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PHYSICS-BASED MODELLING OF THE LIFE CYCLE OF ENERGY IN THE SOLAR SYSTEM

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Abstract. Energy in the solar system is constantly being converted from one form to another. Often these processes take the form of dramatic events such as solar eruptions or geomagnetic storms with important societal impacts. Understanding energy conversion and magnetic storms is one of the grand challenges facing science and poses a great cultural and scientific puzzle. We plan to use a new modelling approach based on combining state of the art supercomputers with state of the art numerical methods that allow us to capture the key aspect in energy conversion: the interplay of small and large scales. At the core of energy conversion is the ability of macroscopic systems to store and process vast amounts of energy while at the same time requiring microscopic processes at the moment the energy is released. To describe and predict how energy can be stored for long periods and why it is then suddenly released, a complete description down to the level of tracking the trajectory of single particles is needed.

1 Introduction

The Sun is the central engine of our solar system. Matter is converted into energy by nuclear fusion in the core of the Sun and it propagates outward providing for the light and heat that make life possible on the Earth.

Light and electromagnetic radiation are not the only form of energy emanating from the Sun. A flow of ionized gas, called solar wind, is emitted from the Sun. The solar wind is highly variable in space and time and is accompanied by a magnetic field generated by the Sun. The matter inside the Sun is so hot that electrons and ions that normally form atoms become separated and are able to move more freely in what is called the forth state of matter: the plasma. The motion of matter within the Sun produces strong electric currents that in turn produce magnetic fields via the dynamo process. As the name suggests the principle is the same as

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in a bicycle, where the motion of the wheel is turned into electrical energy. The electrical energy produced in the Sun is of course of extremely large magnitude and can affect the whole solar system.

The solar wind is far from being a constant uniform flow and it is perturbed irregularly by large disturbances called magnetic storms. The sun atmosphere, the Corona, forms regions where matter and energy are stored and suddenly released in the form of large eruptions (called coronal mass ejections) or of solar flares. The solar wind and its disturbances propagate outward in the solar system, eventually reaching the Earth environment and provoking a rich and diverse range of events and evolutions collectively referred to as space weather. The Earth has its own magnetic field that encases and protects the Earth environment, called magnetosphere. The solar wind shapes the magnetosphere and makes its structure, shape and size dependent on time in consequence of the variations of the solar wind and of the arrival of space storms.

The goal of the present discussion is to describe how to advance the state of the art in our understanding of the life cycle of the energy produced by the Sun and interacting with the Earth in the form of electric currents, magnetic fields and solar wind. Our approach is theoretical and aimed at modelling the processes using the most modern supercomputers. Our ultimate goal is not only to understand the underlying physics but also to use our software tools to predict the evolution of the space storms of greatest societal impact.

2 The crucible of uncertainty

The current state of the art in modelling energy transfer events in the space weather is summarised by Gombosi (2004), Quinn *et al.* (2009), Tóth *et al.* (2005). Several models have been developed to cover the different regions of space (solar photosphere, solar corona, interplanetary space) and of the Earth environment. The science community is now facing the challenge of coupling these models (Kumar 2010). At the core of the problem is that some of the models are fluid and others are kinetic. A fluid model describes space via average quantities such as density, flow or temperature. A kinetic model, instead, is based on a more in depth knowledge of the distribution function of the particles in the system. The basic description of the two approaches is different, fluids on one side and particles on the other. Joining this two approaches is at the centre of the complexity we are facing in dealing with energy conversion in space. This is a common challenge in many frontier areas of science and engineering where micro-macro coupling is relevant and the present project will benefit from the current state of the art in many other fields (related fields such as plasma physics or climate research but also industrial processes and many more). Micro-macro coupling is perhaps the key problem for all modellers and designers.

The crucial puzzle in understanding the life cycle of energy in space is that the macroscopic evolution of the whole system hinges on the onset of localized processes (Birn & Priest 2007; Daughton 2011; Intrator *et al.* 2011). For magnetic energy to be converted in other forms, primarily in the kinetic energy of particle flows and heat, local dissipations need to become active. The key to grasp the challenge is that within a macroscopic description energy conversion requires resistivity. Just like electrical energy is converted into heat in a wire by electrical resistance, the magnetic energy of the Sun needs resistivity to be converted into kinetic energy. Yet all macroscopic models and observations at the large scales point to the presence of very small resistivity in the real space plasmas. Only small-scale processes at the microscopic level where single particle trajectories become important have the ability to provide the effective dissipation mechanisms that enable energy conversion.

3 Our approach

We focus here on a new approach that allows us to model the macroscopic evolution of space storms while retaining sufficient local resolution to capture the microscopic physics that leads to the energy conversion. The spear of our effort is the implicit moment method, a technique to capture multiple scales developed at the Los Alamos National Laboratory (Brackbill & Forslund 1982; Lapenta *et al.* 2006) and currently being developed by the research group of the KU Leuven led by the author (Markidis *et al.* 2010; Lapenta 2011).

The philosophy of our approach to address the fundamental questions in modelling the space environment is to develop new methods (mathematical models, algorithms and software) and use new upcoming computing resources forming a combined plan to use the most advanced understanding and the best available resources to arrive at a predictive tool. These two coordinated lines of investigations are summarized next.

First, we want to further develop the implicit moment method to include an adaptive capability. The implicit moment method uses a common mathematical infrastructure (see Brackbill & Forslund 1982; Lapenta *et al.* 2006; Lapenta 2011) for details) that includes both moments (*i.e.* fluid quantities and fields) and particles. The method handles therefore both description and has the best potential to allow the needed multiphysics coupling. To reach that goal we need to add the ability to treat multiple levels of resolution. Previous research has used only one level of description per each simulation. The same code is able to treat fluid or kinetic levels just changing the parameters that are used to run. But we need now the ability to run multiple levels at the same time and have them communicated with each other and transfer information. This is a ground breaking new capability but one that is an incremental change to what we are already doing. Adaptive methods have now been used for a number of years to adapt the resolution but the new frontier in developing physics-based predictive tools is to adapt the physics model. At the macroscopic level there is no need to track particles and it is sufficient to describe only average fluid quantities (such as density, flow or temperature, the fluid approach) but in regions of energy conversion the particle motion becomes important and a different more advanced approach is needed: the kinetic description where a statistical sample of particles is tracked and their motion is followed in detail. The challenge is to couple correctly the fluid and kinetic approach. The implicit moment method provides the ability to do that.

Second, we want to harvest the ever increasing power of supercomputers. To model great challenges such as the evolution of space storms and their impact on the Earth it is not enough to focus on the physics and on the sophistication of the models used. One has to pay attention to the ability of such models to run with maximum efficiency on the modern computers composed by thousands and soon millions of computing cores. This high parallelism requires the physics model to be able to be distributed over such an extremely large computing base. We have developed a new approach in our iPIC3D effort to handle such complexity (Markidis *et al.* 2010). IPIC3D benefits by being the target application of the INTEL Exascience Lab Europe (`www.exascience.com`). The author is the leader of the Applications Division of this INTEL lab and the expertise of tens of the world leading computer scientists is brought to bear on maximizing the efficiency of the simulations describe here to study space events.

This two-pronged approach, focusing both on the physics and on the computing aspects of the modelling of space events, has the highest chances to lead Europe towards its needed space-forecasting infrastructure. While our approach is theoretical, observations from satellites and form the ground are a crucial aspect, providing verification of the results and needed input to drive the predictive tools.

4 The implicit moment method

The key to address the multiple scale challenge is the use of the most advanced algorithms to deal with the computational implementation of the proposed prediction simulations. Computationally, both fluid and kinetic approaches have been dominated by explicit methods. Explicit techniques are well known for being conceptually simple and of straightforward implementation.

The concept is illustrated in Figure 1. In the explicit approach, the coupled equations for particles (Newtons equations) and fields (Maxwells equations) are decoupled and solved in sequence. The simplicity of breaking the coupling is paid in terms of the flexibility of the method.

For explicit kinetic modelling, two constraints need to be satisfied. First, they need to resolve the fastest time scale (typically the electron plasma frequency for space plasma simulations) supported by the model, which may be orders of magnitude faster than the dynamical time scale of interest. Furthermore, explicit methods need to resolve also the smallest spatial scale, the Debye length that is typically several orders of magnitude smaller than the other scales of interest. In the hourglass representation of scales, the explicit method is stuck at the bottom of the hourglass. The explicit methods fail completely (energy is no longer conserved) if an attempt is made to reduce the resolution. Even in areas of space where no processes of significance are developing at the smallest scales still the explicit approach needs to be dialed to the maximum resolution or it would fail. Given these limitations, the fact is that 3D explicit fully kinetic simulations for realistic choice of parameters will remain out of reach in the foreseeable future. Therefore,

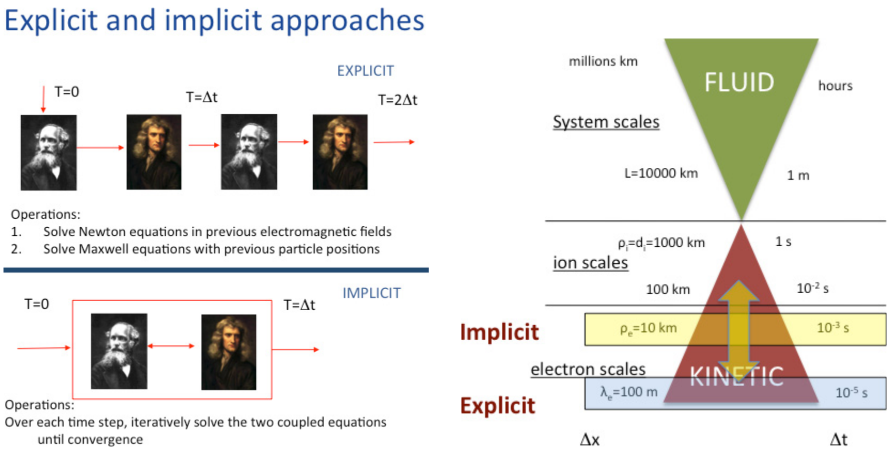

Fig. 1. Explicit and Implicit methods compared. The principle is shown on the left, the stability constraints are illustrated on the right. The explicit method (cyan) is forced to resolve all scales everywhere at all times. The implicit method (yellow) is mathematically more difficult but can select the local resolution as needed, without waste of unnecessary resources.

we have taken a different approach that serves as the motivation for the proposed work: the use of implicit methods.

In implicit methods the coupling of fields and particles is retained correctly and is dealt with using advanced numerical methods (Brackbill & Forslund 1982; Lapenta *et al.* 2006; Lapenta 2011). Implicit methods allow one to average over fast time scales and small length scales to focus on the dynamical scales of interest. Implicit methods have been shown to be free from both spatial and temporal limitations, and as a consequence have been able to push the limits of kinetic plasma physics simulation to regimes that explicit methods have not been able to reach, even with the use of powerful supercomputers. In the hourglass representation of scales of Figure 1, the implicit methods allow us to move the level of resolution up and down the hourglass as needed by the local conditions, allowing us to reach full resolution where required and avoiding unnecessary waste where no important process is developing on small scales. Thus, implicit kinetic approaches not only deal with multiple time scales, but are by design ideally suited to deal with multiple length scales in a reliable manner.

Our approach is condensed in the iPIC3D code (Markidis *et al.* 2010). The core idea of the implicit moment method is described intuitively in Figure 2. The fields and the particles are studied together in a coupled manner. The word implicit refers to the ability of the method to advance both fields and particles together without any lag between the two (the time lag is a typical aspect of the explicit methods, instead). The word moment refers to the use of moments of the particle distribution. The moments are local statistical averages that characterize the

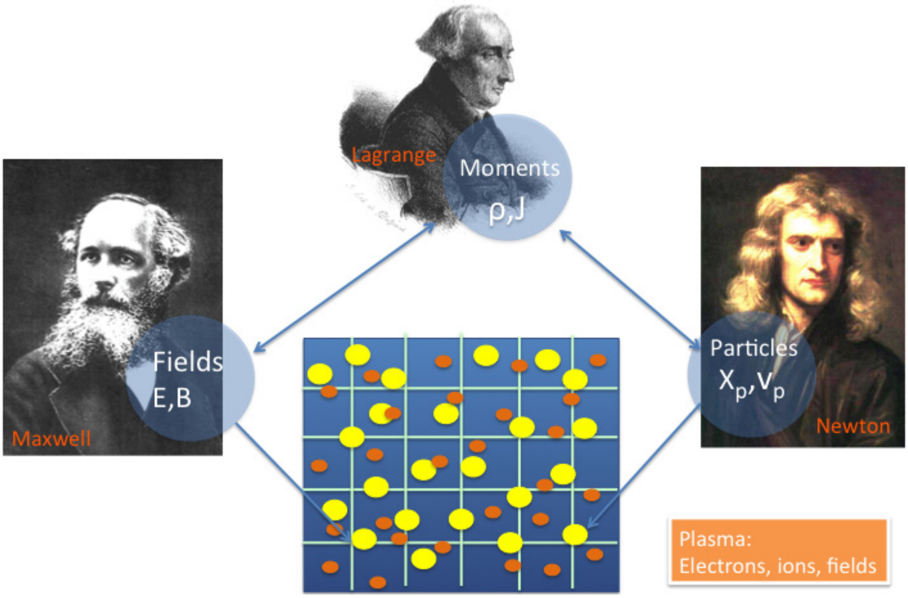

Fig. 2. Agents in the implicit moment method. The plasma particles (electrons in orange and ions in yellow) evolve in a grid for the electric and magnetic fields. The Maxwell equations controls the fields and the Newton equations the particle. The Implicit Moment Method introduces the moments in Lagrangian form to handle the multiple scales and to allow the user the desired accuracy.

particle properties. The implicit moment method allows us to select the local level of resolution according to the scales of the local processes. This feature allows to model space events with the minimum effort, increasing the resolution only where absolutely needed.

Recently the approach has been extended to include a multilevel formulation (Innocenti *et al.* 2011) where different levels of resolution are applied in different regions according to the local scales of the processes developing.

5 The impact

The moment for the research described here could not be more ripe: all major space-faring powers are developing space-forecasting tools. There is a strong recognition of the grave impact that space storms can have on the economy and on human life. Recently a new discipline has been introduced, space weather (Bothmer 2006), to refer to the study of the space environment in analogy to the meteorology of the Earth. Space weather tracks the space magnetic storms and their impact on the Earth just as meteorology tracks atmospheric storms. Space weather can have a very dramatic impact. Remaining at a sound scientific level

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without yielding an inch to the dramatization of certain popular media inspired by the infamous Maya calendar, one can briefly identify three serious and internationally recognized impacts:

First, space activities and human life are in constant danger in space. Space is a highly hostile environment ripe with radiation produced by the Sun and by space weather events, with the threats peaking dramatically during storms. The risk is present for the current space activities with many instances of lost or damaged satellites. But in light of an optimistic view towards future space exploration, manned and robotic missions to the Moon and Mars or to deep space are at a great danger from space weather events.

Second, ground infrastructures, telecommunications and global positioning systems are affected very negatively by space weather. Examples of black outs have been numerous and related to even relatively minor events, leaving the troubling question as to what will be the impact of the most powerful events. The most cited example is that of the great storm observed by Carrington (1859). At the time the damage was limited to the telegraph lines, but the modern infrastructure is much more complex and much more subject to damage with extremely high economical costs. Space-based global positioning systems (GPS) produce incorrect readings during magnetic storms. Other communication infrastructures are also impaired with costly impact for example to airlines and to the ever expanding sectors relying on GPS.

Third, the Earth climate is affected by space events. Two routes are under investigation: the variability of the radiation emitted by the Sun (both the total integrated energy called total solar irradiance and its spectrum) as well as the variability of the cosmic ray flux. Both have different impacts on different strata of the atmosphere and on the cloud cover, contributing to the cooling or heating of the Earth. Of course, this aspect of space weather modelling has an acute present interest.

6 Conclusions

The research described addresses a grand challenge, but one that comes as the natural evolution of the current state of the art. At the core of modern high performance computing research is the ability to model the complexity of real systems where a complex interplay exists between different processes developing on different scales and behaving according to different physics, modelled by different mathematical models. The application to space is an important example, particularly so for the limited access to space that prevents the direct experimental approach and limits the availability of direct *in situ* data. Computer simulation is a cornerstone in the prediction of space events and in the planning of human and robotic missions. But the results of the present investigation will open new possibilities in many others areas of science where the coupling of multiple scales and multiple physical descriptions is a key issue. And there are no shortages of those.

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