Advances and challenges in geomagnetic storm prediction

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Reliable prediction of potentially dangerous geomagnetic activity has become increasingly important, particularly following the loss of satellites during recent severe storms. Geomagnetic storm prognoses aim to forecast geomagnetic indices in case of short-term predictions and provide probabilistic estimates in mid-term and long-term forecasts. The main challenge is to deliver reliable predictions with sufficient lead time and accuracy for operational use. Forecasts are generally divided into three classes: long-range (days–months) based on solar cycle evolution and recurrent high-speed streams; event-based (1–3 days) using observations and modeling of coronal mass ejections (CMEs); and L1-based, derived from in situ solar wind measurements at the L1 Lagrangian point, including short-term ($\sim$ 1 hour) and mid-term ($>$ 3 hours) predictions.

The biggest problem is that the effectiveness of the prognoses is affected by the limitations of specific methods used, while mixed types of forecasts are rare. For example, empirical coupling functions (e.g., VB_z) provide rapid estimates of geomagnetic response but fail under strongly nonstationary conditions. Physics-based MHD models, such as ENLIL and EUHFORIA, simulate the propagation of geoeffective CMEs and stream interaction regions and predict their arrival at the Earth. They are useful for visualizing dynamic processes in interplanetary space, but uncertainties of 10–15 hours between predicted and observed arrivals strongly limit their forecasting capability. Machine learning methods (e.g., neural networks, LSTM-based models) can improve short-term predictions of Dst and Kp by capturing nonlinear solar wind–magnetosphere coupling, yet mid-term ($>$ 3 hours) forecasts remain unreliable because they assume conditions typical for ongoing storms rather than pre-storm environments. A further limitation across all forecast types is the intrinsic unpredictability of the southward interplanetary magnetic field component.

Recent advances in geomagnetic storm prediction suggest that extending forecast lead times may be achieved by additional observables beyond standard solar wind parameters typically used in models. A combined analysis of pre-storm trends in energetic particle fluxes and solar wind ULF variations in near-Earth space along with pre-history of the conditions of the geomagnetic field have been proposed to identify potential precursors of geomagnetic storms. Integration of these peculiarities with heliospheric remote sensing imaging and IPS-based modeling, multi-point in situ measurements of the solar wind conditions, and hybrid MHD–AI frameworks may improve both forecast reliability and the lead time.

Reference:

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