Cosmic Structure Formation and Dynamics: Magnetohydrodynamic Simulations of Coronal Heating

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By implementing a three-dimensional magnetohydrodynamic (MHD) code based on the CIP-MOCCT scheme, we carried out large scale MHD simulations of the solar atmosphere covering the region from the convection zone to the corona. We found that in regions with weak magnetic fields (B~100G), horizontal magnetic loops created in the upflow regions of the convection generate high frequency waves by reconnecting with the ambient magnetic fields. The corona can be heated up by direct heating by magnetic reconnection and dissipation of high frequency waves generated by the magnetic reconnection.

Keywords: Astrophysics, Magnetohydrodynamics, Solar Activities

1. Introduction

Magnetic fields play essential roles in various activities observed in the solar atmosphere, star forming regions, galaxies, and clusters of galaxies. By implementing the three-dimensional magnetohydrodynamic (MHD) code CANS (Coordinated Astronomical Numerical Simulator) to the Earth simulator, we have carried out simulations of the formation of filamentary structures on the Sun [1] and launching of collimated outflows (jets) from accretion disks.

In astrophysical objects, gravity creates stratification consisting of the dense inner region and the outer low-density atmosphere (corona). The solar corona, for example, is the hot outer atmosphere of the Sun where temperature is above 1 million K, which is much higher than the temperature at the solar surface (about 6000K). The mechanism that heats the corona has been a long-standing puzzle in astrophysics. From the solar corona, high speed (>400 km/s) plasma flow called the solar wind is continuously flowing out. The solar wind determines the space environment around the Earth. Understanding the heating and acceleration of the plasma in the solar corona is hence important both in academic and in practical points of view. Hot corona also exists in galaxies and in accretion disks. In accretion disks, inverse Compton scattering in the corona can be the origin of power law component in X-rays observed in black hole candidates.

The energy source of coronal heating and solar wind acceleration is the interaction of magnetic field and convection at the solar surface. The magnetic disturbance produced by this interaction is transported to the upper layer via magnetic fields and dissipate there. The remaining problem is to pin down the transportation and dissipation mechanisms. There are two possibilities: MHD waves and magnetic reconnection. The difference of the two models comes from the difference in the time scale. If the time scale of disturbances generated by the interaction of magnetic field and convection is smaller than the Alfven time of the corona (time in which Alfven waves travel across the coronal magnetic loop), the disturbances will propagate as MHD waves. If the time scale of the disturbances is longer than the Alfven time, the disturbance will tangle the coronal magnetic fields. In the latter case, magnetic reconnection occurs between the tangled field lines. Therefore, in order to distinguish the two models, it is essential to understand the mode and spectra of the disturbance generated by the interaction of magnetic fields and convection. In order to address this problem, we carried out MHD simulations of the domain covering the region from the upper convection zone up to the corona.

2. Magnetohydrodynamic Simulations of Solar Coronal Heating

We have revised a three-dimensional MHD code based on the CIP-MOCCT scheme [2] and implemented it to the Earth simulator. In this scheme, the magnetic induction equation is solved by MOCCT (Method of Characteristics, Constrained Transport) scheme [3], which preserves the div B = 0 condition, and other equations are solved by the CIP scheme [4,5]. The CIP-MOCCT scheme is more robust and accurate in magnetically dominated regions where $\beta = P_{gas}/P_{mag} < 1$ than the schemes based on the conservation form of the energy equation. The vectorization ratio and the parallelization ratio of the code are 98.890%, and 99.81%, respectively on the Earth simulator for simulations using 400^3 grid points.

The size of the simulation box is 10000km in horizontal direction, 1600 km below the photosphere and 12000km above the photosphere. The grid points are uniform in horizontal directions but we used non-uniform grid in the vertical direction. The number of grid points is 400^3. Periodic boundary condition is imposed in the horizontal direction. Radiative cooling in the photosphere is treated by Newton approximation, so that the temperature in the photosphere is maintained almost constant at 6000K. Hence convection is maintained in a self-consistent way. To start the simulation, at first we run the simulation without magnetic field until the convection develops to statistically steady state. Then we impose vertical and uniform magnetic field with various strength and continue the calculation.

Figure 1 shows a three-dimensional visualization of a simulation result with field strength similar to a sunspot (about 1kG). In this case the convection is relatively weak and oscillatory, and magnetic fields in the photosphere remain nearly vertical. Small amplitude Alfven wave is generated and propagates into the corona.

The solution is drastically different in the weak field regime. Figure 2 shows the result of relatively weak field case corresponding to the solar plage region (about 100G), namely near but outside sunspots. In this case the convection is vigorous enough to create turbulent fields in the convection zone. Occasionally a bundle of strong (about 500G) magnetic flux is driven by the convective upflow and emerges above the photosphere. The emerging fluxes undergo magnetic reconnection with the ambient vertical fields, and generate high frequency waves propagating to the corona. Indeed, such small-scale emergence of magnetic flux has been found by recent observation by the Solar Optical Telescope on board the Hinode, a Japanese solar observation satellite.

Figure 3 and 4 show the wavelet spectra of horizontal velocity at a fixed point in the corona in strong field case and weak field case, respectively. Remarkable feature is the intermittent emission of high frequency waves in the weak field case, whereas in the strong field case most of the power is in time scale of 100s, which is similar to the time scale of convection.

Two conclusions can be drawn from the simulation result. Firstly, at least in the weak field regime the heating mechanism can be a combination of two mechanisms, i.e, magnetic reconnection results in both direct heating and generation of high frequency waves which eventually dissipate later. Secondly, the chromosphere plays an essential role in coronal heating and solar wind acceleration. In particular, generation of waves cannot be properly addressed if one looks at only the photosphere. Future solar observation should strengthen the capability of plasma diagnostics in the chromosphere.

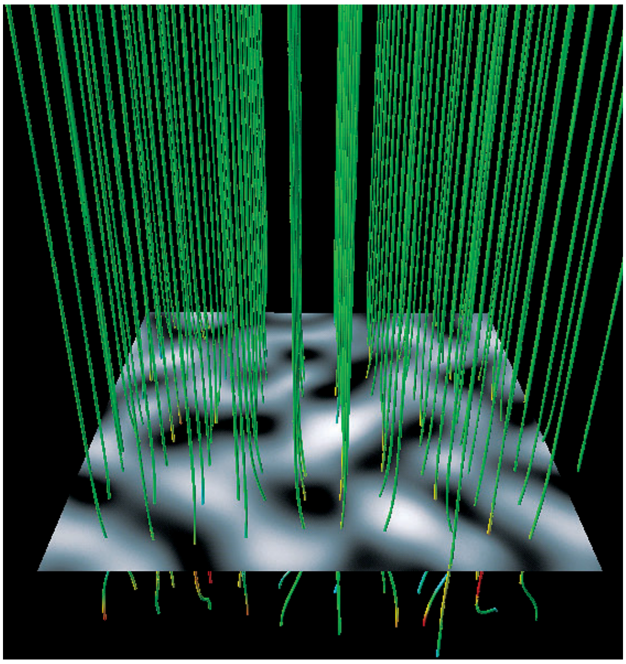

Fig. 1 Result of a simulation for strong magnetic fields (B ~ 1kG). Solid curves show magnetic fields and grey scale shows vertical component of photospheric magnetic fields.

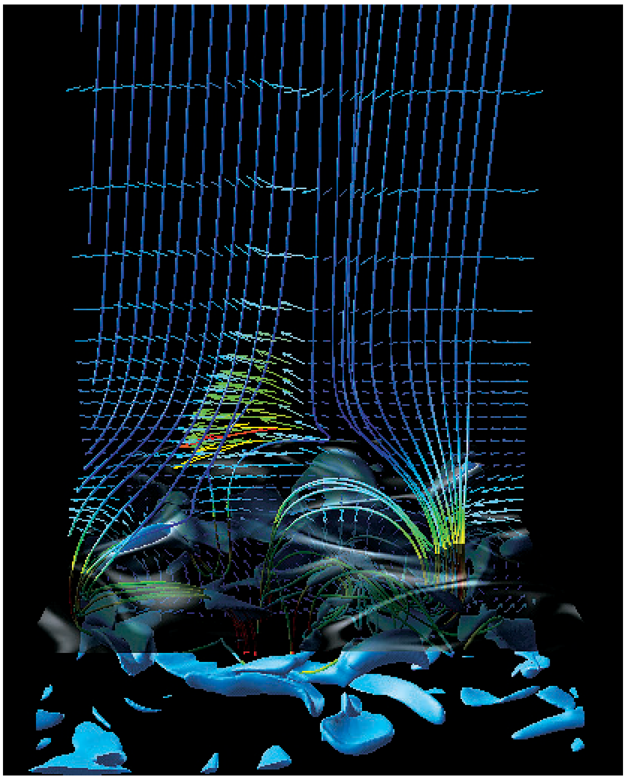

Fig. 2 Result of a simulation for weak magnetic fields (B ~ 100G). Solid curves show magnetic fields. Arrows show velocity vectors.

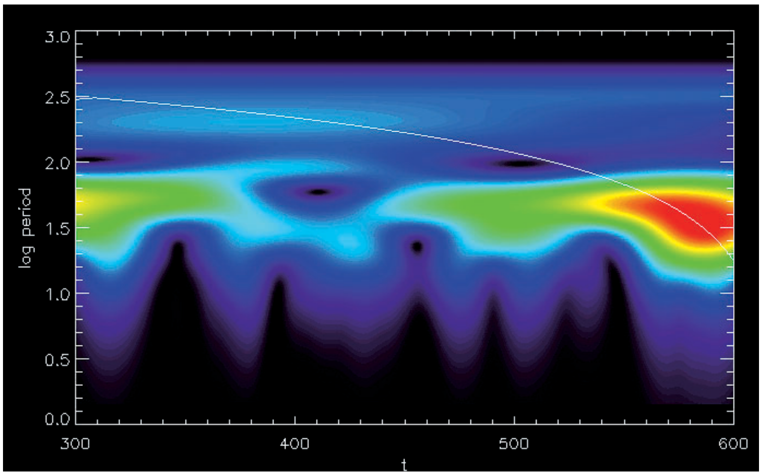

Fig. 3 Wavelet spectra for the horizontal velocity obtained from the result for strong magnetic fields (B ~ 1kG). Horizontal axis shows time in unit of sec, and the vertical axis shows the period of oscillation.

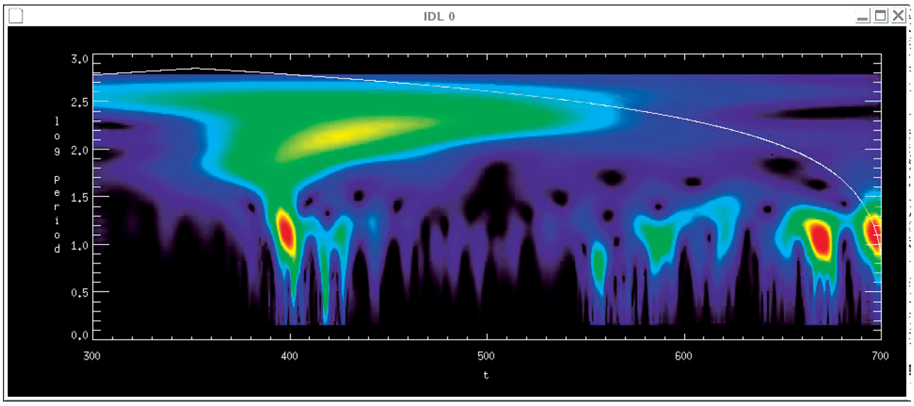

Fig. 4 The same as figure 3 but for weak magnetic fields (B ~ 100G).

3. Summary

We reported the results of three-dimensional MHD simulations of the solar atmosphere covering the region from the convection zone to the corona. Numerical simulations have been carried out on the Earth simulator by using a MHD code based on the CIP-MOCCT scheme. We found that in the weak field region horizontal magnetic fields emerging with the convective motion reconnects with the ambient vertical fields, and generate high frequency waves. Such waves propagating in the corona will be dissipated and heat the corona. Numerical results will be compared with the observations of the Hinode satellite.

These studies are now revealing how magnetic energy is transported from the inner dense regions of the gravitationally stratified atmosphere to the outer low-density corona. We would like to apply this mechanism to Comptonizing corona above accretion disks, and heating of the hot X-ray emitting plasmas in cluster of galaxies.

References

[1] H. Isobe, T. Miyagoshi, K. Shibata, and T. Yokoyama, "Filamentary structure on the Sun from the magnetic Rayleigh-Taylor instability", Nature, 434, pp.478–481, 2005.

[2] T. Kudoh, R. Matsumoto, and K. Shibata, "Numerical MHD simulation of astrophysical problems by using CIP-MOCCT method", CFD journal, 8, pp.56–68, 1999.

[3] J. Stone, and M. Norman, "ZEUS-2D: A Radiation Magnetohydrodynamics Code for Astrophysical Flows in Two Space Dimensions II. The Magnetohydrodynamic Algorithm and Tests", Astrophys. J. Suppl. 80, pp.791–818, 1992.

[4] T. Yabe, and T. Aoki, "A Universal Solver for Hyperbolic Equations by Cubic-Polynomial Interpolation I. One-dimensional Solver", Computer Physics Communications 66, pp.219–232, 1991.

[5] T. Yabe, T. Ishikawa, P.Y. Wang, T. Aoki, Y. Kadota, and F. Ikeda, "A Universal Solver for Hyperbolic Equations by Cubic-Polynomial Interpolation II. Two and Three-dimensional Solvers", Computer Physics Communications 66, pp.233–242, 1991.

宇宙の構造形成とダイナミックス：
コロナ加熱の磁気流体シミュレーション

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地球シミュレータに実装したCIP-MOCCT法に基づく磁気流体シミュレーションコードを用いて、太陽大気の対流層からコロナまでを含む領域の3次元磁気流体シミュレーションを行った。その結果、平均磁場が100G程度以下と比較的弱い場合は対流層の磁場が乱流的になり、その乱流磁場が対流層のすぐ上の彩層で磁気リコネクションを起こして高周波数（>0.1Hz）の波が発生するが、磁場が強く乱流磁場が発生しない場合は、コロナへ伝わる波は対流と同程度の低周波（<0.01Hz）の波しか発生しないことがわかった。波のスペクトルはその散逸メカニズムと密接に関係しているため、我々の結果は、磁場の強さによりコロナ加熱、太陽風加速のメカニズムが変わりうること、彩層での磁気リコネクションと波動の発生が重要な役割を果たすことを示唆する。これらの結果を太陽観測衛星「ひので」の観測結果と比較することにより、種々の天体で観測されるコロナの加熱機構についての理解を深めることができる。

キーワード：宇宙物理学, 磁気流体力学, 太陽活動