Visualization and analysis of coherent structures, intermittent turbulence, and dissipation in high-temperature plasmas

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Abstract

An unsolved problem in plasma turbulence is how energy is dissipated at small scales. Particle collisions are too infrequent in hot plasmas to provide the necessary dissipation. Simulations either treat the fluid scales and impose an ad hoc form of dissipation (e.g., resistivity) or consider dissipation arising from resonant damping of small amplitude disturbances where damping rates are found to be comparable to that predicted from linear theory. Here, we report kinetic simulations that span the macroscopic fluid scales down to the motion of electrons. We find that turbulent cascade leads to generation of coherent structures in the form of current sheets that steepen to electron scales, triggering strong localized heating of the plasma. The dominant heating mechanism is due to parallel electric fields associated with the current sheets, leading to anisotropic electron and ion distributions which can be measured with NASA's upcoming Magnetospheric Multiscale mission. The motion of coherent structures also generates waves that are emitted into the ambient plasma in form of highly oblique compressional and shear Alfven modes. In 3D, modes propagating at other angles can also be generated. This indicates that intermittent plasma turbulence will in general consist of both coherent structures and waves. However, the current sheet heating is found to be locally several orders of magnitude more efficient than wave damping and is sufficient to explain the observed heating rates in the solar wind. In this work the visualization and analysis; visualization software developed by RDAV and LBNL; and the use of supercomputing visualization resources

lead to breakthroughs in the understanding of fundamental physical processes responsible for turbulent heating of the solar wind. We present the following figures and movies that were a key to the success of this collaboration.

1 Links to the Presentation

Our SC13 visualization showcase presentation is a series of animations of all 508 time steps of the simulation introduced by a short clips that provide background information and briefly show still frame visualizations. The movies created in 1080p resolution are too large to stream over the Internet. Therefor the entire presentation should be downloaded before attempting to play it. The presentation should be played by opening “sc13-vis-showcase-loring-mp4.m3u” which is a portable play list.

The easiest way to get the material is through the following zip'ed archive.

description	**link**
Entire presentation in zip format.	**sc13-vis-showcase-loring-mp4.zip**

Alternatively each of the following links could downloaded to the same folder.

description	**link**
Play list	**sc13-vis-showcase-loring-mp4.m3u**
Title	**01-title.mp4**
Simulation ICs	**02-simulation-ibc.mp4**
Simulation Phases	**03-phases.mp4**
Current sheet visualization	**04-vis-current-sheets.mp4**
Tearing instability onset	**05-tearing-instability-early.mp4**
Tearing instability end-of-life	**06-tearing-instability-late.mp4**
Magnetic island visualization	**07-vis-magnetic-islands.mp4**
Excited waves intro	**08-waves-intro.mp4**
Excited waves visualization	**09-vis-waves.mp4**
Eddies in mag. plasmas	**10-eddies.mp4**
Electron flow vorticity visualization	**11-vis-electron-vorticity.mp4**
Conclusion	**12-conclusion.mp4**

The following URL may be useful for downloading the above files using the wget utility. **http://hpcvis.com/vis/images/sc13/sc13-vis-showcase-loring-mp4/**

We've verified that our presentation plays on Windows, Linux, and Mac OSX using the VLC media player, therefor we suggest that if any problems are encountered the reviewer download and use the **VLC player**. Note, Mac's Quicktime player will not play our movies.

2 Summary of the Simulations, Visualizations, and Analyses

In this work we analyzed a data sets from 2D and 3D simulations of hot magnetized plasmas[2]. The simulations were configured with initial conditions corresponding to the strongly growing regime of a Kelvin-Helmholtz instability. The simulations were run using the vector particle in cell(VPIC) simulation code on Jaguar using 50,000 cores for approximately 72 hours. The powerful advantage of these simulations is that they let us study turbulent heating at kinetic scales.

Our investigation focused on the more highly resolved and physically representative 2D simulation data. The 2D simulation run consisted of a grid size of 16384×8192 each with 150 electrons and 150 ions for a total of approximately 4×10^{10} particles. During the run 508 time steps were saved to disk. Each time step contains 2 symmetric tensors, 5 vectors, and 2 scalars resulting in an intial dataset size of approximately 7.2TB. Note that all 3 components of vectors and all 6 components of symmetric tensors are computed and visualized.

Discrete particle noise is a numerical issue of PIC simulation codes that can make visualization and further numerical analysys challenging. Prior to visualization and analysis, all of the fields were denoised using a Gaussian kernel convolution with a kernel width of 19 cells which corresponds approximately to 1 electron inertial length unit. Filtering on this scale preserves physical features while damping non-physical discrete particle noise. We also computed vorticity, vector gradients, and a number of other scalar derived quantities during analysis. The computation of the derived quantities approximately doubled the dataset size.

During visualization and analysis we used both subsets of the data and renderings of the entire simulation grid. In renderings of the full simulation grid 268 million triangles along with necessary vertex attributes were sent to the rendering devices. Despite being 2D, the dataset is sufficiently large that parallel visualization is necessary. Our analysis and visualization was done using ParaView on a number of supercomputing resources. Both I/O and rendering performance were improved by increasing the number of ParaView processes. Our ParaView I/O component makes use of MPI-I/O. In order to address issues in ParaView's Surface LIC algorithm we developed a new GPGPU Multiblock data parallel Surface LIC algorithm and added a number of existing shading techniques to it. We also resolved a number of issues in VTK so that the new algorithm could be used with Mesa's off screen Gallium llvmpipe renderer on systems without GPU's.

For the denoising and vorticity computations we used ParaView in batch mode on 512 cores at TACC's Longhorn visualization cluster. For scalar pseudocolorings we used 128 cores with 16 NVIDIA Quadro 5800 GPUs on TACC's Longhorn visualization cluster. For Surface LIC renderings we found that the increased computation during rendering and the additional vertex attributes required more processing power and memory than needed to acheive the same level of interactivity as the scalar pseudo color rendering. When using surface LIC rendering algorithm on TACC's Longhorn cluster we typically made use of at least 256 cores with the corresponding 32 NVIDIA Quadro 5800 GPUs. A number of runs were also made on NERSC's Cray XC30 supercomputer Edison using 512 cores. The higher core count was necessary because rendering on Edison was done without GPU's using Mesa's off screen Gallium llvmpipe renderer. We also investigated how best to take advantage of threading in the Gallium llvmpipe renderer when used within ParaView [1]. Various other derived quantities were computed and temporal spectral analysis was made using IDL on NICSs SGI UV1000 Nautilus.

Parallel remote interactive visualization and analysis using ParaView at HPC centers played an essential role in the visual analysis of the simulation data. The parallel denoising filters that we developed for ParaView were essential in removing discrete particle noise and producing clear and precise visualizations. Our subsequent visual analysis lead to the discovery of unexpected "excited waves" which could play a significant role in heating of the solar wind. Surface LIC renderings were used to locate and track coherent structures in time relative to "excited waves". As a result of this analysis we postulate that the motion of coherent structures is responsible for the generation of these waves. A visual analysis was also used to locate secondary tearing instabilities, a key indicator of magnetic reconnection, at their onset and track the resulting magnetic islands throughout their life cycle as the magnetic reconnection occurring as a result of their formation and destruction drove additional turbulence. We used a visual analysis here to characterized the growth rate and physical properties of these island chains and associated current sheets.

3 Summary of The Science Results

In turbulence, energy is often supplied by gradients at large scales, and cascades through nonlinear interactions to small scales where the collective motions are dissipated into heat. A question of substantial importance in extending classical turbulence theory to these space and astrophysical plasmas is the identification of key dissipative mechanisms that transform cascade energy into heat. While large scale motions are well described by fluid theory, the interface between fluid motions and kinetic plasma dynamics, and the details of the dissipation process, remains enigmatic. However, the advent of petascale supercomputers has now made it possible to reveal these features through fully kinetic simulations that span the range of scales from fluid to kinetic range. Here, we reported on the first results from these simulations with a focus on the solar wind turbulence problem where the availability of in situ spacecraft measurements provides stringent constraints on the results. Starting with a laminar, large scale velocity shear, the fluid-scale cascade drives a strongly nonlinear kinetic cascade characterized by a hierarchy of dissipative coherent structures extending down to electron scales. The cascade is punctuated by secondary tearing and Kelvin-Helmholtz instabilities. The largest percentage of the dissipated energy is found to go into heating of electrons and ions with progressively smaller percentages going into magnetic field generation, production of energetic particles, and excitation of waves (highly oblique magnetosonic waves). The main heating mechanism is associated with anisotropic electron heating in current sheets, and is reminiscent of collisionless magnetic reconnection, with much weaker heating associated with the waves. Another interesting finding is that the motion of coherent structures, including the vortex and the embedded magnetic islands, leads to emission of waves that propagate away from the vortex region. This is analogous to sound wave generation due to turbulent fluid motion in aeroacoustics.This wave mechanism has not been considered in the solar wind and may lead to generation of waves that may otherwise not be possible. The properties of such waves would be related to the size and speed of the coherent structures. In most cases, the waves are expected to remain at small amplitudes. But we have verified that for high enough Mach number, the waves steepen and form shocks. However, regardless of the source of waves, the dissipation efficiency due to waves is several orders of magnitude smaller than that due to reconnection as a simple estimate demonstrates. We compare the energy gain of a particle from interacting with a wave versus a reconnection site. The potential of a KAW Φ_{KAW}, a leading candidate in wave damping models, is given by $e^{\Phi_{KAW}}/T_e \approx (1/\sqrt{\beta_i(1+\beta_i)})(\delta B/B_0)$. Here, δB is the wave amplitude, $q_i = e$, and we have assumed $T_i = T_e$. The potential due to magnetic reconnection is $e^{\Phi_{rec}}/T_e \approx 1/\sqrt{\beta_e}$ for moderate values of electron beta $\beta_e > 0.01$. Here for simplicity, we have neglected other mechanisms of heating associated with current sheets such as heating of ions due to the perpendicular electric field. Thus we get $\Phi_{KAW} = \Phi_{rec} \approx \delta B/B_0 \approx 1$, where we have used inferred wave amplitude at kinetic scales in the solar wind. This indicates that the energy gain due to reconnection in the electron layers is at least 100 larger than that due to KAW. This means that coherent accelerating regions can be at least a factor of 100 less volume filling (1%) than waves and still yield comparable heating. This estimate is remarkably consistent with an observation in the magnetosheath where direct measurement of damping rate from reconnecting current sheets was found to be a factor of 100 larger than the wave damping rate. Note that the volume filling factor is over 20% in the present case. It is interesting to note that in regimes with $\beta_i < 1$, the potential for KAW and reconnection scale in the same manner ($\Phi_{KAW} \propto 1/\sqrt{\beta_i}, \Phi_{rec} \propto 1/\sqrt{B_e}$) implying the relative efficiency is nearly independent of β for a fixed temperature ratio $T_i = T_e$. These results are highly suggestive that in description of solar wind and other plasmas like the interstellar medium, discussion of physics of the cascade needs to go beyond the simple phenomenology for the spectral laws. The total dissipation rate is expected to be set by the large-scale drive. We have in fact verified that in the simulation, as in the solar wind, the turbulence decay rate is roughly consistent with the directly measured heating rate (Sec. VI). These two estimates indicate that the cascade into current sheets and the ensuing strong heating is sufficient to explain the observed heating rates in the solar wind. The first-principle simulations here pave the way for future studies of turbulence, collisionless dynamo, and MRI. We have already started on 3D fully kinetic simulations of wave turbulence and will report the results elsewhere. Our preliminary results suggest that electron scale current sheet generation may be a generic feature of collisionless turbulence.

References

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