Contribution ID: **274** Type: **Poster**

On the causal inference in magnetosphere / solar wind system during geomagnetic storms

Solar storms are emissions of energy and charged particles from the Sun, such as Coronal Mass Ejection (CME), and can affect Earth's magnetic field, if directed toward Earth. The magnetosphere can usually shield Earth from solar storms, but sometimes, they can cause saturation of transformers, blackout of power systems, disturbances of international communications, damage satellites and be responsible for exposing astronauts to abnormal levels of radiation.

The energy transferred from a solar storm to Earth's magnetic field is primarily determined by the relative orientation of the interplanetary magnetic field within the CME, the source of the geomagnetic storms. If the magnetic field has a southward component for enough time, the interplanetary plasma can penetrate the magnetosphere, intensifying its current systems. This intensification, particularly of the ring current circulating in the magnetospheric equatorial plane, triggers geomagnetic storms. These events are typically monitored through the *SYM-H* geomagnetic index. Therefore, a comprehensive understanding and accurate modeling of the *SYM-H* index's dynamic features are essential for investigating about geomagnetic storms.

This work aims to study the causal relations between magnetospheric dynamics and external drivers, using a bivariate time series causality analysis, which allow us to reconstruct the causal graph of the system, following the methodology outlined by. This method takes as input a linear 2D continuous-time stochastic system for $(X(t), Y(t))$, henceforth the dependence on time is understood, and provides an estimation of the information transfer, $T_{Y\to X}$, between X and Y and vice versa. These values are normalized and subjected to statistical significance testing. Practically, each time series corresponds to a vertex in the causal graph, and a causal link is drawn between a vertex pair, say (Y, X), if the associated information flow, $T_{Y\to X}$, is statistically significant at an α level, and $|T_{Y\to X}|$ represents the weight of the edge.

The analysis focuses on finding the more relevant solar wind / magnetosphere coupling functions in terms of the normalized information transfer with respect to *SYM-H*. In detail, in order to study the response time of the magnetosphere to external solar wind drivers, we used a delayed\footnote{In this work only Y (driver) is lagged forward in time while the past of X (response) keeps unchanged.} version of the net normalized information flow, i.e., $\Delta\mathcal{T}_{Y\leftrightarrow X}(\tau) = |\mathcal{T}_{Y\to X}(\tau)| - |\mathcal{T}_{X\to Y}(\tau)|$\footnote{In causal inference only the absolute value is considered.}, where $\mathcal{T}$ denotes the normalized information transfer. Preliminary results show important qualitatively agreement with linear correlation analysis.

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