Collisions of Solitons

Fully kinetic simulation of plasmas

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Solitary waves

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in 1834 by John Scott Russell (Scottish civil engineer) accidentally

Soliton on the Scott Russell Aqueduct on the Union Canal near Heriot-Watt University, 12 July 1995.)
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Solitons survives collisions.)
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Kink solitons in DNA.

Importance:
- fundamental mode of nonlinear regime
- building block for our understanding of nonlinear world

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from plasma to Bose-Einstein condensates, to biophysics systems and to solit state physics,

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Soliton profiles in three different quantities, e.g. $n E \phi$.

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Solitary waves and solitons of different types have been observed in variety of plasma environments.

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first to be discovered, largely studied and observed

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Pros and Cons

♦ Reductive perturbation method:
   Pros: yields to KdV or KdV-like equations hence predicts temporal evolution,
   Cons: limited to small amplitude, ignoring kinetic effect such as wave-particle interaction

♦ Sagdeev approach:
   Pros: not limited in amplitude range,
   Cons: losing temporal evolution, ignoring kinetic effects

♦ Schamel Solutions:
   Pros: covering the kinetic effects
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The model

♦ Regime:
electrostatics, unmagnetized, collisionless

The set of Vlasov-Poisson equations:

\[
\frac{\partial f_s(x,v,t)}{\partial t} + v \frac{\partial f_s(x,v,t)}{\partial x} + q_s m_s E(x,t) \frac{\partial f_s(x,v,t)}{\partial v} = 0,
\]

\[
\frac{\partial^2 \phi(x,t)}{\partial x^2} = n_e(x,t) - n_i(x,t),
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coupled with the density integral over distribution function:

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Schematic representation of one time step.

Extrapolation

Poisson Solver

Pusher

Interpolation

Integration

Initial DF
Adopting the code to study solitons

♦ Initial condition:
- how to excite solitons self-consistently?
- we need to have distribution functions for each species
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any pulse breaks into a number of solitons
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Schamel Distribution Function

Definition:

\[ f_s(v) = \begin{cases} 
  A \exp \left[ - \left( \sqrt{\frac{\xi_s}{2}} v_0 + \sqrt{\varepsilon(v)} \right)^2 \right] & \text{if } v < v_0 - \sqrt{\frac{2\varepsilon_\phi}{m_s}} \\
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\[ A = \sqrt{\frac{\xi_s}{2\pi}} n_{0s} \text{ (amplitude)} \]
\[ \xi_s = \frac{m_s}{T_s} \text{ (normalization factors)} \]
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Schamel Distribution Function

♦ trapping parameters:

- $\beta$ controls the shape of trapped particles distribution functions,
- hollow ($\beta < 0$)
- plateau ($\beta = 0$)
- hump ($\beta > 0$)

cross section of distribution function on the velocity direction.
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Steps before Collision Study

♦ Starting Point:
a stationary pulse $v_0 = 0$ accompanied by a hole in electron distribution function
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♦ First Part of simulation:
-the stationary pulse breaks into two similar but counter-propagating pulses

♦ Second Step of simulation:
the chain formation takes place and number of solitons appears

♦ Third Step of simulation:
We isolate these solitons, then we have a zoo of solitons with different features (e.g. amplitude, height, velocity and $\beta$)

♦ Now we can study collisions:
insert these solitons into simulation box and study different scenarios
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One soliton

what soliton looks like on kientic and fluid level.

2_one_soliton_propgation.avi
Chain formation process creates 3 ion-acoustic solitons.
Evolution in Phase Space

First Step: break up of the stationary hole into two counter-propagating holes

Second Step: break up of the moving hole into number of holes (chain formation)
1) Overtaking Collisions

Scenario:
Collision of solitons propagating in the same direction with large relative velocity.

temporal evolution of number density.
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Findings:
- stability against mutual collisions
- exchange of trapped populations
- phase shift can be understood as a consequence of exchange of trapped populations
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1) Overtaking Collisions:

Evolution of electron holes

temporal evolution in phase space during overtaking collision.
2) Head-on Collisions

♦ Scenario:
Collision of solitons propagating in the opposite direction

♦ Findings:
Stability against mutual collisions, exchange of trapped populations, however, the dynamics of exchange is different from overtaking collisions.

♦ Collision movie:
3_Collision_two_soliton.avi
2) Head-on Collisions

♢ Scenario:
Collision of solitons propagating in the opposite direction

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Evolution of electron holes

Trapped populations rotate around each other during head-on collisions, some parts of trapped populations being exchanged [3].
Scattering Collisions

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Findings:
- solitons repel each other instead of just passing each other

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Evolution of electron holes

In case of overtaking collisions and small relative velocity the effect of trapped population cause two solitons to repel each other. **Solitons scatter** from each other instead of passing through.
Future steps:

Solitons in Multi-species Plasmas:

- usual solitons: dust-ion-acoustic solitons, and ...
- unusual solitons: **Supersolitons** are solitons with more complicated profile than usual solitons
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  • **Kappa distribution function** as the most successful candidate of modeling high-energy particles
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  - adopting **Sagdeev pseudo-potential** provides total control over the parameters
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Publications on Solitons

♦ Physical Review E:
Published 2 May 2017
Volume: 95, Issue: 5
Study of ion-acoustic solitons in presence of trapped electrons with a fully kinetic simulation approach

♦ Physics of Plasmas:
Published 16 March 2017
Volume: 24, Issue: 3
Simulation study of overtaking of ion-acoustic solitons in the fully kinetic regime

♦ Physics of Plasmas:
Published October 2016
Volume: 23, Issue: 10
Study of trapping effect on ion-acoustic solitary waves based on a fully kinetic simulation approach

♦ IEEE Transactions on Plasma Science:
Published June 2017
Volume: 45, Issue: 8
Kinetic simulation study of electron holes dynamics during collisions of ion-acoustic solitons
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