論文の内容の要旨

Fast solar wind driven by parametric decay instability and Alfvén wave turbulence

(減衰不安定とアルフベン波乱流により駆動される高速太陽風)

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A continuous injection of energy and momentum is required to sustain the high-temperature corona and high-speed solar wind. A widely accepted idea is that the origin of such energy and momentum lies in the convective motion of the solar surface (photosphere) and the magnetic field transports them to upper atmosphere via Alfvén wave, which is called Alfvén-wave modeling or Alfvén wave scenario of the (fast) solar wind. Although the general framework of Alfvén-wave modeling is, at least theoretically, of little doubt, the detailed physics inside is yet controversial. Specifically, the thermalization mechanism of Alfvén wave in the corona and solar wind is unclear. Bearing in mind that the (magnetic) Reynolds number is quite large, turbulence and resultant cascading are required to obtain adequate heating.

A standard model, called reflection-driven Alfvén wave turbulence model, assumes that inward Alfvén waves generated by a partial reflection in the solar wind collide with outward Alfvén waves, triggering Alfvén wave turbulence to heat the solar wind. One problem that recently arose regarding this model is that the heating rate is insufficient. Therefore, we need to revisit and modify the standard model, incorporating new physics.

The standard model is based on reduced MHD equations in which compressional waves are ruled out. We assume that the shortage of heating is attributed to neglecting compressional waves. An overall motivation of this thesis is to update the standard model including compressional waves. Permission of compressibility is crucial in the solar wind, where plasma beta is low, because parametric decay instability works with a comparable

time scale to Alfvén wave turbulence. For this purpose, we have performed two different simulations: one-dimensional and three-dimensional simulations.

In Chapter 3, we report the results of one-dimensional simulations. To consider the turbulent heating in one-dimensional geometry, we introduce a phenomenological turbulence model of Alfvén wave turbulence into compressible MHD equations. The turbulence model is set so that the model becomes equivalent with commonly used Alfvén wave turbulence model in the limit of incompressibility. Similarly, in the limit of infinite turn over time of turbulence, this model is identical to the previous work without turbulence. We have found that the dominant heating process in the solar wind is correlation-length dependent; with small correlation length most of the heating is by turbulence and with large correlation length shock heating is dominant. With the realistic correlation length, the turbulence is slightly stronger than shock. Using parameter survey, we have revealed several conclusions. First, the solar wind velocity is strongly affected by correlation length while the magnitude of energy injection determines the mass-loss rate. This result is consistent with previous works. Second, the observed large density fluctuation in the solar wind acceleration region is explained by parametric decay instability. Specifically, the largest-density-fluctuation region is the same as the largest-growth-rate region of parametric decay instability. Third, the cross-helicity evolution is explained based on linear reflection. These indicate that parametric decay instability plays a crucial role in the solar wind acceleration region but not in the distant solar wind.

In Chapter 4, we show the results of the three-dimensional simulation, the motivations of which are to validate the 1D model and to predict the data of *Parker Solar Probe.* Our simulation is the first-ever three-dimensional self-consistent simulation of the solar wind acceleration. Large density fluctuation is generated by parametric decay instability in the wind acceleration region consistently with 1D simulation. The turbulence in the solar wind is characterized by an imbalanced MHD turbulence in which the power spectra of outward and inward waves have different power indices. As a prediction of *Parker Solar Probe*, we have shown that the positive correlation between density and parallel-velocity fluctuations would be observed.

As a conclusion of this thesis, we propose an updated standard model of the solar wind acceleration: the PDI-driven Alfvén wave turbulence model. Alfvén wave reflection, the source of turbulence in the solar wind, is triggered not only by simple linear refection but also by the parametric decay instability. The compressible waves play a crucial role in the solar wind turbulence and therefore is never ignorable in the simulation.