1 The Interaction Between the Solar Wind and Planets

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To study the interaction between planets and the solar wind, in-situ observations need to be complemented by computer modeling for several reasons. First of all, observations are local in time and space, and secondly, using computer models it is possible to make parametric studies that would be difficult or impossible from observational data. Modeling of the interaction between the solar wind and planets are usually done by fluid magnetohydrodynamic models (MHD), or hybrid particle models where ions are particles and electrons are a massless fluid. The MHD fluid approximation is however questionable when the gyro radius of the ions are large compared to the object studied, as is the case for, e.g., the Moon and for Mars. The advantage of MHD models is that they are less computational expensive than particle models. That particle models are computationally expensive means that their accuracy suffers. For example, in my opinion, no particle simulations of the Moon-solar wind interaction has been done to date with a sufficient number of particles to produce reliable results. All simulations has been sequential, limiting the number of ions to tens of millions, and limiting the simulation time so that convergence to a steady state is not achieved.

During several years we have developed a general simulation software for modeling the interaction between the solar wind and Solar System objects. The development and verification of the simulation software is closely linked to the unique observations by our instruments measuring ions, electrons and energetic neutral atoms (ENAs) at Earth, the Moon, Mars and Venus; and at Mercury and a comet (and possibly Jupiter) in the future. The software is built on the public available FLASH software, developed at the University of Chicago, that provide adaptive grids and is fully parallelized. FLASH is a general parallel solver for compressible flow problems. It is written in Fortran 90, well structured into modules, has good support, and is open source. The parallelization is to a large extent handled by the Paramesh library that implements a block-structured adaptive cartesian grid with the Message-Passing Interface (MPI) library as the underlying communication layer. What we add is the problem specific software to solve solar wind-planet interaction problems. We have already added the modules needed for magneto hydrodynamic (MHD) fluid simulations of the interactions. This was used to study the ENA emissions from comets[2]. Also, we have studied the production of ENAs at extrasolar planets[1, 3]. Recently we have developed a hybrid solver (ions as particles and electrons as a fluid) based on the same software[6]. It is a general solver that is applicable to all interactions between the solar wind and solar system objects. The software has undergone testing and verification against published results, e.g., ion beams and shocks. The first application has been to model the Moon-solar wind interaction. In particular, we have examined the effects of reflected solar wind protons on the global interaction, and compared the model results with observations by our SWIM ion detector on Chandrayaan-1[5].

With our hybrid model, the fact that the solver is parallel has allowed us to do giga-particle simulations, i.e. a factor of 100 times more particles than used in previously published 3D simulations of the Moon-solar wind interaction. Along with a cell size down to 35 km, this allows us to not only resolve the ion inertial length for the first time, but it also enables time dependent simulations, e.g., studying variations in solar wind conditions. In contrast, most published hybrid model results for the interaction between the solar wind and solar system objects are for steady state solutions and have been averaged over many time steps. That the code scales well for large problems is shown in Figure 1. This means that we can handle ever increasing problem sizes by adding more processors. In this case up to more than three billion particles, but nothing in the code should prevent scaling to even larger problem sizes given more available processors.

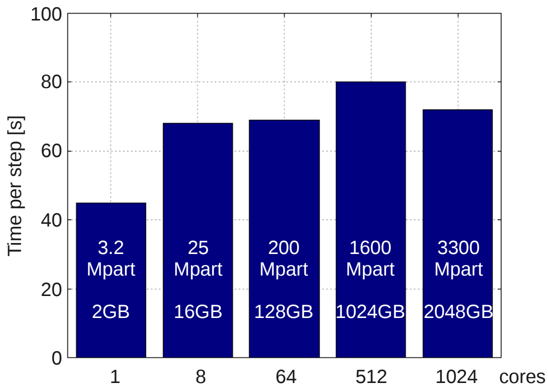

Figure 1: Timings for the hybrid solver, illustrating that the code scales well for large problems. Ideally, when we increase the problem size (the number of particles and the number of grid cells), and the number of processors, by the same factor, the run time should be constant (weak scaling). Since there always is some overhead for the communication between the processors, this ideal will never be achieved. However, we see that the wall clock time required for a time step for this particlular test is constant around 70 seconds independent of the number of cores. All runs were done on the Akka cluster at the High Performance Computing Center North (HPC2N) at Umeå University, Sweden. A 672 node cluster with an Infiniband interconnect, where each cluster node has two quad core Intel Xeon processors and 16 GB of RAM.

This ability of the code to handle high resolution grids, and the associated large number of particles, enables new insights into the studied processes. An example of this is shown in Figure 2 where we have run the code for the same Moon-solar wind interaction parameters with decresing cell sizes. New features of the interaction emerges when the resolution is increased, e.g., magnetic field disturbances similar to Alfven wings are clearly seen in the high resolution runs, and the wake field increase moves closer to the Moon. Such high resolution runs are especally important for comparison with Chandrayaan-1 observations with its orbit at only 100 km altitude.

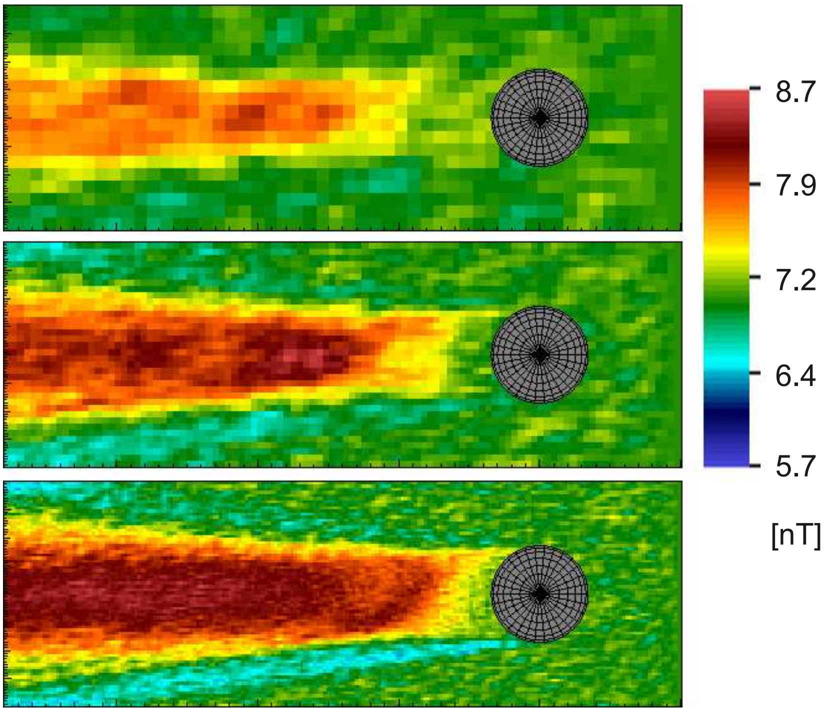

Figure 2: The effect of increased spatial resolution. Magnetic field magnitude [nT] in the ecliptic plane for the Moon-solar wind interaction. From top to bottom the cell size is halved for each panel (the total numer of cells is multiplied by eight). The cell sizes are 440, 220, and 110 km. The number of particles per cell is kept constant at 60. The wall clock time is three hours for all three runs since they are executed on 1, 8, and 64 cores.

Publications

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[2] A. Ekenbäck, M. Holmström, S. Barabash and H. Gunell: *Energetic neutral atom imaging of comets*, Geophysical Research Letters, **35**, pp. L05103, 2008.

[3] M. Holmström, A. Ekenbäck, F. Selsis, T. Penz, H. Lammer and P. Wurz: *The origin of hydrogen around HD 209458b — reply*, Nature, **456**, pp. E1, 2008.

[4] A. Ekenbäck, M. Holmström, P. Wurz, J-M. Grießmeier, H. Lammer, F. Selsis and T. Penz: *Energetic neutral atoms around HD 209458b: Estimations of magnetospheric properties*, The Astrophysical Journal, **709**, pp. 670, 2010.

[5] M. Holmström, M. Wieser, S. Barabash, Y. Futaana and A. Bhardwaj: *Dynamics of solar wind protons reflected by the Moon*, Journal of Geophysical Research, in press, 2010.

[6] M. Holmström: *Hybrid modeling of plasmas*, Proceedings of the 8th European Conference on Numerical Mathematics and Advanced Applications, in press, 2010.