A calculation for the formation of sunspots in an unprecedentedly deep domain

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We carry out a calculation for the formation of the sunspot in an unprecedentedly deep calculation domain, which covers the whole convection zone from the base to the surface (200 Mm). The sunspot is the most prominent phenomenon at the solar surface, which occasionally causes explosive events such as flare and coronal mass ejection. It is thought that the sunspots are generated in the deep convection zone by the dynamo action and rise to the surface by the magnetic buoyancy or the turbulent convection. Previous studies cover only a fraction of the convection zone (<30 Mm), and they need to control the behavior of the sunspot at the bottom boundary. To exclude this artificial setting, we extend our calculation box to the base of the convection zone by using our new code R2D2 (Hotta et al., 2019). We succeed in reproducing the formation of sunspot from a simple flux tube with a combination of turbulent convection. Our new findings in this study are summarized as 1. The rising speed of flux tube exceeds typical convection upflow velocity due to the high entropy in the flux tube maintained by the suppression of the mixing by the magnetic field itself. 2. The previous constraint on the rising velocity at 18 Mm depth, 140 m/s, is relaxed to 250 m/s in our calculation. 3. Our understanding of the overall structure of the sunspot is revised. In the deep region, the center of the flux tube is upflow with high temperature, which is consistent to some extent with the helioseismic inversion of the sunspot.

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