Modelling of Solar Wind Plasma Turbulence for Space Missions of ESA and NASA

H. Comişel, U. Motschmann, Y. Narita

published in

NIC Symposium 2018
K. Binder, M. Müller, A. Trautmann (Editors)

Forschungszentrum Jülich GmbH,
John von Neumann Institute for Computing (NIC),
Schriften des Forschungszentrums Jülich, NIC Series, Vol. 49,
ISBN 978-3-95806-285-6, pp. 107.
http://hdl.handle.net/2128/17544

Modelling of Solar Wind Plasma Turbulence for Space Missions of ESA and NASA

Horia Comişel[1], **Uwe Motschmann**[1,2], **and Yasuhito Narita**[3,4]

[1] Institut für Theoretische Physik, Technische Universität Braunschweig,
Mendelssohnstr. 3, 38106 Braunschweig, Germany
E-mail: {*h.comisel, u.motschmann*}*@tu-braunschweig.de*

[2] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Planetenforschung,
Rutherfordstr. 2, 12489 Berlin, Germany

[3] Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, 8042 Graz, Austria
E-mail: y.narita@oeaw.ac.at

[4] Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig,
Mendelssohnstr. 3, 38106 Braunschweig, Germany

The space between planets, stars and galaxies seems to be empty but it is not. It is completely filled with ionised gas called plasma. In our interplanetary neighbourhood this plasma is launched by the Sun. This continuous stream of solar particles interstratified by the interplanetary magnetic field got the name solar wind. It carries a lot of information from the Sun and it is a unique laboratory to study fundamental physics. The solar wind develops quickly into a turbulent state but the driver for this development is far from complete understanding. Especially multi spacecraft missions supported by high performance computer simulations allow a remarkable progress in turbulence physics. The picture of plasma turbulence in the interplanetary space can be now extended in two fashions by means of the numerical parallelised simulation codes. One is the extension to the fifth dimension by including the time or radial evolution of the turbulent state of the solar wind, i.e. the energy spectrum as a function of wave vectors, frequencies, and radial distance or elapsed time from the Sun. The other extension is a wider coverage of scales ranging from fluid treatment of plasmas (10,000 km or larger) down to the kinetic scales of the ion gyroradius (about 100 km). For this purpose the turbulence is generated by DNS (direct numerical simulation) using hybrid - PIC (Particle-In-Cell) codes. The spatial structure of plasma turbulence and its temperature dependence is obtained by incorporating the hybrid plasma code A.I.K.E.F. into direct numerical simulation of astrophysical kinetic turbulence. The resulting ion-scale turbulence is related to the solar wind distance from the Sun by using a mapping procedure.

1 Introduction

Turbulence is a ubiquitous phenomenon in space. Not only neutral fluids as water or atmospheric flows but also astrophysical plasmas and magnetic fields are known to be in a turbulent state. Examples can be found in interstellar medium, stellar interior, and stellar atmosphere. Interstellar medium represents a mixture of ionised gas with neutral components (gas and dust). Scintillation measurements in radio astronomy have discovered the existence of turbulence in interstellar medium. Once a star is formed with nuclear fusion process in the core, turbulent convection sets to transport the heat from the stellar interior into interstellar space. Turbulence appears in the stellar atmosphere in various ways. The steady radial outflow (called the stellar wind) is believed to be in a fully-developed turbulent state, as confirmed by many spacecraft *in situ* in the interplanetary space of the solar system. Turbulence is also driven by the shock waves in the stellar eruptions (such as flares or coronal mass ejections). In the astrophysical systems, both turbulence and shock waves can be extremely violent, such as in supernova explosions, and produce thus high-energy particles called galactic cosmic rays. Studying turbulence is a challenge in astrophysics, both for theoretical and observational aspects. Difficulty in theory is that eddies and electromagnetic waves may co-exist and developing a theoretical model must assume a specific type of fluctuations, e.g., Alfvén waves, which are low-frequency, incompressible fluctuation of plasma as a magneto-fluid. Difficulty in observations is that the methods are limited either to remote sensing (i.e. indirect measurements) or single spacecraft measurements *in situ* in the interplanetary space. Only in the last decade the first multi spacecraft fleets are in operation which allow immediate space-time analysis of plasma. An extremely successful spacecraft fleet is CLUSTER which was launched by the European Space Agency (ESA) in 2001. This mission pushed our understanding of plasma turbulence down to a 100 km scale very much. NASA's MMS spacecraft fleet orbits the Earth since 2015 and opens new insight especially in small scale turbulence down to 10 km. Our institutes contribute to the missions by hardware, modelling and data handling.

2 Direct Numerical Simulations (DNS) for Astrophysical Plasma Turbulence

Various theoretical methods have been developed to study astrophysical turbulence in direct numerical simulations (DNS), e.g. single fluid model (magnetohydrodynamic picture), multi-fluid model, gyro-kinetic model, full-particle model, and hybrid model. They differ in modelling plasmas as represented by equation of motion. For example, the hybrid model gives the best performance in plasma turbulence studies at ion-kinetic scales. It treats ions as individual particles (which requires a huge amount of processors and memory) and electrons as an electrically conducting, charge-neutralising fluid. Because of the high mass ratio between ions and electrons (the proton-to-electron mass ratio is about 1837), dynamics of plasma turbulence is largely dominated by ions as they contribute most to the mass and momentum of plasmas. In comparison, single-fluid and multi-fluid models cannot resolve energy and momentum exchange processes between ions and electromagnetic fields. Gyro-kinetic simulation assumes *a priori* that the particle motion and electromagnetic fields are axis-symmetric around the directions of the large-scale magnetic field, giving only a time-averaged picture over gyromotion. Full-particle simulation, under the current computational resource, can resolve plasma turbulence on a shorter time scale as dynamics of individual electrons must be solved.

The multi-scale nature of plasma turbulence and its consequences for large scale processes as magnetic reconnection is a well known fact in many plasmas from the laboratory to the solar system and astrophysical plasmas besides the Sun. A central problem in the numerical modelling of collisionless astrophysical plasmas, of their turbulent and laminar behaviour, is to consistently consider physical processes which simultaneously act over a large range of spatial and temporal scales from micro-scales at the particle level to macro-scales where magnetohydrodynamic approaches apply. In the collisionless astro-plasmas micro-turbulence balances electric fields, provides irreversibility as well as the dissipation of currents and plasma kinetic energy. Their correct consideration is particularly important for the usual fluid modelling of the macro-scale dynamics of astrophysical plasmas, like, e.g., by large eddy simulations in which the calculations on a grid neglect sub-grid-scale processes.

2.1 Numerical Methods and Algorithms

The hybrid simulation code A.I.K.E.F.[1] (Adaptive Ion Kinetic Electron Fluid) is used to perform the plasma simulations for the plasma profiles. A.I.K.E.F. has been developed by the Numerical Plasma Simulation's group at the Institute of Theoretical Physics of the Technical University of Braunschweig. The ions of the plasma are treated as particles and the electrons as massless, charge-neutralising fluid. The interaction of the charged particles is determined by the electromagnetic fields. So the equation of motion and Maxwell's equations have to be solved simultaneously. The simulations are made within the three-dimensional space by discretisation with a numerical grid. The macroscopic quantities like electric and magnetic fields are determined by the cloud-in-cell method. This method interpolates the densities and currents by calculating the contribution of each particle to the grid nodes. The particles are not restricted to the grid nodes and can move freely inside the entire simulation box. A sketch of the model is shown in Fig. 1. The equation of motion for the particles can be solved by using a 4th order Runge-Kutta. These cycles are repeated until steady-state conditions. We use hundreds of grid cells per spatial direction. In each cell are about 500 particles or more to represent the velocity distribution and reduce statistical noise through fluctuations. Thus, it is necessary to compute the trajectories of billions of particles at each time step. The Leap-Frog method is used to solve Maxwell's equations. Additionally, Successive-Over-Relaxation- and Crank-Nicholson-methods are used, e.g., to shroud a possible divergence of the magnetic field. The hybrid code can use an adaptive grid. This means that the grid resolution can be increased dynamically for locations with sharp gradients in the plasma quantities. This occurs either automatically during run-time or predefined. Thus, the simulations permit both a high resolution in regions of interest and a lower computation time by lower resolution in regions of less interest.

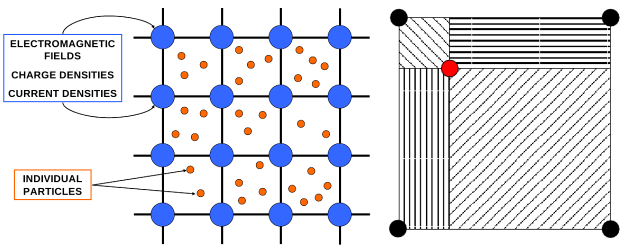

Figure 1. Particle-In-Cell code. The electromagnetic fields and moments of the distribution function are only evaluated on the grid nodes (blue). In contrast the particles (red) move freely within the cells of the numerical grid (left panel). Depending on the relative position to the grid nodes every grid node is assigned a certain volume proportional to the size of the opposing volume (right panel).

2.2 Code Performance and Workflow

The hybrid simulation code A.I.K.E.F. was mainly designed to approach the processes of interaction between magnetised space plasmas and obstacles such as comets, asteroids, and planets which occur on different lengths and time scales. However, A.I.K.E.F. code also proved its versatility in studies on elementary processes in the collisionless plasma which eventually conduct to plasma turbulence and energy cascades from large Magnetohydrodynamics (MHD) scales to the electron scales. The studies on the normal modes developed in plasma turbulence assume high resolutions for the spatial and temporal scales as well as low levels of numerical noise. Consequently, the runs are significantly demanding in computational resources: large amount of super-particles in the computational cell (up to thousands of super-particles), large sizes of the simulation system - e.g., hundreds to thousands of ion inertial lengths in order to cover the MHD scales, and a large number of computational grids (in order to solve for the ion gyration and for the high frequency waves at kinetic scales). The code uses for the parallelisation purpose the Message Passing Interface (MPI) libraries. A various number of speedup scaling tests have been performed in different setups on JURECA (2x12 core Xeon Ivy Bridge CPUs, E5-2680 v3@2.5 GHz) located at Jülich Supercomputing Centre. In order to increase the efficiency of the computational load, the mesh size of the hybrid simulations was adapted to fulfil the architecture of a computing node (2x12 cores). Here we present two representative speedup tests performed for a 2-D and a 3-D configuration.

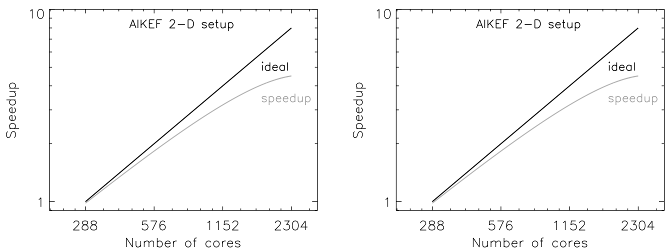

Figure 2. A.I.K.E.F. benchmarks for plasma turbulence in 2-D (left) and in 3-D (right) setups.

Fig. 2 left shows the benchmarks obtained for a 2-D setup with the lengths of the simulation box, L_x=L_y=288d_i, the integration step length 1/4d_i, and 400 super-particles/cell are used. Here d_i is the ion inertial length. For the 3-D setup (Fig. 2 right) the lengths of the simulation box are L_x=L_y=144d_i, and L_z=420d_i, respectively, the integration step lengths for the perpendicular and parallel directions are $1d_i$, and $0.25d_i$, respectively, and a number of 200 super-particles is used. As one can see, the speedup scaling is efficient for the 2-dimensional setup up to 1152 cores (see also Tab. 1). The limit for the scaling of the 3-dimensional setup (Tab. 1) ends at 576 cores. For a 3-D configuration (L_x=L_y=L_z=144d_i, and $0.25d_i$ integration step), a number of 576 cores still provides an acceptable scaling when 400 super-particles are used for a computational cell.

Results close with those shown here are obtained when the number of grids are lowered while the number of super-particles is increased. For example, our extended study on the decay instability in space plasmas requires a significant large number of particles, e.g.,

2-D Setup			
cores	CPU time/ion-gyroper.	speedup	eff. loss
288	152.2s	1.	ref
576	69.6s	1.8	10.5%
1152	39.0s	3.2	19.7%
2304	27.5s	4.5	43.7%
3-D Setup			
cores	CPU time/ion-gyroper.	speedup	eff. loss
288	477.1s	1.	ref
576	282.0s	1.7	15%
1152	224.2s	2.1	47%
2304	202.0s	2.3	71%

Table 1. Speedup scaling for A.I.K.E.F. code.

N=2000 instead of N=200 super-particles used in our previous runs. The number of grids has been decreased accordingly by approximately 10 times (2 times for each direction which means a double value for the integration step) while the computational time has been maintained close to the reference time.

3 Turbulence Structure and Evolution

3.1 Waves and Filaments

Numerical simulations generate fluctuations in plasmas and magnetic fields at wavelengths smaller than the ion inertial length. Fig. 3 displays an example of the magnetic field structure at beta 0.05 at the time 700 ion-gyroperiods. As is seen in the figure, the wave dynamics produces filamentary structure along the large-scale magnetic field, confirming the earlier results of the wavevector anisotropy. The energy spectrum was determined in the

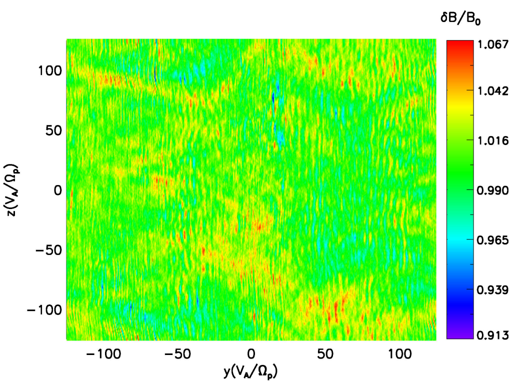

Figure 3. Snapshot of magnetic field distribution (normalised to the large-scale field magnitude) in the spatial coordinate spanned by the perpendicular distance (the y component) and the parallel distance (the z component) in units of the ion inertial length. Data represent ion beta 0.05 and the time of 700 ion-gyroperiods (adapted from Comisel *et al.*[2]).

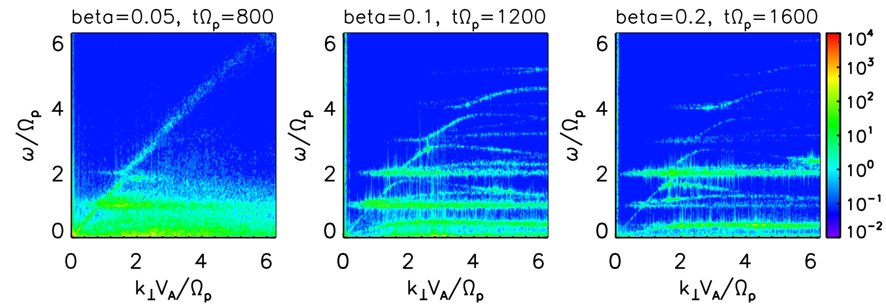

Figure 4. Ion beta dependence of the magnetic energy spectra in the spectral domain spanned by the perpendicular wavevector $k_\perp$ (normalised to the ion inertial scale using the Alfvén speed V_A and the ion gyrofrequency Ω_p) and the frequencies (normalised to Ω_p). Left column shows the snapshot for ion beta 0.05 at time 800 gyroperiods, middle column for ion beta 0.1 at 1200 gyroperiods, and right column for ion beta 0.2 at 1600 gyroperiods (adapted from Comisel *et al.*[3]).

Fourier space spanned by the frequencies and two-dimensional wave vectors as a function of time. It clearly shows that the wave vectors are pointing perpendicular to the large-scale magnetic field direction. It was also possible to determine wave modes that constitute plasma turbulence on the kinetic scales: Alfvén/ion cyclotron mode, ion Bernstein mode, whistler mode, and zero-frequency mode. In addition, the energy contribution of each wave mode and its nonlinear effect have been determined. From A.I.K.E.F. turbulence study we were able to derive the conclusion that the filamentation hypothesis is a valid approach in low-beta, two-dimensional astrophysical plasma turbulence. In the setting of Comisel *et al.*[2], it was possible to produce not only the growth of turbulence but also the decay of turbulence in various fashions in simulation.

Astrophysical plasmas exhibit a wide range of varieties of temperature or of plasma parameter beta, the ratio of thermal to magnetic pressure. For example, solar corona is characterised by a very high temperature, of the order of 10^6 K, yet its beta is low (0.01 or lower) because of the presence of the strong magnetic field. Plasmas in interplanetary space, in contrast to the corona, have moderate values of temperature (of the order of 10^5 K) because of the cooling effect associated with the radial expansion of the plasma. But the value of beta becomes higher (reaching nearly unity) in interplanetary space. Fig. 4 shows the dispersion diagram (wave activity in the wave number-frequency domain) at different temperatures (or ion beta values) obtained by numerically solving the plasma equations without assuming any waves *a priori*. Ion Bernstein modes are predicted by the hybrid simulation as transition from discrete waves into turbulence. Now that the wave modes are identified in plasma turbulence, this knowledge is used to reveal the time or radial evolution of the wave modes in the turbulent stellar wind, i.e. the energy spectrum as a function of wave vectors, frequencies, and radial distance or elapsed time from the emitting star.

3.2 Radial Evolution of Ion-Scale Turbulence from the Sun

Comisel *et al.*[3] proposed a mapping procedure to accompany any study of plasma turbulence simulation that is measured as a function of time. Hybrid simulations at ion-scales are particularly important for the mapping at radial distances near the Sun (e.g., about 0.3

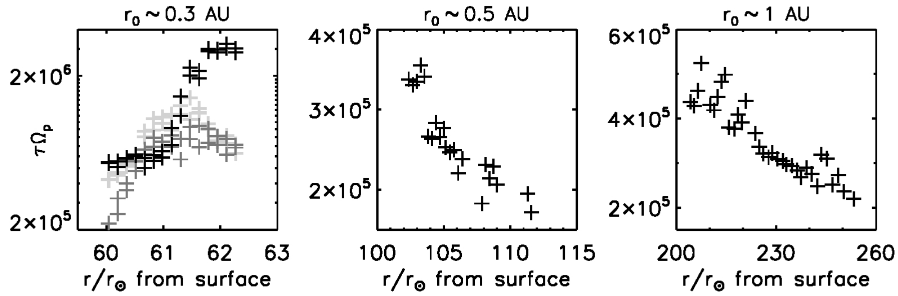

Figure 5. Radial evolution of the wave brake time for the ion Bernstein (light grey - IB1 and dark grey - IB2) and the ion cyclotron (black) normal mode waves and for the ion cyclotron wave mode (middle and right) at different distances from the Sun surface (adapted from Comisel *et al.*[3]).

AU), because their predictions can be compared with the *in situ* observations of the spacecraft missions. By mapping plasma turbulence at MHD scales, the radial evolution is too rough, while by mapping plasma turbulence at electron scales, the radial evolution is too tiny, due to the time-scale limitations of the PIC simulations. First, the radial evolution of the solar wind element and the mapping into time evolution is studied. Starting from a given profile of the magnetic field of a flux tube, we derive the radial dependence of the solar wind by using a numerical code based on the modified Parker model. The transformation into time evolution is obtained by integrating the inverse radial profile of the solar wind velocity. To provide compatibility with the output of the hybrid simulation, the radial evolution of the solar wind element is given in terms of the elapsed ion gyro-phase. Second step of the present study is to apply the above devised method to map the ion-scale plasma turbulence evolution onto the radial expanding of the solar wind. Fig. 5 is an example obtained by mapping the brake time (or inverse of the broadening width in the dispersion relation diagram) of a normal mode.

3.3 Ion-Scale Whistler Waves and Plasma Turbulence

The problem on how the solar wind and its turbulent state could evolve from the solar corona to the interplanetary space is investigated by means of hybrid numerical simulations. The energy cascade mechanism in solar wind plasma turbulence is not yet fully understood. Here we discussed by using a 3-D simulation box and large-scale Alfvén pump waves the competition between high oblique whistlers and kinetic Alfvén waves in transporting energy between MHD turbulence and electron-scale turbulence. The interplanetary magnetic field breaks the isotropy of the problem which makes it more challenging than the nonmagnetic hydrodynamic fluid turbulence. In our anisotropic scenarios, the whistler mode with perpendicular propagation with respect to the mean magnetic field appears to be the major energy carrier to the electron scales. The persistency of whistler modes at ion kinetic scales sustain the recent findings from *in situ* measurements of whistler turbulence at electron scales in the solar wind, see Narita *et al.*[5]. However, strong kinetic Alfvén waves with highly oblique propagation could be also important. The investigation of the linear modes in solar wind plasma conditions is a suitable task to understand the turbulent heating process in the inner heliosphere in the upcoming Solar Orbiter and Solar Probe Plus missions by the space agencies ESA and NASA, respectively.

4 Conclusions

By using hybrid simulations, plasma turbulence has been investigated by examining the spatial structures and various wave modes whose non-linear evolution leads to turbulence. The steady radial outflow (called the solar wind) is believed to be in a fully-developed turbulent state, as confirmed by many spacecraft *in situ* in the interplanetary space of the solar system. The radial evolution of the solar wind turbulence is analysed from a wide range of scales by associating the plasma parameters for hybrid-code turbulence simulations to the radial distance from the Sun via a mapping procedure and a Solar wind model. The solar wind element is traced in terms of ion-gyroperiods along its expansion travel from the Sun towards the interplanetary space by using, e.g., Parker model. Two- and three-dimensional hybrid simulations have been performed using the kinetic code A.I.K.E.F., which treats ions as individual particles and is suitable for resolving detailed turbulence structures on various spatial scales. The resulting wave break time for the developed wave modes is related to the solar wind distance from the Sun by using a mapping procedure. Scientific outputs have impacts on the explanation of coronal heating mechanism and solar wind structure and can provide predictions to guide the *in situ* measurements by the upcoming ESA and NASA space missions.

Acknowledgements

The work is supported by the Deutsche Forschungemeinschaft (DFG) through grants CRC963 and MO539/20-1. The authors gratefully acknowledge the computing time granted by the John von Neumann Institute for Computing (NIC) and provided on the supercomputer JURECA at Jülich Supercomputing Centre (JSC).

References

1. J. Mueller, S. Simon, U. Motschmann, J. Schle, K. -H Glassmeier and G. J. Pringle, *A.I.K.E.F.: Adaptive hybrid model for space plasma simulations*, Comp. Phys. Comm. **182**, 946–966, 2011.
2. H. Comişel, Y. Narita and U. Motschmann, *Dispersion relation as a channel of plasma turbulence evolution*, Earth Planet Space **67**, 32, 2015.
3. H. Comişel, U. Motschmann, J. Buechner, Y. Narita and Y Nariyuki, *Ion-scale turbulence in the inner-heliosphere: radial dependence*, Astrophys. J. **812**, 175, 2015.
4. H. Comişel, Y. Nariyuki, Y. Narita and U. Motschmann, *On the role of ion-scale whistler waves in space and astrophysical plasma turbulence*, Ann. Geophys. **34**, 975–984, 2016.
5. Y. Narita, R. Nakamura, W. Baumjohann,K. -H. Glassmeier, U. Motschmann, B. Giles, W. Magnes, D. Fischer, R. B. Torbert, C. T. Russell, R. J. Strangeway, J. L. Burch, Y. Nariyuki, S. Saito and S. P. Gary, *On electron-scale whistler turbulence in the solar wind*, Astrophys. J. Lett. **827**, L8, 2016.