Understanding and Predicting the Onset of Solar Eruptions

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Solar eruptions, such as solar flares and coronal mass ejections (CMEs), are the most catastrophic phenomena in our solar system. Although they are widely believed to be driven by magnetic energy contained in the solar corona, the onset mechanism of solar eruptions is not well understood yet. Therefore, when, where and why solar eruptions suddenly occur is still the long-standing enigma, and the answering to this question is important also for the understanding of nonlinear plasma dynamics. Solar eruption may affect terrestrial environments and infrastructure. Therefore, the prediction of solar eruptions is required to protect the socio-economic system from severe space weather disaster, and the understanding and predicting the onset of soar eruption are crucial not only as scientific research but also as a social challenge.

We have investigated what kind of magnetic structure on the solar surface can trigger solar eruptions by systematically surveying the nonlinear dynamics caused by a wide variety of magnetic structures in terms of three-dimensional magnetohydrodynamic (MHD) simulations (Fig. 1) and the detail analysis of solar magnetic field data observed by Japanese solar physics satellite Hinode. As the result, we determined that two different types of small magnetic structures favor the onset of solar eruptions. These structures, which should appear near the magnetic polarity inversion line (PIL), include magnetic fluxes reversed to the potential component or the nonpotential component of major field on the PIL. In addition, we analyzed different large flares using imaging data provided by the Hinode and SDO satellites, and we demonstrated that they conform to the simulation predictions. These results suggest that forecasting of solar eruptions is possible with sophisticated observation of a solar magnetic field, although the lead time must be limited by the timescale of changes in the small magnetic structures.

Why the two small magnetic fields work for triggering solar eruptions can be explained by the fact that these fields are easy to cause the so-called tether cutting reconnection, which can connect twisted two magnetic field lines and form a double-arc twisted flux loop. We numerically analyzed the stability of the double-arc loop, and derive a new parameter κ, which determines the critical condition of stability. The parameter κ is given by multiplying the magnetic flux subject to tether-cutting reconnection by the magnetic twist. It indicates that the magnetic twist and the tether-cutting reconnection play a complementary role for triggering solar eruptions. If the twist is high enough, even small amount of tether-cutting reconnection may trigger them, whereas more reconnection is required in the region of weaker twist.

We also developed the data-driven numerical experiments, in which the three-dimensional force-free magnetic field extrapolated from magnetic field data on the solar surface was used on the initial state and different small magnetic bi-pole is imposed onto the solar surface boundary, to analyze the nonlinear stability of coronal magnetic field. The results demonstrate that the parameter κ is useful for predicting the probability of solar eruptions.

All the results above indicate that the analysis of MHD stability based on the observation data of solar magnetic field and the new technique of MHD simulation is capable to predict the onset of solar eruptions. We also briefly introduce the recent work of Project for Solar-Terrestrial Environment Prediction (PSTEP, http://www.pstep.jp), which is the nation-wide space weather and space climate project in Japan.

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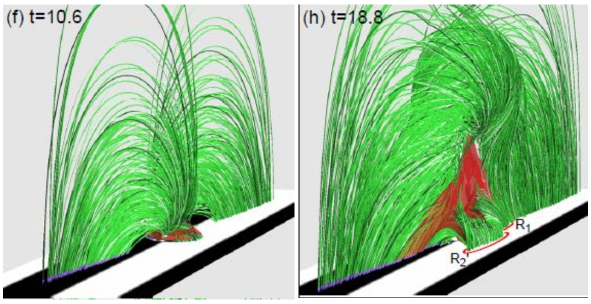

Figure 1: The result of numerical simulation of solar eruption. Reconnected field lines are ejected from the solar surface due to the MHD instability of double-arc twisted loop