How solar atmosphere may change photospheric dynamics
Example: differential rotation

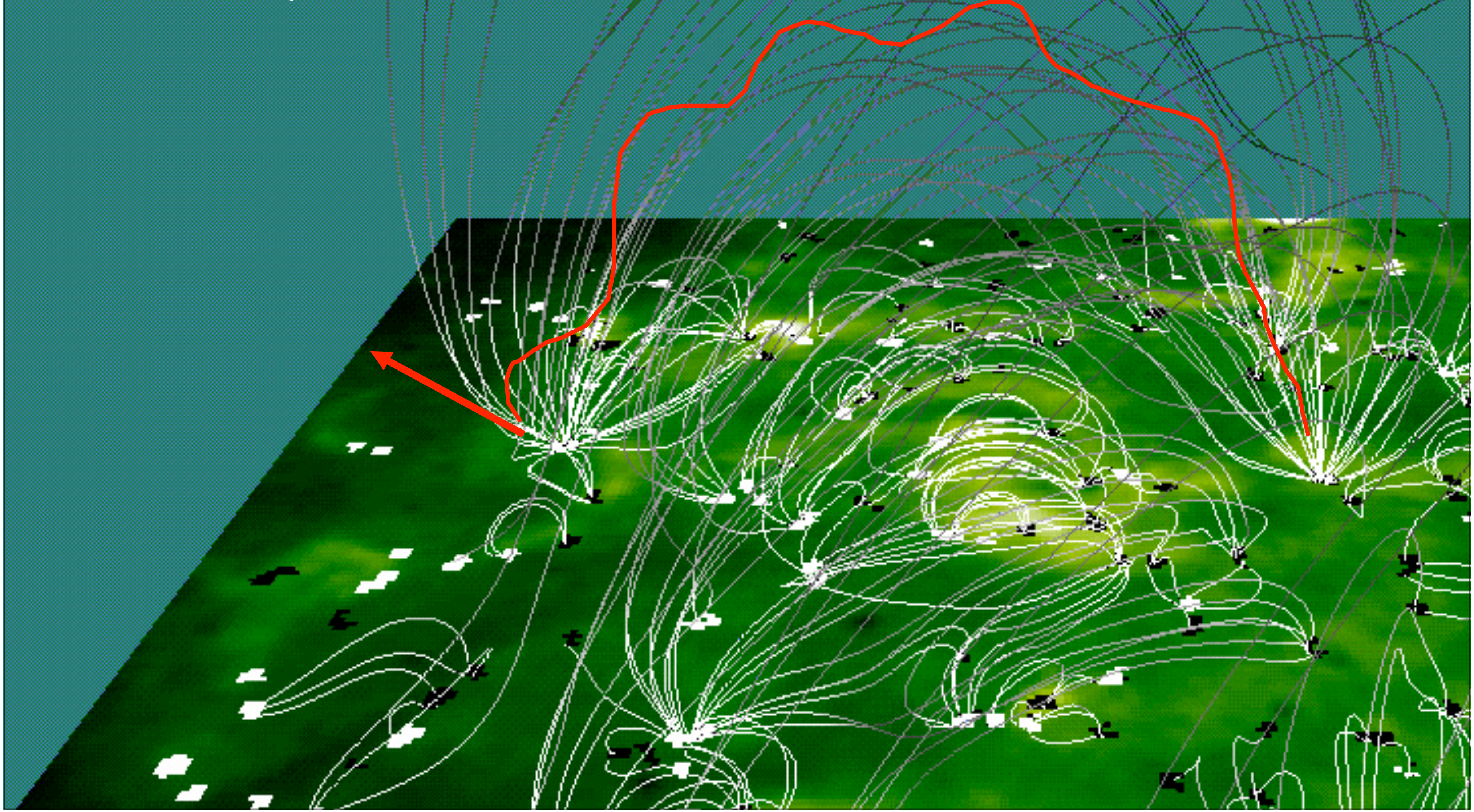
R. Grappin (Meudon)+ R. Pinto (Saclay) + M. Velli + A. Verdini

Slow photospheric movements may trigger rapid and catastrophic events like CMEs.
Simple usual hypothesis to describe coronal-photospheric coupling is the line-tied hyp. (limit $\varepsilon = V_A^{phot}/V_A^{corona} = 0$):
photospheric movements are given AND no coronal feedback is possible
However, feedback necessary to explain loss of solar angular momentum with time - couple exerted by open lines on solar surface
The magnetic braking feedback is shown here numerically by using axisymmetric isothermal simulation with simple modeling of coronal-photosphere interface as an Alfvén speed jump

Arcetri 2010 workshop on Plasma Astrophysics

Motivation

Can magnetic loops transport momentum from one point to other point of solar surface?
Is surface dynamics modified due to corona?



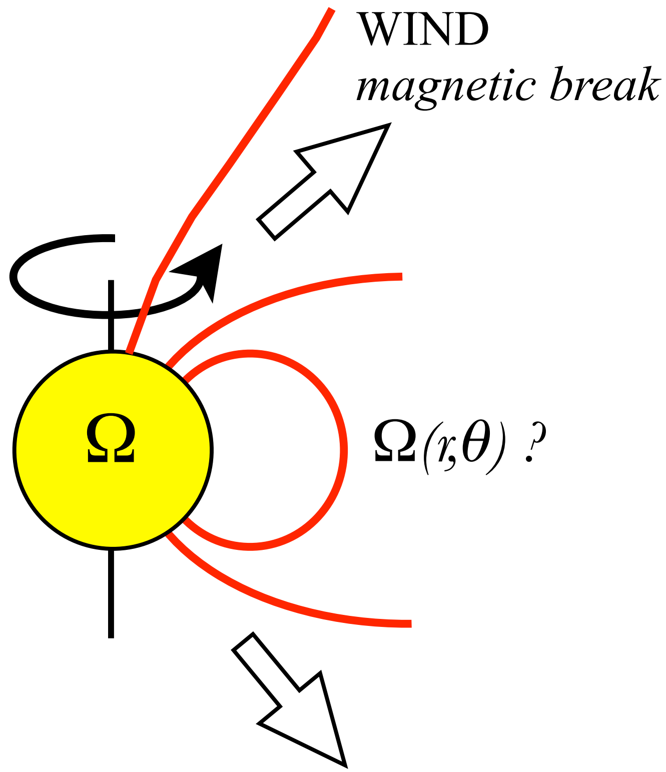
Differential rotation: how the different layers couple

How is rotation transported?

1. Internal layers → surface : internal CONVECTION
2. Surface → atmosphere up to M_A=1:
Lorenz force ; Alfvén waves
3. Atmosphere → surface ?

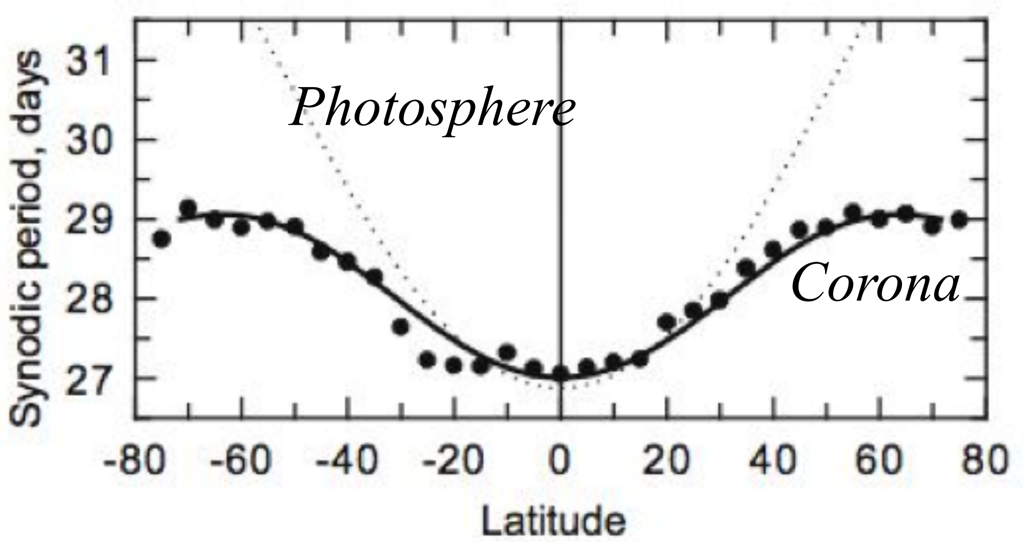
•Line-tied hypothesis: velocity imposed by photospheric dynamics
- no feedback possible: corona forced to turn WITH solar surface
- no momentum transport between foot points

•Other numerical models possible !



Observed difference between surface and coronal rotation

Average rotation period vs latitude



Badalyan. New Astronomy, **15** , 135, 2010

Rotation of solar corona

Fe XIV

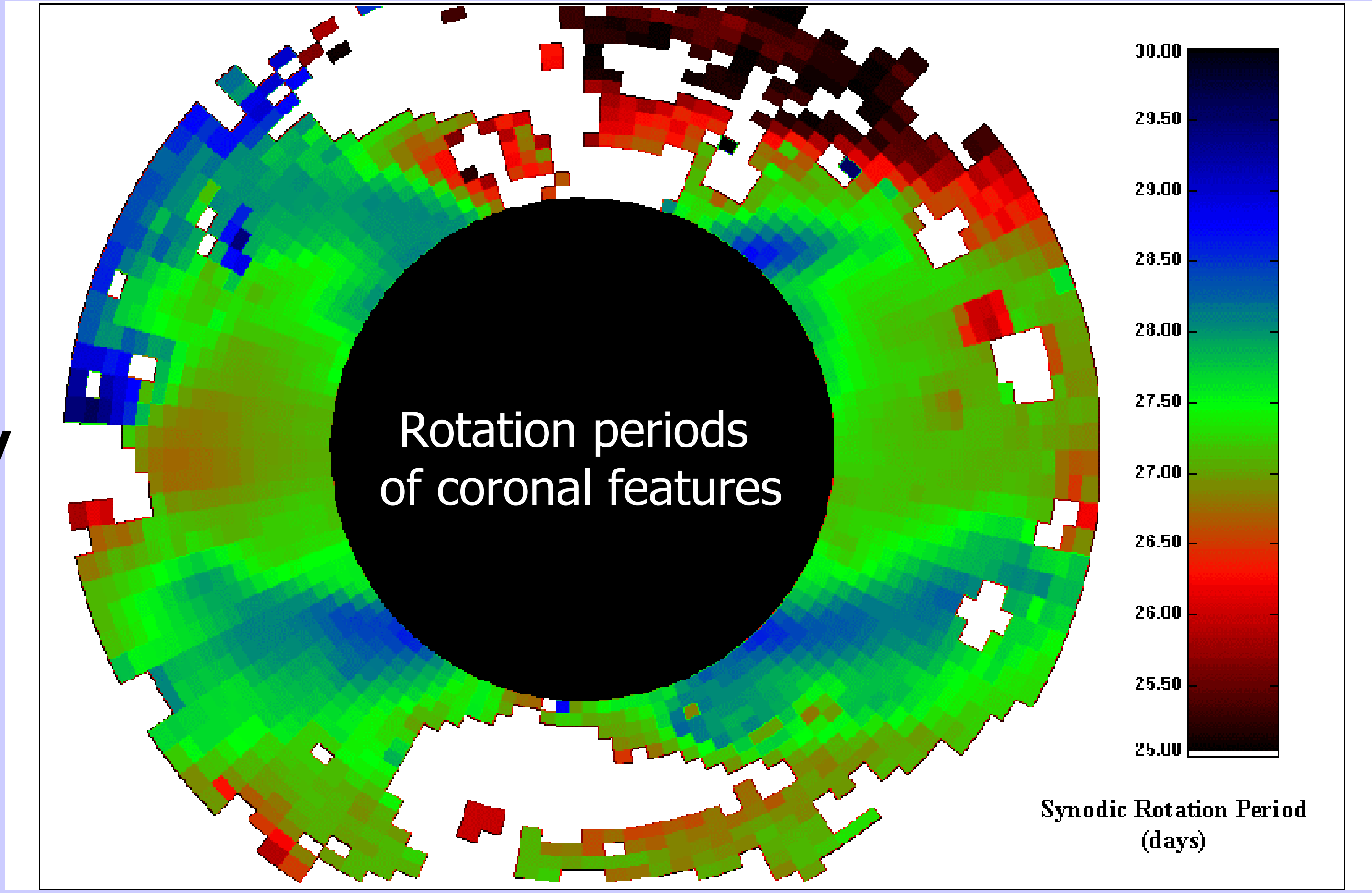
5303 Å

Time series:

1 image/day

(24-hour

averages)



27.2 days

LASCO /SOHO

Stenborg et al., 1999

Long-lived coronal patterns exhibit uniform rotation at the equatorial rotation period!

Sun's loss of angular momentum carried by the solar wind

Induction equation:

$\nabla \times (\mathbf{V} \times \mathbf{B}) = 0$ **-->** $r\,(V_r B_\phi - B_r V_\phi) = -\,r_0 B_0 \Omega_0 r_0$

Momentum equation:

$\rho \mathbf{V} \bullet \nabla V_\phi = 1/4\pi\, \mathbf{B} \bullet \nabla B_\phi$ **-->** $r\,(\rho\, V_r V_\phi - B_r B_\phi) = 0$

$\mathbf{L = \Omega_0 r_A{}^2}$ (specific angular momentum)

$V_\phi = \Omega_0 r\,(M_A{}^2 (r_A/r)^2 - 1)/(M_A{}^2 - 1)$

$M_A = V_r (4\pi\rho)^{1/2}/B_r$

Alfvén Machnumber

Helios: $r_A = 10\text{-}20\ R_S$

Weber & Davis, ApJ, **148**, 217, 1967

Evolution of solar rotation

Young stars are seen to rotate up to 100 times faster than the Sun
Did the Sun also rotate faster when it was young?
Skumanich law: $\Omega \approx t^{-1/2}$, where t = age of star
(deduced from obs. stars in clusters of different ages). i.e, old stars also rotate slowly

→Sun also rotated faster as a young star

Question: where did all the angular momentum go?

Evolution of solar rotation (2)

Question: where did all angular momentum go?

Answer part 1: Solar wind ! The SW carries away ang. momentum with it.
Torque j, i.e. rate of change of angular momentum, exerted by SW (no B):

$$j = \Omega R_s \, dm/dt$$

Here dm/dt is the solar mass-loss rate (mass carried away by solar wind)

Problem: j is too small by fact. 100 to cause significant braking of solar rotation

Evolution of solar rotation (3)

Answer part 2: Magnetic field !

Below Alfvén radius R_A, wind is channelled by the field. Up to that radius, the wind rotates rigidly with the solar surface (forced to do so by rigid field lines), i.e., wind carries ang. mom. away only beyond R_A.

Is is **as if** the Sun had radius
True torque is

$$j = \Omega R_A \, dm/dt \approx 20 \, \Omega R_s \, dm/dt$$

Evolution of solar rotation (4)

$j = \Omega R_A \, dm/dt \approx 20 \, \Omega R_s \, dm/dt$

The faster the star rotates, the quicker it spins down

Corrections:
dm/dt, and R_A depend on Ω => in general, $j \approx \Omega^\alpha$ (α>1)

Solar rotation velocity evolution

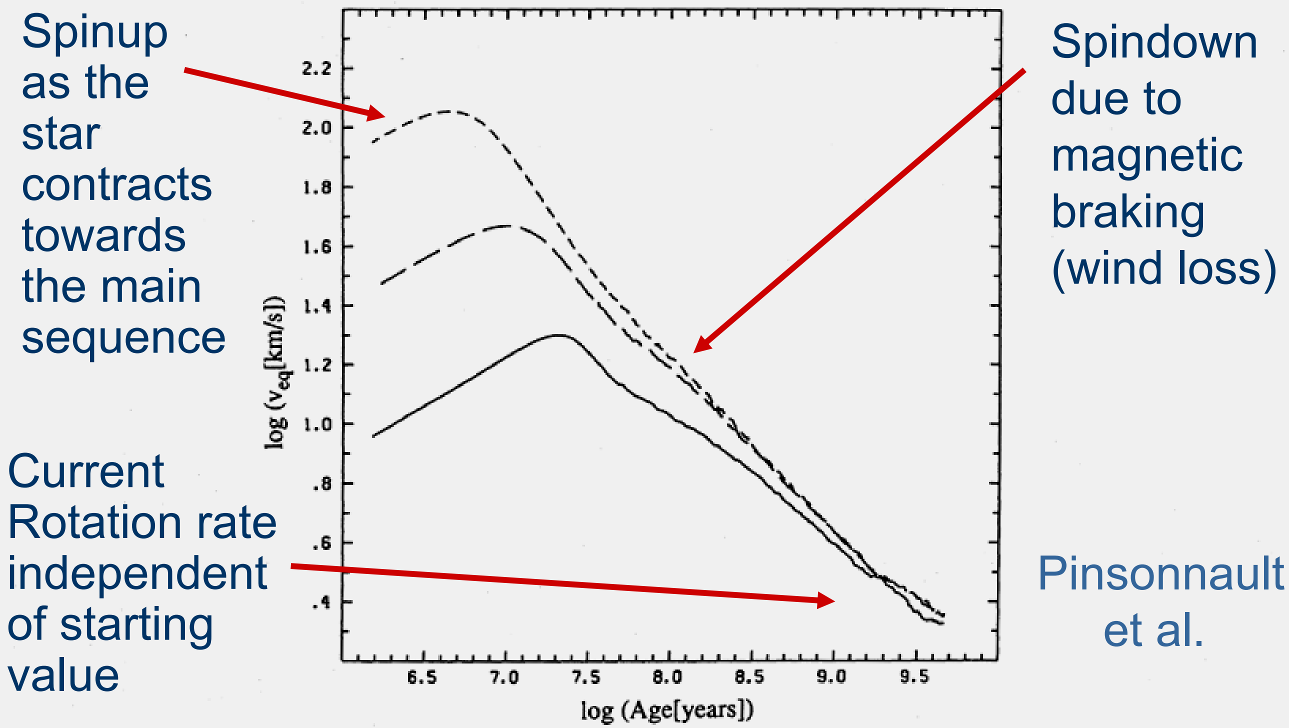


FIG. 3.—Surface rotation velocity as a function of time for three models differing only in initial angular momentum. The solid line is the reference solar model (case A in Table 2) with $J_0 = 5 \times 10^{49}$ g cm^2 s^{-1}. The long-dashed line is a model with $J_0 = 1.63 \times 10^{50}$ g cm^2 s^{-1} (case B). The short-dashed line is a model with $J_0 = 5 \times 10^{50}$ g cm^2 s^{-1} (case C). An order of magnitude in J_0 produces only a small variation in the surface rotation velocity on the main sequence ($\log t > 8$).

Transmission of rotation from phot. to corona

•Transmission of rotation is done via magnetic field "elasticity" => via Alfvén waves

•Definitions

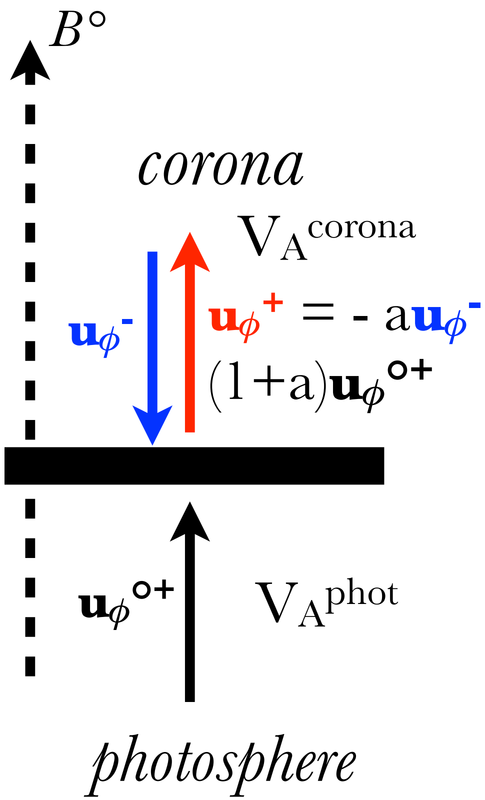
Alfvén speed ratio: $\varepsilon = V_A^{phot}/V_A^{corona}$

Reflection coefficient: $a = (1-\varepsilon)/(1+\varepsilon)$

Upward wave $\mathbf{u_\phi^+ \approx 1/2\ (u - sign(B°)b/\sqrt{n})}$

Downward wave $\mathbf{u_\phi^- \approx\ 1/2\ (\ u + sign(B°)b/\sqrt{n})}$

=> $u = u^+ + u^-$



•Two limits

1. high frequency (WKB) (smooth stratification)

$\mathbf{u_\phi}^+ \approx \mathbf{u_\phi}^{\circ +}/\sqrt{\varepsilon}$, $\mathbf{u_\phi}^- \to 0$

2. low frequency (discontinuous stratification)

continuity of u and b at interface) implies:

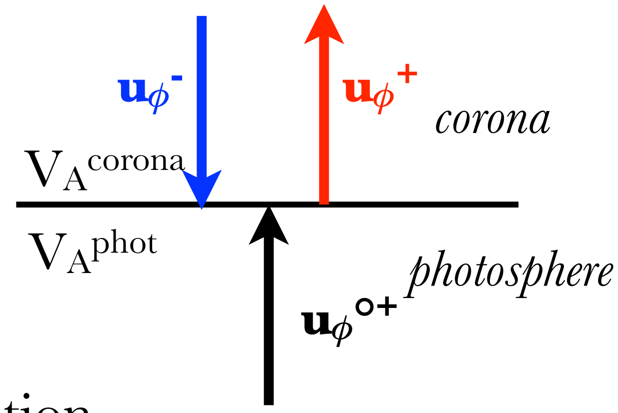
$\mathbf{u_\phi}^+ = -\,a\mathbf{u_\phi}^- + (1+a)\mathbf{u_\phi}^{\circ +}$

Modeling the corona/photosphere interface

•Boundary conditions (non-linear) on THREE components of velocity:

$\partial_t \mathbf{u}_\phi^{+} = (1+a)\partial_t \mathbf{u}_\phi^{o+} - a\partial_t \mathbf{u}_\phi^{-}$ (low-freq. limit)

$\partial_t u_r^{+} = \partial_t u_\theta^{+} = 0$ (transparency for u_r, u_θ)



$\varepsilon = V_A^{phot}/V_A^{corona}$

•Remarks

$\mathbf{u}_\phi^{o+}$ = photospheric input = physical assumption

$\mathbf{u}_\phi^{+}$ = transmitted input = numerical boundary condition

$\mathbf{u}_\phi^{-}$ = coronal output = output of coronal evolution

$a=(1-\varepsilon)/(1+\varepsilon)$ to be chosen at will (realistic $\varepsilon \approx 0.1$?)

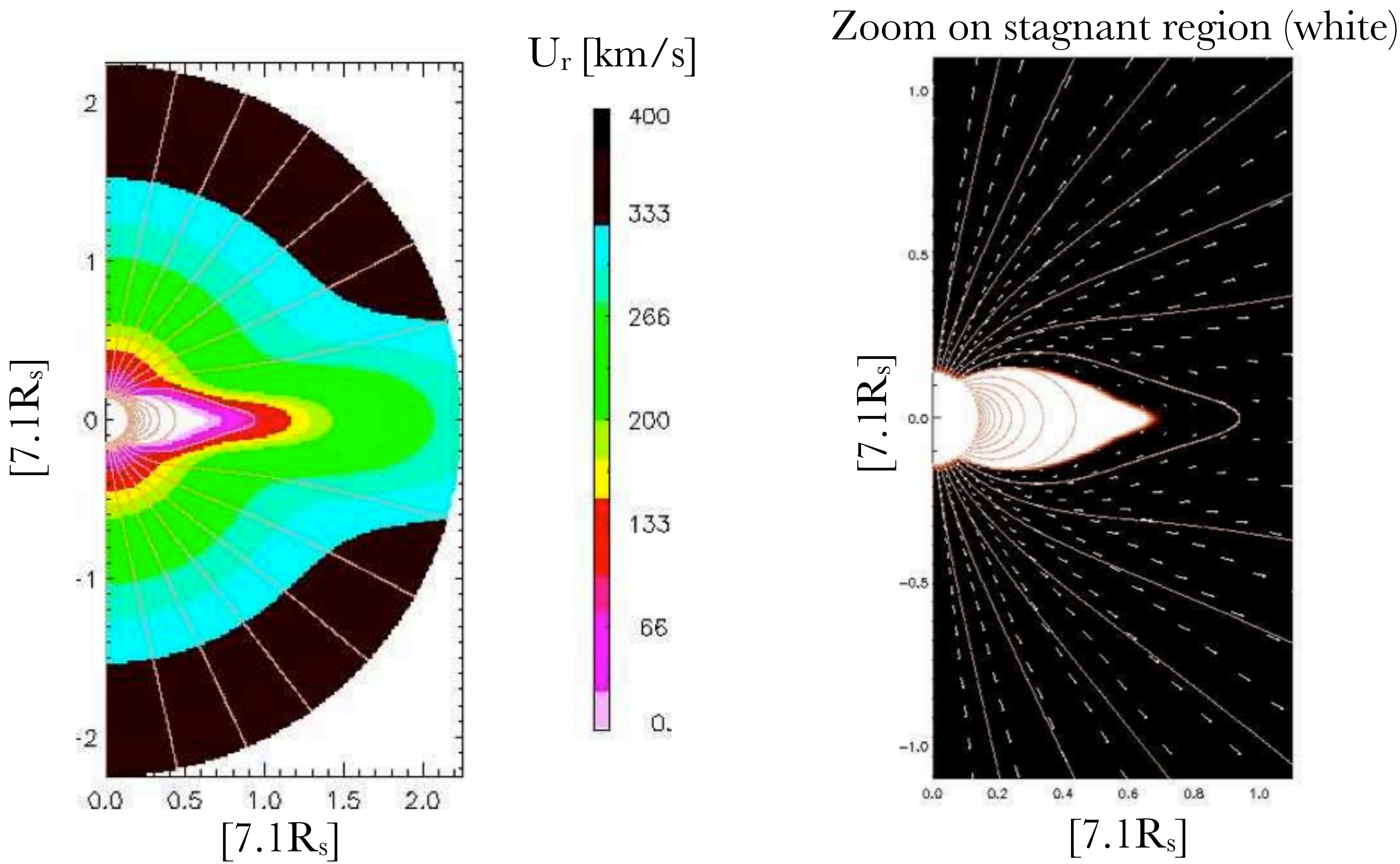
Two limits:

- LINE-tied limit: $\varepsilon=0$ ($a=1$), velocity $u_\phi = u_\phi^{+}+u_\phi^{-}$ fixed
- Transparent limit: $\varepsilon=1$ ($a=0$), only UPWARD velocity u_ϕ^{+} fixed

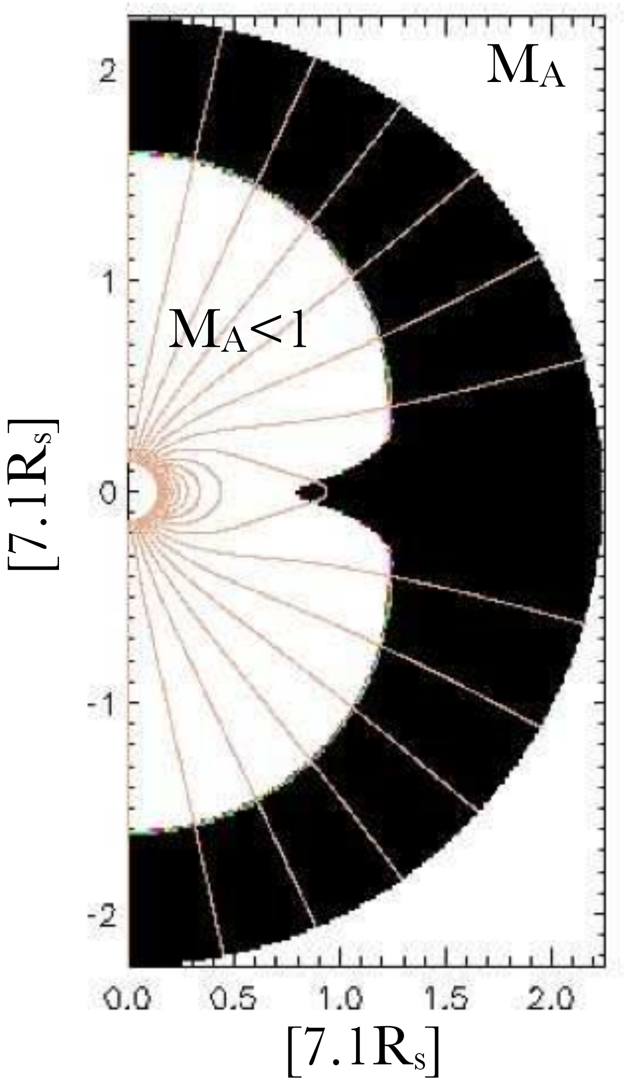
•Application: consider isothermal axisymmetric solar wind with external dipole field, in a quasi-stationary regime

Numerical wind solution - B and U_r

•Application: consider isothermal axisymmetric solar wind with external dipole field, in a quasi-stationary regime



Numerical wind solution - Alfvén Mach number



White: $M_A=U_r/V_A<1$
Black: $M_A=U_r/V_A>1$

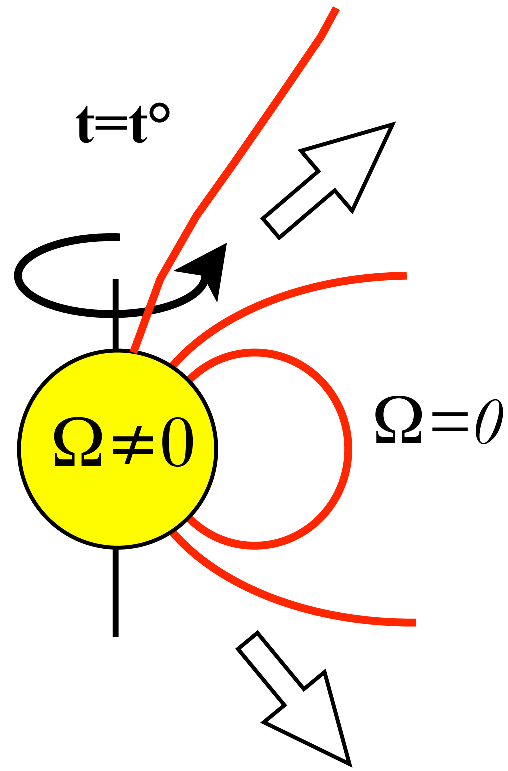
In region $M_A<1$ only Alfvén waves allow back-reaction of the solar atmosphere to propagate downward

Two effects are expected with ROTATION:

- open regions => magnetic break due to formation of trailing Parker spiral
- closed regions => coupling two footpoints

Numerical wind solution + solar rotation

•Initial time $t=t°$, assume:
- Rigid rotation of interior Sun with $\Omega=\Omega°\neq 0$
- NO rotation of atmosphere $\Omega=0$

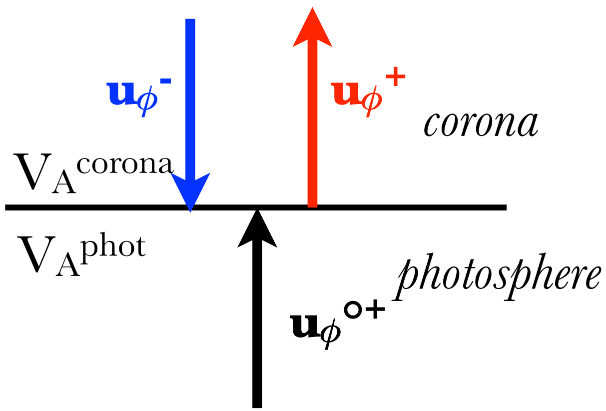


•The rotation jump leads to an Alfvén wave propagating upward starting from photosphere at time $t=t°+\Delta t$

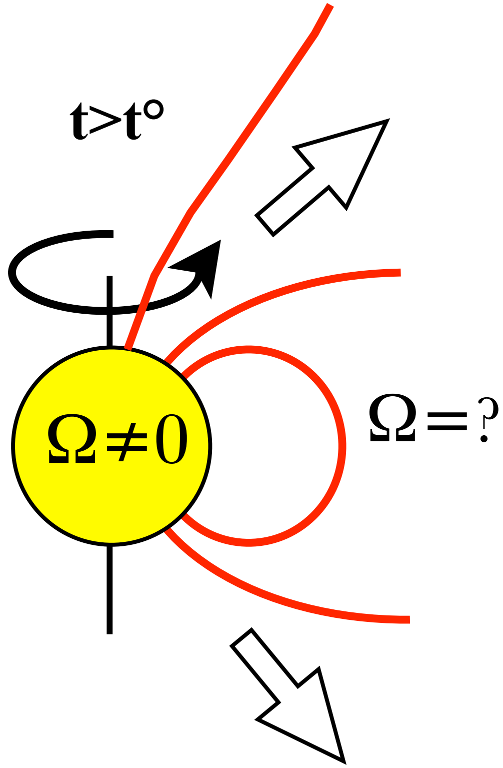
•Photospheric input:
$\mathbf{u}_\phi{}^{\circ+}$: $0 \rightarrow \Omega/2 \sin\theta$ in a time $\Delta t=0.1$

•Three boundary conditions:
(1) line-tied (a=0)
$\partial_t \mathbf{u}_\phi = \partial_t \mathbf{u}_\phi{}^{\circ+}$
(2) transparent (a=1)
$\partial_t \mathbf{u}_\phi{}^{+} = \partial_t \mathbf{u}_\phi{}^{\circ+}$
(3) general (semi-reflecting 0<a<1)
$\partial_t \mathbf{u}_\phi{}^{+} = (1+\mathbf{a})\, \partial_t \mathbf{u}_\phi{}^{\circ+} - \mathbf{a}\partial_t \mathbf{u}_\phi{}^{-}$

$\varepsilon = V_A{}^{phot}/V_A{}^{corona}$



Simple predictions



Definition: $u = u^{+} + u^{-}$

Line-tied: u fixed = $2u^{\circ+}$ (because $u^{+}=2u^{\circ+} - u^{-}$)
Transparent: *only* u^{+} *fixed* = $u^{\circ+}$

<u>1. closed equatorial region:</u>
when plasma is transparent, signal transmitted from other foot point leads to u- ≈ $u^{\circ+}$ also, so : => $\mathbf{u \approx 2u^{\circ+}}$

<u>2. Polar regions</u>
- transparent: small reflected u^{-} (eg WKB) => $\mathbf{u \approx u^{\circ+}}$
- line-tied: => $\mathbf{u \approx 2u^{\circ+}}$

•So polar regions should depend on ε, not equatorial regions

Transparent case ε=1- surface rotation

Photospheric input:

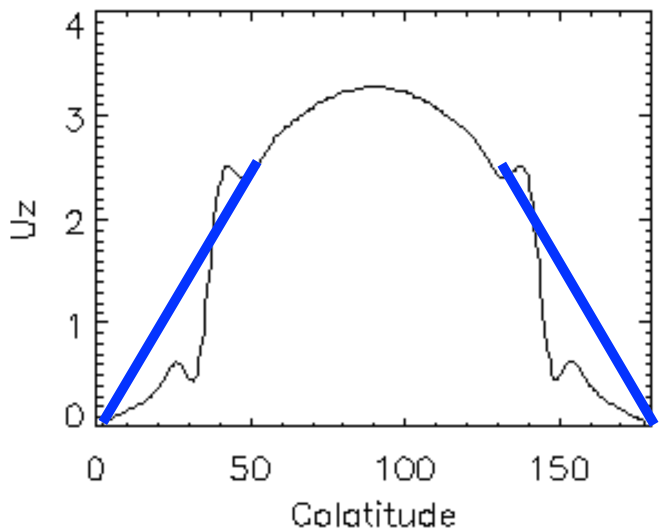
$\mathbf{u}_\phi^{\circ +}$: $0 \rightarrow \Omega/2 \sin\theta$ in Δt=0.1 (solid rotation)

t>t°: $u_\phi^{+} = \Omega/2 \sin\theta$

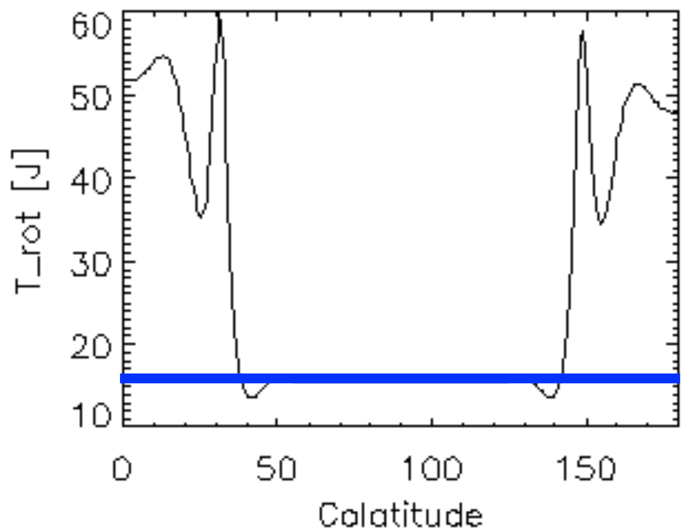
line-tied solution ($u_\phi = \Omega \sin\theta$)

transparent solution $t = t° + 8hrs$

Surface U_ϕ [km/s]

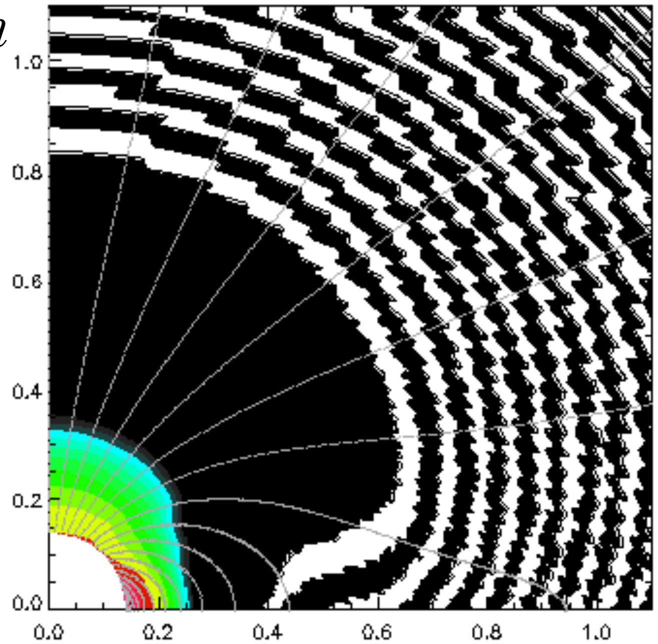


Rotation period [Day]



Growth and decay of coronal rotation (transparent, cont.)

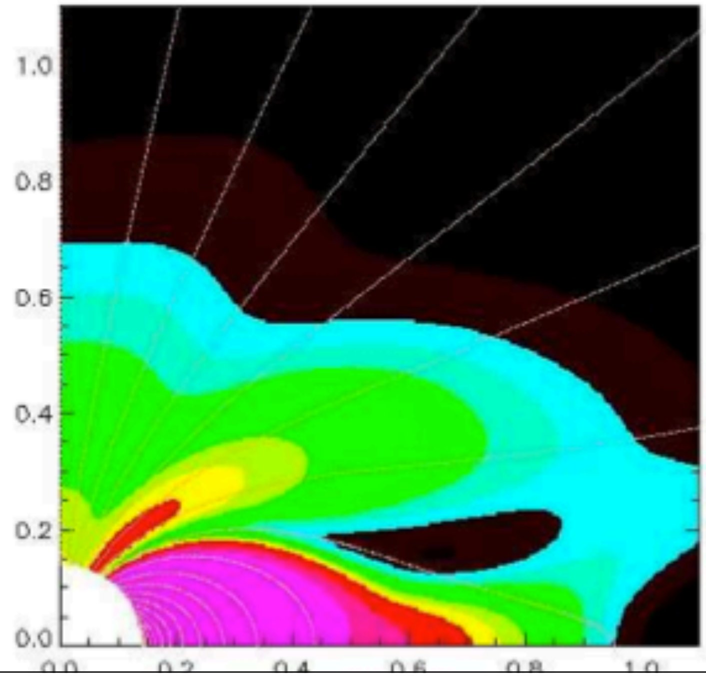
Δt=50 min

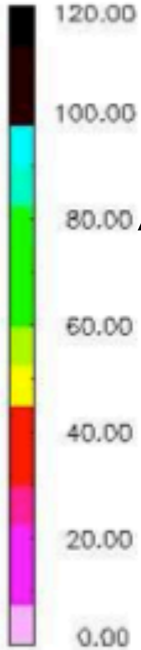


Rotation period [Day]

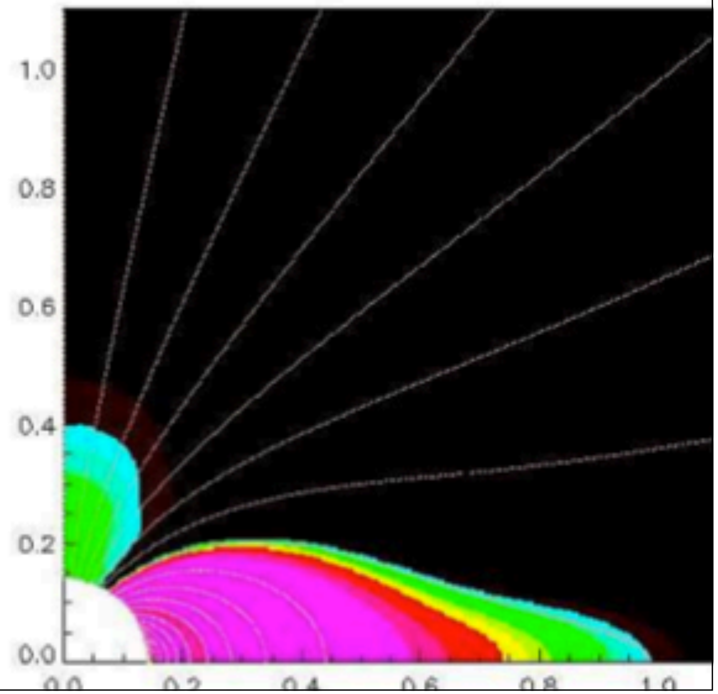
Equator relaxes in time t_{relax} =3000s ≈ 1 Alfvén time (ΔL≈4Rs)
Polar regions show much longer relaxation time

Δt=8 hrs



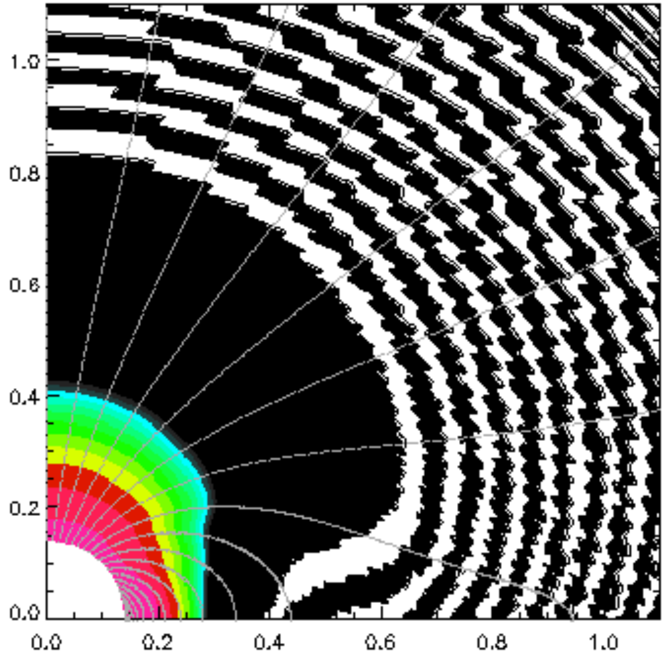


Δt=54 hrs

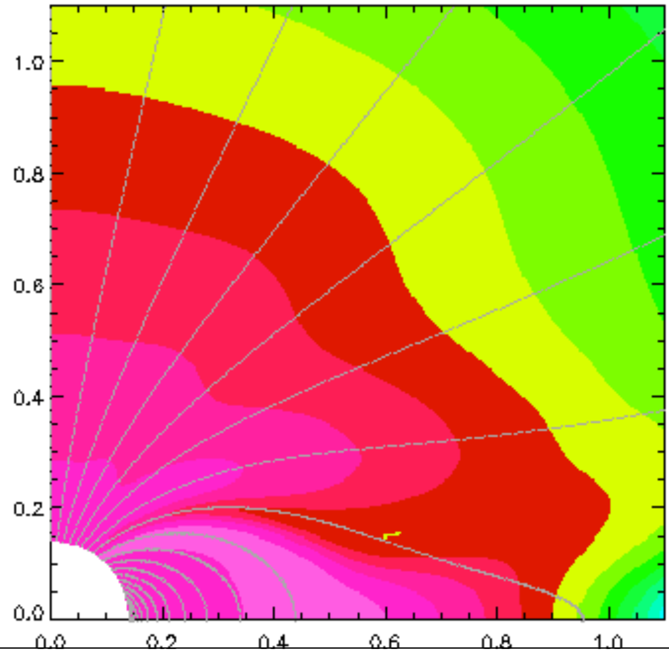


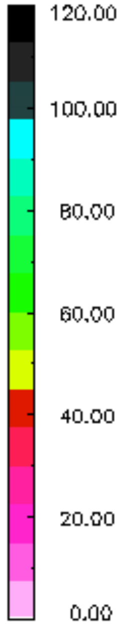
Growth and decay of coronal rotation (ε=0.1)

Δt=*50 min*



Δt=*8 hrs*



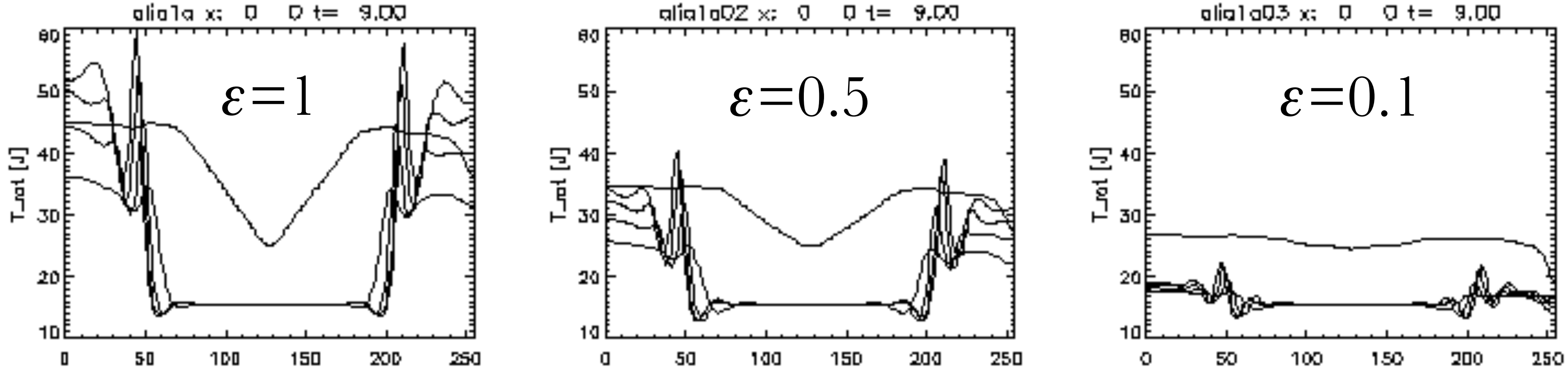


Rotation period [Day]

Equator : same rotation period
Polar regions: closer to equator - more reasonable !

Varying ε: 1, 0.5, 0.1

Surface rotation period vs latitude at successive times from 55 min to 8 hrs



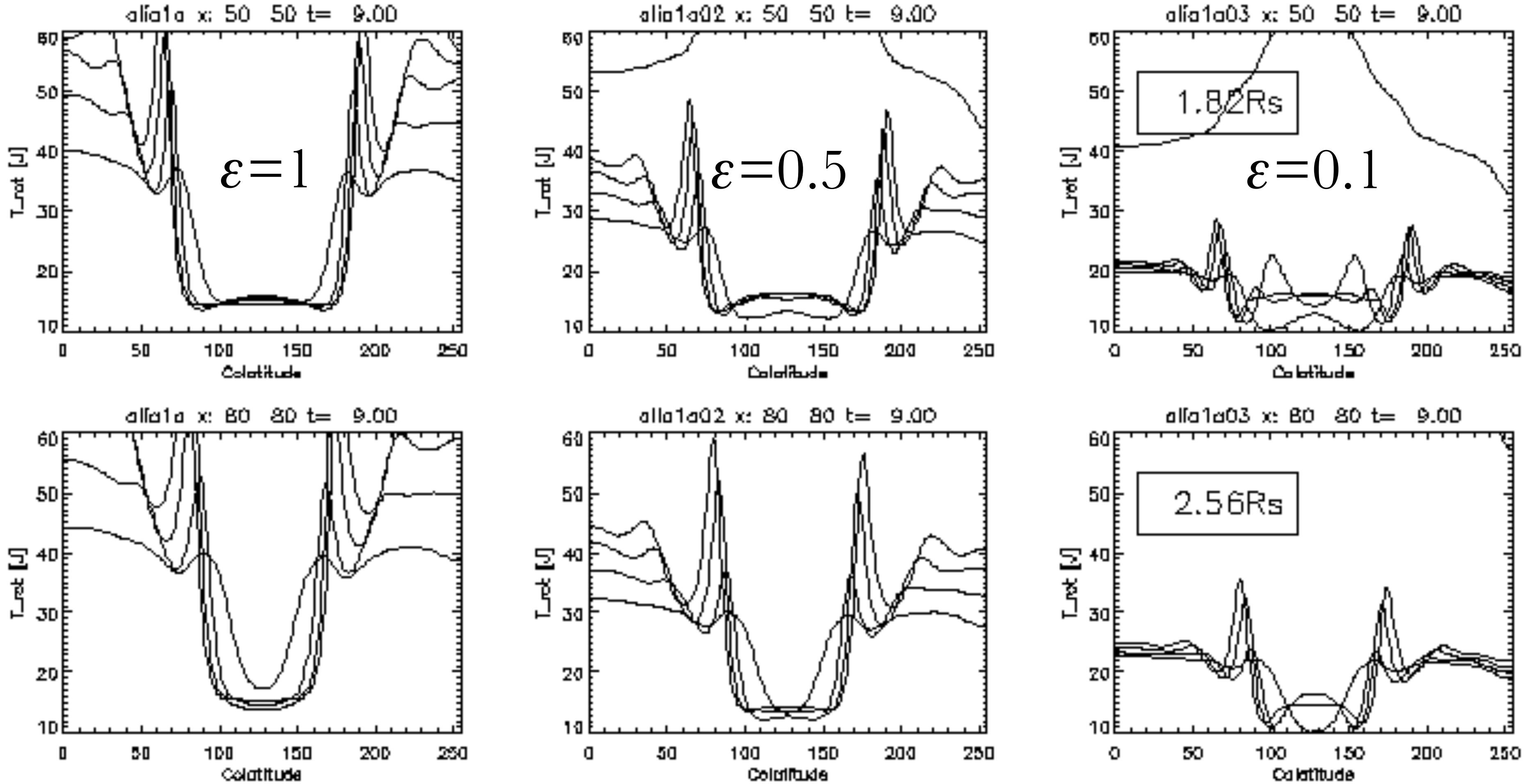
Summary
Equatorial rotation period independent of ε
Polar/equatorial period reasonable only when ε=0.1
- magnetic break

Bizarre variations occur at boundary (reconnection?)
Only low ε case relax rapidly

higher in the corona

Same thing occurs at larger distances: here 1.8 R_s and 2.6 R_s
NB Equator not relaxed after 8 hrs at large distance and small ε

Higher layers rotation period vs latitude



Conclusion

With a transparent corona/photosphere boundary,
a uniformy rotating Sun leads to the equator turning as a solid and the poles asymptotically at rest, due to excessive magnetic brake of open regions
The first region to brake is the coronal streamer boundary region.

The brake of polar regions is decreased to more reasonable values when a finite coronal/phosphere Alfvén ratio is used.

To test more realistic situations, we need to install more generic magnetic field structures on the Sun.

Conclusion

Changing model?