Vlasiator – Understanding near-Earth space in six dimensions

Minna Palmroth\textsuperscript{1,2}, Sebastian von Alfthan\textsuperscript{3}, Urs Ganse\textsuperscript{1}, Yann Pfau-Kempf\textsuperscript{1}, Sanni Hoilijoki\textsuperscript{1}

\textsuperscript{1}University of Helsinki, Helsinki, Finland
\textsuperscript{2}Finnish Meteorological Institute, Helsinki, Finland
\textsuperscript{3}CSC – IT Center for Science, Espoo, Finland
OUTLINE

Near-Earth space
- Plasma lab & space weather environment

Predicting space environment by modelling
- Present techniques
- Vlasiator: Paradigm change in physics & modelling
  - Technological highlights
  - Science highlights

Future
Space weather
Satellite environment

Satellites sail in plasma
1. Single event upsets
2. Aging due to harsh radiation

- Navigation satellites
- Weather satellites
EMERGING MEGATREND

Number of all spacecraft

2017: 600 launches booked (most of them commercial)

Commercial “New Space”

Cold war
Worst case scenario


Power System Disturbance and Outage Scenario of Unprecedented Scale

Areas of Probable Power System Collapse Resulting from Severe Geomagnetic Storm

Direct damage: $2.6 \cdot 10^{12} (€2.1 \cdot 10^{12})
Recovery time 4 – 10 years

Affected regions involve population of >130 million

Dot size reflects risk of power node failure
“there is one risk that is head-and-shoulders above all the rest in terms of the scope of potential damage adjusted for the likelihood of occurrence”
- Paul Singer, Elliott Management Corp.
Future space weather forecasts are based on Modelling
Charged particles in a magnetic field

Ion physics: 10 – 100 km

Electron physics: 1 – 10 km
Present modelling tools make a lot of approximations.

- Plasma is a fluid having one temperature.
### GLOBAL MODELLING TECHNIQUES

<table>
<thead>
<tr>
<th></th>
<th>Global fluid (MHD)</th>
<th>Hybrid particle-in-cell</th>
<th>Hybrid-Vlasov (Vlasiator)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ions</strong></td>
<td>Fluid</td>
<td>Particles</td>
<td>Distribution functions</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td>Fluid</td>
<td>Fluid</td>
<td>Fluid</td>
</tr>
<tr>
<td><strong>Run time</strong></td>
<td>Real-time to weeks</td>
<td>Weeks</td>
<td>Weeks – months</td>
</tr>
<tr>
<td><strong>Scale of applications</strong></td>
<td>Fluid scale (1000 km)</td>
<td>Ion kinetic effects (10 – 1000 km)</td>
<td>Global = Solar wind, magnetosphere (+ ionosphere)</td>
</tr>
</tbody>
</table>

Now: Solar system

Image credits: Karimabadi, 2014; vlasiator.fmi.fi
GLOBAL MODELLING TECHNIQUES

<table>
<thead>
<tr>
<th>Data</th>
<th>Particle-in-cell (PIC)</th>
<th>VLASIACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D cut of 3D distribution function</td>
<td>2D distribution function</td>
<td>3D distribution function</td>
</tr>
<tr>
<td><strong>Blanco-Cano et al. [2006]</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Global fluid (MHD)</th>
<th>Hybrid particle-in-cell</th>
<th>Hybrid-Vlasov (Vlasiator)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ions</strong></td>
<td>Fluid</td>
<td>Particles</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td>Fluid</td>
<td>Fluid</td>
</tr>
<tr>
<td><strong>Run time</strong></td>
<td>Real-time to weeks</td>
<td>Weeks</td>
</tr>
<tr>
<td><strong>Scale of applications</strong></td>
<td>Fluid scale (1000 km) Now: Solar system</td>
<td>Ion kinetic effects (10 – 1000 km) Global = Solar wind, magnetosphere (+ ionosphere)</td>
</tr>
</tbody>
</table>

**GLOBAL MODELLING TECHNIQUES**

- **GLOBAL MODELLING TECHNIQUES**
- **VLASIATOR**
- **DATA**
- **Particle-in-cell (PIC)**
- **VLASIATOR**

**Data**

- 2D cut of 3D distribution function

**Table**

<table>
<thead>
<tr>
<th><strong>Global fluid (MHD)</strong></th>
<th><strong>Hybrid particle-in-cell</strong></th>
<th><strong>Hybrid-Vlasov (Vlasiator)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ions</strong></td>
<td>Fluid</td>
<td>Particles</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td>Fluid</td>
<td>Fluid</td>
</tr>
<tr>
<td><strong>Run time</strong></td>
<td>Real-time to weeks</td>
<td>Weeks</td>
</tr>
<tr>
<td><strong>Scale of applications</strong></td>
<td>Fluid scale (1000 km) Now: Solar system</td>
<td>Ion kinetic effects (10 – 1000 km) Global = Solar wind, magnetosphere (+ ionosphere)</td>
</tr>
</tbody>
</table>

**Blanco-Cano et al. [2006]**

**2D cut of 3D distribution function**

**3D distribution function**
\[
\frac{1}{t} f(r, v, t) + v \cdot \nabla f(r, v, t) + a \cdot \nabla f(r, v, t) = 0
\]

- **Advection (R)**
- **Advection & rotation (V)**

- **e^{-} charge-neutralising fluid**
- **p^{+} distribution functions**
  - Multi-temperature physics
  - Noise-free

- Divide real space into grid cells
- Compute \( \mathbf{E}, \mathbf{B} \) fields in real space
- Each real space cell contains a 3D velocity space
- In 6D, propagate distribution function using Vlasov equation
  - Couple back to ordinary space to compute \( \mathbf{E}, \mathbf{B} \) fields
Challenges in a nutshell

- Huge volume
- Dense (ion-scale) grid
- Grid calculations in six dimensions, in time
  - 5 - 10 M real space cells
  - In total $10^{12}$ total phase space cells
  - Over $10^5$ time steps
PARALLELIZATION ON THREE LEVELS

1. Across nodes on clusters & supercomputers - MPI
   - Domain decomposition of real space
   - Implemented by DCCRG library (https://github.com/fmihpc/dccrg)
   - Frequent load balancing
2. Across cores on nodes – OpenMP
3. Across core – Vectorization
VLASIACTOR
VERSION HISTORY

ERC grant 2007
- Literature
- Prototypes

2009

Finite volume Vlasov
- EM-fields from global MHD

2011

Coupled hybrid-Vlasov
- New field solver
- Access to Europe’s largest machines
- First global runs

2012

2015

- New solver (Hall)
- Optimized parallel computations
- Ecliptic and polar runs
- Several papers
- Ecliptic runs released for collaborators
NEWEST PROGRESS

- Support for multiple ions
- Improved boundary conditions
- New scaling results

Relative performance* of Vlasiator

- Hi-res 3D
- Hi-res 2D 5th order solver
- Lo-res 2D
- Temporal subcycling
- Ordinary space AMR
- Velocity space adaptive mesh refinement (AMR)
- Sparse distributions

Performance development of supercomputers (www.top500.org)

*) Normalised to effective physical resolution simulated in identical wall-time

HLRS, Stuttgart
NEWEST PROGRESS

1. CSC’s Intel Parallel Computing Center optimisation results
   • 45% faster on KNL node than original performance on one Haswell node
   • 112% faster than original performance on KNL
2. PRACE and national grants
   • 2012: Tier-0 Hornet (30 M CPUh)
   • 2013: Tier-1 grant (4 M CPUh)
   • 2014: Tier-0 Hazelhen (24 M CPUh)
   • 2016: Tier-0 Marconi (75 M CPUh)
   • + 2 Grand Challenge national grants (25 MCPuh)
3. Simultaneous algorithm development
   • Normalising 75 M CPUh KNL-Marconi corresponds to
     • 30 M CPUh on national sisu
     • 38 M CPUh on Hazelhen
4. Excellent scalability on Cray XC and Marconi
   • Flexible & fast, portable on almost any architecture – Vlasiator core strategy!
Old paradigm
Science highlights
Small-scale physics affects large scales and vice versa.

Palmroth et al., 2015
Pfau-Kempf et al., 2016

- Wave
- Bulge
- Additional reflection
- Transient foreshock
**SECOND ERC GRANT IN 2015**

**Prestissimo project:**
**ERC Consolidator grant 2015 (2016 – 2021, 2 M€)**

<table>
<thead>
<tr>
<th>Assets</th>
<th>Target</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERC StG 2007</td>
<td>Observational energy transfer</td>
<td>Is global Vlasov simulation possible?</td>
</tr>
<tr>
<td>3D description of near-Earth space</td>
<td>World’s only global hybrid-Vlasov code “Vlasiator”</td>
<td>Answering grand questions</td>
</tr>
<tr>
<td>Local physics</td>
<td>- Shocks</td>
<td>Other applications:</td>
</tr>
<tr>
<td>- Reconnection</td>
<td>- Acceleration</td>
<td>- 24/7 space weather service</td>
</tr>
<tr>
<td>- Precipitation</td>
<td>Global context</td>
<td>- Climate effects</td>
</tr>
</tbody>
</table>

**Yes!**

- Cutting-edge computing architecture
- Newest spacecraft
- 24/7 space weather service
- Climate effects
- Heliosphere

Open tools and data: Multiply gain
OTHER AVENUES

• In future: Space weather
• Fusion: First back-of-the-envelope estimations
  • 6D tokamak geometry in ion scales
  • Possibly other geometries as well
• Spacecraft instrument optimisation
• Testing code for different HPC architectures
  • Experience on different architectures
  • Scaling benchmarks from largest European machines
Success is not final, failure is not fatal. It is the courage to continue that counts.

Winston Churchill