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The implicit moment method to treat micro-macro coupling and multiple physics in space weather modelling

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The simulation of the physics of the space environment connecting the Earth and the Sun requires handling a multiplicity of temporal and spatial scales ranging from the microscopic physics where the single particles (electrons and ions) interact with each other and with local electric and magnetic fluctuations to the macroscopic scales encompassing the whole system. Similar or even more extreme ranges of scales also develop in time and are typical of all solar and space problems. Furthermore, a multiplicity of physics models needs to be deployed. For the smaller scales it is necessary to retain a full kinetic model where the statistical behaviour of the particles is described in terms of the probability of finding particles in a certain position with a certain speed. For larger scales this detailed approach is not feasible and not necessary: fluid models need to be used to provide just the spatial distribution of average properties of the plasma (such as density or temperature). Finally in many processes, the effects of radiation, interaction with neutral particles form planetary atmospheres and other physics need to be included.

The implicit moment particle in cell (ImPIC) method provides a possible route to address the presence of multiple scales and multiple physics effectively. The present work has three goals. First, we review the state of the art in the ImPIC technology and present the most modern implementation as found in the single processor CELESTE3D code and in the parallel PARSEK code. While many of the algorithms involved have been developed in the past, the present work reports how the ImPIC is currently implemented and what specific algorithms have been found to work best. We focus specifically on the latest developments: a new implementation of the Maxwell solver and a new particle mover based on a Newton-Krylov nonlinear solver for the discretized Newton's equations and the performance improvements of the parallel implementation. Second, a key aspect of our research is to develop and deploy novel methods to describe such multi-scale and multi-physics coupling using tools already at our disposal. In particular, the ImPIC method already couples the fluid and kinetic description required for multiple scales and multiple physics applications. In the existing version, the coupling is homogenous in space so that both fluid and kinetic models are solved together in the whole domain. The major new development is the generalization of the method so that only the fluid model is solved everywhere, but the kinetic model (much more costly) is solved only where needed. Furthermore, we are expanding the range of physics handled by including relativistic effects, interaction with neutrals and with radiation. Finally, two paradigmatic examples are shown: 1) the formation and extension of a reconnection x-line in the solar wind and 2) the interaction of small-scale instabilities with large-scale reconnection in the Earth magnetopause and magnetotail.

1. Extended reconnection x-lines in the solar wind: The dynamics of x-line formation and evolution in 3D magnetic reconnection is studied using a fully kinetic approach. An x-line of small length is initialized using a perturbation localized in the current direction. The electrons and ions drift diamagnetically along the current direction of the initial x-line and are further accelerated by the reconnection electric field. The electron and ion motion is in opposite directions and each species extends one end of the x-line. Several predictions based on this picture are formulated and studied and confirmed under parameter variation. Expansion can proceed at a significant fraction of the Alfvén speed, in both directions.

2. Micro-macro coupling in space-weather reconnection Reconnection processes and microscopic current aligned instabilities develop concurrently with a strong mutual interaction. The two processes develop on widely separated scales but the ImPIC approach presented here can effectively handle it. We present the results of the application of our method to realistic configurations relevant to space weather reconnection events. The true cause of the onset of reconnection is linked to the modes propagating in the current direction and particularly to the lower hybrid drift instability (LHDI). The LHDI is shown to cause 3 modifications of the initial Harris configuration: creation of a velocity shear, introduction of temperature anisotropy and thinning of the initial current profile. These effects cannot simply be summarized in terms of anomalous resistivity added to standard fluid models and can be represented accurately only relying on the full kinetic model of ImPIC.

References:

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