DUST IN PLASMA, DUSTY PLASMA AND PLASMA IN LUNAR ENVIRONMENT

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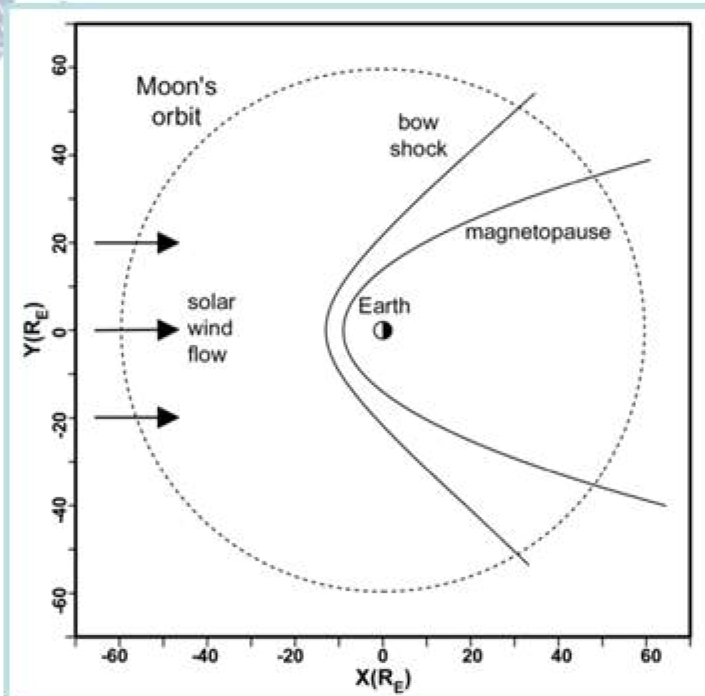
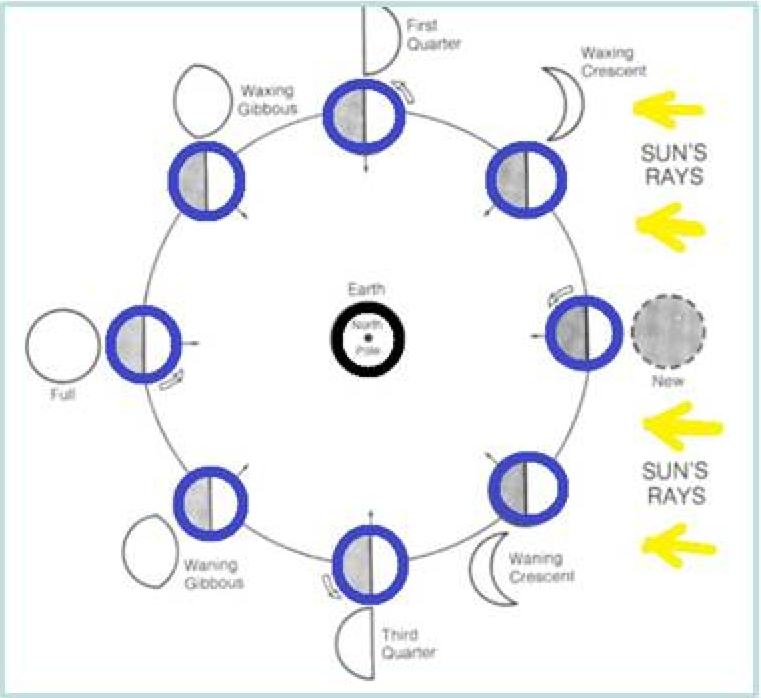
Lunar orbiter photomozaic of orientale Basib showing groved ejecta pattern(hevelius Formation .JPL photo #LO-4-193M)-Lunar Sample Compendium

This research is supported by grant O N517 418440





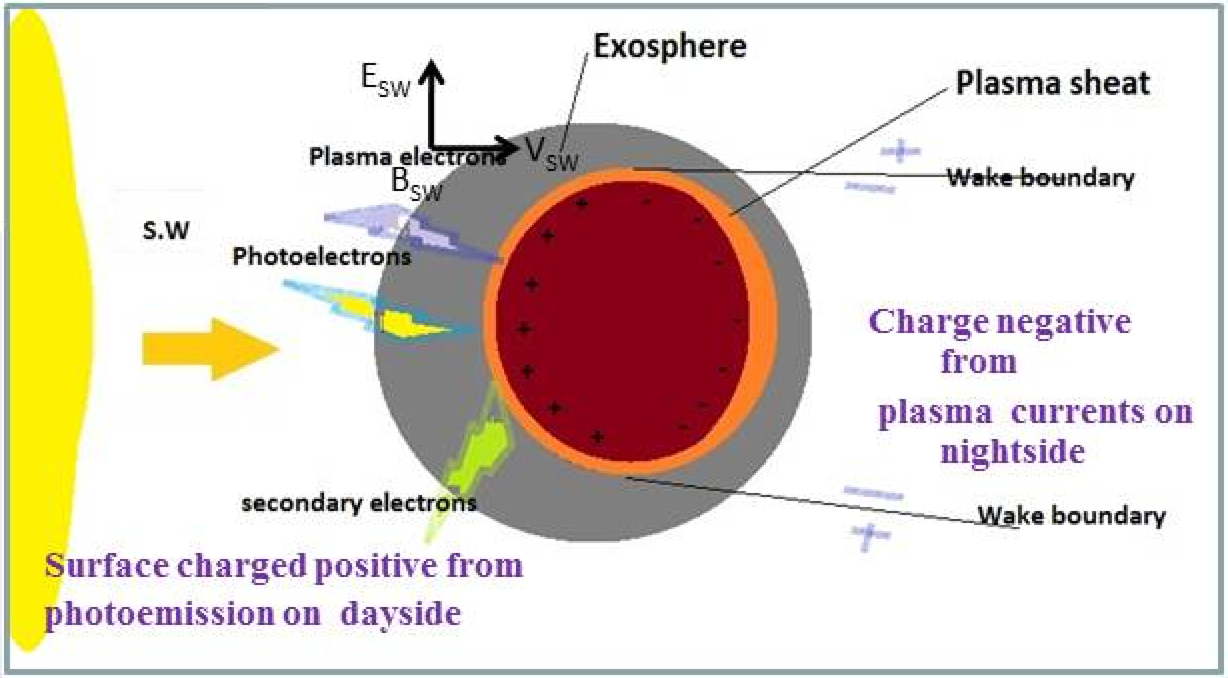
- The Moon occasionally encounters dense hot plasma of the Earth's plasmasheet.
- Moon crosses Earth's magnetotail around Full Moon.

– Approx. 4 to 5 days per month.

This can have consequences ranging from lunar 'dust storms' to electrostatic discharges

Dust Populations

- Dust evolved under Pointing-Robertson effect from asteroidal and cometary sources (near circular orbits)
- Dust directly injected from comets (bursts of dust)
- Fragments from meteoroid collisions inside 1 AU (eccentric orbits)
- Beta-meteoroids and nano dust (at high speeds from solar direction)
- Interstellar grains (high speed directional flux)
- Lunar impact ejecta (high speed: > 1 km/s)
- Fast lunar dust above 300 m height (> 100 m/s)
- Slow lunar dust at about 1 m height (~ 1 m/s)



The lunar dust environment is expected to be dominated by submicron-sized dust particles released from the Moon due to the continual bombardment by micrometeoroids, and due to plasma induced near-surface intense electric fields.

The motion of charged particles is influenced by the presence of electric and magnetic fields, resulting in complex dust dynamics and transport.

The dust grains and lunar surface are electrostatically charged by the Moon's interaction with the local plasma environment and the photoemission of electrons due to solar UV and X-rays or just by contacts with other dust particles. **This effect causes the like-charged surface and dust particles to repel each other, and creates a near-surface electric field.** ***Lunar dust must be treated as dusty plasma.***

Whenever dust becomes charged, interplanetary electromagnetic forces will alter the dynamics of such charged grains of matter in unexpected ways.

The lunar surface is mostly covered

with a layer of micron/sub-micron size dust grains formed by meteoritic impact over billions of years. Theoretical models indicate that the dust grains on the lunar surface are charged by the solar UV radiation as well as the solar wind plasma, and are levitated and transported over long distances on the lunar surface, as exhibited by a horizon glow and transient dust clouds during the Apollo missions.

In addition to the dust,

the Moon has a tenuous atmosphere with evidence for the existence of very-low-density CH_4, CO_2, NH_3, along with some rare gases/
Definitive information on dust/gas distributions in the global lunar environment is currently unavailable and is essential for addressing a variety of issues dealing with lunar environment.

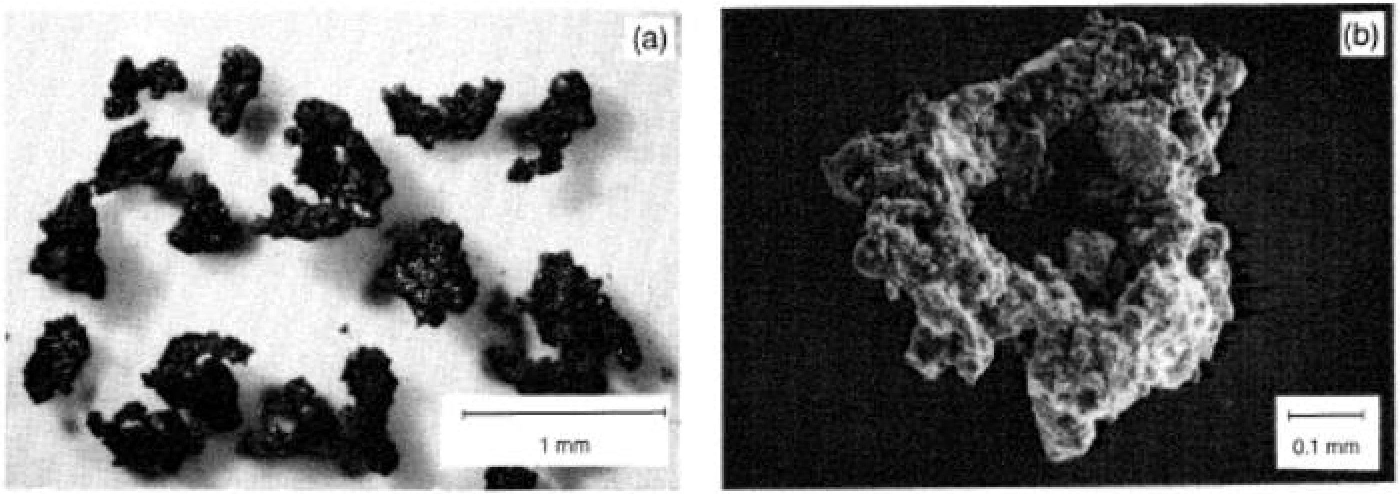


Fig. 7.2. Typical lunar soil agglutinates. **(a)** Optical microscope photograph of a number of agglutinates separated from Apollo 11 soil sample 10084, showing a variety of irregular agglutinate shapes (NASA Photo S69-54827). **(b)** Scanning electron photomicrograph of a doughnut-shaped agglutinate. This agglutinate, removed from soil 10084, has a glassy surface that is extensively coated with small soil fragments. A few larger vesicles are also visible (NASA Photo S87-38812).

Lunar regolith refers to all the fragmented rock material that covers the moon.
Lunar soil is technically regolith excluding rocks larger than 1 cm in size.
Lunar dust is technically defined as having particle sizes less the 20 µm with a bulk density of 1.5 g/cm3.

Apollo12

NASA ph. AS12-48-7110

Some fraction of the lunar dust moves

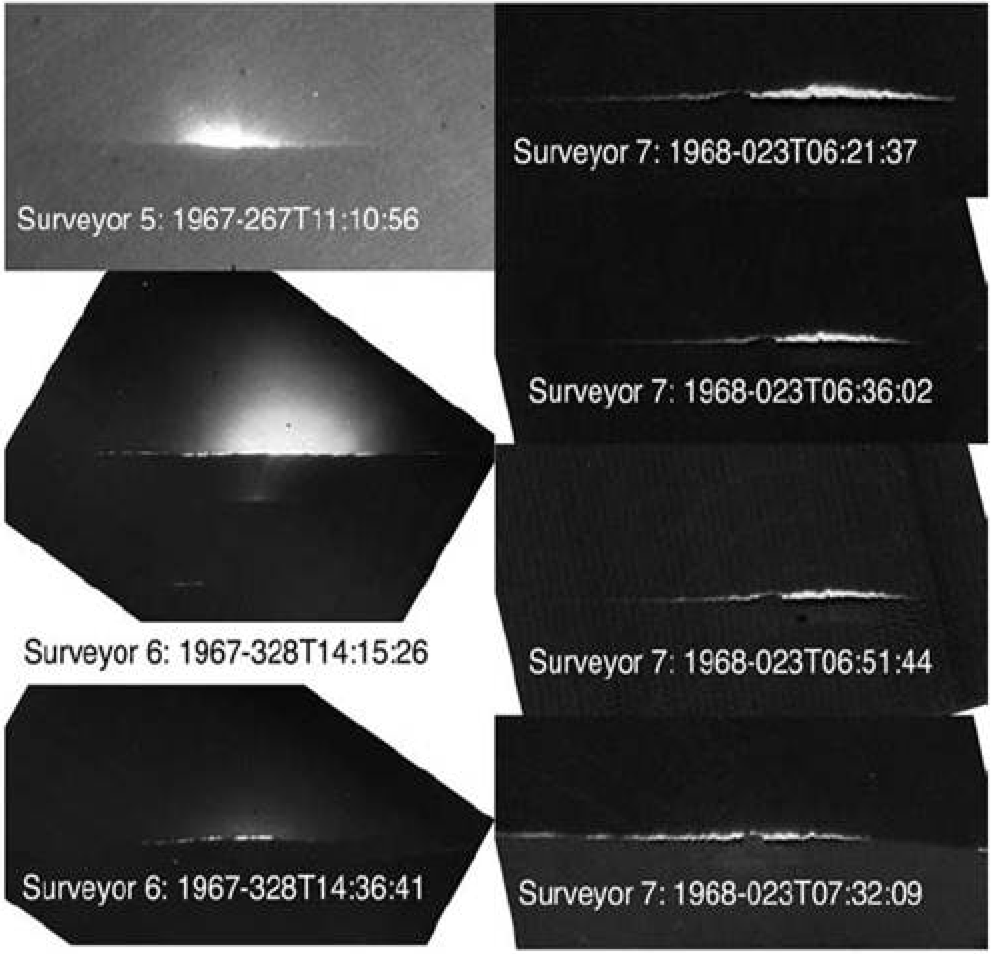
Surface charged positive from photoemission on dayside

Charge negative from plasma currents on nightside

Like-charged grains can then be levitated/lofted

Creates a dusty-plasma

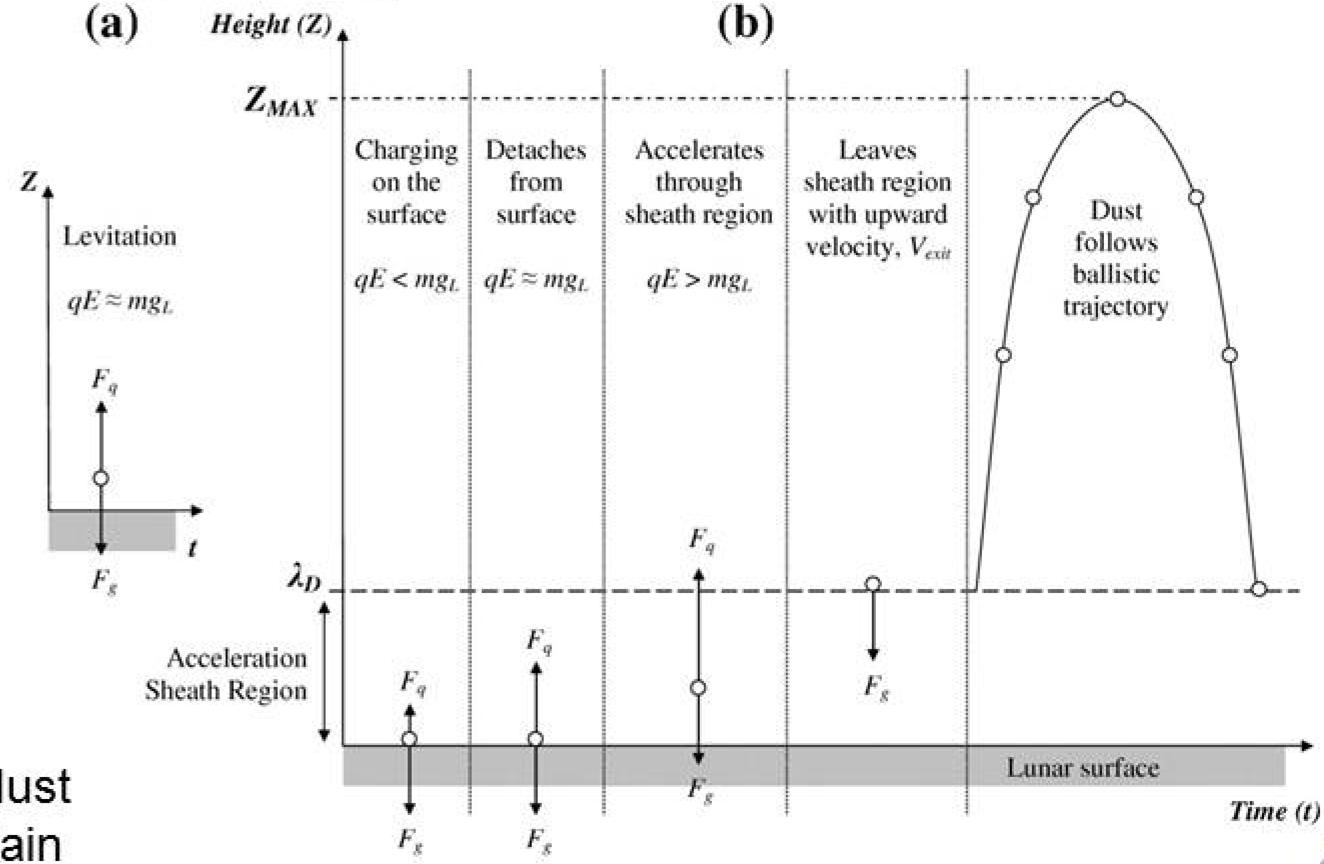
Lunar Horizon Glow



LunarHorizonGlowCriswell, 1973; Rennilsonand Criswell, 1974, Colwellet al., 2007

Observations from the Apollo command module imply the presence of a high-altitude component of lunar dust extending up to 100 km [Rennilson, J.J., *et al. (1974) Moon, 10, p. 121. McCoy, J.E., et al. (1974). in LPS, Vol. 5*]. Visible to the naked eye, these dust concentrations are too high to be explained by impactrelated processes alone, leading to the concept of dust fountains, in which large surface potentials expected near the terminator regions ballistically loft smaller dust grains to high altitudes.

[Halekas, J.S., *et al.*(2007) GRL, **34**,
***Halekas, J.S.*., et al.** (2005) GRL, **32**,
***Manka, R.H.*., et al.**(1973). in *LPS*, *Vol. 4*
Colwell, J.E., *et al.*(2005) *Icarus*, ***175(1)***
[Stubbs, T.J., *et al. (2006)* ASR, ***37(1)***]

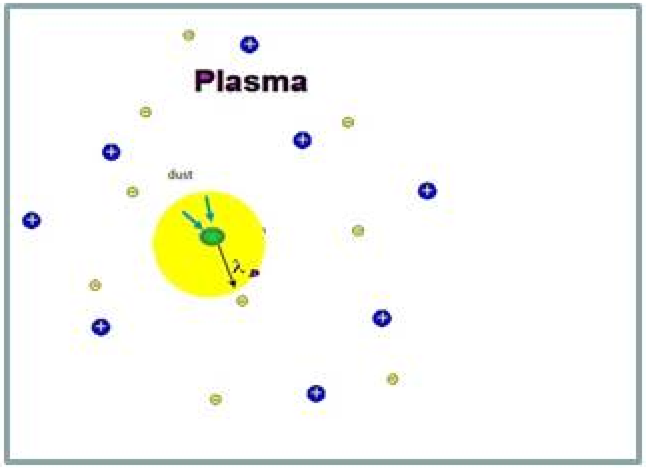


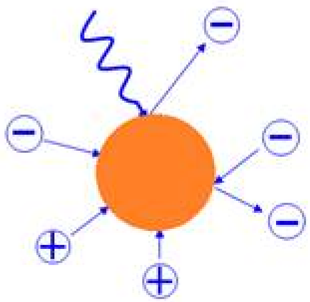
(a) the static levitation concept
(b) the evolution of a dust grain in dynamic fountain model.

plasma = electrons + ions

dusty plasma - number of grains in Debye sphere is greater than one.

„dust in a plasma" - when number density of grains is less than one.





Charging

- electron, positive and negative ion collection
- secondary emission
- UV induced photoelectron emission

Temporal and spatial variations of the lunar surface potential occur due to charging from photo-emission and plasma currents, and range from ~+10V to ~-4 kV

Halekas, J.S., *et al.*(2007) *GRL, 34, Halekas, J.S., et al.* (2005) *GRL, 32, Manka, R.H., et al.*(1973). in *LPS, Vol. 4*, Colwell, J.E., *et al.*(2005) *Icarus, 175(1)*).

„Physics On The Moon"

- **MHD**

  Magneto(magnetic field)-hydro(liquid)-dynamics(motion).
  Gravitation and electromagnetism + Fluid mechanics

- **Kinetic**

  Boltzmann- Maxwell

  Vlasov- Maxwell – (or Amper ==Poisson)

MHD Does Work on the Moon because:

- *The Moon has no appreciable magnetic dipole field – hence no magnetosphere.*
- *However, the Moon has magnetic anomalies imbedded in its surface.*
- *These anomalies can creat mini-bow shocks.*
- *They can be modelled with mini-dipoles.*

MHD Not Work

the existence of discrete particles becomes important.

- **The physics is very often nonlinear**

Waves in dusty plasmas

The wave behaviour of a dusty plasmas differs from the behaviour of usual plasmas, because of several reasons:

1. Characteristic frequencies of the dust components are much smaller than those corresponding with electrons or ions, and therefore the most interesting dusty plasma effects occur for low frequencies.
2. The mass of the dust grains is much higher than the mass of the plasma particles, and therefore in some cases the gravity forces come into play.
3. The number of free electrons is less than the number of ions, because some of the electrons are captured by the grains, and are therefore immobilized by the high dust masses.
4. The charge of the dust grain depends on the local plasma conditions (temperature and plasma density), which will vary with the waves coming by and therefore the dust grain charge has to be taken into account as an extra independent variable.
5. In most space applications the grain size is not fixed, but one encounters a power law for the grain size distribution. This induces a whole continuous range of different charge over mass ratios, whereas these ratios are fixed for usual plasmas.

Vlasov-Ampère/Poisson system of equations for multicomponent plasmas

$$\left[\partial_t + u\partial_x + \frac{q_\alpha}{m_\alpha}E(x,t)\partial_u\right]F_\alpha(u,x,t) = 0, \quad \partial/\partial u = \partial_u$$ Vlasov

$$\varepsilon_0\partial_t E(x,t) + \sum_\alpha q_\alpha \int_{-\infty}^{\infty} uF_\alpha(u.x.t)du = 0, \quad \partial/\partial x = \partial_x, \qquad \partial/\partial t = \partial$$ Ampère

$$\varepsilon_0\partial_x E(x,t) + \sum_\alpha q_\alpha \int_{-\infty}^{\infty} F_\alpha(u.x.t)du = 0, \quad E = -\partial_x\phi$$ Poisson

Let us assume $F_\alpha(u,x,t) \cong N_0^\alpha F_{0\alpha}(u) + F_{1\alpha}(u,x,t)$

where $N_0^\alpha,\ F_{0\alpha}$ are the equilibrium particle concentration and the velocity distribution for E=0, and is of the order E.

Substituting (4) into (1), we derive the well-known linear equation:

For the initial-value problem

$$F_{1\alpha}(u,x,0) = g_\alpha(u,x), \quad g_\alpha(u,x=\pm\infty) = 0 \quad and \quad E(x,t) = 0 \ \ for \ \ t \le 0$$

KiNETIC Vlasov-Poisson

$$\left[\partial_t + u\partial_x + \frac{q_\alpha}{m_\alpha} E\partial_u\right] f_\alpha(u,x,t) = 0,\ \partial_u \equiv \frac{\partial}{\partial u} \quad \text{(Vlasov)},\ 2.1$$

$$\epsilon_0 \partial_t E + \sum_\alpha q_\alpha \int u f_\alpha du = 0 \ \text{(Ampere)}, \quad 2.2$$

$$\epsilon_0 \partial_x E = \int_{-\infty}^{\infty} f_\alpha du \equiv \sum_\alpha \rho_\alpha,\ E = -\partial_x \phi \quad \text{(Gauss)},\ 2.3$$

where x, u and t are space, velocity and time variables, respectively.

$E(x,t),\ \phi(x,t),\ f_\alpha(u,x,t),\ q_\alpha, m_\alpha$ **are electric field, potential, function of velocity distribution, charge and mass of - α particles, respectively.**

if the solution $f_\alpha(u,x,t)$ exists for a given equilibrium $f_{0\alpha}(u)$, then it takes the following form:

$$\left[\partial_t + u\partial_x + \frac{q_\alpha}{m_\alpha}E(x,t)\partial_u\right] W_\alpha(u,x,t) = -\frac{q_\alpha}{m_\alpha}E(x,t).$$

Where:

$$f_\alpha(u,x,t) = N_0^\alpha f_{0\alpha}(u + W_\alpha(u,x,t)),$$

This relation exhibits an equilibrium distribution memory of Vlasov plasmas. The plasma response to an initial disturbance of plasma equilibrium as well as "far field " solutions cannot be composed by use of arbitrary stationary solutions. In particular, if one assumes the Maxwellian equilibrium distribution for "hot electrons" and a proper equilibrium distribution for "cold electrons" then the "far field" solution does not exist, (no solution), for any initial disturbances, It appears that (2.4) is divergent due to wave- particle interactions, that is due to nonlinear Landau instabilities.

A.J.Turski, B.Atamaniuk:on J. Techn. Phys.2 (30),(1989) 147
Barbara Atamaniuk "Kinetic Description of Localized Plasma Structure in Dusty Plasmas". Czechoslovak Journal of Physics Vol.54 C 2004

Let us consider three components of a dusty plasma having the following equilibrium distributions

$$f_{0d}(u) = \delta(u) \qquad \text{(dust)},$$

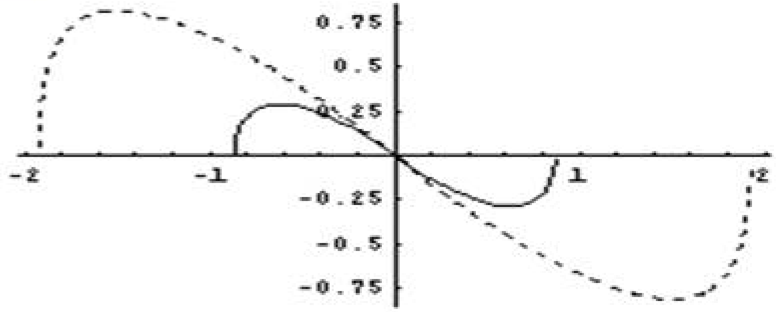
$$f_{0e}(u) = \frac{1}{2a_e}[H(u + a_e) - H(u - a_e)] \quad \text{(hot electrons)},$$

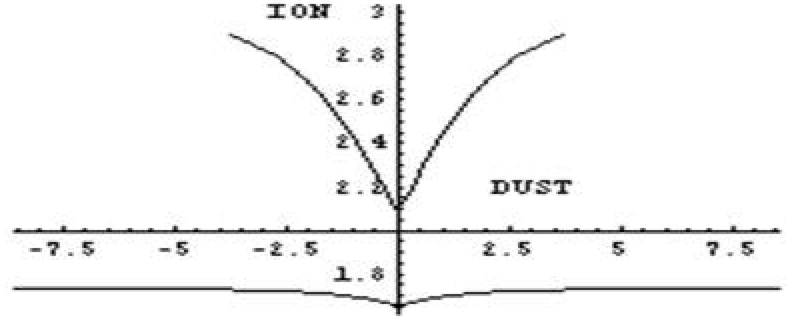
$$f_{0i}(u) = \frac{1}{2a_i}[H(u + a_i) - H(u - a_i)] \quad \text{(hot ions)},$$

$\omega_\alpha^2 = \dfrac{N_0^\alpha q_\alpha^2}{\varepsilon_0 m_\alpha}$ is the plasma α- component frequency and $a_\circ$

is the thermal velocity.

Then after some calculations we obtain the dispersion relation for longitudinal plasma waves

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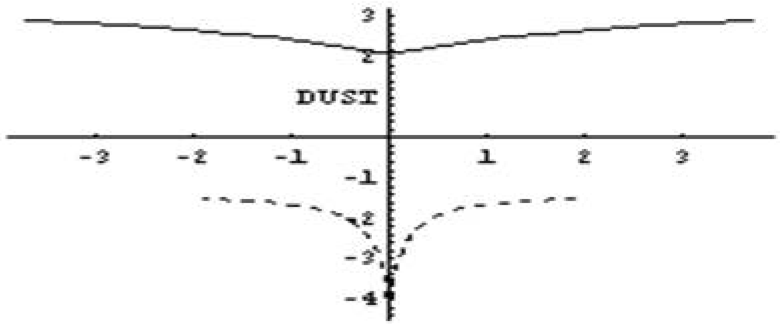
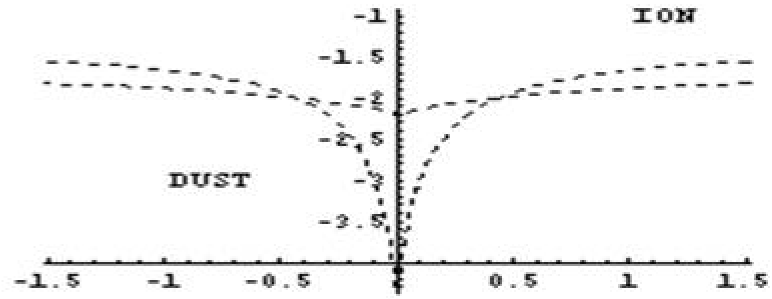
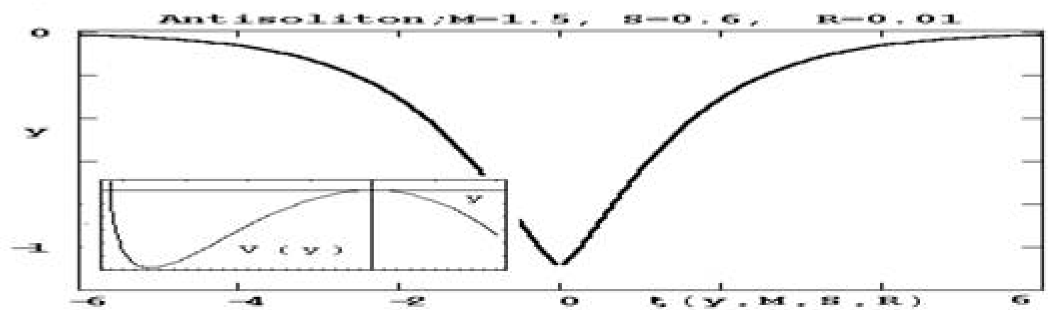
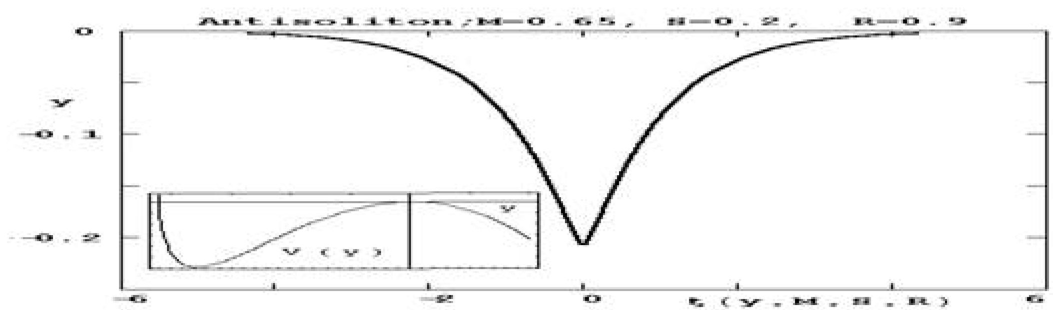
DUST


DUST


ION
DUST


Antisoliton;M=1.5, S=0.6, R=0.01
y
V(y)
t(y,M,S,R)


Antisoliton;M=0.65, S=0.2, R=0.9
y
V(y)
t(y,M,S,R)

Main equations of collisional magnetized plasma

$$m_e n_e \nu_e \mathbf{v}_e + \nabla P_e = -e n_e(\mathbf{E}_0 - \nabla\varphi) - \frac{e n_e}{c}[\mathbf{v}_e \mathbf{B}],$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right) n_e + n_e \nabla \cdot \mathbf{v}_e = 0$$

$$\frac{3}{2} n_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right) T_e + n_e T_e \nabla \cdot \mathbf{v}_e = -\nabla \cdot \mathbf{q}_e,$$

$$m_i n_i \left(\frac{d}{dt} + \nu_i\right) \mathbf{v}_i + \nabla P_i = e n_i(\mathbf{E}_0 - \nabla\varphi),$$

$$\frac{3}{2} n_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right) T_i + n_i T_i \nabla \cdot \mathbf{v}_i = -\nabla \cdot \mathbf{q}_i = \nabla \cdot \kappa_i \nabla T_i,$$

$$\Delta\varphi = 4\pi e(n_e - n_i).$$

i=i,d (d--dust)

$$\mathbf{q}_i = -\kappa_i \nabla T_i,\ \mathbf{q}_e = -\kappa_\parallel^e \nabla_\parallel T_e - \kappa_\perp^e \nabla_\perp T_e - \kappa_\wedge^e \mathbf{b} \times \nabla_\perp T_e$$

Nonlinear equations

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_d \nabla_\perp\right)\frac{\delta n_e}{n} + \frac{c}{B}[\nabla \ln n_0, \nabla\Psi]_z + \frac{c}{B}\frac{\nu_e}{\omega_e}\left(\nabla_\perp^2 + \frac{\omega_e^2}{\nu_e^2}\frac{\partial^2}{\partial z^2}\right)\Psi -$$

$$= \frac{c}{B}\left[\nabla\Psi, \nabla\frac{\delta n_e}{n}\right]_z - \frac{\nu_e}{\omega_e}\frac{c}{B}\left(\frac{\omega_e^2}{\nu_e^2}\frac{\partial\Psi}{\partial z}\frac{\partial}{\partial z} + \nabla_\perp\Psi\nabla_\perp\right)\frac{\delta n_e}{n}$$

nonlinearity

$$\nabla^2\left[\left(\frac{\partial}{\partial t} + \nu_i\right)\Phi + \frac{e\varphi}{m_i} + \frac{T_i}{m_i}\left(\frac{\delta T_i}{T_i} + \frac{\delta n_i}{n_0}\right)\right] = 0$$

$$\frac{c}{B}\frac{\nu_e}{\omega_e}\left(\nabla_\perp^2\Psi + \frac{\omega_e^2}{\nu_e^2}\frac{\partial^2\Psi}{\partial z^2}\right) + \frac{c}{B}[\nabla\Psi, \nabla_\perp \ln n]_z + (\mathbf{v}_D\nabla_\perp)\frac{\delta n}{n} - \frac{\nu_e}{\omega_e}[\mathbf{v}_D, \nabla_\perp]\frac{\delta n}{n}$$

$$+ \frac{c}{B}\left[\nabla\Psi, \nabla_\perp\frac{\delta n}{n}\right] + \frac{c}{B}\frac{\nu_e}{\omega_e}\left(\nabla_\perp\frac{\delta n}{n}\nabla_\perp\Psi + \frac{\omega_e^2}{\nu_e^2}\frac{\partial}{\partial z}\frac{\delta n}{n}\frac{\partial\Psi}{\partial z}\right) = \nabla^2\Phi$$

$$\mathbf{v}_i = \nabla\Phi$$

Reduced nonlinear description

$$n_k \simeq n_k(t)\exp(-i\Omega_k t),\ \frac{\partial}{\partial t} n_k(t) \ll \Omega_k n_k(t)$$

$$A_k \frac{\partial n_k}{\partial t} = \gamma_k n_k + \frac{\omega_e}{2} \sum_{\mathbf{k}=\mathbf{k}_1+\mathbf{k}_2} G_{12} n_{k_1} n_{k_2}$$

$$G_{12} \simeq \frac{[\mathbf{k}_1,\mathbf{k}_2]_z}{\omega_{lh}^2}\left[\frac{\Omega_{k_2}\mathbf{v}_d\mathbf{k}_{2\perp}}{k_2^2} - \frac{\Omega_{k_1}\mathbf{v}_d\mathbf{k}_{1\perp}}{k_1^2}\right]$$

$$A_k \simeq 1 + \frac{\nu_e\rho_e^2}{c_e^2k^2}\left(\mathbf{k}_\perp^2 + \frac{\omega_e^2}{v_e^2}k_z^2\right)\left(i\Omega_k + \frac{i\mathbf{v}_d\mathbf{k}_\perp + \frac{5}{3}\nu_e\rho_e^2\left(\mathbf{k}_\perp^2 + \frac{\omega_e^2}{v_e^2}k_z^2\right)\left(1 + \frac{T_i}{T_e}\right)}{1 + \frac{(\nu_i - i\Omega_k)}{c_e^2k^2}\nu_e\rho_e^2\left(\mathbf{k}_\perp^2 + \frac{\omega_e^2}{v_e^2}k_z^2\right)}\right)$$

Three wave decay processes in active media

$$\left(\frac{\partial}{\partial t} + i\Omega_1 - \gamma_1\right)n_1 = \frac{\omega_e}{2} G_{23}(k_2, k_3) n_2 n_3$$

$$\left(\frac{\partial}{\partial t} + i\Omega_2 - \gamma_2\right)n_2 = \frac{\omega_e}{2} G_{13}(k_1, -k_3) n_1 n_3^*$$

$$\left(\frac{\partial}{\partial t} + i\Omega_3 - \gamma_3\right)n_3 = \frac{\omega_e}{2} G_{12}(k_1, -k_2) n_1 n_2^*$$

$$\Omega_1 \simeq \Omega_2 + \Omega_3$$

$$\Gamma_{\max} \sim \frac{\omega_e}{2} \rho_e^2 |[\mathbf{k}_3, \mathbf{k}_2]_z| \frac{\Omega_3 \Omega_2}{\omega_{lh}^2} \frac{\delta n_{k_1}}{n}$$

$$i\left(\frac{d}{dt} - \gamma_0\right)C_0 = VC_1C_2\exp(-i\delta t),$$

$$i\left(\frac{d}{dt} - \gamma_1\right)C_1 = -VC_0C_2^*\exp(i\delta t),$$

$$i\left(\frac{d}{dt} - \gamma_2\right)C_2 = -VC_0C_1^*\exp(i\delta t),$$

$$(\Gamma - \gamma_{k_2})(\Gamma - \gamma_{k_3}) = \frac{\omega_e}{2} k_2^2 \rho_e^2 \frac{\omega_e}{2} k_3^2 \rho_e^2 G_{12}^* G_{13} |n_{k_1}|^2$$

$$\frac{\delta n_{k_1}}{n} \geq \frac{\nu_e}{\omega_e} \frac{\omega_{lh}^2}{c_e^2 k^2}$$

After long calculations the equation set of reduced equations which describe evolution of a spectrum of oscillations of density at development of two stream instability (*taking into account non-linear interaction of waves and effects of ion Landau damping*)is obtained

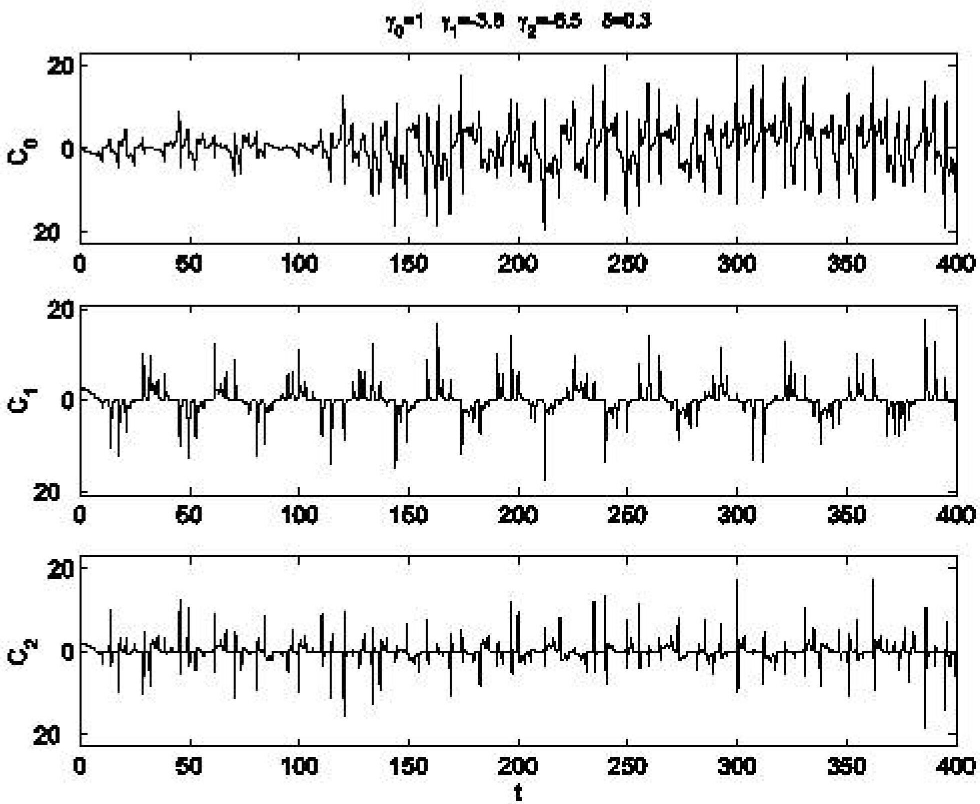
Three wave

With DUST the equations looks simmilar – more complicated coefficients . Numerical results are in progress yet.

Chaotic regime of nonlinear stabilization of current instability by three wave process

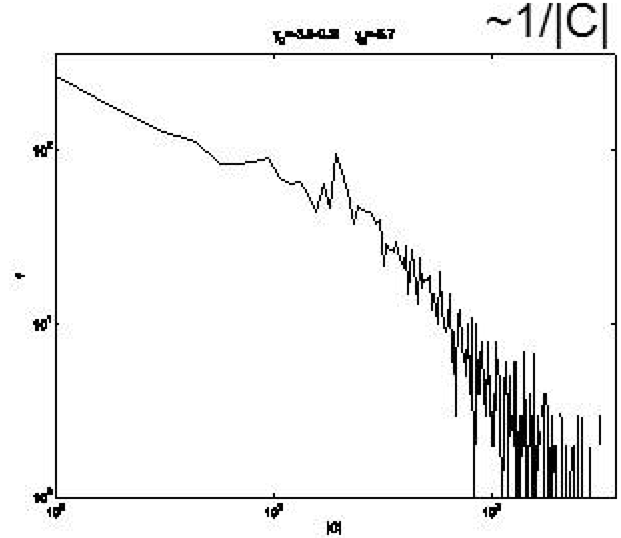
$\Omega_1 \simeq \Omega_2 + \Omega_3$ **k**1= **k**2+ **k**3

$$i\left(\frac{d}{dt} - \gamma_0\right)C_0 = VC_1C_2\exp(-i\delta t),$$
$$i\left(\frac{d}{dt} - \gamma_1\right)C_1 = -VC_0C_2^*\exp(i\delta t),$$
$$i\left(\frac{d}{dt} - \gamma_2\right)C_2 = -VC_0C_1^*\exp(i\delta t),$$

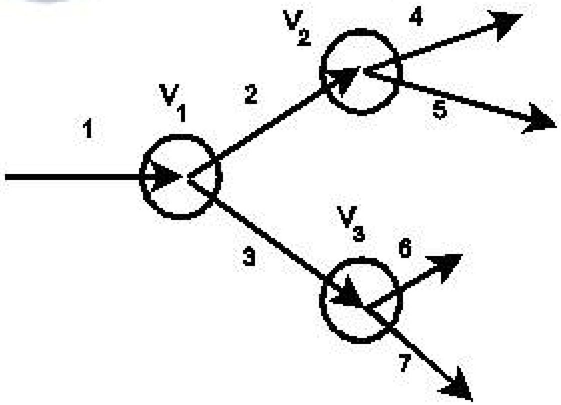


Probability distribution of the wave amplitude

~1/|C|



Examples of few wave systems in active media



Two step, 7 wave cascade:

$k_1=k_2+k_3, \quad k_2=k_4+k_5, \quad k_3=k_6+k_7,$

all wave vectors are different

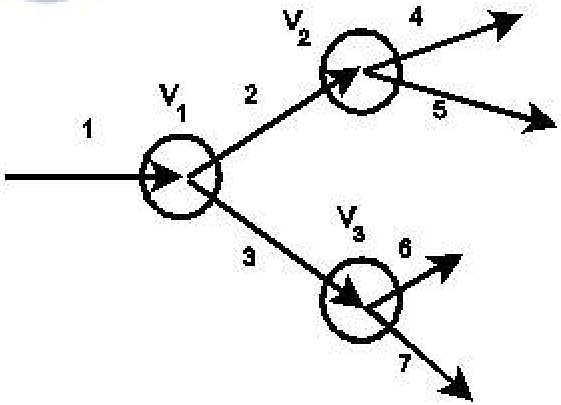
$$\left(\frac{\partial}{\partial t}-\gamma_1\right)C_1 = iV_1C_2C_3 \qquad \left(\frac{\partial}{\partial t}-\gamma_2+i\delta\omega_2\right)C_2 = iV_1C_1C_3^* + iV_2C_4C_5$$

$$\left(\frac{\partial}{\partial t}-\gamma_3+i\delta\omega_3\right)C_3 = iV_1C_1C_2^* + iV_3C_6C_7,$$

$$\left(\frac{\partial}{\partial t}-\gamma_4+i\delta\omega_4\right)C_4 = iV_2C_2C_5^* \qquad \left(\frac{\partial}{\partial t}-\gamma_5+i\delta\omega_5\right)C_5 = iV_2C_2C_4^*$$

$$\left(\frac{\partial}{\partial t}-\gamma_6+i\delta\omega_6\right)C_6 = iV_3C_3C_7^* \qquad \left(\frac{\partial}{\partial t}-\gamma_7+i\delta\omega_7\right)C_7 = iV_3C_3C_6^*$$

Examples of few wave systems in active media



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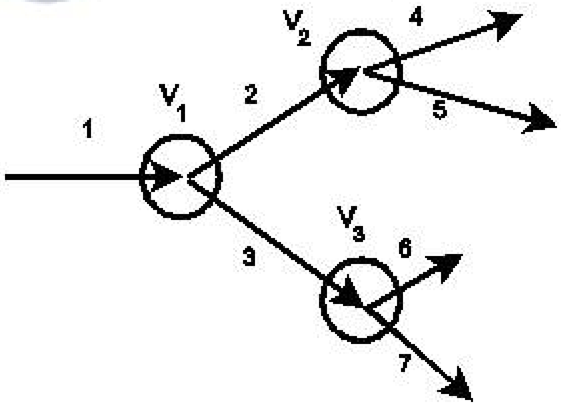
$$\left(\frac{\partial}{\partial t}-\gamma_3+i\delta\omega_3\right)C_3 = iV_1C_1C_2^* + iV_3C_6C_7,$$

$$\left(\frac{\partial}{\partial t}-\gamma_4+i\delta\omega_4\right)C_4 = iV_2C_2C_5^* \qquad \left(\frac{\partial}{\partial t}-\gamma_5+i\delta\omega_5\right)C_5 = iV_2C_2C_4^*$$

$$\left(\frac{\partial}{\partial t}-\gamma_6+i\delta\omega_6\right)C_6 = iV_3C_3C_7^* \qquad \left(\frac{\partial}{\partial t}-\gamma_7+i\delta\omega_7\right)C_7 = iV_3C_3C_6^*$$

Examples of few wave systems in active media



Two step, 7 wave cascade:

$k_1=k_2+k_3, \quad k_2=k_4+k_5, \quad k_3=k_6+k_7,$

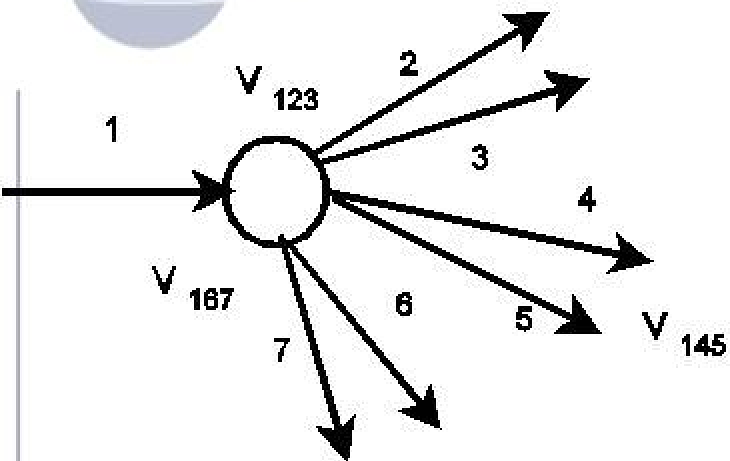
all wave vectors are different

$$\left(\frac{\partial}{\partial t} - \gamma_1\right)C_1 = iV_1 C_2 C_3 \qquad \left(\frac{\partial}{\partial t} - \gamma_2 + i\delta\omega_2\right)C_2 = iV_1 C_1 C_3^* + iV_2 C_4 C_5$$

$$\left(\frac{\partial}{\partial t} - \gamma_3 + i\delta\omega_3\right)C_3 = iV_1 C_1 C_2^* + iV_3 C_6 C_7,$$

$$\left(\frac{\partial}{\partial t} - \gamma_4 + i\delta\omega_4\right)C_4 = iV_2 C_2 C_5^* \qquad \left(\frac{\partial}{\partial t} - \gamma_5 + i\delta\omega_5\right)C_5 = iV_2 C_2 C_4^*$$

$$\left(\frac{\partial}{\partial t} - \gamma_6 + i\delta\omega_6\right)C_6 = iV_3 C_3 C_7^* \qquad \left(\frac{\partial}{\partial t} - \gamma_7 + i\delta\omega_7\right)C_7 = iV_3 C_3 C_6^*$$



Another example of short cascade - one step, many branches

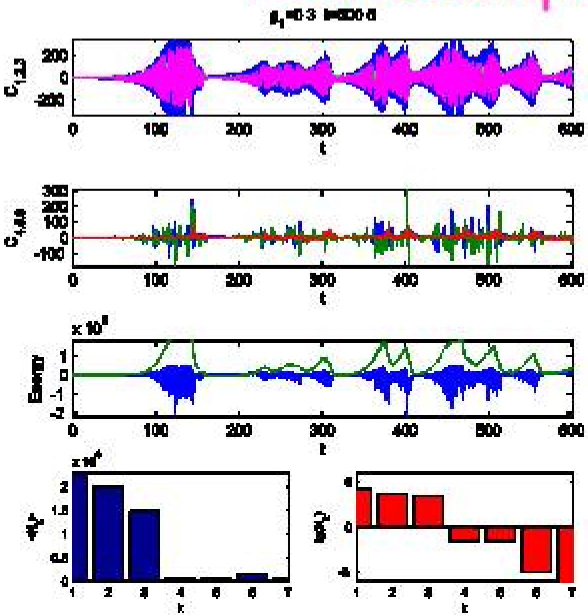
$$\left(\frac{\partial}{\partial t} - \gamma_1\right)C_1 = i\sum_{0}^{n} V_{1+i}C_{2+i}C_{3+i}$$

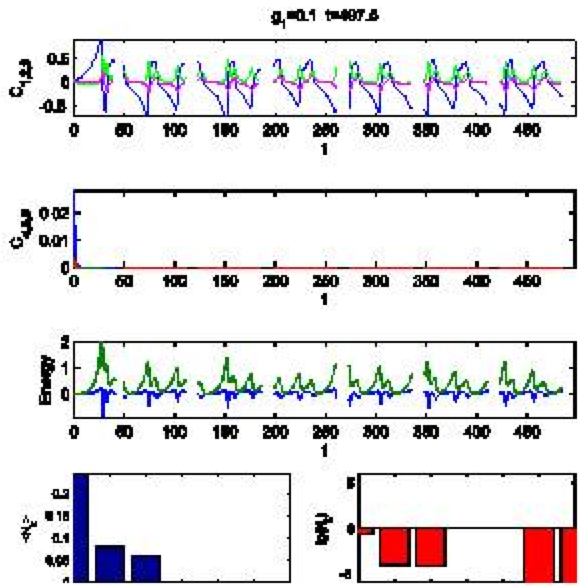
$$\left(\frac{\partial}{\partial t} - \gamma_{2+i} + i\delta\omega_{2+i}\right)C_{2+i} = iV_{1+i}C_1C_{3+i}^*$$

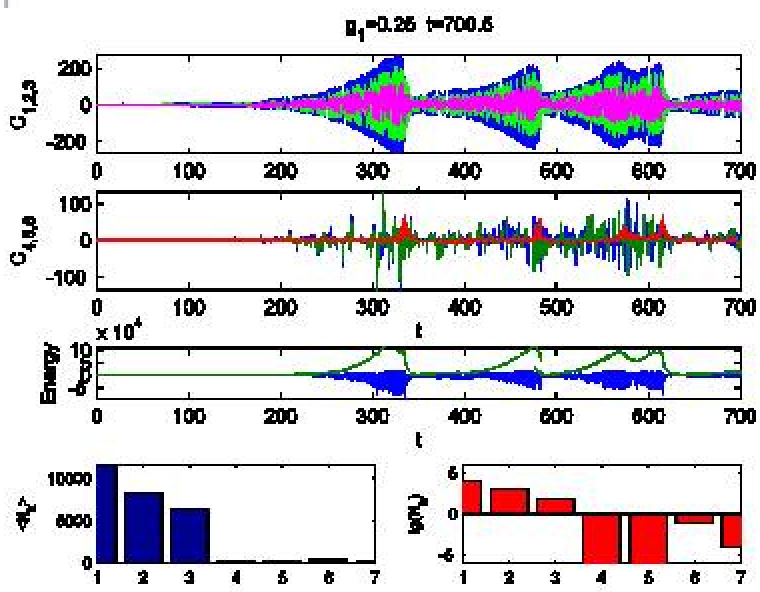
$$\left(\frac{\partial}{\partial t} - \gamma_{3+i} + i\delta\omega_{3+i}\right)C_{3+i} = iV_{1+i}C_1C_{2+i}^*$$

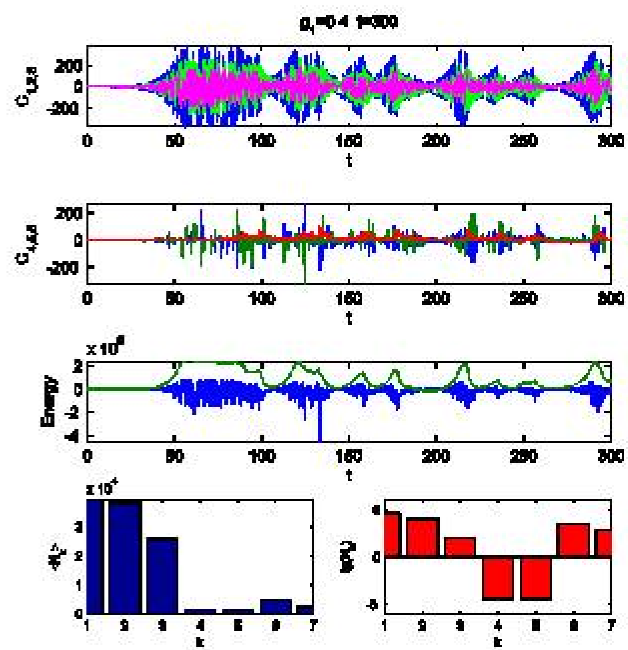
Few examples of simulations

B.Atamaniuk, S.A. Volokitin -Presentetd in Polish – Russian meeting, Warsaw, 16-22.10 2011









On the second figure it is possible to see situation (at given set of parameters) when only three waves really essential, inspite that there are 7 waves in the system.

-Presence of a population of charged dust can change the frequency of the fast wave, lead to additional damping due to ion–dust collisions, and change the conditions for wave growth.

- Heavy charged dust species in a plasma can both modify the properties of k instabilities and lead to new low frequency instabilities associated with the motion of the dust.

Moon is natural plasma laboratory
– dedicated to study turbulent processes in dusty plasma

Natural spacecraft "Moon", payload used for monitoring Sun, solar wind and the different region of magnetosphere.

Lunar orbiter photomosaic of orientale Basib showing groved ejecta pattern(hevelius Formation .JPL photo #LO-4-193M)-Lunar Sample Compendium

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