Flux Cancellation Associated with Flux Emergence on the Sun

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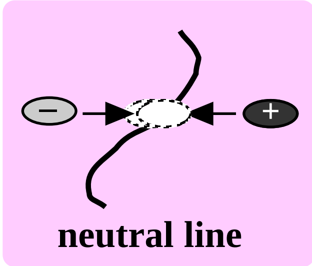
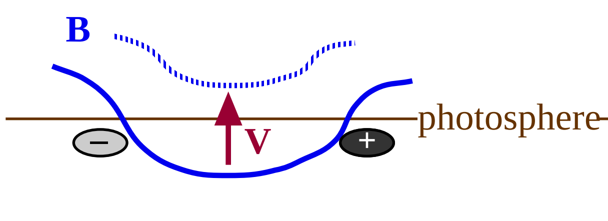
Flux cancellation...

a phenomenon observed on the solar surface in which opposite magnetic polarity regions approach each other and disappear at the neutral line between them (Martin, Livi, and Wang 1985; Livi, Wang, and Martin 1985; Li et al. 2004).

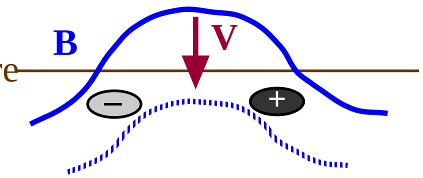


It has been inferred that various solar activities are related to flux cancellation: flares (Livi et al. 1989; Wang and Shi 1993), micro fares/surges/jets (Chae et al. 1999; Liu and Kurokawa 2004), X-ray bright points (Webb et al. 1993), Ellerman bomb (Pariat et al. 2004), sunspot motions (van Driel-Gesztelyi et al. 2000), moving dipolar feature (Bernasconi et al. 2002), filament formation (Martin 1986), filament activation and eruption (Wang, Shi, and Martin 1996; Kim et al. 2001), and coronal mass ejections (Zhang et al .2001).

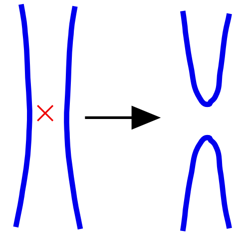
Possible mechanisms for causing flux cancellation



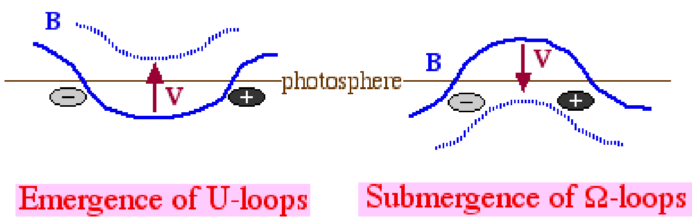
Emergence of U-loops



Submergence of Ω-loops

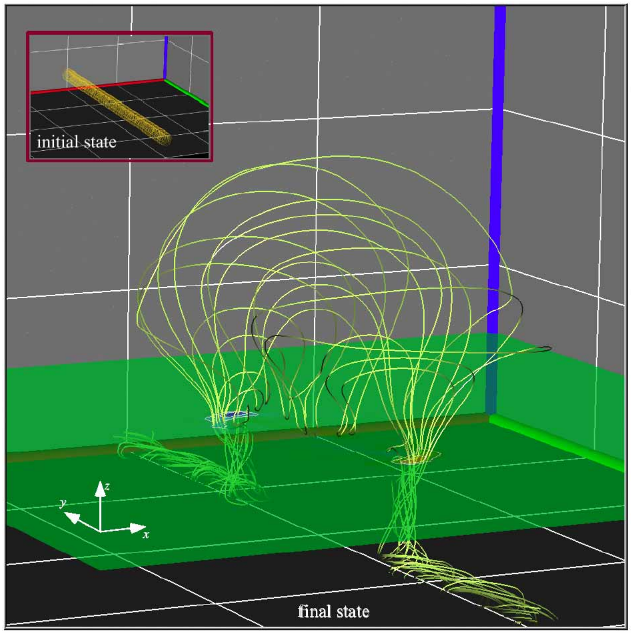


Magnetic reconnection also contributes to flux cancellation by producing both U- and Ω-loops.



Although the magnetic field in the subphotosphere plays an important role in flux cancellation, there have been less studies in which subphotospheric dynamics is incorporated into a model of flux cancellation.

In order to incorporate subphotospheric dynamics into our model, we use a flux emergence MHD simulation in which magnetic field evolves through a highly stratified atmosphere extending from the subphotosphere to the corona (Shibata et al. 1989; Yokoyama & Shibata 1996; Matsumoto et al. 1998; Fan 2001; Magara & Longcope 2003; Abbett & Fisher 2003; Magara 2004; Archontis et al. 2004; Manchester et al. 2004; Fan 2004 and references therein; Isobe et al. 2005; Galsgaard et al. 2005)



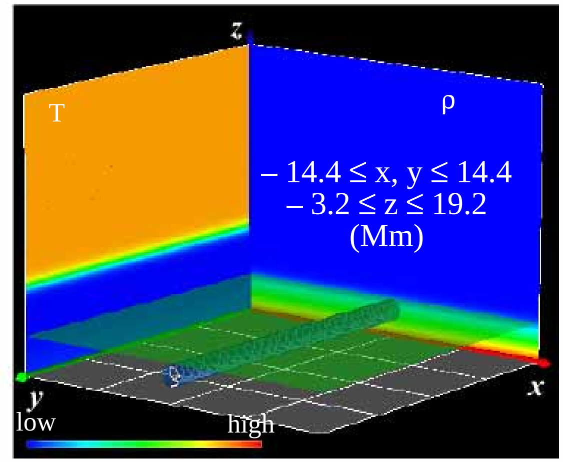
Model description

Initial state of the simulation:

hydrostatic atmosphere extending from the subphotosphere to the corona with an isolated twisted flux tube (Gold-Hoyle flux tube) placed below the photosphere.

$$\mathbf{B} = B_0 \frac{-b\,(z - z_0)\,\hat{\mathbf{x}} + \hat{\mathbf{y}} + b\,(x - x_0)\,\hat{\mathbf{z}}}{1 + b^2\left[(x - x_0)^2 + (z - z_0)^2\right]},$$

$(x_0, z_0) = (0, -1)$ Mm, $B_0 = 4000$ G, $b = 2.5$, r_f (radius) = 0.8 Mm



Grid size:
(0.1 Mm)^3 for z < 4.8 Mm
(0.2 Mm)^3 for z > 4.8 Mm

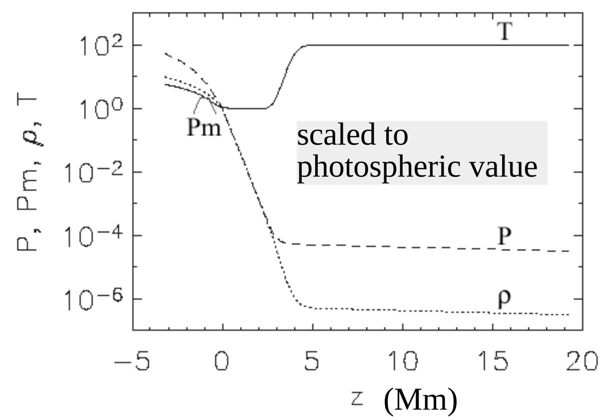
Initial perturbation:

impose an upward flow localized in the middle of the flux tube for a short time

$$v_z = v_0 \cos\left(\pi \frac{y}{2y_0}\right) \frac{1 - \cos(\pi t / t_0)}{2}$$

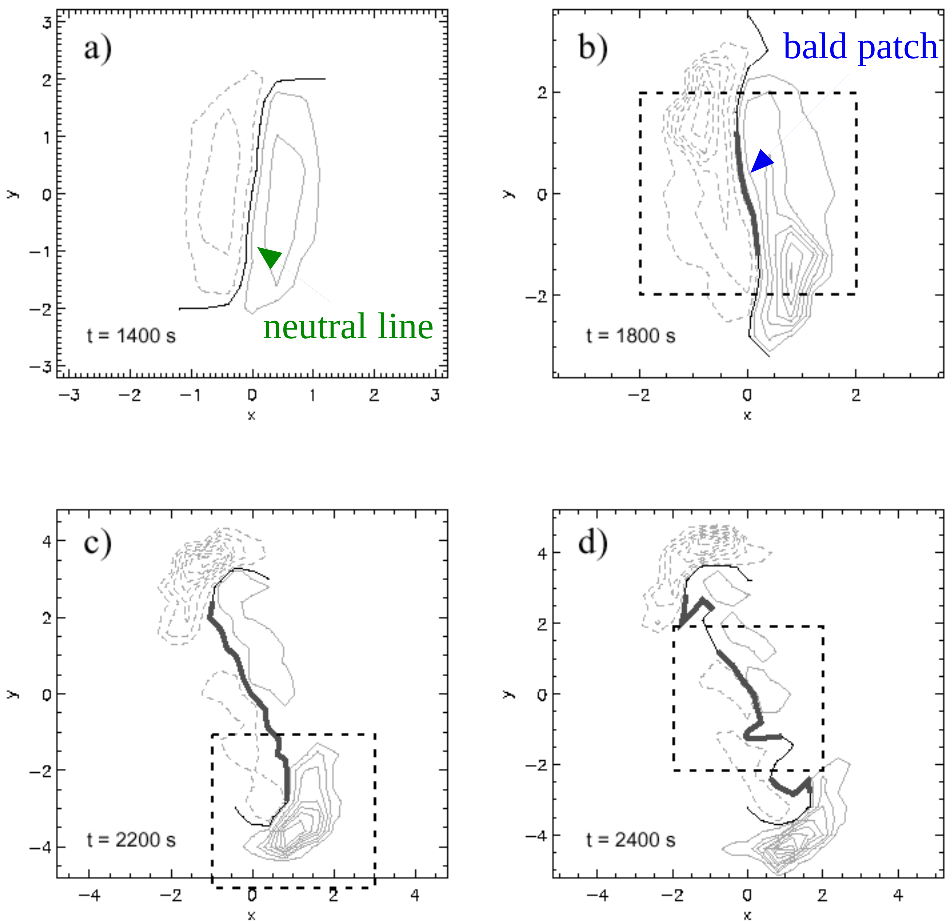
for $(x - x_0)^2 + (z - z_0)^2 \le r_f^2,\ -y_0 \le y \le y_0,\ 0 \le t \le t_0$

$v_0 = 500$ m/s, $y_0 = 3.6$ Mm, $t_0 = 10$ s



The simulation is based on ideal MHD and it has been performed using the Adaptively Refined Mhd Solver (ARMS) (DeVore 1991, MacNeice et al. 2000; DeVore et al. 2005).

Emergence of U-loops... *appearance of 'bald patch'*



Photospheric vertical magnetic flux (at z = 0)

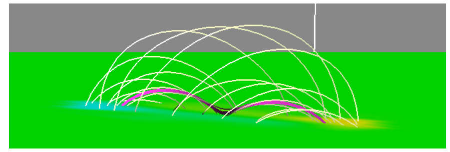
The region where U-loops emerge is called '***bald patch***' (Titov et al. 1993), which lies on the neutral line of photospheric vertical magnetic flux and satisfies the following relation:

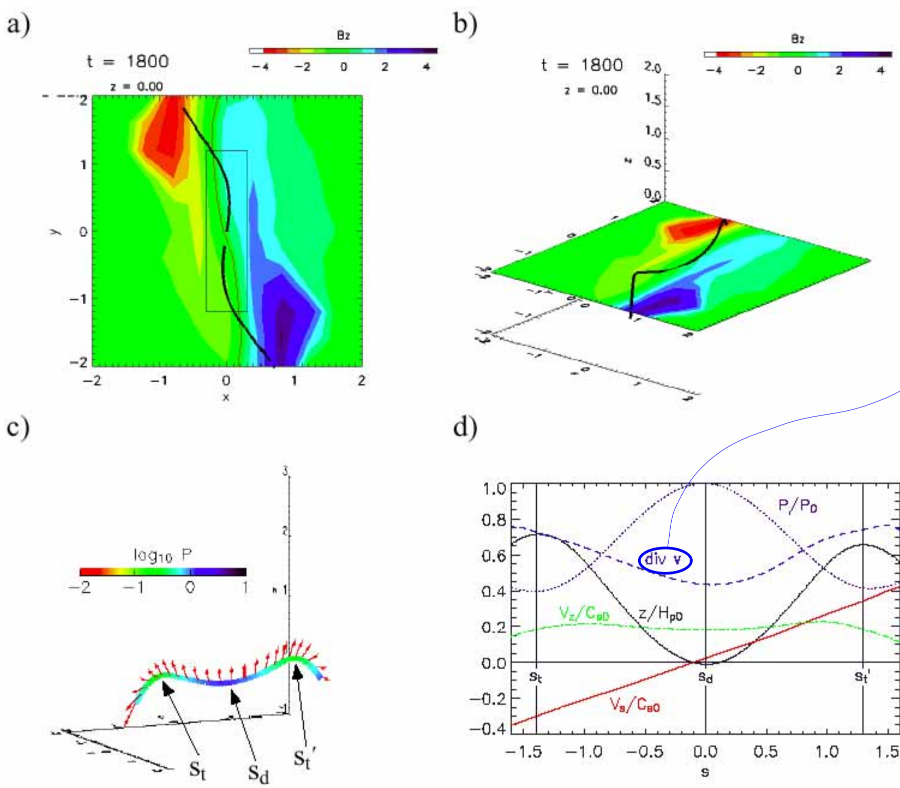
$$\left(B_x \frac{\partial}{\partial x} + B_y \frac{\partial}{\partial y} \right) B_z > 0$$

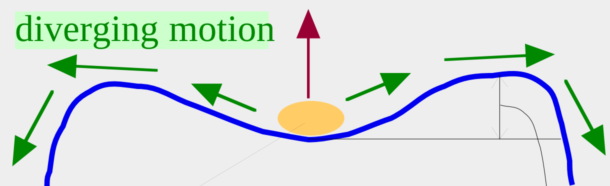
At the early phase of emergence, Ω-loops emerge into the photosphere without forming bald patch (figure a). As emergence proceeds, U-loops originally distributed at the lower half of the flux tube has started to emerge, forming bald patch (figures b, c, d).

Flow distribution in the bald patch... *motions in emerging U-loops*

Early phase at the central area





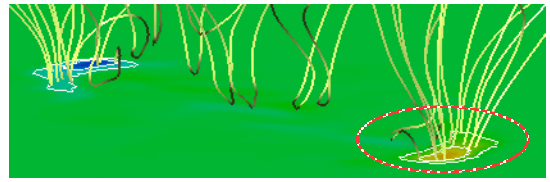


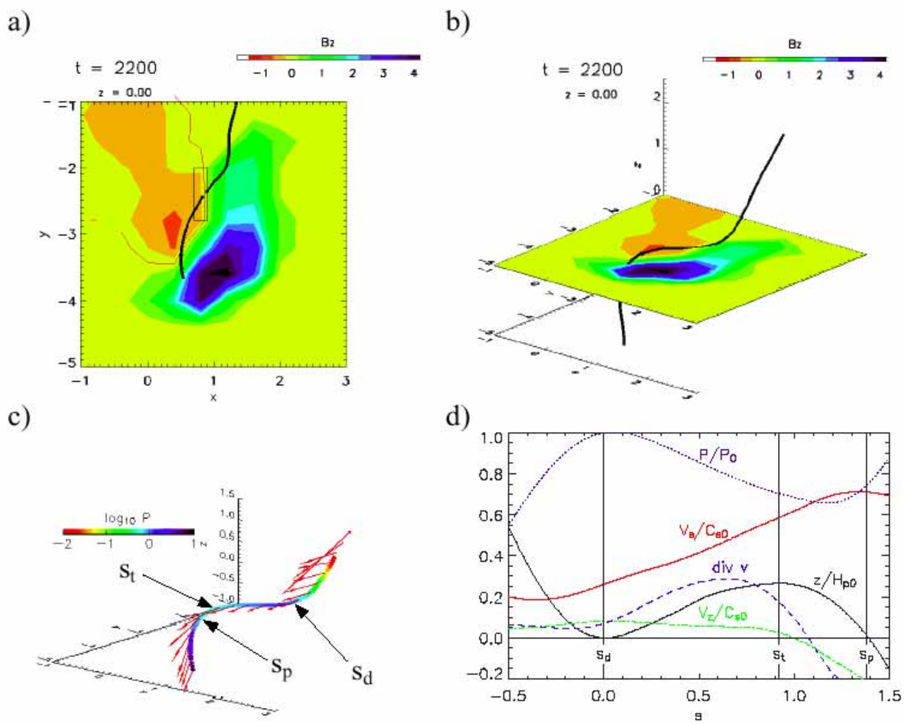
$\nabla \cdot \boldsymbol{v} > 0$

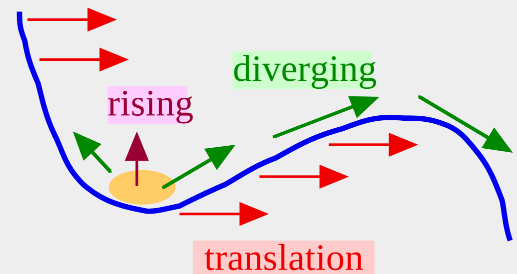
$$\Rightarrow \frac{d\rho}{dt} \equiv \frac{\partial \rho}{\partial t} + v \cdot \nabla \rho < 0$$

Low peak dip... height difference between the dip (s_d) and the top (s_t) is less than a pressure scale height. In this case a diverging flow enhances the buoyancy of the dip.

Late phase at the footpoint area

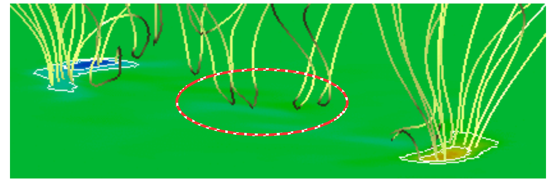


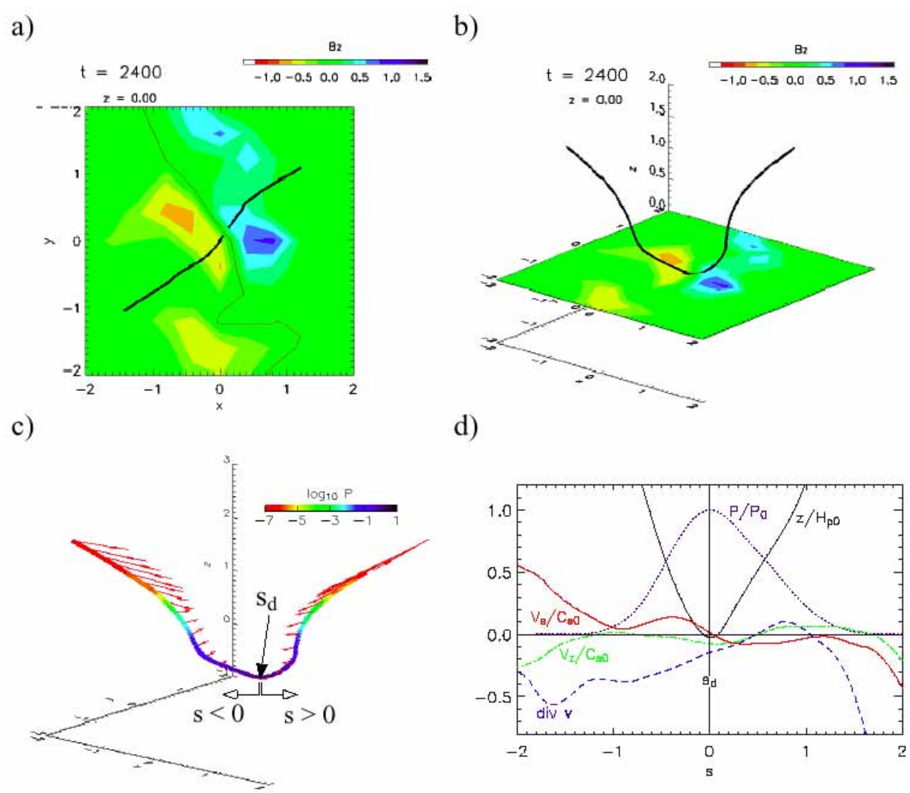


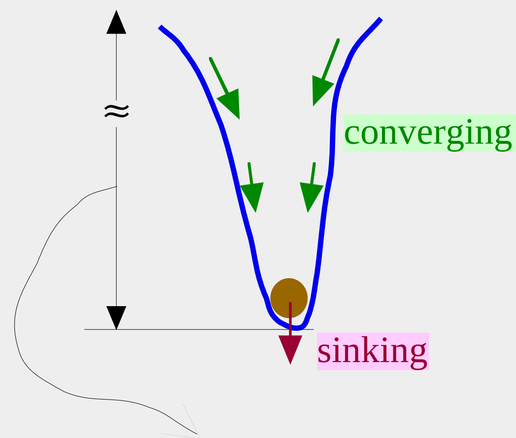


Another example of a low peak dip... even in the case where only one peak is sufficiently low (difference of height between the dip and the top is less than a pressure scale height), the diverging process works to help the dip emerge.

Late phase at the central area

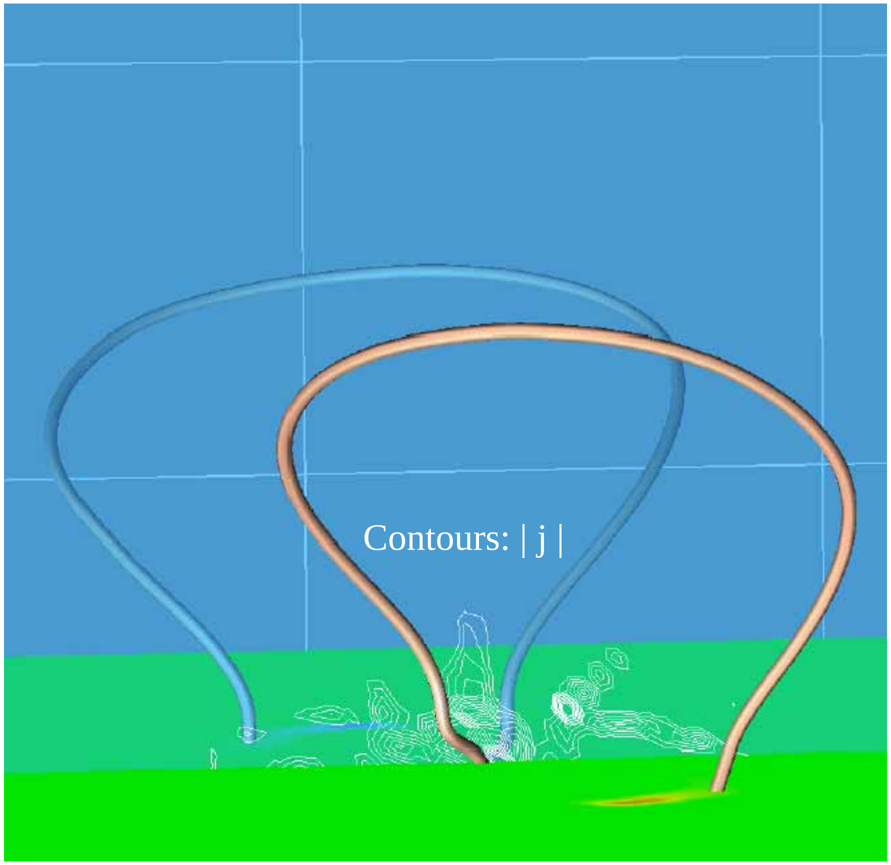


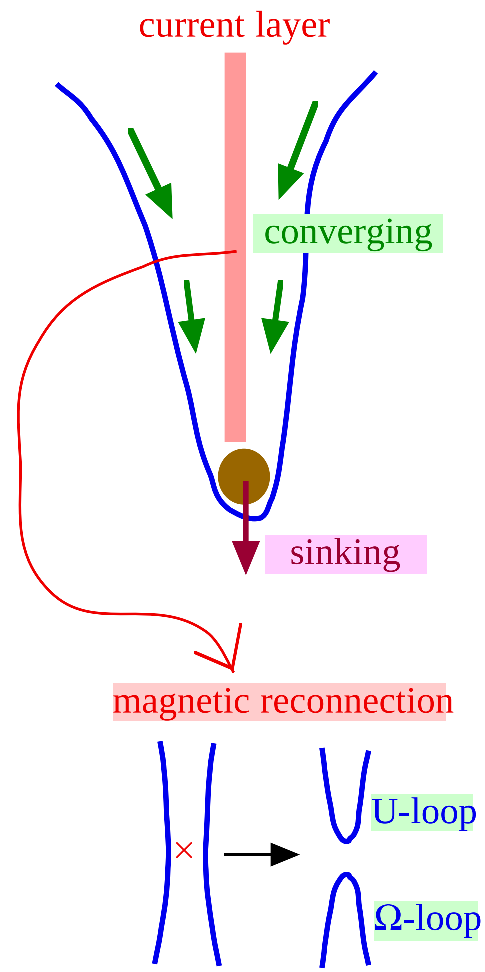




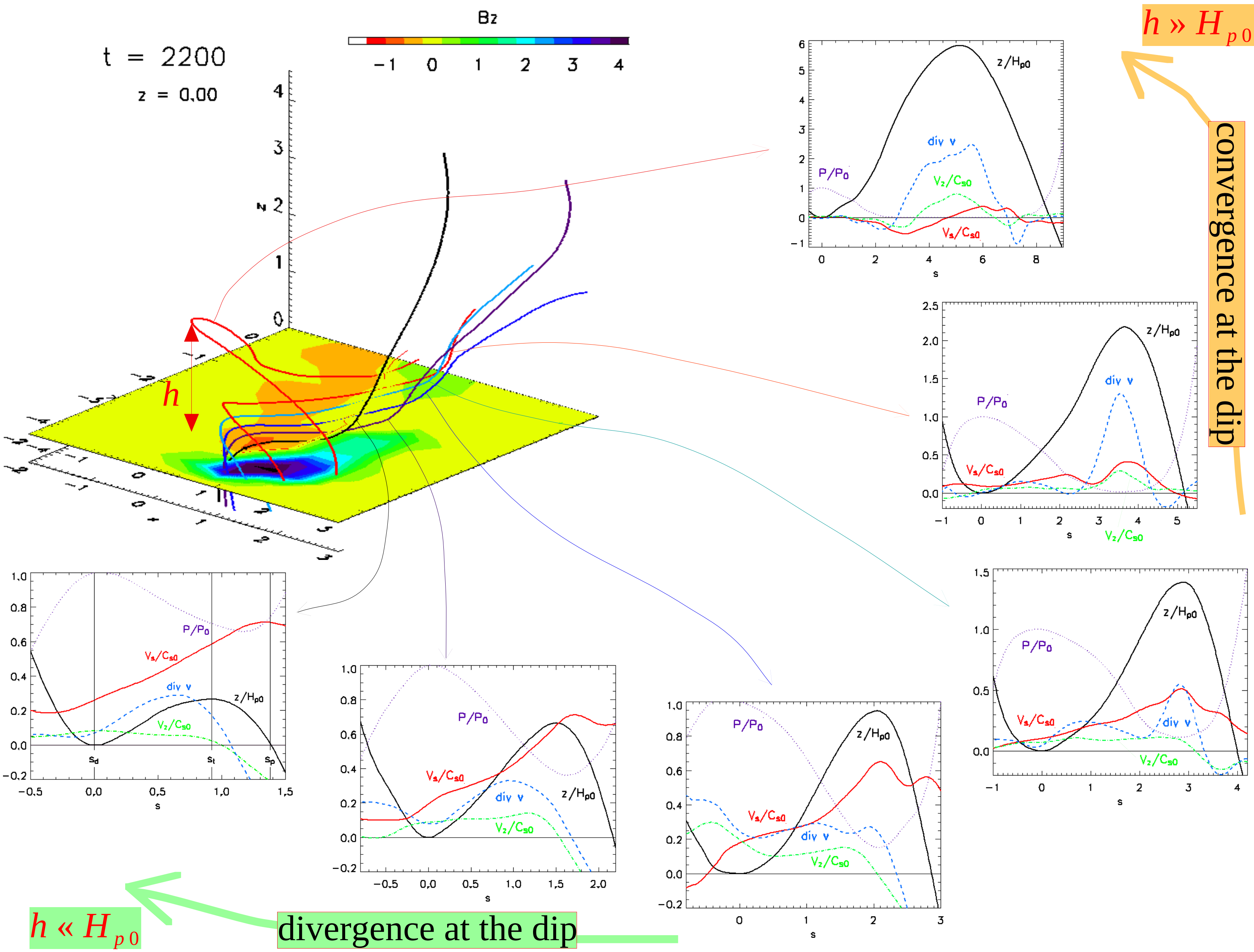
When the difference of height between the dip and the top is much more than a pressure scale height, a converging flow appears on the U-loop, which contributes to forming the deep dip.

Current enhancement at the deep dip





Magnetic reconnection that might occur at the current layer developed inside the deep dip produces Ω- and U-loops. The emergence of the U-loop or submergence of the Ω-loop could cause flux cancellation in the central area of emergence during the late phase, although this was not observed in this simulation.

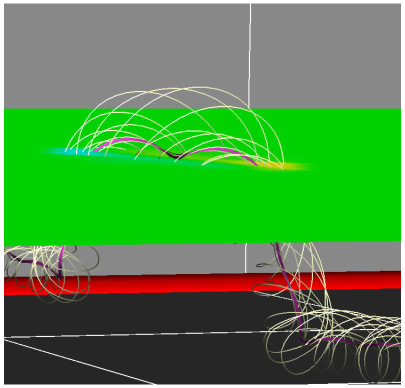


t = 2200
z = 0.00
Bz
h
h » H_{p0}
convergence at the dip
h « H_{p0}
divergence at the dip
z/Hp0
div v
P/P0
Vz/Cs0
Vs/Cs0
s
sd
st
sp

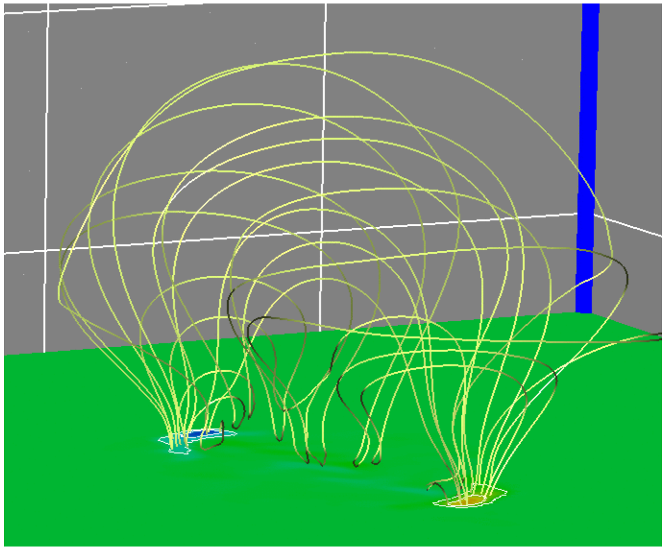
Flux cancellation associated with flux emergence

Early phase of emergence

During this phase, flux emergence is so vigorous that some of the U-loops originally distributed at the lower half of the flux tube emerge into the photosphere, which causes flux cancellation at the emergence area between the footpoints of the emerging flux tube.



Late phase of emergence

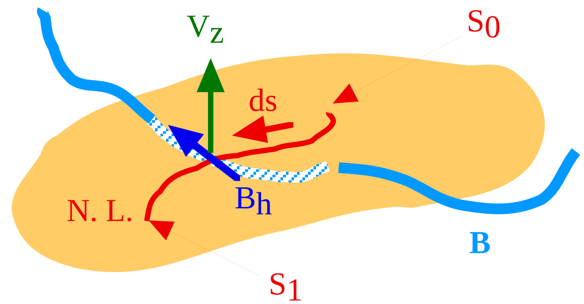


At the footpoint of the emerging flux tube, twisted field lines that partially have a U shape emerge into the photosphere. This causes flux cancellation which is observed as a satellite polarity being successively absorbed into the main polarity.

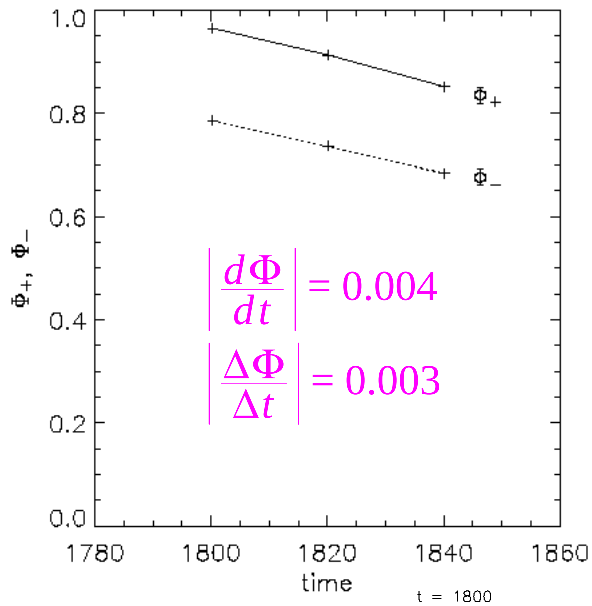
At the central area between the footpoints, a current enhancement occurs at the deep dip developed by a converging flow. Magnetic reconnection might happen at this dip and this gives a seed of another flux cancellation caused by emergence of reconnected U-loops or submergence of reconnected Ω-loops.

The rate of flux cancellation

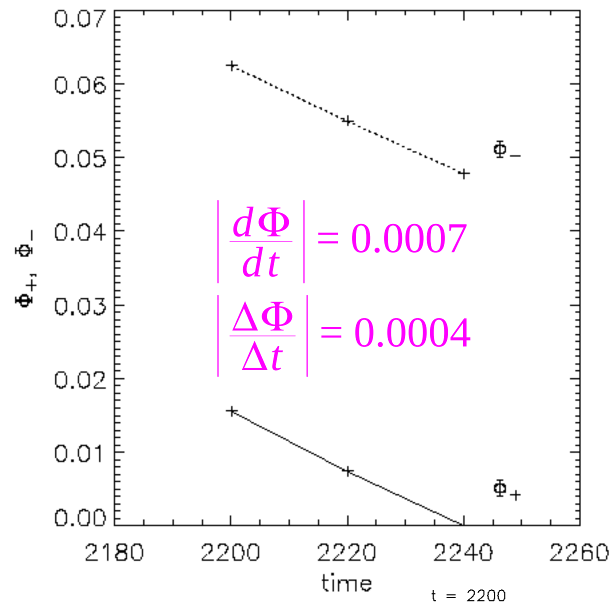
$$\ldots \frac{d\Phi}{dt} = \int_{s_0}^{s_1} B_h \, v_z \, ds$$

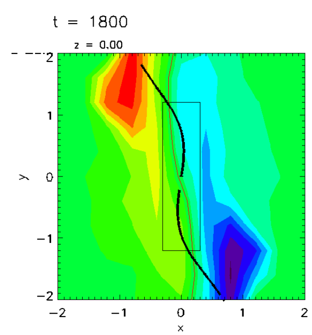


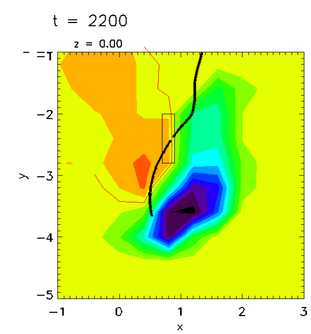
a)



b)







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