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MHD Heliosphere with Enhanced Background Solar Wind and Coronal Mass Ejections

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14. ABSTRACT
The modern technologies and infrastructure are highly vulnerable to space weather events, which are primarily driven by solar activity. Consisting of charged particles emitted by the Sun, the solar wind carries the Sun's energy and magnetic field outward and interacts with the Earth's magnetosphere. Therefore, modeling the propagation of the solar wind between the Sun and the Earth - including interactions between fast and slow streams and transients such as coronal mass ejections (CMEs) - is a significant component of space weather research, which directly relates to a DoD mission to develop operational models of the solar-terrestrial system. Our main objective is to improve the quality of our heliospheric simulations by building on the strengths of the Wang-Sheeley-Arge (WSA)+Enlil model, which NOAA currently uses for operational forecasts of the solar wind and CME propagations to Earth, and therefore to enhance the capability of making reliable predictions of the solar wind conditions at Earth. We will accomplish our goal by developing a three-dimensional magnetohydrodynamic (MHD) solar wind model of higher accuracy with time-dependent boundary conditions from the WSA model and ground-based observations. We emphasize that we will estimate the density and temperature for the ambient solar wind at the inner boundary of the heliospheric MHD model from empirical correlations with velocity based on spacecraft data instead of using ad hoc prescriptions as currently done by WSA-Enlil. The proposed work will result in a new heliospheric model consisting of two major components: (a) Improved ambient solar wind structure based on WSA maps and (b) Propagation of CMEs to Earth's orbit as flux ropes, which are more realistic than the Cone CME model employed by WSA-Enlil. We will evaluate our model for certain historical CME events by comparing with the current operational model
(e.g., WSA+Enlil+Cone) and with in situ measurements at Earth's orbit.

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Technical Report

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1. Accomplishments

The main objective of this project is to improve the quality of our heliospheric simulations by building on the strengths of some of the most successful models and observations available to the heliophysics community, and therefore to enhance the capability of making reliable predictions of the solar wind conditions at Earth. To fulfill these goals, we proposed to develop a new heliospheric model consisting of two major components: (1) Improved ambient solar wind structure based on the Wang-Sheeley-Arge (WSA) coronal model and (2) Propagation of coronal mass ejections (CMEs) to Earth's orbit as flux ropes that are more realistic than the Cone CME model employed by the WSA-Enlil model, which is currently used by NOAA for operational forecasts of the solar wind and CME propagations to Earth.

During the fourth year of the project on a no-cost extension (NCE), we continued the analysis of the ambient solar wind models for a quiet period in 2007 as described in the proposal. One of the major goals of the project was to improve Model 1, which is the WSA-driven heliospheric MHD model, by blending interplanetary scintillation (IPS) velocity data into the Model-1 boundary conditions to develop what was labeled as Model 3 (i.e., WSA+IPS), since Model 2 driven by IPS velocity data projected onto the inner boundary compared considerably better with Ulysses data away from the ecliptic plane. Improving the accuracy of the ambient solar wind model (Model 1) at higher latitudes is particularly important for simulating the ICME propagation to Earth due to the large latitude extent of its interaction with the background solar wind in interplanetary space. Preliminary results indicate that projecting the IPS velocity data used in Model 2 onto the Model 1 boundary at higher latitudes, indeed, improved the model comparison with Ulysses data at high latitudes, as expected. We are currently working on a manuscript describing the simulations, with a goal to publish in a major journal within 6 months.

Meanwhile, the PI repeatedly informed the WSA model developers about the inaccuracies at higher latitudes. As a result, the latest WSA model version 5.3.2 now includes important corrections to the calculation of the solar wind speed, primarily at higher latitudes, by tracing the magnetic field lines from one grid cell above the photosphere and changing the monopole subtraction method. The previous versions traced the magnetic field lines directly from the photosphere, where the approximation of the magnetic field using the spherical harmonic expansion method exhibited "ringing" effects that erroneously identified the magnetic polarity in very weak field regions. Since the WSA solar wind speed calculation is sensitive to the angular distance from the nearest open field region, the "ringing" effect could cause large errors around very weak field spots. Preliminary simulation results using Model 1 coupled with WSA v5.3.2 show vast improvements at high latitudes, where the comparison with Ulysses data is just as good as for Models 2 and 3, if not better. We are currently extending the model analysis to 2008 to compare with Ulysses data at high latitudes in the opposite (northern) hemisphere. We plan to finish a manuscript describing the simulations within the next two months, with a goal to publish in a major journal within 6 months. Using this model, we contributed to the Parker Solar Probe (PSP) magnetic footpoint prediction campaign for the solar encounters #11, #12, and #13 in 2022, which aided ground- and space-based solar observatories to coordinate and plan their observations of the most-likely source regions of the solar wind streams encountered by PSP during the close approach to the Sun. We will again participate in the upcoming prediction campaign for the solar encounter #14 in December 2022.

Apparently, the latest improvements in the WSA model have somewhat diminished the value of IPS data to drive the heliospheric MHD model at higher latitudes (Model 3) as described in the original proposal. However, IPS data can still be tremendously valuable for model validation. The WSA model is widely used by the space weather community for operation and research, with validation primarily against near-Earth, near-ecliptic single-point data. Hence, it would be interesting to see how the ADAPT-WSA ensemble velocities compare with the IPS velocities in the 3D inner heliosphere, particularly away from Earth, where such comparisons are reasonable. For IPS lines of sight mostly through the undisturbed, ambient solar wind, the IPS velocity can be approximately attributed to the point nearest to the Sun along the line of sight and easily mapped to the WSA outer boundary for direct comparison. Indeed, we recently presented such comparisons at the 20th annual International Astrophysics Conference in Santa Fe, NM for a (small) set of carefully selected IPS data, which showed that IPS data could be a useful tool for validating/ranking the ADAPT-WSA ensemble in the 3D inner heliosphere, particularly away from Earth or the ecliptic plane, where most of the model validation/ranking is currently performed against single-point probe data. The use of near-real time IPS data can be particularly valuable for ranking the ADAPT-WSA ensemble forecast, when there is limited or no real-time L1 probe data. Furthermore, IPS data could serve as quantitative 3D constraints in the selection of the best ADAPT-WSA ensemble member for ICME simulations. We are currently working on a manuscript describing the WSA and IPS velocity comparisons, with a goal to publish it in the conference proceedings book within 6 months.

In the previous (third) year, in order to further improve our CME simulations, we considered several alternative flux-rope CME geometries and found the "constant-turn" flux rope model (Vandas & Romashets 2017, Astronomy & Astrophysics) to be the most promising. Indeed, this model enabled us to correctly reproduce all three magnetic field components of the 12 July 2012 CME at 1 AU. In the fourth year on NCE, we completed an uncertainty quantification study for ensemble simulations using the constant-turn flux rope model (Singh et al. 2022, ApJ, 933, 123), which has fully replaced the modified spheromak model in our CME simulations.

In the meantime, we hired an undergraduate student Mr. Syed Raza in October 2021 as a research assistant to perform 3D fitting of a number of well-observed CMEs between 2010 and 2012 for the constant-turn flux-rope CME model. Mr. Raza presented the initial results for the 2012 July 12 CME at the Fall AGU Meeting in December 2021. We planned to complete the study and publish the CME simulation results earlier this year, but the progress was very slow due to Mr. Raza's priority to complete his undergraduate degree in fall 2022 to return to UAH as a graduate student in spring 2023 to continue his work. Despite the delay, we finished a manuscript (Singh, Benson, Raza, Kim, et al.) describing the CME simulations that is currently going through internal review for submission to the Astrophysical Journal, with a goal to publish within 6 months. In early 2023 we plan to simulate additional historical CMEs to validate and test the robustness of the constant-turn flux-rope CME model.

2. Impacts

The work performed during this reporting period resulted in an improved ambient solar wind model based on ADAPT-WSA maps and more realistic simulations of CME propagation to Earth's orbit, with quantification of model uncertainties. This project has enabled collaboration between early career scientists, including undergraduate, graduate, and postdoctoral researchers. The PI mentored a Research Experience for Undergraduates (REU) student in the summer of 2022 who performed a data analysis work that is directly relevant to this project. The REU student's poster was selected as the best out of 10 competitors at the REU final presentations at UAH/CSPAR. For the prize, the REU program will support the student to travel to an international conference of his choice, in addition to the upcoming 2022 AGU Fall Meeting in Chicago, IL.

PI Tae Kim has presented updates on the progress of the ambient solar wind model at these major scientific conferences:

- Kim, T., Hegde, D. V., Singh, T., Jones, S., Arge, C., and Pogorelov, N., Predicting the Solar Wind Using Empirically-driven Data-constrained Heliospheric MHD Model, AGU Fall Meeting, New Orleans, Louisiana, December 2021
- Kim, T., Ranking, the ADAPT-WSA Coronal Model Ensemble Using Observations of Interplanetary Scintillation in the Inner Heliosphere, 20th Annual International Astrophysics Conference, Santa Fe, New Mexico, October 2022.

Former graduate student and postdoctoral research assistant (now a research scientist) Talwinder Singh has presented updates on the progress of the flux-rope CME model at these major scientific conferences:

- Singh, T., Kim, T., Pogorelov, N., and Smith, W., Coronal Mass Ejection Forecasting Using Magnetohydrodynamic Simulations of a Data-Constrained Constant-Turn Flux-Rope-Based Model, AGU Fall Meeting, New Orleans, Louisiana, December 2021
- Singh, T., Benson, B. V., Raza, S., Kim, T., and Pogorelov, N., Improving the Arrival Time Prediction of Coronal Mass Ejections using Magnetohydrodynamic Ensemble Modeling, Heliospheric Imager Data and Machine Learning, ML-Helio Conference, Boulder, Colorado and Virtual, March 2022
- Singh, T., Benson, B., Raza, S., Kim, T., and Pogorelov, N., Improving the Arrival Time Prediction of Coronal Mass Ejections using Magnetohydrodynamic Ensemble Modeling, Heliospheric Imager data and Machine Learning, EGU General Assembly, Vienna, Austria, May 2022
- Singh, T., Benson, B., Raza, S., Kim, T., and Pogorelov, N., Improving the Arrival Time Prediction of Coronal Mass Ejections using Magnetohydrodynamic Ensemble Modeling,

Heliospheric Imager Data and Machine Learning, 20th Annual International Astrophysics Conference, Santa Fe, New Mexico, October 2022.

Graduate student Dinesh Hegde has presented updates on the progress of the ambient solar wind model constrained by multi-spacecraft observations (primarily PSP and Wind/ACE) at these major scientific conferences:

- Hegde, D. V., Kim, T., Pogorelov, N., Arge, C., and Jones, S., Solar Wind Simulations along the Parker Solar Probe Trajectory, AGU Fall Meeting, New Orleans, Louisiana, December 2021
- Hegde, D. V., Kim, T. K., Pogorelov, N. V., Arge, C. N., and Jones, S. I., Solar Wind Simulations along the Parker Solar Probe Trajectory, Parker Two Conference, Laurel, Maryland, June 2022
- Hegde, D. V., Kim, T. K., Pogorelov, N. V., Arge, C. N., and Jones, S. I., Improving Solar Wind Predictions Using Multi-Satellite In Situ Observations, SHINE Conference, Honolulu, Hawaii, July 2022
- Hegde, D. V., Pogorelov, N. V., Kim, T. K., Arge, C. N., and Jones, S. I., Solar Wind Simulations along the Parker Solar Probe Trajectory, COSPAR-2022, Athens, Greece, July 2022
- Hegde, D. V., Kim, T. K., Pogorelov, N. V., Arge, C. N., and Jones, S. I., Improving Solar Wind Predictions Using Multi-Point Observations, Triennial Earth-Sun Summit, Bellevue/Seattle, Washington, August 2022
- Hegde, D. V., Kim, T. K., Pogorelov, N. V., Arge, C. N., and Jones, S. I., Validation of Data-Driven MHD Models of the Solar Wind Using Multi-Spacecraft In-Situ Observations, 20th Annual International Astrophysics Conference, Santa Fe, New Mexico, October 2022.

Undergraduate research assistant Syed Raza has presented updates on the progress of the flux-rope CME model constrained by STEREO coronagraph and heliospheric imager observations at the following conference:

- Raza, S., Constraining CME Models using STEREO data for Space Weather, AGU Fall Meeting, New Orleans, Louisiana, December 2021

REU student John O'Toole will present the analysis of the optimal source surface height of a potential field coronal model at the final REU presentations:

- O'Toole, J. R. and Kim, T. K., Optimizing the Source Surface Height of an Empirical Coronal Model During Solar Cycle 23 Minimum Using Remote and In Situ Measurements, Final Presentations of the NSF-REU at UAH and NASA MSFC, July 2022

The following publications or manuscripts are relevant to the project:

- Singh, T., Kim, T. K., Pogorelov, N. V., and Arge, C. N. (2022), Ensemble simulations of the 2012 July 12 Coronal Mass Ejection with the Constant-turn Flux Rope Model, *Astrophysical Journal*, 933, 123, https://doi.org/10.3847/1538-4357/ac73f3

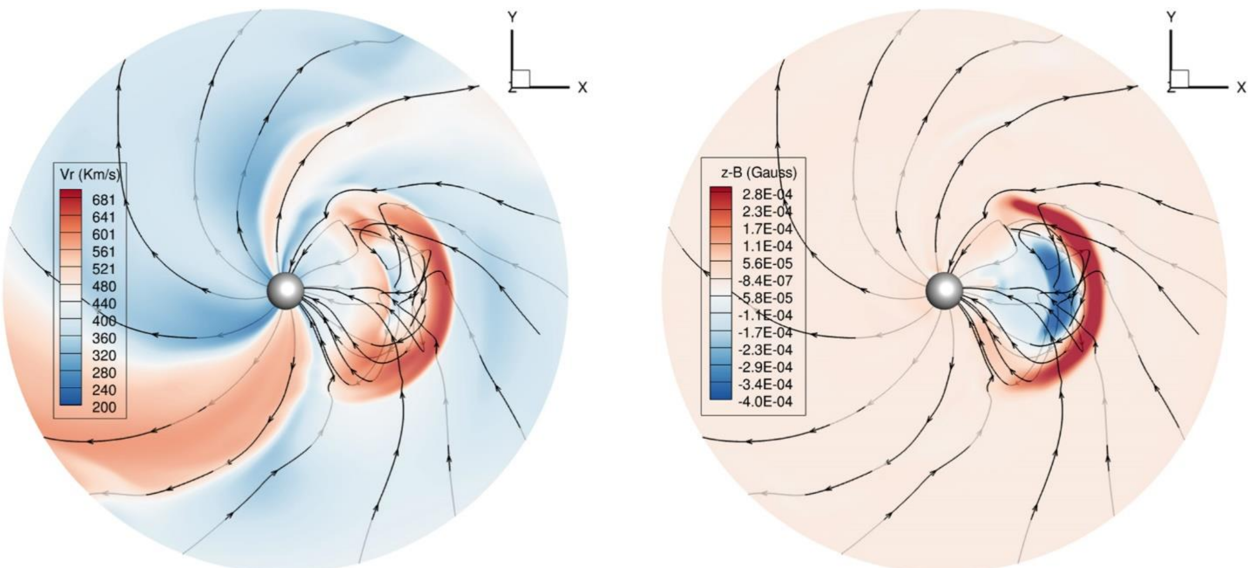
- Singh, T., Benson, B., Raza, S. A., Kim, T., Smith, W., Pogorelov, N. V., and Arge, C. N., Improving the Arrival Time Estimates of Coronal Mass Ejections by Using Magnetohydrodynamic Ensemble Modeling, Heliospheric Imager Data, and Machine Learning, Manuscript in preparation for *The Astrophysical Journal*
- Singh, T., Kim, T. K., and Pogorelov, N. V., Magnetohydrodynamic simulation of a magnetic cloud observed during the near-radial alignment of Solar Orbiter and Wind Spacecraft, Manuscript in preparation for *The Astrophysical Journal*
- Kim, T. K., Jones, S. I., Arge, C. N., and Pogorelov, N. V., Stream Interaction Regions during Solar Cycle 23 Minima, Manuscript in preparation for the *WHPI Special AGU Journal Issue entitled "Understanding the interconnected sun-heliospheric-planetary system during solar minimum"*
- Kim, T. K., Jones, S. I., Arge, C. N., Pogorelov, N. V., and Manoharan, P. K., Time-dependent Model of the Ambient Solar Wind Driven by Boundary Conditions from Observations of Interplanetary Scintillation, Manuscript in preparation for *The Astrophysical Journal*
- Kim, T. K., Arge, C. N., Jones, S. I., Pogorelov, N. V., and Tokumaru , M., Ranking the ADAPT-WSA Coronal Model Ensemble Using Observations of Interplanetary Scintillation in the Inner Heliosphere, Manuscript in preparation for the *Conference Proceedings of the 20th Annual International Astrophysics Conference*, Santa Fe, New Mexico, October 2022
- Hegde, D. V., Kim, T. K., Pogorelov, N. V., Arge, C. N., and Jones, S. I., Validation of Data-Driven MHD Models of the Solar Wind Using Multi-Spacecraft In-Situ Observations, Manuscript in preparation for the *Conference Proceedings of the 20th Annual International Astrophysics Conference*, Santa Fe, New Mexico, October 2022

3. Changes

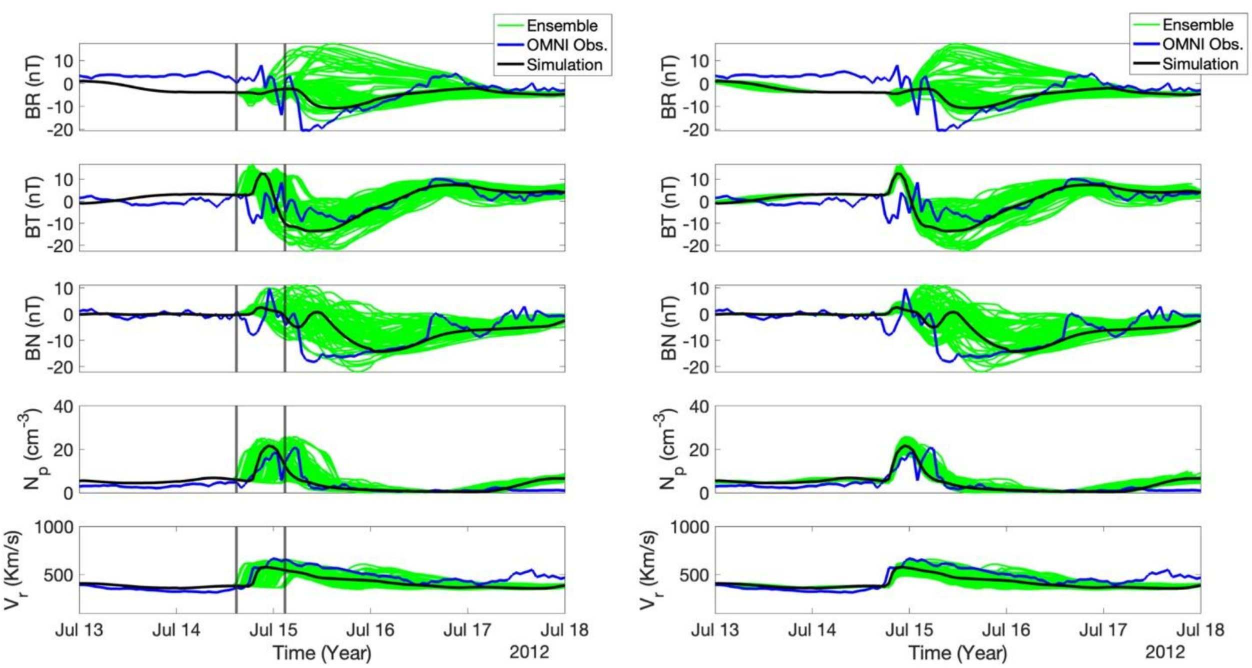
We would like to request a second NCE for six months (to 05/31/2023) to allow us to finalize and publish the manuscripts described in the previous sections.

4. Technical Updates

Some images highlighting the work done during this period:



Constant-turn flux rope CME shown in the solar equatorial plane 30 hours after the initial insertion. The gray sphere in the center represents the inner boundary of the heliospheric MHD model at 21.5 solar radii. The outer circle marks the MHD simulation upper boundary at 1.5 AU. The *z* = 0 semi-translucent slices of radial velocity (left panel) and B_z (right panel) are shown along with the magnetic field lines. (Singh et al. 2022)



Left: Hourly averaged OMNI data (blue) and simulation results probed at Earth (black and green). The black line represents the first ensemble member with our own GCS parameters. The green lines represent the entire 76 ensemble members with all known GCS parameters used by the community. The gray vertical lines show the 12 hour wide arrival time window of all the ensemble members. Right: same as the left panel, but with the arrival time of all ensemble members matched with the first member. (Singh et al. 2022)