

ADVANCE WARNINGS OF SPACE WEATHER

New research by SwRI and the National Science Foundation's National Center for Atmospheric Research (NSF-NCAR) has developed a new tool providing a first step toward the ability to forecast space weather weeks in advance, instead of just hours. This advance warning could allow agencies and industries to mitigate impacts to GPS, power grids, astronaut safety and more.

"Understanding where and when large, flare-producing active regions (ARs) on the Sun would emerge is a long-standing problem in heliophysics," said SwRI's Dr. Subhamoy Chatterjee, an early-career scientist who co-authored a new *Astrophysical Journal* paper about this research. "These regions display tangled magnetic fields and produce explosive solar events, potentially causing hazardous space weather such as solar flares and coronal mass ejections (CMEs)."

Solar active regions do not emerge randomly. Instead, they cluster along large-scale, warped magnetic "toroidal bands." Using magnetic measurements from the Solar Dynamics Observatory Helioseismic and Magnetic Imager (SDO/HMI) from February 14, 2024, the team demonstrated that surface patterns can be inverted to reconstruct critical states beneath the surface.

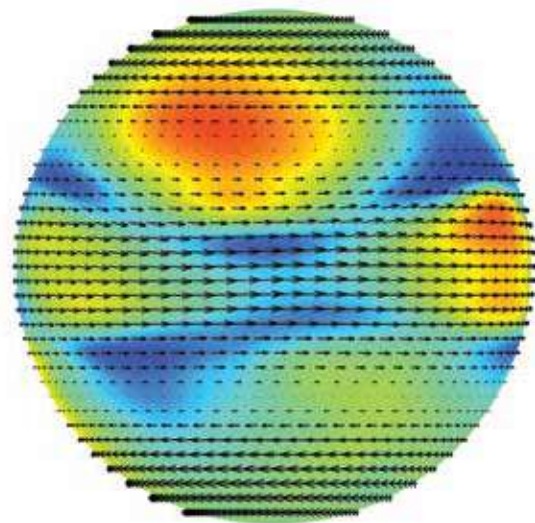
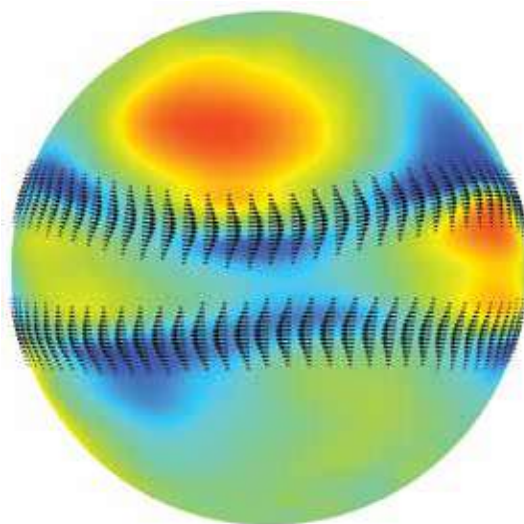
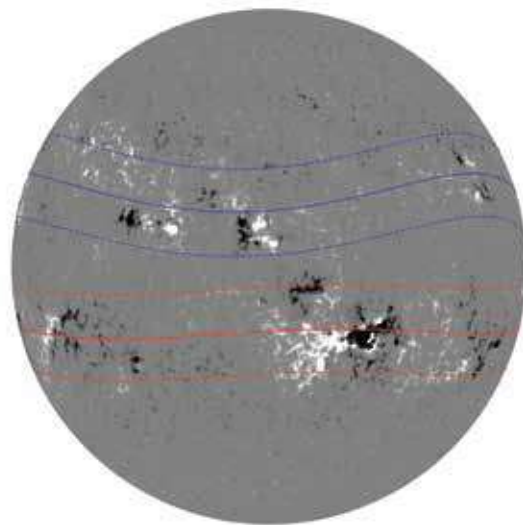
Most current forecasting tools rely on small-scale magnetic signatures that become predictive only hours before eruption. The SwRI, NSF-NCAR team developed PINNBARDS, a Physics-Informed Neural Network-Based AR Distribution Simulator, to connect surface observations of solar active regions to the deep magnetic dynamics of the Sun's tachocline region. This thin transition layer is located between the uniformly rotating radiative interior and the more turbulent rotations of the outer convection zone.

By bridging surface observations and deep solar magnetic dynamics, SwRI and NCAR scientists are advancing a new generation of physics-informed, AI-enabled forecasting tools to better understand and anticipate extreme space weather. Using global magnetic information, the PINNBARDS framework offers the potential for substantially longer forecast lead times, which is critical for safeguarding satellites, communications infrastructure and future human space exploration.

"The reconstructed subsurface states from PINNBARDS provide initial conditions for forward simulations of solar magnetic evolution, opening the door to predicting where and when large, flare-producing active regions are likely to emerge weeks in advance," said Dr. Mausumi Dikpati, a senior scientist from NSF-NCAR who led the team and co-authored the paper.

The latitude and longitude of emerging active regions are critical because the location determines if resulting bursts of solar particles are destined to reach our region of the solar system.

The research was funded by NASA's Heliophysics Guest Investigator Open (HGIO) program, NSF-NCAR, and Stanford's Consequences of Fields and Flows in the Interior and Exterior of the Sun center, a NASA-funded initiative with the goal of solving some of the most difficult mysteries hidden in the deep interior of our Sun.



Joint research by Southwest Research Institute and NSF-NCAR developed PINNBARDS — a physics-informed neural network that connects surface observations of solar active regions to the deep magnetic dynamics of the Sun. The top figure shows solar observations of two warped toroid patterns (derived from SDO/HMI magnetograms) in the southern and northern hemispheres. PINNBARDS-derived results (center) show magnetic vectors (black arrows) overlaid on bulges (red) and depressions (blue) match with observed toroidal bands. The velocity field is marked with black arrows in the bottom image. These results provide clues about the global sources of active regions that produce space weather, which can impact our technological society.

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