MHD and kinetic aspects in solar wind modeling

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Abstract

We present solar wind modeling efforts with both magnetohydrodynamic (MHD) and kinetic treatments. An observation-driven MHD model is used to constrain a kinetic solar wind model with anisotropic kappa velocity distribution functions (VDF) for the electrons. Photospheric magnetograms serve as observational input in semi-empirical coronal models for estimating the plasma characteristics up to a heliocentric distance of 0.1AU. A full MHD model is employed for computing the three-dimensional evolution of the solar wind macroscopic variables up to 2AU. The results of the MHD model obtained at 0.1AU serve to constrain the parameters used in an exospheric kinetic solar wind model. The assumption of Maxwell and kappa VDF at the exobase, for protons and electrons respectively, is used to determine the solar wind solution using appropriate boundary conditions, estimated to obtain the best comparison with available observations at the Earth. The kinetic description sheds light on processes such as coronal heating and solar wind acceleration, that naturally appear by inclusion of suprathermal electrons in the model. We are focusing on the profile and variation of solar wind parameters, such as the solar wind speed, temperature and density at 1 AU, on characterizing the slow and fast source regions of the wind and on comparing its features with results of exospheric models in similar conditions. In order to compare MHD and kinetic approaches with observations, we start from similar boundary conditions at the 0.1AU and propagate the global kinetic solution up to 2AU.

MHD and kinetic models

We are interested in exploring the complementarity of the MHD and kinetic approaches in a combined study of the solar wind. As observationally-driven MHD model we use Euhforia[1], the specifics of which are discussed in [1]. Euhforia is a fully 3D observationally driven model that is already tested for several cases and can be used operationally for space weather stud-

[1]Euhforia (European heliospheric forecasting information asset) can be found at the Solar Influences Data Analysis Center (SIDC) of the Royal Observatory of Belgium (`http://www.sidc.be`).

ies. Euhforia uses a finite volume discretization scheme to solve the hyperbolic conservative MHD equations. Ideal MHD is used taking into account gravity as a source term in the momentum and energy equations. The rotation of the Sun is taken into account and the magnetic field topology can be as complicated as the observations demand and it is calculated at every point of the computational grid. The initial magnetic field is reconstructed using a potential field source surface (PFSS) scheme and an observational input of a photospheric magnetogram. Semi-empirical models, inspired by the success of the WSA (Wang-Sheeley-Arge) [2, 3] solar wind speed quantifications, are recruited to provide the solution at a distance of about 21.5 $R_{\odot}$ and avoid the inclusion of the sonic point in the computational domain. The MHD model is able to provide density and speed profiles at the Earth's orbit, it allows for slow and fast solar wind source regions tracing, and can serve as the MHD counterpart in a comparison project together with kinetic exospheric models that correspond to similar initial and boundary conditions at 0.1 AU. The disadvantages of Euhforia come down to the following: it is computationally expensive, it requires assumptions for extra heat deposition to accelerate the solar wind and it can only resolve the macrophysics of the solar wind.

The kinetic model we make use of in this study, is the kinetic exospheric model described in [4, 5, 6, 7]. Unlike single fluid prescriptions, it includes different characteristics for each particle species, such as e.g. different electron and proton temperatures as indeed observed [8]. The solar atmosphere is considered to have a collision-dominated barosphere at low altitude (below 1.1-10$R_{\odot}$ according to [7]) and a collisionless exosphere, which is the region modeled kinetically. The model is essentially 1D and it gives the solar wind evolution along a magnetic field line, but approaches towards 3D are of increasing interest [9]. In this work, we present a 3D generalization of this exospheric model, i.e. we find the solar wind characteristics along a collection of magnetic field lines each passing through a point on the spherical shell at the exobase level in latitude and longitude (θ, ϕ). We use Maxwellian VDF for the protons and Lorentzian VDF for the electrons inspired by observed particle VDF in the solar wind. The analytic expressions for the kinetic moments of the exospheric models were derived for a Maxwellian VDF by [4] and for a Lorentzian VDF by [5]. The semi-analytic kinetic models have the advantage that they are easy to compute as they are computationally economic and energetically self-consistent with acceleration and heating fluxes.

Analysis and results

We compare both, MHD and kinetic, approaches in a manner where the kinetic model is interfaced with the MHD inner boundary at 0.1AU and the results of both models are compared with observations at large heliocentric distances. We are constraining the kinetic input based on observationally driven results at Euhforia's inner radial boundary $21.5R_\odot$ and examine both models' efficiency on capturing the important solar wind processes by comparing with observations at 1AU and observations of Ulysses beyond the Earth's orbit, i.e. forward modeling. We run the kinetic model up to $21.5R_\odot$ for $r_0 = r_s = 2.5R_\odot$ (with r_0 being the exobase level and r_s the source surface altitude), with an electron temperature of $T_e = 1MK$, a proton temperature of $T_p = 1MK$ and 600 κ-indexes in range [2,8] with step 0.01. With the results we create a matrix with solar wind speeds at $21.5R_\odot$ and by comparison with the Euhforia results for v_r, we estimate the appropriate κ for every speed in the internal boundary of the MHD run. We obtain a 2D map of dimensions $(N_\theta \times N_\phi)$ for $\kappa(\theta,\phi)$-values each corresponding to a field line. From the matrix, we also compare the Euhforia densities at the same distance (0.1AU) with the kinetic number density there and get a scaling factor that we assume being the same throughout the distribution and thus we can estimate the appropriate initial density at the exobase that would give us the same density with Euhforia at 0.1 AU. For the temperatures, the relation is more complicated and for convenience we take $T_e = T_p =$ 1MK for all the latitudes and longitudes at $r_0 = 2.5R_\odot$ and focus more on the κ and the density parameters. Note that Euhforia is not providing MHD information below 0.1AU, while the kinetic model provides results at any distance above the exobase and especially in the crucial region close to the Sun where the solar wind is being accelerated.

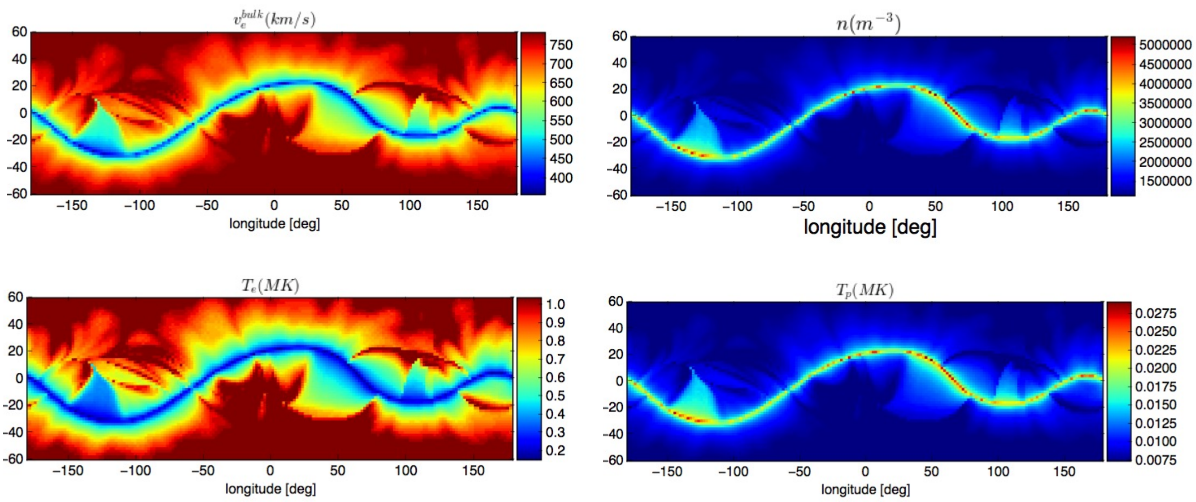

Figure 1: *Color maps in heliographic longitude and latitude from top left to bottom right panels: of the speed, the number density, the electron and proton solar wind temperatures for results of the kinetic model on the 10th of August 2007 at Ulysses' orbit ($r = 300.14R_\odot$).*

In this study, we are interested in the year 2007, as it was a mostly quiet year regarding the solar activity and it coincides with the third orbit of Ulysses. Here we are presenting the results for the 10th of August, 2007 when Ulysses was close to the equatorial region. The results of the kinetic model at the orbit of Ulysses starting from boundary conditions similar to Euhforia at 0.1AU are illustrated in figure 1, showing high speed solar wind at high latitudes and slow speed solar wind along the undulating neutral sheet.

Conclusions

It's the first time that such a comparison between MHD and kinetic models in 3D is performed. The kinetic model gives higher speeds than Euhforia at 1AU, because the acceleration of the solar wind continues in a higher rate in the kinetic model after $21.5R_\odot$. The number of peaks in the velocity is reproduced by both models in the time period of about 27 days (2 weeks before and after 10 August 2007) at the Ulysses position. There are differences in the position of the peaks due to differences in rotation and stream interaction implementations, with the kinetic model keeping the exact same sources for slow and fast wind at higher distances as at the photoshere, assuming that each spherical shell of plasma rotates as a solid body with the same longitudinal speed at every point on each spherical shell. Whereas Euhforia solves the MHD equations and accounts for stream interactions in the solar wind. The MHD temperature is one order of magnitude smaller than T_e and one order of magnitude bigger than T_p. There are physical differences in the two approaches, such as the heat flux which is a natural consequence in the kinetic model, but an assumption for the MHD model. The kinetic model is a computationally efficient model, as it is semi-analytic ignoring stream interactions, but capturing the acceleration mechanisms from the exobase level on. The boundary conditions at the Earth's orbit have been adjusted to constrain the MHD model so that it provides more realistic results. Appropriate boundary conditions in the corona will help to reproduce solar wind observations at large heliocentric distances also with the kinetic model. In the future we will constrain the kinetic model using observational data at the Earth's and Ulysses' orbits and examine the characteristics of the solar wind close to the Sun in the inverse process with respect to the abovementioned, i.e. backwards modeling.

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