A local approach to the numerical study of a Coronal Mass Ejection in its interplanetary evolution

Student : Mattia Sangalli (mattia.sangalli@unifi.it)
Supervisors : Dr. Andrea Verdini (andrea.verdini@unifi.it)
Prof. Simone Landi (simone.landi@unifi.it)

Scholarship title: Development and application of computational methods for studying the interaction of coronal mass ejections with the solar wind and Earth magnetosphere

Research interests

My research interests as a Ph.D. student are mainly focused on numerical methods and computational physics, especially regarding fluid dynamics, magnetohydrodynamics, plasma physics and their application to solar physics. In particular, during my Ph.D. I'm going to study the evolution of a coronal mass ejection (a product of solar activity) during its evolution through the heliosphere. Using a "local" approach, I intend to investigate the role of the small-scale physical processes (such as turbulence) in the propagation and evolution of coronal mass ejections, through high-resolution magnetohydrodynamic numerical simulations.

Research project

Coronal mass ejections (CMEs) are large-scale expulsions of plasma and magnetic field from the cromospheric and coronal regions of the Sun. They are known to be one of the most important drivers of large geomagnetic disturbances. After being ejected, they expand as they propagate in the heliosphere [1] with speeds ranging from about 100 km/s up to peaks of 3000 km/s (average speeds around $400 \div 500$ km/s), reaching $R = 1$ AU with average Sun-to-Earth transit times of ≈ 80 hours. These interplanetary counterparts of the CMEs are called Interplanetary CMEs (ICMEs). The fastest-moving ICMEs can reach 1 AU in as little as 15 h.

Since the eruptions on the Sun's surface are rather abrupt and sudden, the main way to come up with predictions for the Sun-Earth transit time of an ICME is to understand its interplanetary evolution.

It is known from observations (see e.g. [2]) that ICMEs usually accelerate or decelerate towards the ambient solar wind velocity. A common physical interpretation is based on a drag force acting on the ICME, caused by the velocity difference between the ICME itself and the ambient SW [3]. Similar descriptions are used in (semi)analytical models for forecasting the ICMEs' arrival time at Earth, such as the Drag-Based Model (DBM) [4].

The Sun-Earth transit time of an ICME is one of the fundamental parameters for defining its "geo-effectiveness" (how probably it might produce disturbances on the Earth's magnetosphere); other important parameters include the angular direction of the ICME motion (with respect to the Sun-Earth direction) and the presence of a magnetic field component in a direction opposite to the Earth's magnetic field, which would possibly cause a magnetic reconnection event, yielding a topology change and an energy release when the ICME impacts on Earth.

A good fraction of the observed ICMEs, usually estimated as 30%, contains a magnetic cloud, more precisely a magnetic flux rope [5]; the solar wind also has a magnetic field, namely Parker's spiral [6]; such magnetic structures can interact and magnetic reconnection processes ("flux rope erosion") are reportedly common [7]. In addition, both the solar wind and the ICMEs present turbulent fluctuations.

The current leading models for operational space weather forecasting are semi-analytical models (e.g. the DBM) and "global" MHD simulations, which yield similar errors in their estimates; the former however are computationally lighter and thus preferable.

Both approaches have limitations: the semi-analytical models rely on the aerodynamic drag force interpretation, which however may not be appropriate for describing a magnetic flux rope moving in the magnetized solar wind. The "global" simulations, despite capturing the large-scale dynamics of the CME-SW interaction, cannot achieve large Reynolds numbers that instead characterize nonlinear processes such as turbulence and magnetic reconnection.

My aim for this Ph.D. is to follow the evolution of an ICME through the heliosphere using a local, comoving reference frame; this makes it possible to fully exploit the high numerical resolution and focus on the meso- and small-scale interaction between the magnetic flux rope and the ambient solar wind. By doing so, the lack of "microphysics" in global simulations can be addressed, and the results might be used to improve the theoretical basis of the better-performing semi-analytical models.

In particular, the current idea is to use a 2.5D (2-dimensional dynamics, 3-dimensional vector fields) visco-resistive compressible MHD simulation code, with advanced boundary treatment via projected characteristics [8, 9] to describe a reference frame which is initially comoving with the ICME/flux rope. The numerical experiment consists in injecting a constant velocity and mass flux from one boundary (to simulate a slower/faster SW) and let the system evolve.

On one hand, the dynamics of the ICME-SW interaction can be thoroughly studied, including the small-scale processes such as turbulence and magnetic reconnection; on the other hand, the motion of the flux rope can be traced and compared to the one expected for an aerodynamic drag force.

Both the dynamics and the flux rope motion can be studied parametrically, that is, varying some of the main physical parameters that are supposed to influence the aerodynamic drag force.

Such local simulations can also be coupled with both observations and global simulations: for example, the initial conditions could be obtained from observations and the results could be compared to the large-scale ones.

The turbulent features of the dynamic evolution could be compared to the turbulent spectra observations as well.

In addition, this approach could also help predict the ICME magnetic field evolution, that is, the actual "magnetic geo-effectiveness".

There are several ways in which this Ph.D. program could develop, based on the results of the simulations. In particular:

- further methods for advanced boundary treatment may be developed, e.g. to inject not only a velocity and mass flux, but also the Parker magnetic field and the SW turbulent fluctuations;
- the SW and ICME expansion may be included in the local description, e.g. using the Expanding Box Model [10];
- shock-capturing methods may be used to better describe the shock waves propagation;
- a full 3D upgrade from the present 2.5D code, including advanced border treatment, could lead to more realistic simulations.

Since the acceleration of Solar Energetic Particles (SEPs) is observed inside the ICMEs, this framework may also be used in the future to study such processes in the local comoving reference frame; the SEPs are also geo-effective with respect to the Earth environment.

References

[1] W. Manchester IV et al., Space Sci Rev (2017) 212:1159–1219

[2] Lindsay, G. M. et al. (1999), J. Geophys. Res. 104:12,515-12,524

[3] Cargill P. J., Solar Physics 221: 135–149, 2004.

[4] Vršnak B, Žic T et al. 2013. 285: 295

[5] Richardson I.V. and Cane H.V., Solar Phys (2010) 264: 189–237

[6] Parker, E. N. (1958), ApJ, 128: 664

[7] Ruffenach, A. et al. (2015), J. Geophys. Res. 120,1,43-60

[8] Thompson K. W., J. Comp. Phys, 68:1–24, 1987

[9] Thompson K. W., J. Comp. Phys, 89:439–461, 1990

[10] Grappin R., Velli M., JGR, 1996, 101, A1, 425