\partial k_{0z}}$, we get

$$\omega_r = \frac{\omega_0}{k_{0z}} \left\{ 1 - \frac{\left[1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\left(1 + \frac{i\beta}{\omega + i\eta}\right)\right]\omega_0^2}{\omega_{pi}^2 \left[1 + \frac{i\beta}{(\omega + i\eta)}\right]\frac{m_i}{m_e} + \omega_{pi}^2 \left[1 + \frac{i\beta}{(\omega + i\eta)\delta}\right] + \omega_{pd}^2} \right\} k_z \quad (25)$$

and

$$\gamma = \frac{\sqrt{\mu - \delta_1 \delta_2 + B_1(\delta_1 + \delta_2 - B_1)}}{A_1} \quad (26)$$

where

$$A_1 = \frac{2\omega_{pi}^2 m_i}{\omega_0^3 m_e M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]k_{0z}^2,$$

$$B_1 = \frac{3\omega_r^2\omega_{pi}^2 m_i}{\omega_0^4 m_e M}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]k_{0z}^2 + \frac{k_z^2}{M}\left\{\frac{\omega_{pi}^2 m_i}{\omega_0^2 m_e}\left[1+\frac{i\beta}{(\omega+i\eta)}\right]-1\right\}.$$

Now we will discuss two cases of interest:

Case I: In the presence of dust charge fluctuations i.e., dust charging rate η is finite .

Case II: In the absence of dust charge fluctuations i.e., $Q_{d_1} = 0$ when dust charging rate $\eta \to \infty$. In the absence of dust grains i.e., δ=1and β=0, we recover the dispersion relation of Konar *et al* .[23] (cf. pages 3799 and 3800).

III. RESULTS AND DISCUSSIONS

We solve Eqs. (25) and (26) numerically to obtain real frequency (ω_r) and growth rate (γ) of the unstable mode using following parameters: n_{i0}=5.0x10^{10}cm^{-3}, $n_{d0} = 2.0\times10^4 cm^{-3}$, T_e=T_i=0.2eV, $m_i/m_e \approx 7.16\text{x}10^4$ (Potassium), a=10^{-4}cm, $\omega_0 = 7.0\times10^9 rad/\text{sec.}$, k_{0z}=3.25cm^{-1} and k_{lz}=0.035cm^{-1} and B_s=2KG. We vary δ from 1.0 to 5.0.

Fig. 1 shows the variation of ω_r (rad./sec.) of the unstable mode with $\delta(=n_{io}/n_{eo})$ in presence and absence of dust charge fluctuations . It can seen from Fig. 1 that ω_r increases with δ in both the cases and gets saturated for higher values of δ and increase is more significant in case of dust charge fluctuations. Fig. 2, depicts the variation of γ (sec.$^{-1}$) as a function of δ for the pump amplitude $\phi_0 = 0.023$ esu. Fig. 2, shows that γ increases by a factor ~1.73 (for B_s=2KG) [in presence of dust charge fluctuations] as δ is varied from one to four. The growth rate results are consistent with the experimental finding of Barkan *et al*. [16] where growth rate becomes appro. twice under similar circumstances. In Eq. (26), $\mu \approx \delta_1\delta_2$ and since B_1 is positive, the growth is only possible when $\delta_1 + \delta_2 > B_1$ and this condition is satisfied when $\omega_r^2 > \omega_{pi}^2 I$, where $I = 1+\frac{i\beta}{(\omega+i\eta)\delta}$. The growth rate is found proportional to pump amplitude as $\delta_1 \approx \delta_2$ and $B_1 < 2\delta$. Thus the presence of dust charge fluctuations make the lower hybrid pump more modulationally unstable to low frequency quasimode for a particular value of δ.

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FIGURE CAPTIONS

Fig.1 : Dispersion curves of the unstable mode as a function of the density ratio of negatively charged dust grains to electrons $\delta\left(=n_{i0}/n_{e0}\right)$ in presence and absence of dust charge fluctuations. The parameters are given in the text.

Fig.2: Growth rate γ (rad./sec) of the unstable mode as a function of $\delta\left(=n_{i0}/n_{e0}\right)$ for the same parameters as in Fig.1 and in presence and absence of dust charge fluctuations.

$\times 10^{7}$

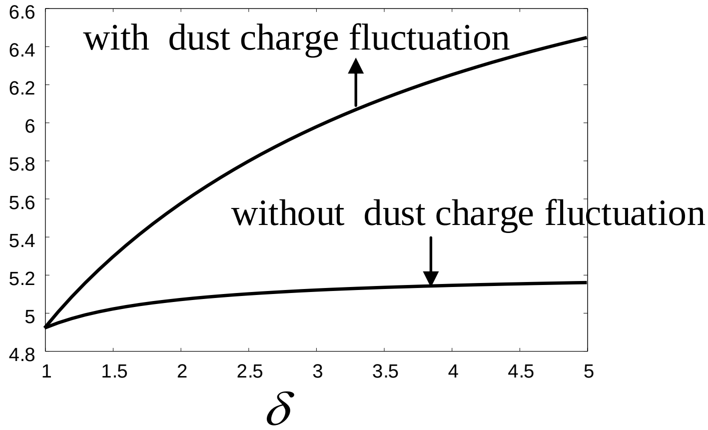
with dust charge fluctuation
without dust charge fluctuation
6.6
6.4
6.2
6
5.8
5.6
5.4
5.2
5
4.8
1
1.5
2
2.5
3
3.5
4
4.5
5
δ

Fig.1

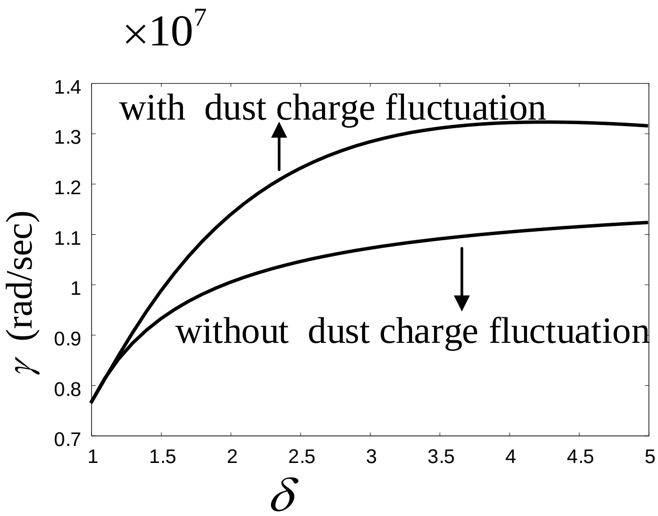
×10^7
with dust charge fluctuation
without dust charge fluctuation
γ (rad/sec)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
1
1.5
2
2.5
3
3.5
4
4.5
5
δ

Fig.2