

# Diffusion of Open Magnetic Flux and Its Consequences

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# Provide a Brief Review of the Work to Date on the Transport and Distribution of Open Magnetic Flux of the Sun

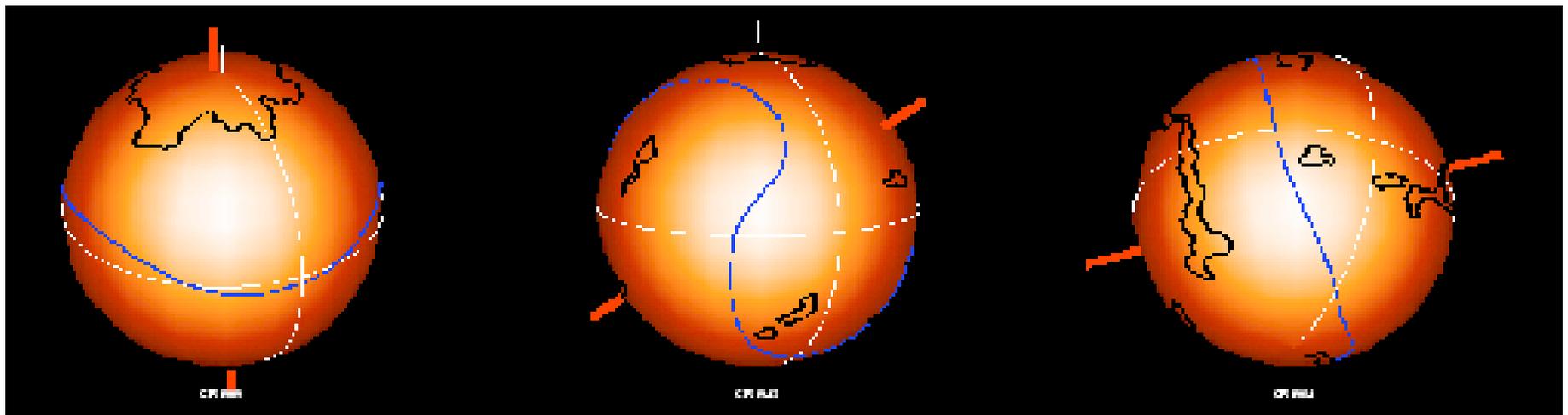
- There has been a philosophical difference between this work and that of other, more solar-oriented approaches.
- We came at problem from heliospheric perspective and take constraints of heliospheric observations very seriously.
- If the approach or model is not consistent with some key heliospheric observations, we reject it.

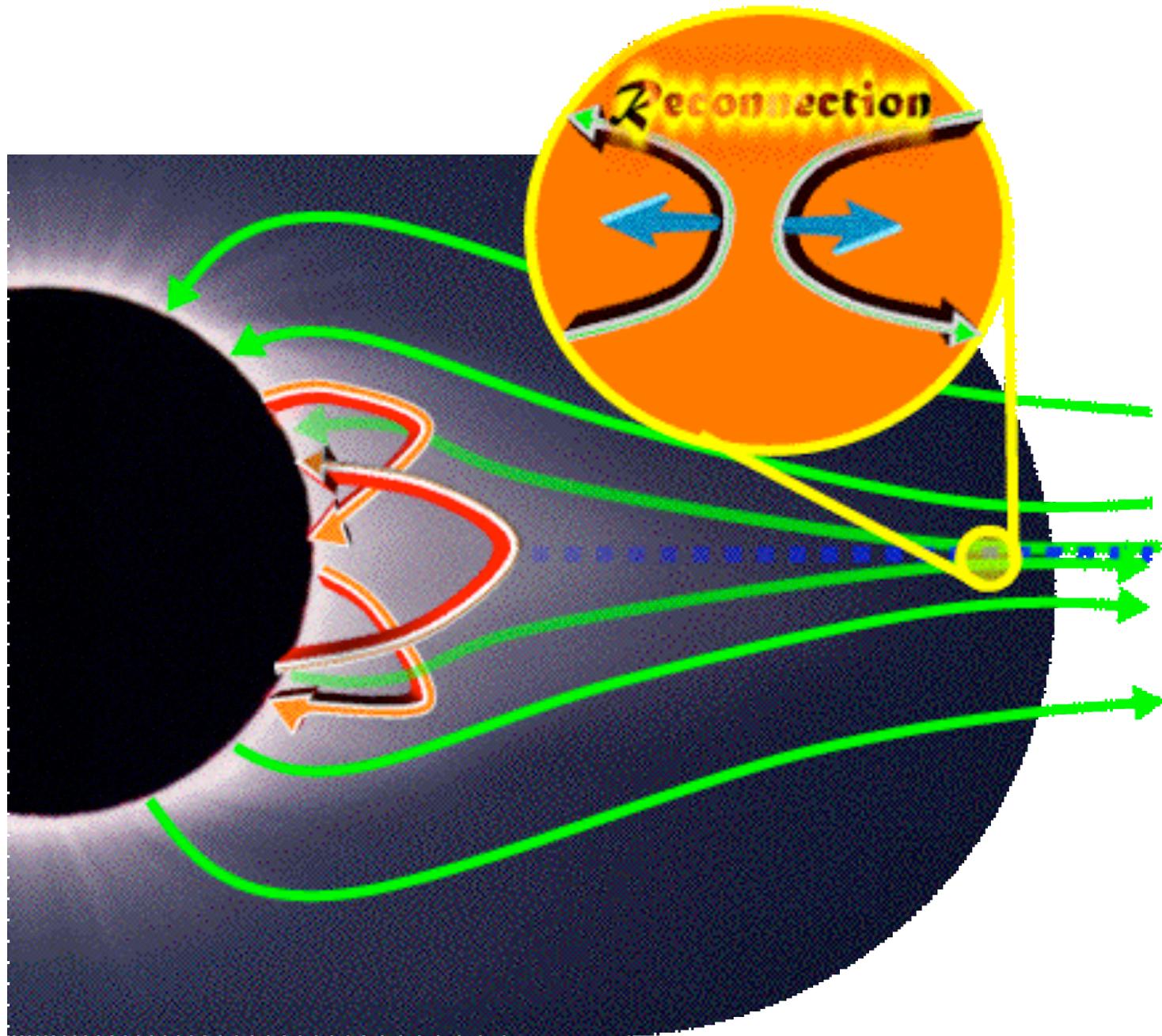
## Three Key Heliospheric Observations

- Open magnetic flux is well organized throughout the solar cycle; there is a single current sheet that rotates through the poles as the field reversal of the Sun occurs.
- Very little evidence of disconnection of open magnetic flux of the Sun -- at most a low, upper limit [Pagel, Crooker & Larson, 2005].
- Composition of slow and fast solar wind distinctly different.

# Location of Current Sheet During Solar Cycle

Sanderson et al. 2001.





## Difficult to Hide Heat Flux Dropouts

- The basic unit of the solar magnetic field is a flux concentration in the photosphere, which contains magnetic flux of  $\sim 3 \cdot 10^{18}$  Maxwells.
- If this field expands to form the heliospheric magnetic field, it will have a cross section at Earth corresponding to a linear dimension of  $\sim 0.02$  AU, which takes  $\sim 2$  hours to be convected past Earth.
- We observe the electrons with much higher time resolution and should see any of these flux concentrations being disconnected.

# Interchange Reconnection



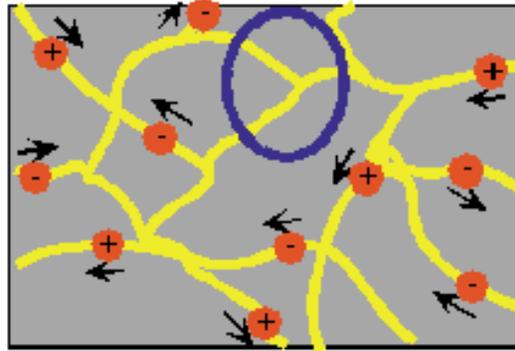
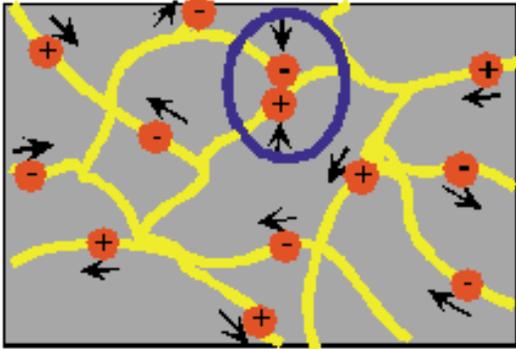
## Treating Behavior of Open Flux as a Transport Problem

- Our basic argument then is that you are not disconnecting open flux; and you are not adding to it [interchange reconnection], but you must account for the changes in distribution on the Sun during the solar cycle.
- We need then to move open flux around on the Sun.
- The behavior of the open flux thus becomes a transport problem; but we know how to do that.

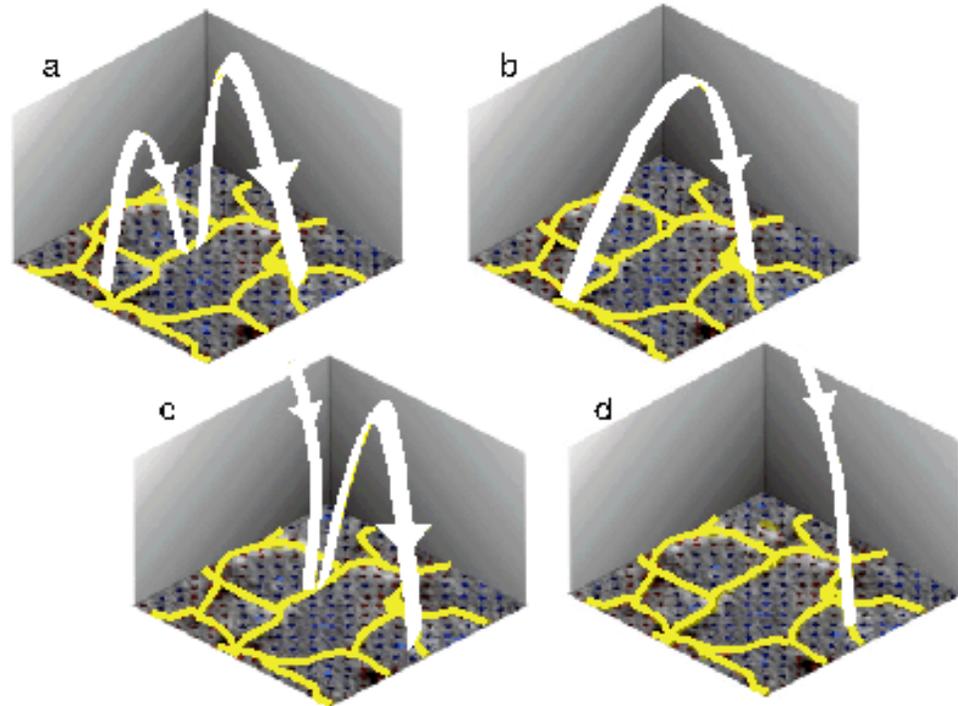
# Processes that control distribution of open flux

- Diffusion by random convective motions [Leighton, 1964].
- Convective flow due to differential rotation or meridional flow.
- Diffusion by reconnection at the base of coronal loops.
- Diffusion by reconnection in the canopy of loops.
- Diffusion by braiding and twisting of open field lines in the overlying corona, driven by diffusion at the base of the corona.

# Footpoint Motions on the Solar Surface

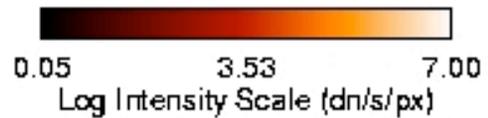
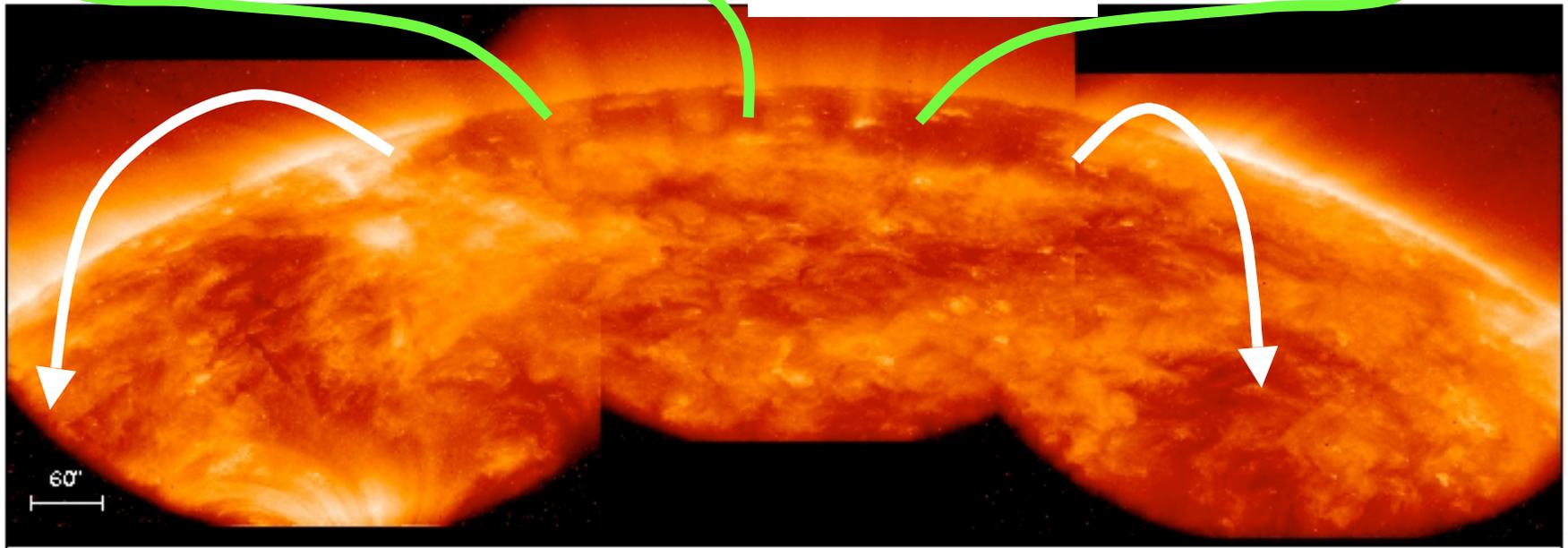


## Three-Dimensional Perspective

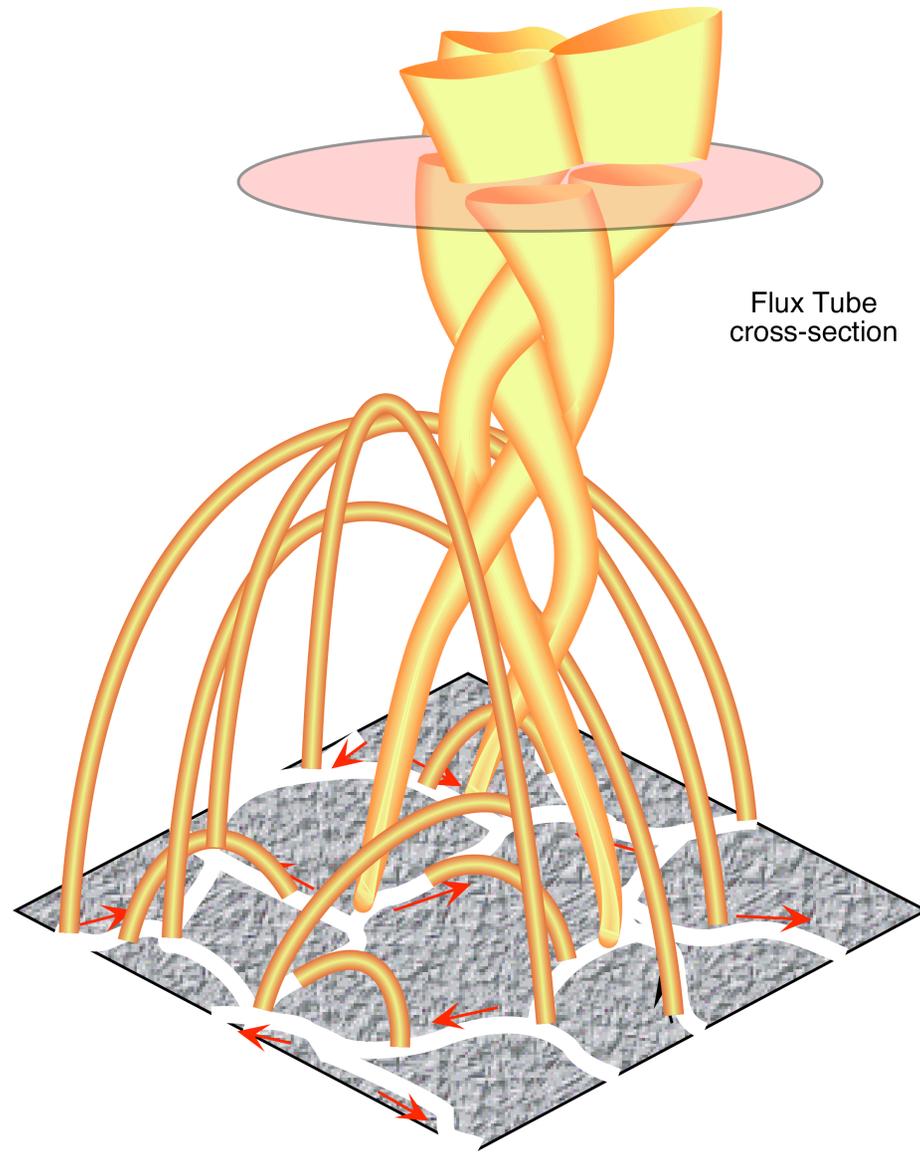


# A Canopy of Loops In the Quiet Corona

Coronal hole

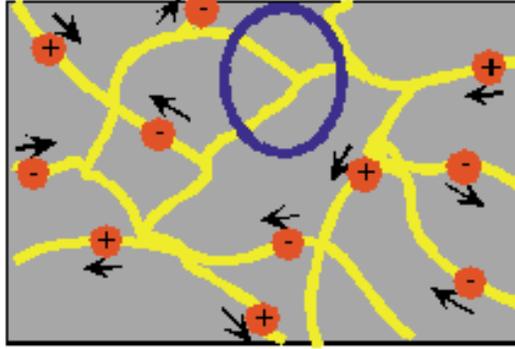
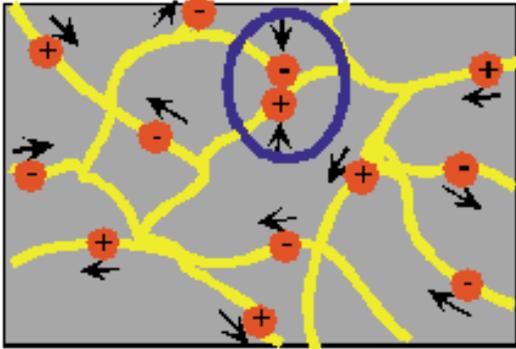


From Feldman et al., 2000.

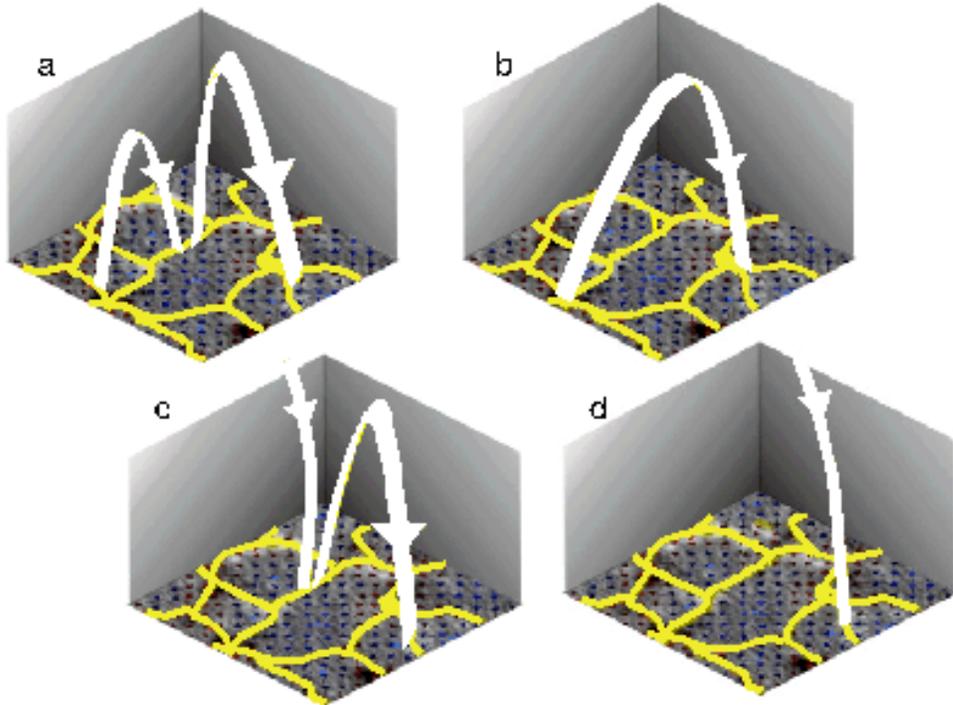


Flux Tube  
cross-section

# Footpoint Motions on the Solar Surface



## Three-Dimensional Perspective



## Interaction of Open Flux with Small Coronal Loops

- The two forms of diffusion along the solar surface – random convection and reconnection at the base of coronal loops – result in a surface diffusion equation [Fisk, ApJ, 2005]:

$$\kappa B_o = \frac{\delta h^2}{2\delta t} (B_o + B_l)$$

- Here,  $B_o$  is the mean magnetic field strength in open flux;  $B_l$  is the mean magnetic field strength in loops;  $\delta h^2 / 2\delta t$  is the diffusion coefficient for random convective motions.
- Theory also shows that open flux determines size of small loops such that

$$\bar{h}^2 = \frac{3\phi}{8B_o}$$

where  $\phi$  is the mean flux per flux concentration on the Sun.

## Interactions of Open Flux with Small Coronal Loops

- Can also relate interaction of open field lines with small coronal loops to the rate of emergence of new magnetic flux on the Sun,  $\dot{\Phi}_e$ , per unit area [unsigned flux]:

$$B_l(B_l + B_o) = \frac{2}{3} \varphi \dot{\Phi}_e \frac{\delta t}{\delta h^2}$$

- The important point is that there are various quantities, which are in principle observable, which can be used to determine the diffusion of open field lines due to random convection and reconnections with loops at their base.

## Use in a Diffusion Equation

- We can apply these results in a surface diffusion equation for the time evolution of the open magnetic flux:

$$\frac{\partial B_o}{\partial t} = \nabla^2 \left( \frac{\delta h^2}{2\delta t} (B_o + B_l) \right) - \nabla \cdot (\mathbf{u}B_o)$$

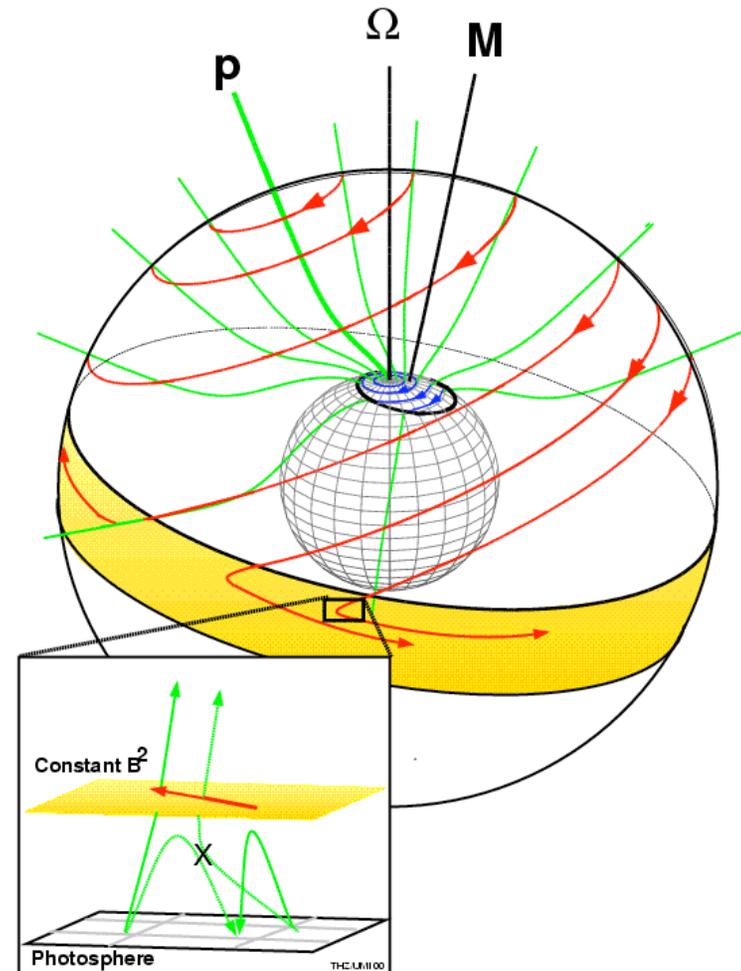
- All these relationships for diffusion on the solar surface [by random convection and by reconnections with loops at their base] can be used to show that the corona will naturally separate into concentrations of open flux, and regions devoid of open flux.
- And that open flux is likely to accumulate, i.e. a coronal hole will form, at locations on the Sun where the rate of emergence of new magnetic flux,  $\dot{\Phi}_e$ , is a minimum.

## Summary to this point and Canopy Diffusion

- Diffusion by random convective motions and by reconnection at the base of coronal loops is relatively easy to describe and in principle can be related to solar observations.
- What then about canopy diffusion, where the reconnections occur in the canopy of loops at the Sun not at their base.
- Canopy diffusion is an intrinsically harder problem. The reconnection at the base of loops is governed by the random convection motions, which cause field lines of opposite polarity to collide and reconnect.
- Reconnection in the canopy is caused by the motions of open flux in the overlying corona. As an open field line moves in the overlying corona, its base must move in concert. The canopy diffusion must adjust to accomplish this.
- Canopy diffusion must be treated as a coupled, three-dimensional problem between the motions in the overlying corona and the canopy diffusion that must accompany them.

# Motions in the overlying corona driven by differential rotation in the polar coronal holes

- The magnetic flux has to move along the red lines. Note all in one direction on side of Sun shown.
- However, it can not cross the equatorial current sheet [solar minimum conditions]
- Hence, it must turn and move across the loops at low latitudes, and reconnect in the canopy, so as to be able to diffuse around the solar equator, back to the other side of the Sun to continue the motions.

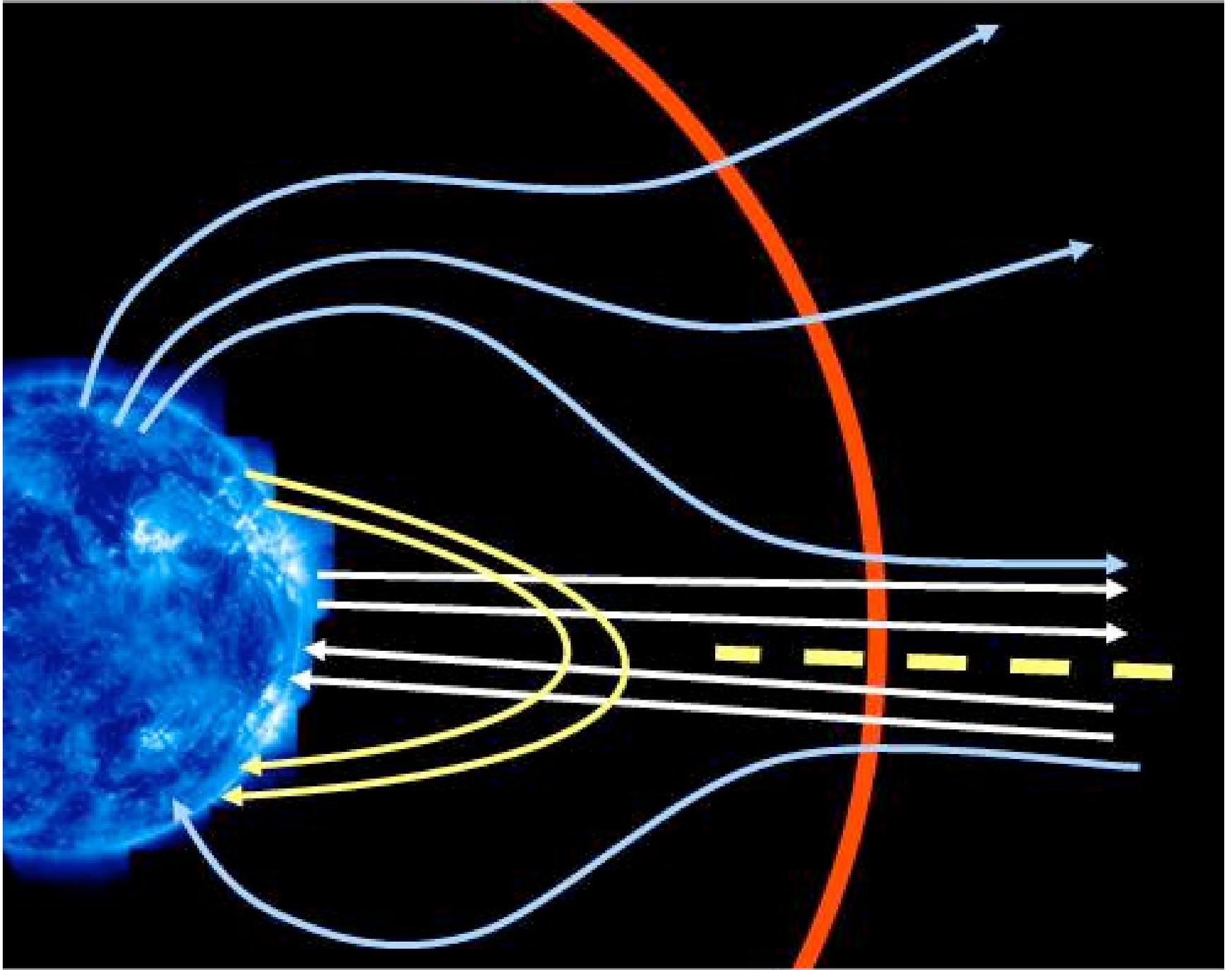


## Treatment of Canopy Diffusion

- The easiest way to treat canopy diffusion is to make the problem somewhat harder.
- Assume that open flux diffuses throughout the corona; random motions near the base of open field lines, e.g. in the canopy drive random motions and diffusion throughout the corona.
- The open flux then behaves according to a three-dimensional diffusion equation, written in the following form:

$$\frac{\partial \mathbf{B}_o}{\partial t} = \nabla \times [-\kappa \nabla \times \mathbf{B}_o - \nabla \kappa \times \mathbf{B}_o]$$

- The steady-state solution to this equation requires a potential field  $[\nabla \times \mathbf{B}_o = 0]$ .
- It is not a usual potential field solution. If it satisfies the outer boundary condition that the field is radial, the solution will be uniform and radial everywhere.



## Consequences of Canopy Diffusion

- We predict that when there is extensive canopy diffusion present, there will be another component of the open flux, besides that which is contained in coronal holes.
- The additional component is uniform and radial. At solar minimum, with the large concentration of open flux in the polar coronal holes, this additional component of open flux is small.
- At solar maximum, the additional component may be larger.
- The extra component is important for the escape of energetic particles, for the distribution of Type III radio bursts, and the differences between fast and slow solar wind.
- See Jason Gilbert's proposal for a mapping technique which takes this extra component into account.

## Velocity/Magnetic Field Correlations An Electric Field

- For a diffusing magnetic field there will be correlations between the random plasma velocities,  $\delta\mathbf{u}$ , and the random magnetic field fluctuations,  $\delta\mathbf{B}$ ; indeed, the random velocities cause the field fluctuations:

$$\left\langle \frac{\delta\mathbf{u}}{c} \times \delta\mathbf{B} \right\rangle = -\frac{\kappa}{c} \nabla \times \mathbf{B}_o = -\mathbf{E}_o$$

which is effectively a large scale electric field.  $\kappa$  is the diffusion coefficient for spatial diffusion of the magnetic field;  $\mathbf{B}_o$  is the mean magnetic field strength.

- Comparing with the current there is an effective conductivity in the plasma

$$\sigma = \frac{c^2}{4\pi\kappa}$$

## Dissipative Heating

- With an electric field we get dissipative heating

$$\mathbf{J} \cdot \mathbf{E}_o = \frac{\kappa}{4\pi} (\nabla \times \mathbf{B}_o)^2$$

- If uncomfortable about getting dissipation in an infinitely conducting plasma, think of this as the correlation between the random velocities and random magnetic forces, i.e. a work term. This is a standard result in any turbulent dissipation problem.

## Coupling the Behavior of the Open Flux to the Acceleration of the Solar Wind

- It is important to treat the open flux and the solar wind as a coupled problem.
- Open flux can be considered to be open only if there is a flow of solar wind along it that is capable of carrying the open flux out into the heliosphere.
- Also if we can relate the acceleration of the solar wind to the parameters that govern the behavior of the open flux and may be observable, we have gone a long way towards being able to predict the solar wind from solar observations.

## Where are we going?

- We have a theory for the distribution of open flux.
- We have a potential technique for mapping the open flux from the solar surface outward.
- We have a theory for how the solar wind is heated/accelerated and how the parameters that govern the heating/acceleration is related to observable parameters at the base of the open field lines.
- Plan: put it all together and see how it works and compares with observations