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A challenge to the physics-based prediction of giant solar flares

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Solar flares are driven by the rapid release of magnetic energy stored in solar active regions (ARs) around visible sunspots, and they potentially cause a space weather disaster which may impact our modern infrastructures. However, although many models have been proposed so far, which parameters of the magnetic field determine the occurrence and properties of solar flares have not yet been completely explained. Therefore, the occurrence, location, size, and features of solar flares are still difficult to accurately predict, and most of the flare forecasts still rely on empirical methods. The objective of this study is to develop a new kind of physics-based model for predicting giant solar flares not only to improve our predictive capability of solar flares but also to have a better understanding of solar flare onset mechanism.

The most reliable mechanism of the catastrophic energy release in solar flares is the positive feedback scenario between magnetohydrodynamic (MHD) instabilities and magnetic reconnection, which reinforce each other and result in a catastrophic energy liberation. However, the analyses of magnetic field data suggested that the models of the kink and torus mode instabilities could not explain the critical condition of solar flares. On the other hand, we proposed a new instability, called the double-arc instability (DAI), which can work as the initial ignition of flares.[1] Because the DAI is a kind of hoop-force-driven instability, it is an extension of the torus instability. However, the DAI can explicitly take into account the triggering effect of magnetic reconnection, unlike the torus instability model. The numerical analysis indicates that if magnetic reconnection between two magnetic loops forms a double arc (DA) and a new parameter κ of the DA becomes larger than about 0.1, the DA becomes unstable, and the feedback process between the DAI and reconnection starts. Here, κ is defined as the ratio between the magnetic twist flux of the DA and the magnetic flux overlying the DA.

Based on the DAI theory, we recently developed a physics-based prediction scheme, called the κ-scheme.[2] This new scheme can evaluate the critical size r_c of magnetic reconnection to trigger the onset of the DAI and estimates the minimum free energy, which is releasable by the DAI at any position on the polarity inversion line (PIL). If a smaller-scale reconnection can trigger the DAI, then the magnetic field might be less stable, and this would be an indicator that a solar flare is more imminent. The κ-scheme can predict not only the possibility of a giant solar flare but also the location where a giant flare will possibly occur.

To evaluate the predictive power of the κ-scheme, we analyzed the magnetic field data observed by the SDO/HMI for the 205 active regions (ARs) with largest sunspot area in solar cycle 24. Only the seven ARs in all the sampled ARs produced the nine giant solar flare larger than class X2. As a result of the analysis, we found that all the nine giant flares started the location where the κ-scheme predicts that an X-class flare would be possible. In particular, the seven flares out of the nine giant flares occurred at the location where the critical size r_c of the flare-triggered reconnection became smaller than 1 Mm. These results are well consistent with our hypothesis that the smaller the critical size of reconnection to trigger the instability, the less stable the magnetic field and the more imminent a giant solar flare.

The results demonstrate the significant power of the κ-scheme to predict giant flares and also indicate that the most of the giant solar flares are triggered by a small-scale magnetic reconnection. It means that the magnetic twist flux density in the vicinity of the magnetic PIL on the solar surface plays a crucial role in determining when, where, and how large solar flares may occur.

The κ-scheme is the first-ever physics-based model that provides better prediction performance for giant solar flares than the previous empirical predictions. For instance, while none of the currently operated flare predictions could reliably predict the first large flare from a solar active region,[3] the κ-scheme can predict even the first large flare in an active region because the κ-scheme use only the instantaneous magnetic data and is totally independent of the history of flares. The universality of the κ-scheme prediction is still an issue to be investigated; however, the results here show that the physics-based analysis of the MHD stability using the magnetic field data can open a new way for flare prediction.

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References

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