CCSOM – Constraining CMEs and Shocks by Observations and Modelling throughout the inner heliosphere

Summary

The Sun is the star closest to Earth where many astrophysical processes can be studied with the help of the numerous observations of Sun's surface activity and immediate consequences of this activity in the interplanetary space. The outermost layer of the solar atmosphere, the corona, is a dynamic plasma system in which the most energetic transient processes in the solar system, i.e. flares and coronal mass ejections (CMEs), occur. CMEs are large amounts of plasma and magnetic flux expelled from the Sun into the interplanetary medium (heliosphere). The fast solar wind, CMEs and CME-driven shock waves are the main drivers of the space weather at Earth and the cause of geomagnetic storms that may disrupt satellite operations, navigation systems (GPS), and radio communications. Therefore, these phenomena are in the focus of the space weather research, and also the main topic of the CCSOM project. As observations of the Sun and its atmosphere do not continuously cover all the distances from the Sun to Earth, they are not sufficient for the forecasting space weather disturbances and their geomagnetic impact at Earth. Thus, to reconstruct the solar wind and CME propagation, we need to rely on models, as e.g. EUHFORIA (EUropean Heliospheric FORecasting Information Asset; Pomoell & Poedts, 2018) The main focus of the CCSOM project was to improve the knowledge on solar wind, CMEs and CME-driven shock waves, and the accuracy of their forecasting at Earth employing EUHFORIA model.

In the framework of the CCSOM project, different methods were used, for combining the observational and modelling results and validation of EUHFORIA. To derive the 3D positions of a CMEs and streamers, observations from two view directions were employed (two STEREO spacecraft, or one STEREO spacecraft and SOHO observations). The most often used method for the CME reconstruction was a forward modeling (Thernisien et al. 2006, 2009; for different reconstruction methods see also Mierla et al. 2009). The main technique for analyzing radio observation was the radio triangulation which employs direction finding observations (Krupar et al. 2012; Magdalenić et al. 2014), and it is the only way for estimation of the 3D position of the radio emission in the interplanetary space. We also used different statistical methods for validation of EUHFORIA (Hinterreiter et al. 2019; Samara et al. 2021).

The overarching science question of CCSOM was: *how do CMEs propagate and evolve through the inner heliosphere?* To address this question, we simulated the background solar wind and the propagation of flux rope CME-ICME structures in the realistic solar wind conditions and compared the modelling results with observations. The main project results are grouped in three parts and summarized below.

Solar wind modeling with EUHFORIA: In the studies of the solar wind modeling with EUHFORIA we employed the so-called default set up of EUHFORIA which is identical to the one presented in the Pomoell & Poedts (2018). The study of the solar wind modeling with default EUHFORIA model showed that the obtained results strongly depend on EUHFORIA's simple coronal model (Hinterreiter et al. 2019; Hofmeister et al. 2020; Asvestari et al. 2019). The comparison of the in situ observations at 1 AU with modeling results show that, in average,

the solar wind speed is underestimated by the model while the solar wind density is overestimated. This result is related to the point that, in particular, small, narrow or elongated coronal holes (CHs) are either not at all reconstructed by the simple coronal model in EUHFORIA or their size is strongly underestimated. This behavior can be observed already in the modeling results at the inner boundary (distances of 0.1 AU) of EUHFORIA, and it becomes more pronounced when the modeling results are compared with the solar wind characteristics at the 1 AU distances. This behavior probably results from the inherent problems of the potential source surface (PFSS) model that is the base of the EUHFORIA's default coronal model (Asvestari et al. 2019). Thus, in order to improve the modelling results, the next step in the study was to implement and test some other coronal models. We have successfully implemented the coronal model MULTI-VP (Pinto et al. 2017) in EUHFORIA, and performed the first validation tests. The results show that EUHFORIA with MULTI-VP performs significantly better than the default EUHFORIA set up (Samara et al. 2021). More extended statistical analysis is still recommended to define exactly the level of accuracy of the solar wind modeling in this new set up, and possible need for the fine tuning of the model. The recommendation is also to implement and test some other, recently developed coronal models. Additionally, in the framework of CCSOM the new statistical method, so called DTW (Dynamic Time Warping; Samara et al. 2022) was adapted and tested for the evaluation of the level of accuracy with which EUHFORIA reconstructs the background solar wind.

In order to understand how exactly the solar wind observed at Earth depends on the CHs characteristics, in parallel to the solar wind modelling with EUHFORIA we performed the study that relates the characteristics of CHs and the associated fast solar wind at Earth (Samara et al. 2022). The aim was to determine what is the best input to EUHFORIA, for more exact modelling of the background solar wind, originating from CHs of morphologically different shapes. The study showed that the CH area, longitudinal extent and geometric CHs characteristics strongly influence the way the fast solar wind impacts Earth. Thus, we recommend that these CH characteristics, have to be taken into account in the models that aim to predict the fast solar wind based on the CH properties observed on the Sun.

*Implementation and testing of the CME models that contain the magnetic field in EUHFORIA***:** One of the objectives of the CCSOM project was implementation and testing of the CME models that contain the magnetic field i.e. magnetic CMEs, in EUHFORIA. The CME modeling was performed mostly using the events from the CCSOM event-list that was constructed at the beginning of the project. The same event-list is already further used in some other projects (e.g. in the H2020 EUHFORIA 2.0 project). In the framework of CCSOM, we analyzed a few different magnetic CME models, and find out that spheromak CME model is easier to implement in EUHFORIA than the Gibson-Low flux rope CME model. In order to understand how well the spheromak model can perform detailed case studies were done (Verbeke et al. 2019; Scolini et al. 2019, 2020a, 2021). The obtained results show good accuracy of the modeling CMEs with spheromak model in the case when the propagation direction is clearly directed towards Earth. Good results were also obtained in the case of interacting CMEs (Kilpua et al. 2019; Scollini et al. 2020b). However, we found that the spheromak CME model has somewhat limited applicability for modeling of the CMEs with propagation direction not clearly directed to Earth (Asvestari et al. 2021). The CMEs which do not directly propagate towards Earth, i.e. the cases of CME flank encounters, are less accurately modelled with the spheromak CME model. We performed several case studies with the aimed to understand how to most efficiently use spheromak model. The main drawback of the spheromak is the lack of the CME legs, which are in the case of side impact of the CME to Earth very important. The recommendation is to employ the spheromak model, but having in mind its limitation. We also continue to work on the overcoming difficulties with the Gibson-Low flux rope model. At the end of the project, we implement the FRi3D model (A. Isavnin, 2016) in EUHFORIA. This “Flux-Rope in 3D” CME model has the full croissant shape and is therefore more applicable for modeling the CME flank encounters. The first validation tests were published (Maharana et al. 2022) and a paper on event study with Fri3D in EUHFORIA is ready for submission. A statistical study of modeling CMEs from the CCSOM list was performed using the CME cone model (Magdalenić et al, in prep). A similar statistical study using the spheromak CME model is ongoing in the framework of the H2020 project EUHFORIA 2.0. During this project we also developed and tested new methods for obtaining the CME parameters needed as the input to EUHFORIA (described in the various publications that resulted from the CCSOM project).

CMEs and shock waves: Modeling of the shock waves with EUHFORIA was a challenging task as the CME models of EUFHORIA had the CME insertion at the height of 0.1 AU, when the CME-driven shock, in the majority of cases is already formed. Thus, preliminary studies were done for implementing different coronal models that would allow us to model the shock already in the low corona. Our results show that the CME-driven shock waves can be modelled by EUHFORIA, but the stand-of distance between CME and the shock is modeled well only at close-to 1 AU distances. Studying the shock waves using radio observations (Palmerio et al. 2019; Magdalenić et al. 2020; Morosan et al. 2020; Mann et al. 2022), and tracking them using radio triangulation resulted in important scientific findings (Jebaraj et al. 2020). We modeld the CME-driven shock waves and associated radio emission (Kouloumvakos et al. 2020, 2021; Jebaraj et al. 2021) employing the Magneto-Hydrodynamic Around a Sphere Thermodynamic model (Lionello et al. 2009; Riley et al. 2011). The recommendation is to implement in EUHFORIA coronal models which include the CME insertion in the low corona.
To improve the shock capturing and speed up the simulations we developed ICARUS a new heliospheric wind model for EUHFORIA. The ICARUS (Verbeke et al. 2022) combines radial grid stretching with solution Adaptive Mesh Refinement (AMR). A publication focusing on the combination of radial grid stretching and different AMR strategies is submitted. We note that combining AMR strategies yields a speed-up in wall-clock time of up to 28.

The new global MHD model COCONUT was developed, in part with CCSOM support. Three publications about the model and its validation are in the process of publishing, as well as paper on the importance of the unstructured grid used in COCONUT (Brchnelova et al. 2022). In addition we implemented the modified Titov-Démoulin CME model in COCONUT, and were able to evolve it time accurate. Without implementing any initial ejection velocity, i.e. letting the initial state evolve self-consistently. This modeling takes a lot of CPU time and we presently work on its optimization (exploiting and fine-tuning the implicit solver).

In conclusion, CCSOM was a very successful project, as it resulted in more than 40 scientific publications in the refereed journals, and significant model improvements The CCSOM also paved the way to other presently ongoing project (e.g. BRAIN project SWiM and H2020 project EUHFORIA 2.0) that aim to further improvements of the EUHFORIA model.