Morphological study of penumbral formation

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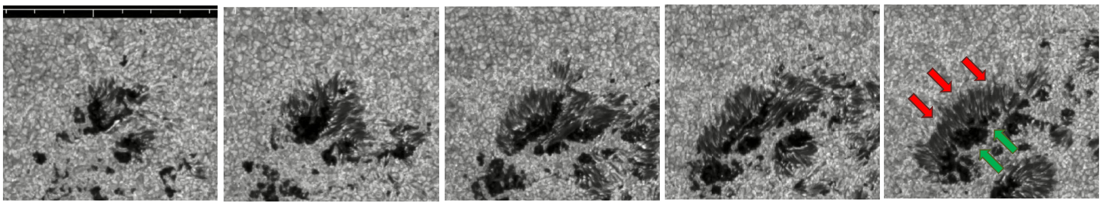
[Introduction] Sunspot penumbrae are known to be area of mainly horizontal magnetic field surrounding umbrae of relatively large and mature sunspots. The formation of penumbrae is discussed in this poster.

[Theoretical Background] Rucklidge (1995) studied the energy flows in a model sunspot including the lateral energy flux from surrounding inclined magnetic field, and showed that sunspot MHD structure has two equilibrium states (pores and sunspots) and that the structure will change abruptly or transit from pore state to sunspot state when the inclination of surrounding magnetic field gets larger than a threshold value. Succeeding numerical simulations by Hurlburt and Rucklidge (2000) and Tildesley and Weiss (2004) led to the idea of magnetic pumping mechanism around sunspots. Cheung et al. (2010) and then Rempel et al. (2012) closely studied the necessary condition of chromospheric boundary conditions for extended penumbral formation.

[Recent Results] Observationally, Shimizu et al. (2012) detected a case of penumbral formation, where appearance of chromospheric dark annular zone, which may correspond to horizontal magnetic field, precedes the formation of photospheric penumbra.

[Our results] We observationally studied the formation of penumbrae in NOAA10978, where several penumbral formations were observed in G-band images of SOT/Hinode. Thanks to the continuous observation by Hinode, we could morphologically follow the evolution of sunspots and found that there are several paths to the penumbral formation:

(1) Active accumulation of magnetic flux

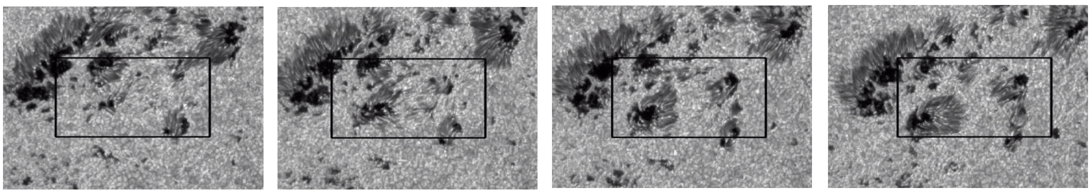


12/05:58 12/14:10 12/23:08 13/05:10 13/20:31

Fig 1 Active accumulation of magnetic flux on Dec 12-13, 2007

The region shows rapid development of magnetic flux accumulation. Since the region is magnetically unipolar, the penumbral area develop only around the outer periphery of the region (indicated by red arrows), where the inclination of magnetic field can be large like a canopy structure. On the other hand, no penumbrae are seen around the umbral edges towards the central part of the unipolar region (indicated by green arrows), where the magnetic fields are expected to be nearly vertical.

(2) Rapid EFR regions



08:23 12:44 15:34 18:55

Fig 2 Rapidly developing EFR on Dec 13, 2007

In this case, flux emergence keeps high activity above ten hours. We can expect the magnetic field will be nearly horizontal in the central part of the emerging region for a long time.

(3) Appearance of twisted or rotating magnetic tubes.

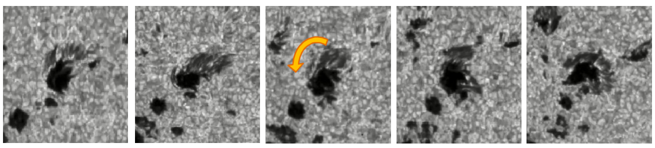


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Fig 3 Rapidly rotating spot on Dec 11, 2007

The region appears rotating counter-clockwise (yellow arrow) or twisted, which can be seen in the spiral pattern of penumbral filaments. Highly inclined magnetic field is expected at the periphery of the umbra.

[Conclusion] In all of these cases, magnetic fields are expected to sustain high inclination at the edges of flux tube concentration longer than the characteristic growth time of magnetic pumping (3-4 hrs), which is estimated as 20 times of thermal diffusion time of photospheric convection (Tildesley et al., 2004). **We may conclude that penumbrae are formed when the magnetic field sustains high inclination long enough for the growth of magnetic pumping.**

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