

Monitoring the Evolution and Activity of Solar Super-Active Regions

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Super-active regions are magnetically complex regions that drive the most extreme forms of solar activity and space weather. During Solar Cycle 25, several such regions produced major impacts throughout the heliosphere and geospace environment, including NOAA 13664, which generated the strongest geomagnetic storm since 2003 and became one of the most eruptive regions of the past two decades. Current space missions now enable us to study these long-lived regions and their diverse impacts on the heliosphere over extended periods, overcoming the observational limitations imposed by solar rotation. Active region NOAA 13664 and its subsequent derivatives, NOAA 13697 and 13723, were monitored nearly continuously using coordinated observations from the Solar Dynamics Observatory and Solar Orbiter over more than three months. This unique dataset allowed us to follow the region from emergence through peak complexity and eventual decay, while investigating the processes that led to its extreme magnetic complexity and fueled its most powerful eruptions. The region exhibited unprecedented complexity, comprising interacting subregions and persistent current-carrying magnetic structures associated with repeated flaring activity. Using the combined observations, we achieved the first long-term characterization of its magnetic non-potentiality, which remained at elevated levels throughout most of the region's lifetime. We further investigated the evolution of its flare and coronal mass ejection productivity and examined how its eruptive behavior changed over time. In addition, coronal spectroscopy enabled the identification of outflow regions that are potential sources of the slow solar wind. Our results demonstrate the many ways in which super-active regions influence the solar atmosphere and heliosphere and highlight the importance of coordinated multi-vantage-point and multi-wavelength observations for monitoring, understanding, and ultimately forecasting extreme space weather.