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Explanation of the sea-serpent magnetic structure of sunspot penumbrae

I.N. Kitiashvili, L.R. Bellot Rubio, A.G. Kosovichev, N.N. Mansour, A. Sainz Dalda, A.A. Wray

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Recent spectro-polarimetric observations of a sunspot showed the formation of bipolar magnetic patches in the mid penumbra and their propagation toward the outer penumbral boundary. The observations were interpreted as being caused by sea-serpent magnetic fields near the solar surface (Sainz Dalda & Bellot Rubio 2008). In this Letter, we develop a 3D radiative MHD numerical model to explain the sea-serpent structure and the wave-like behavior of the penumbral magnetic field lines. The simulations reproduce the observed behavior, suggesting that the sea-serpent phenomenon is a consequence of magnetoconvection in a strongly inclined magnetic field. It involves several physical processes: filamentary structurization, high-speed overturning convective motions in strong, almost horizontal magnetic fields with partially frozen field lines, and traveling convective waves. The results demonstrate a correlation of the bipolar magnetic patches with high-speed Evershed downflows in the penumbra. This is the first time that a 3D numerical model of the penumbra results in downward directed magnetic fields, an essential ingredient of sunspot penumbrae that has eluded explanation until now.

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