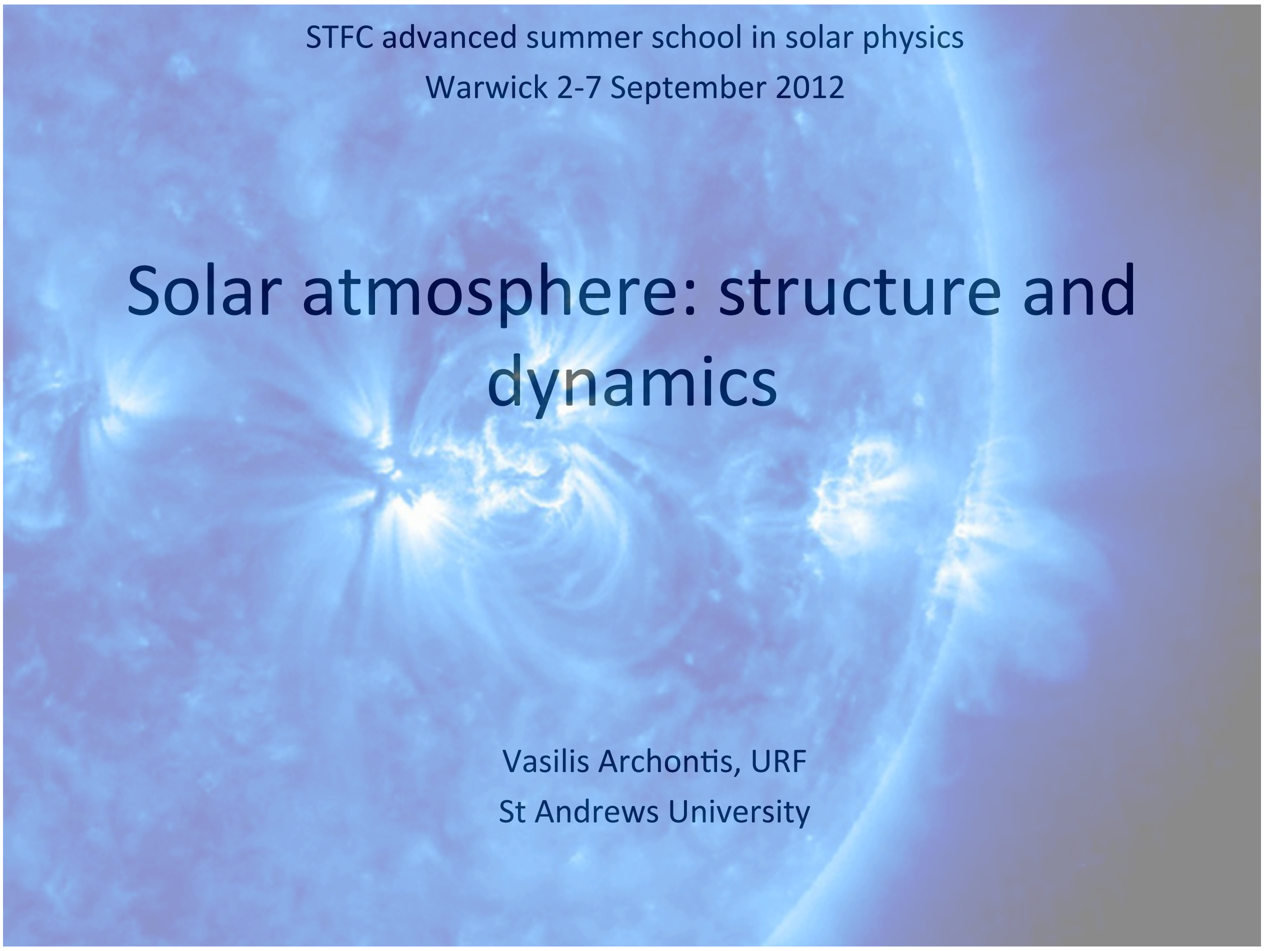


STFC advanced summer school in solar physics

Warwick 2-7 September 2012

Solar atmosphere: structure and dynamics

Vasilis Archontis, URF

St Andrews University

Overview

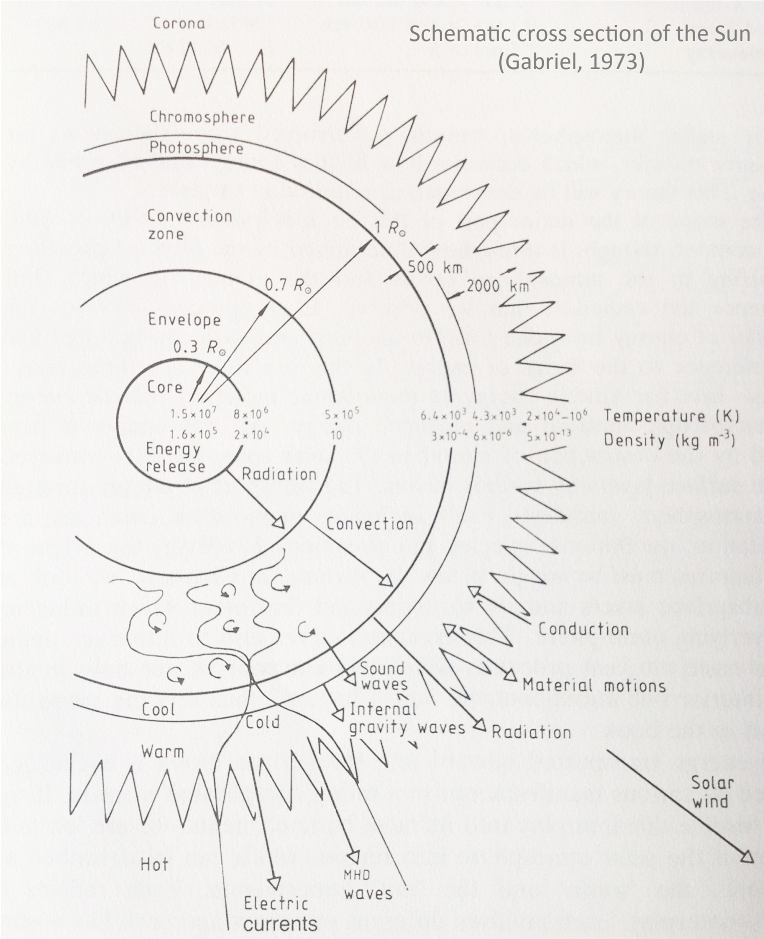
The Sun’s atmosphere
- stratification

Photosphere
- ‘quiet’ vs. ‘active’ sun
- granules / supergranules
- magnetic fields (vertical/horizontal)
- sunspots

Chromosphere
- features (network, prominences, spicules)
- heating

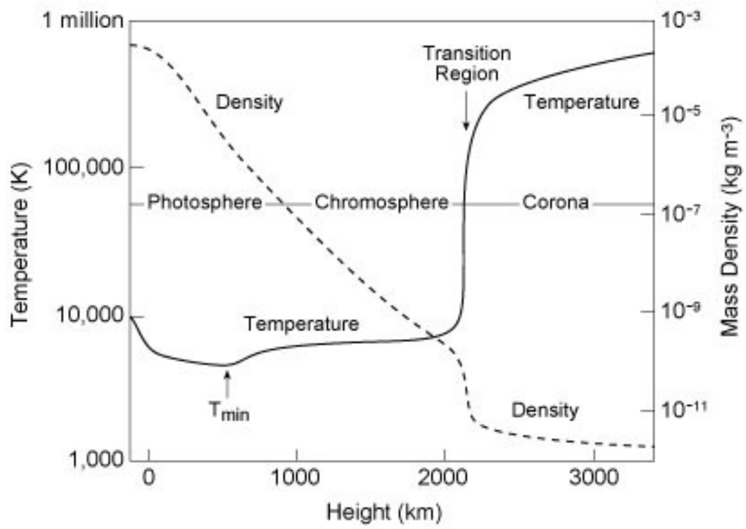
Upper atmosphere
- transition region & corona
- coronal loops
- active regions

Magnetic flux emergence
- simulations
- associated dynamic phenomena (eruptions)



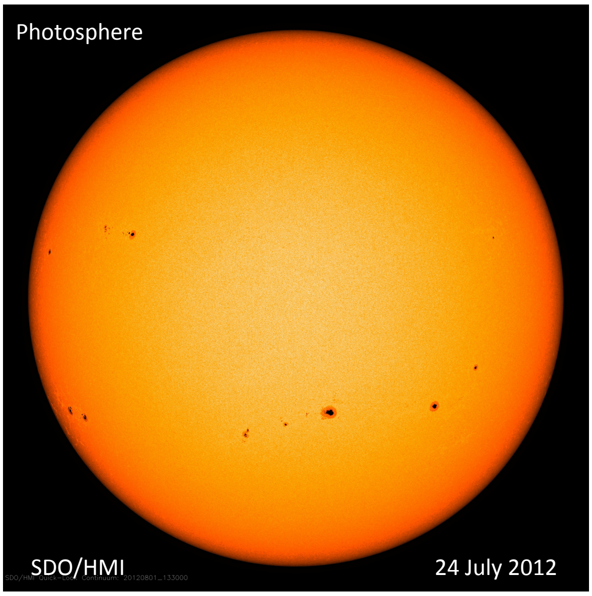
- Core
- Radiative zone
- Convection zone
- Photosphere
- Chromosphere
- Transition region
- Corona

The stratification of the solar atmosphere



- Multi-layer atmosphere.
- Strong stratification.
- Temp: <10^4 → >10^6 K
- Density: 8 orders of magnitude.
- Coupled(?) system.
- Emergence of magnetic fields through stratified atmosphere.
- High-res. observations in different wavelengths.

Photosphere: the visible surface of the Sun



It is the region closest to the subsurface sources of energy and reveals their nature.

It is the layer from which the light, forming the visible disc, emanates.

This layer is in many ways simpler to study and is better understood than other layers.

Physical properties

Thickness ≈ 500 km

Temperature = 4500 – 6000 K

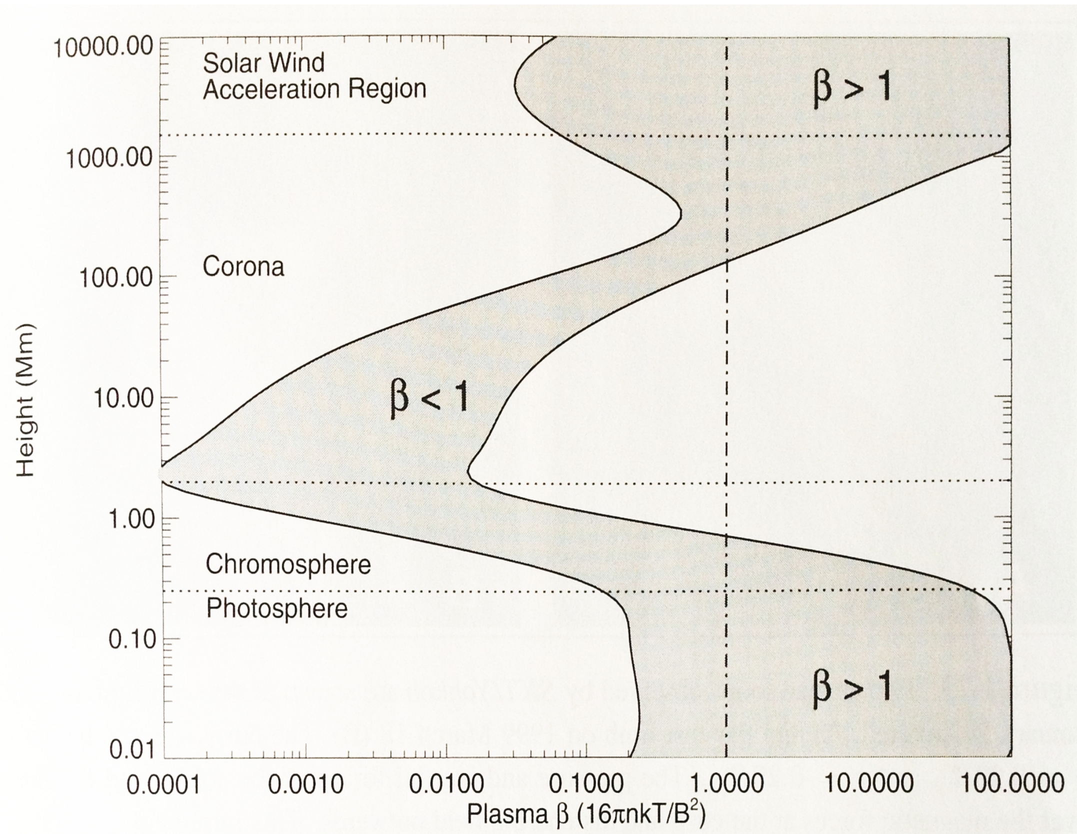
Density (average) = 2×10^4 kg/m^3

Pressure = 6.8x10^(-3) – 1.6x10^(-1) (bars)

‘Quiet’ vs. ‘active’ Sun

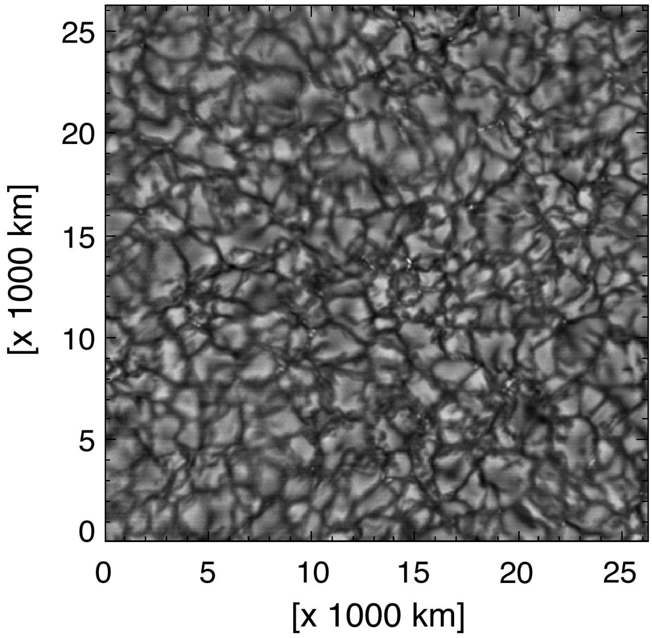
SDO/HMI-intensitygrams 04/03/2011 – 12/03/2011

Plasma-b distribution (Gary 2001)

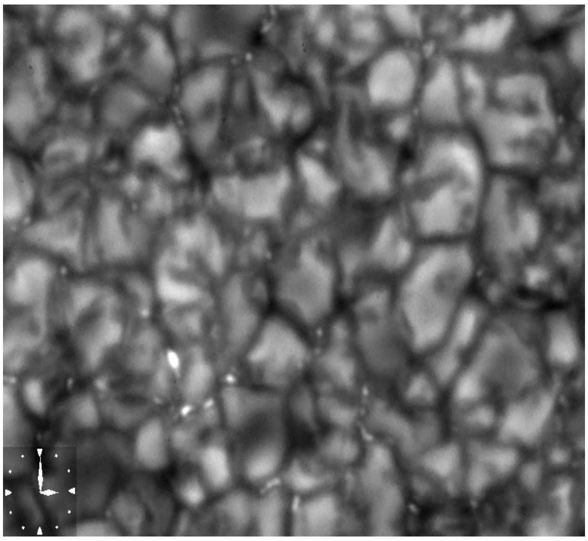


Photosphere: granulation

T.Rimmele/ NOAO



Hinode/G-band (430 nm)



Granule's size ≈ 1000 Km.

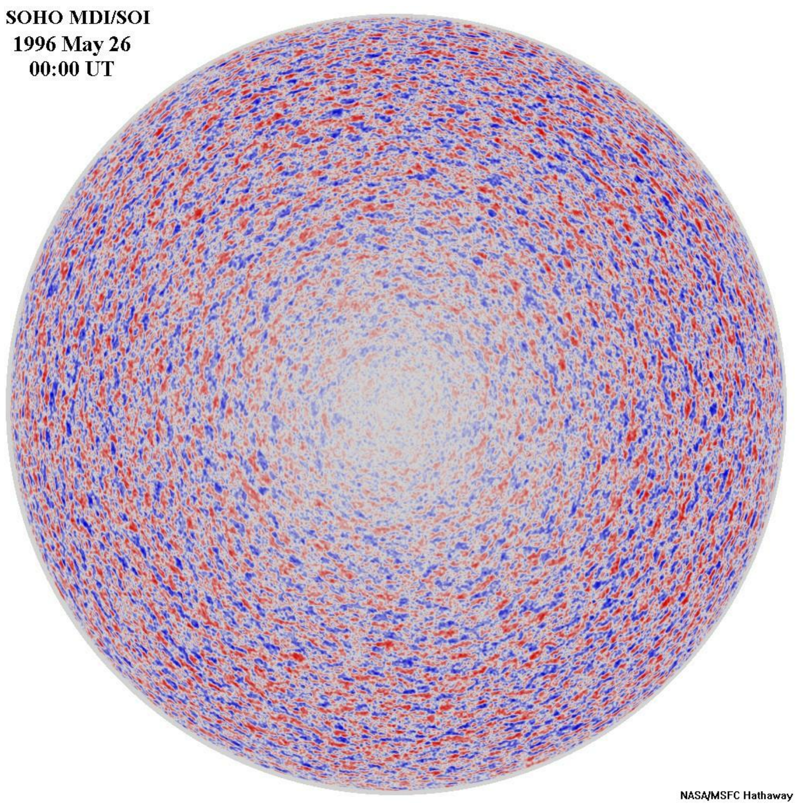
Driven by convection.

Hotter than the darker lanes.

Lifetimes ≈ 20 m.

Flows up to 6-7 km/s

Super-granulation



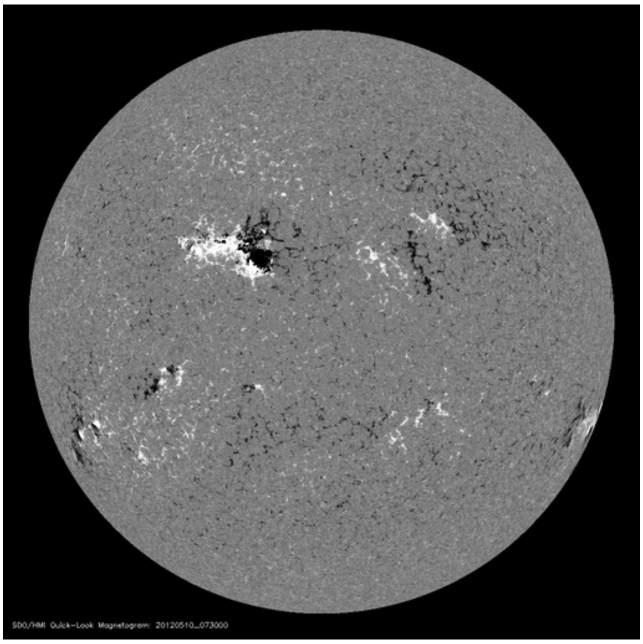
1 hour average of MDI Dopplergrams (averages out rotation and oscillations).

Dark-bright: flows towards/away from observer.

No supergranules visible at disk centre: velocity is mainly horizontal.

size: 20-30 Mm,
lifetime: days,
horiz. speed: 400 m/s,
no contrast in visible.

Photosphere – magnetic fields



SDO/HMI magnetogram

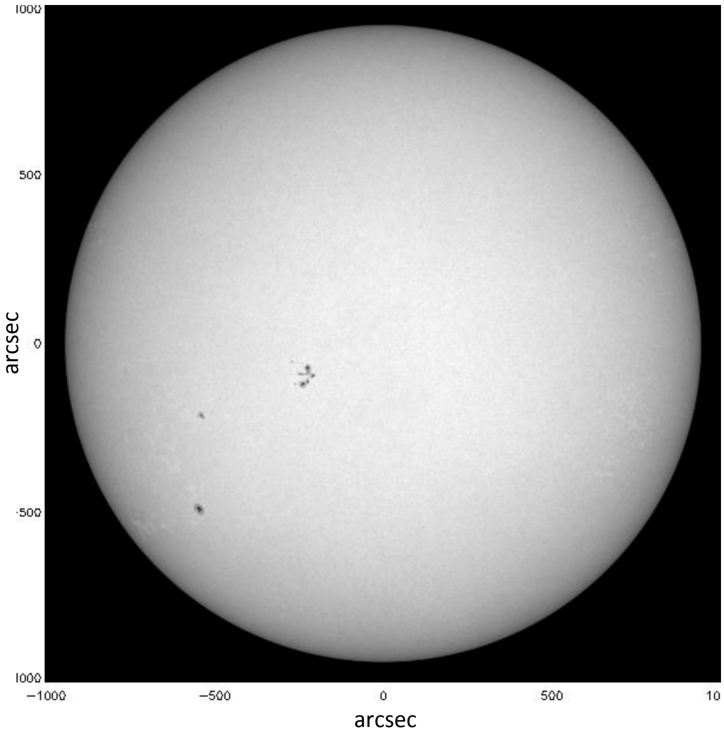
Large-scales (> 30 Mm): ARs.

Small-scales (≈1-2 Mm): magnetic carpet.

- emergence
- flux cancelation
- fragmentation
- coalescence

Zoom in – small scales and MBPs

Swedish Solar Telescope (SST)

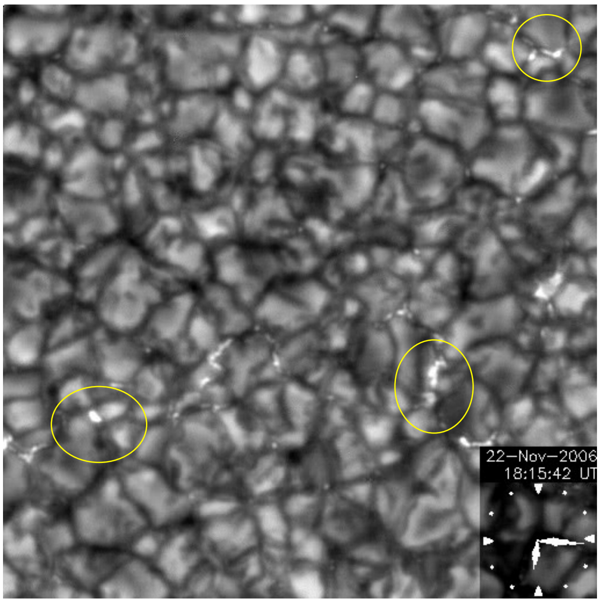


- High-resolution observations.
- White-light images (SST).
- 0.1 arcsec , full disk → 70 km.
- Also, G-band.

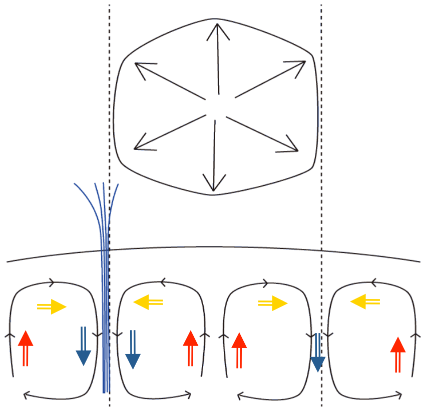
- Bright point-like structures.
- Strong magnetic fields?
- Why bright?
- Pore-like structures.

Ubiquitous vertical B-fields

Hinode

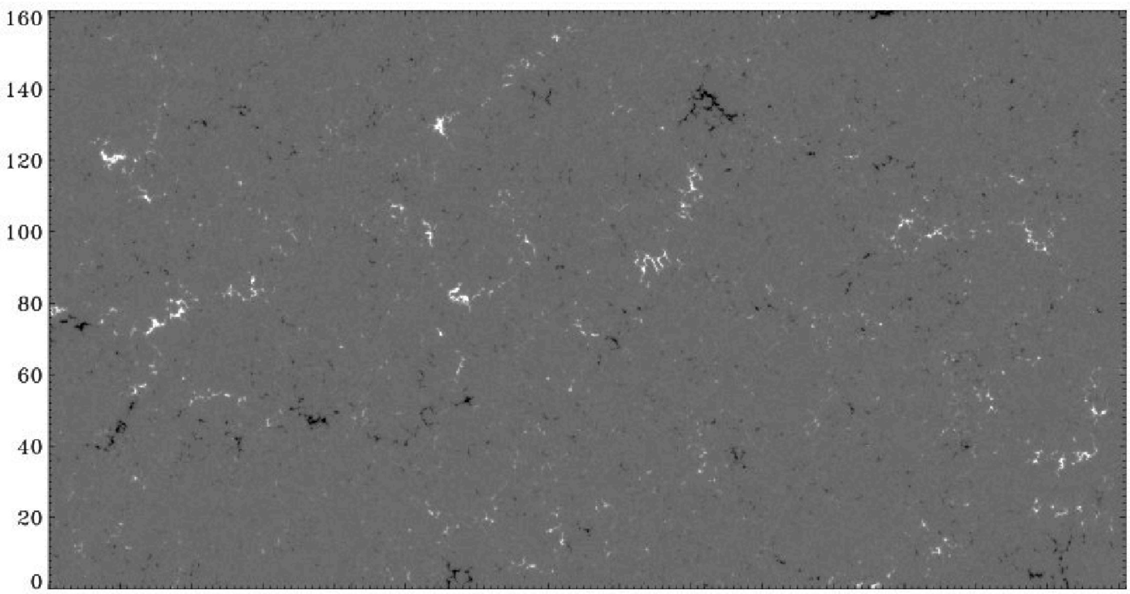


- Both polarities.
- Strong kG magnetic fields.
- Field strength larger than equipartition B (400G).
- Located in inter-granules.



Ubiquitous vertical magnetic fields

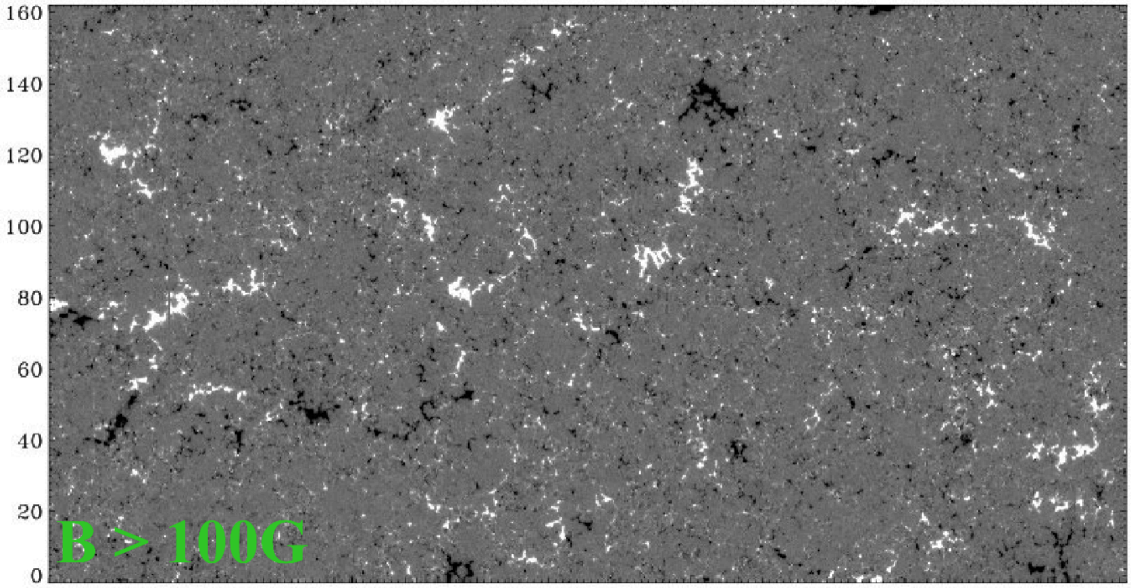
Hinode magnetograms



B saturated at 500G. Magnetic field around supergranule edges.

Ubiquitous vertical magnetic fields

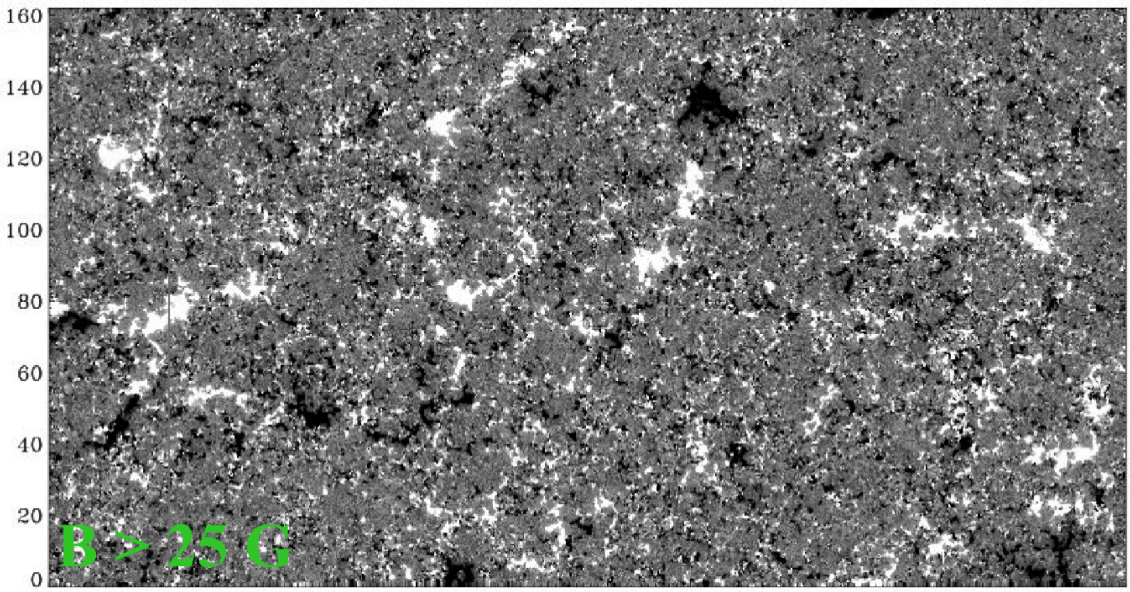
Hinode magnetograms



B saturated at 100G. Main magnetic field around supergranule edges but now also inside.

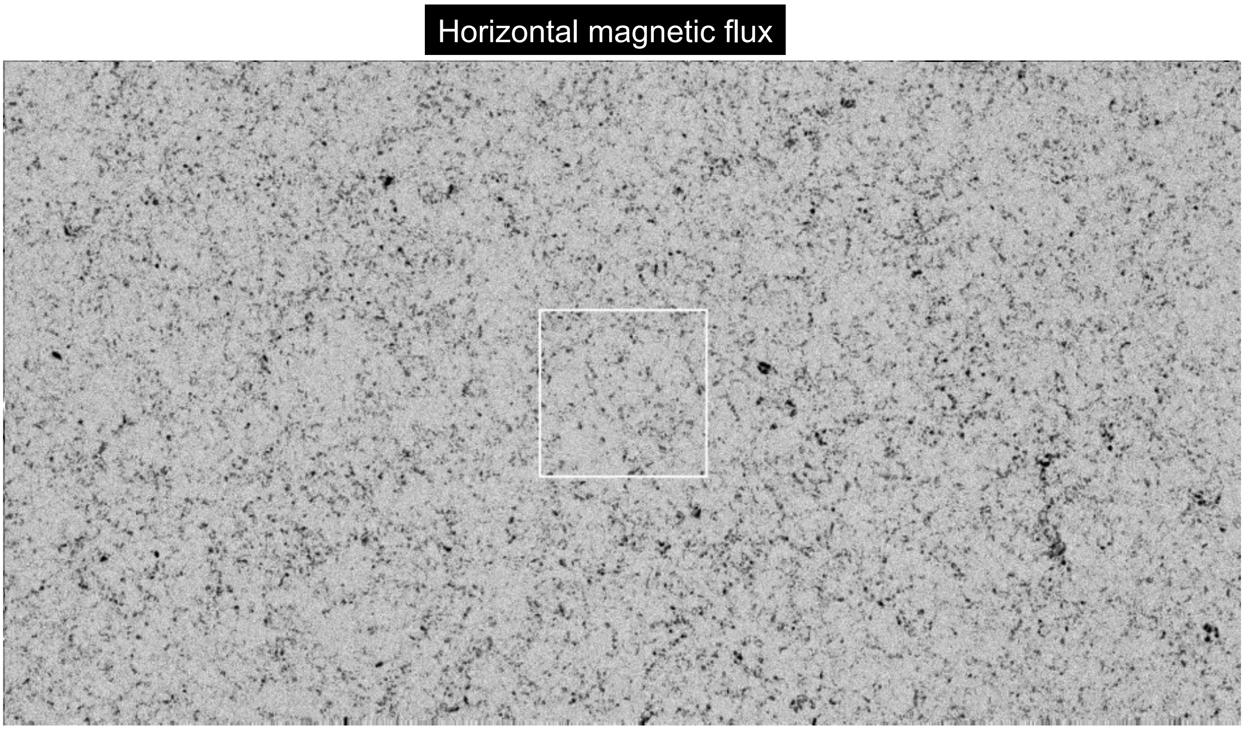
Ubiquitous vertical magnetic fields

Hinode magnetograms

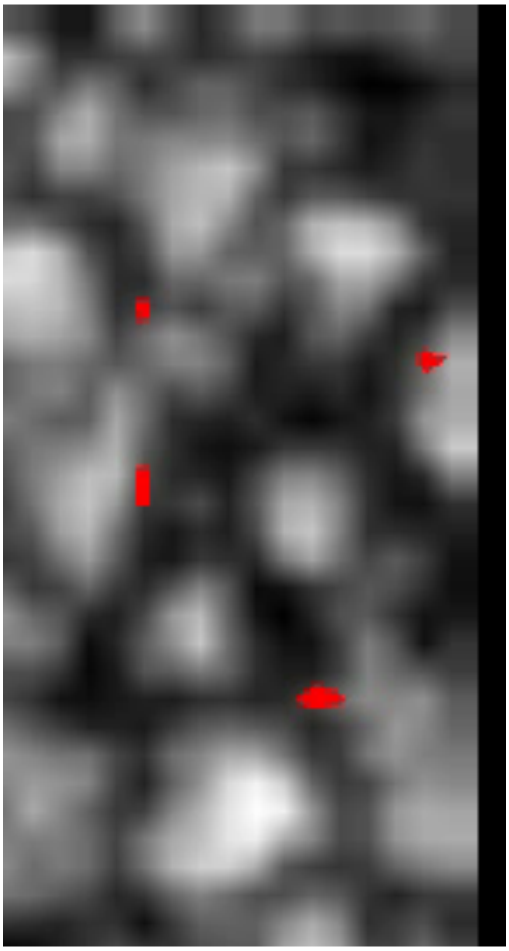


B saturated at 25G. Now field inside granules.

Ubiquitous horizontal magnetic fields



Lites et al. (2007), Orozco et al (2007)



Horizontal field is highly transient!

-Transient Horizontal Magnetic Field (THMF).

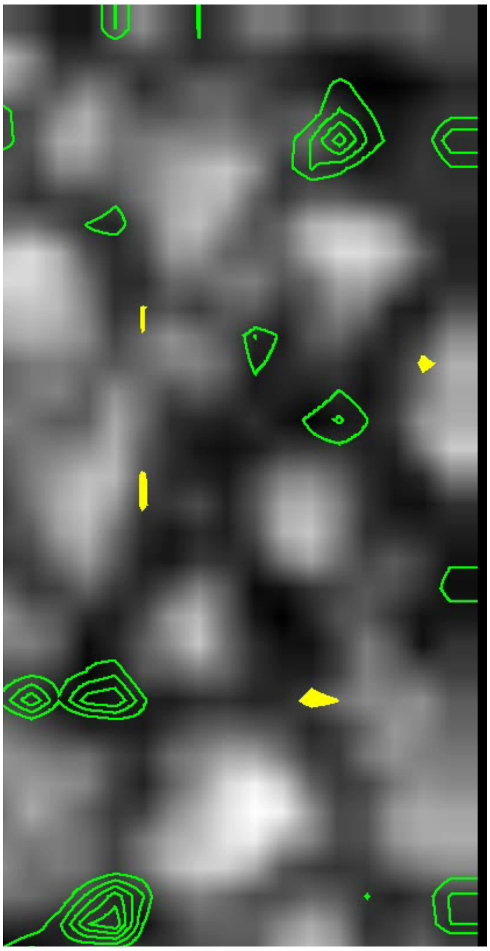
- HMF appear mainly within granules and occasionally in the lanes.

- THMFs in the plage, have lifetimes of ≈ 1-10 minutes (granular scale).

Centeno et al. ApJL 2007

Ishikawa et al A&A 2008

- Sun center - Quiet Sun
- Stokes-Q/U (horizontal field) Red



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Centeno et al. ApJL 2007

Ishikawa et al A&A 2008

- Sun center - Quiet Sun
- Stokes-V (vertical field) Green
- Stokes-Q/U (horizontal field) Yellow

Properties of THMF

Extremely high occurrence rate (e.g. in the plage, 51 events over 40 min).

In the plage region is twice than that in the quiet Sun.

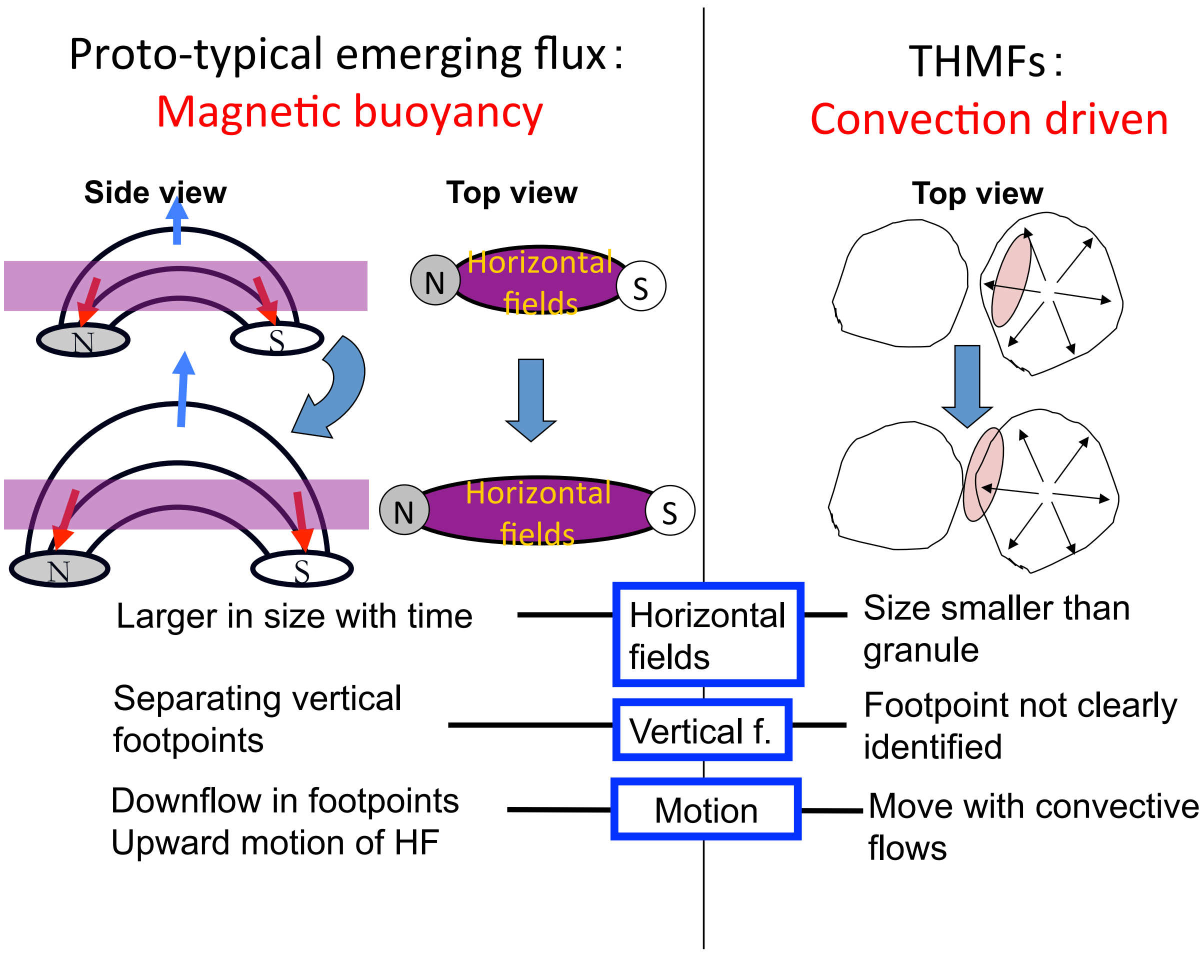
Very high occurrence rate may indicate reservoir in the CZ.
Assumption: all the granules have the horizontal fields uniformly in their flow pattern. HFs move with granular motion, and appear occasionally as THMFs.

Receptive to convective motion (HF rise with nonmagnetic convective flow).
Properties clearly different from emerging flux driven by Parker instability (e.g. Ishikawa et al 2008 A&A).

Magnetic fields strength lower than equi-partition.

Very low filling factor (of 0.2, but need correction for scattering).

Essentially no directivity for all the events.



The origin of HMFs (?)

Is the origin/evolution of THMFs due to:

1. A local (close-to-surface) dynamo process?
Convection zone all over the sun may have statistically-stationary accumulation of HMF (reservoir).

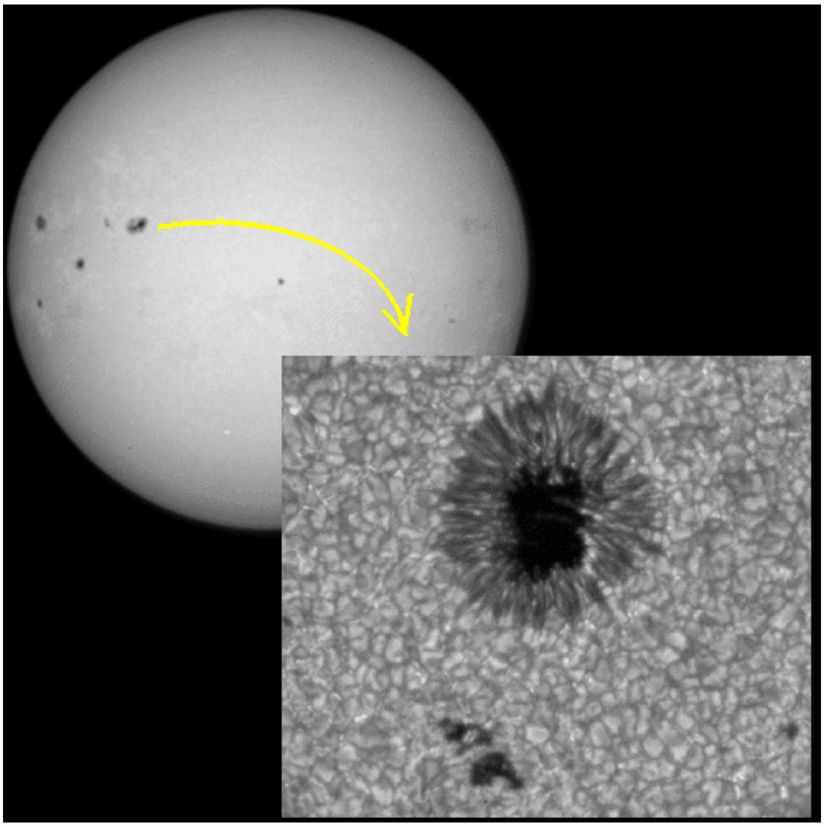
If no or little dissipation (unlikely), dynamo is not needed.

If local dynamo, what is *dissipation process*?
Reconnection with vertical fields?
Reconnection with horizontal fields?
Is turbulent diffusion working for HTMF?
In photosphere and/or in chromosphere?

2. Emergence of magnetic flux ?

3. Are these totally different or related phenomena?

Sunspots



Intense B fields (kG).
Inhibit convection and heat flow -> dark / cool.

~ 3000-4500 K

~ 2.5 – 50 Mm

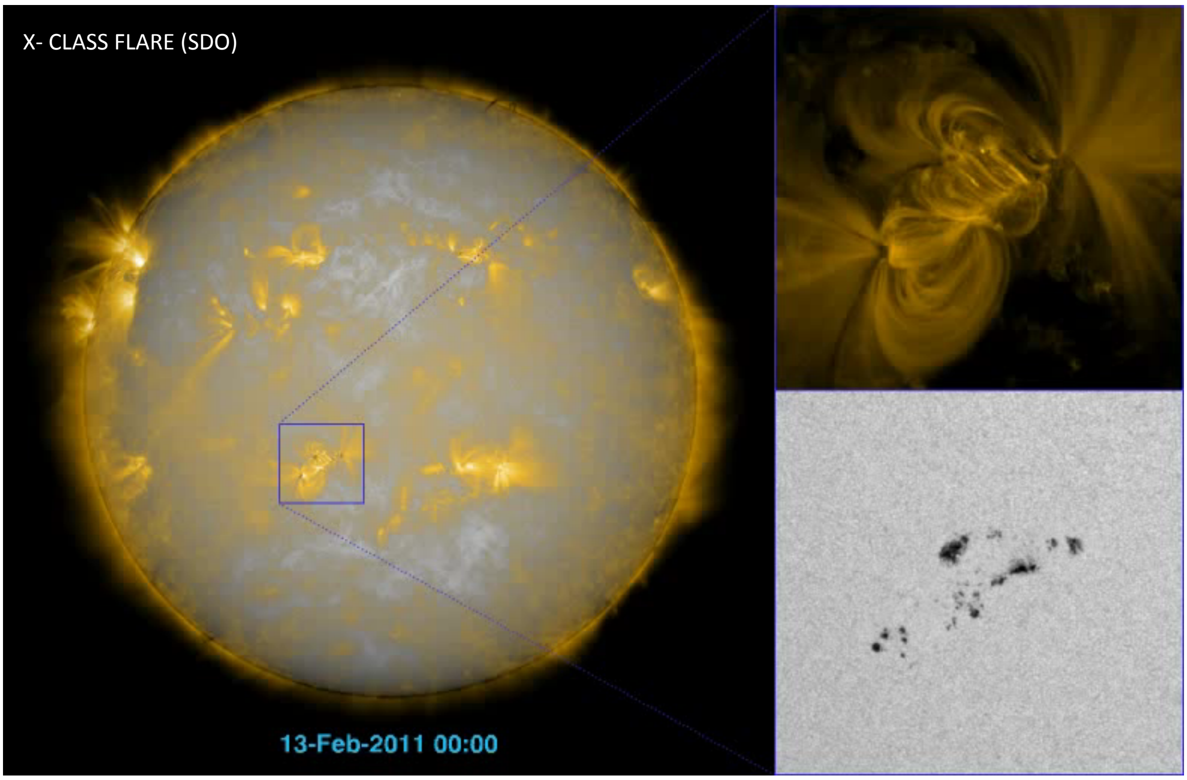
Umbra: vertical B.
Penumbra: horizontal B.

Usually appear in pairs.

Develop in active regions.

Magnetic activity.

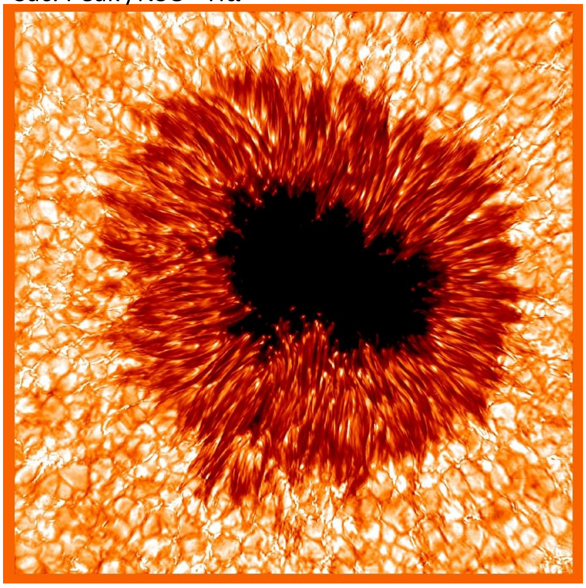
Sunspots and flares

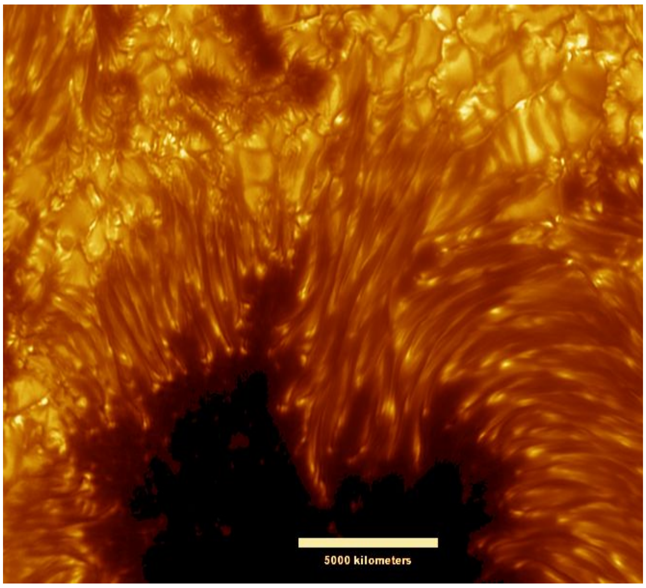


Sunspots

Sac. Peak /NSO - Hα

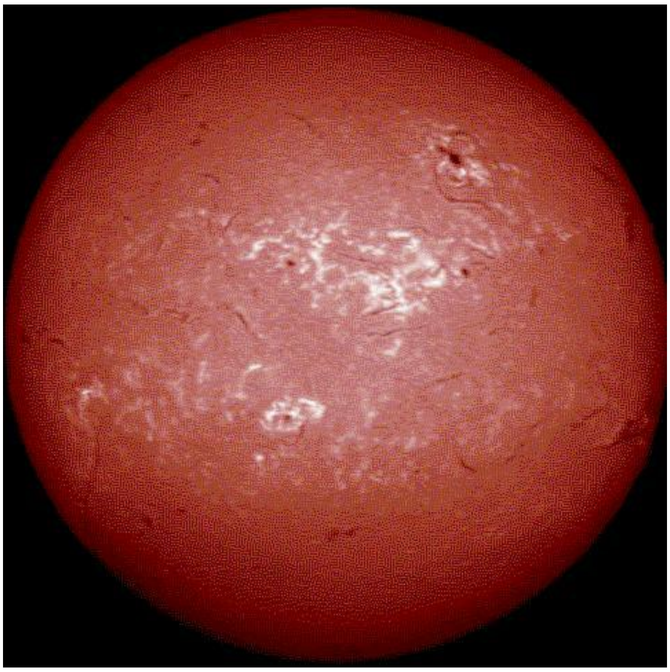
SST/Hα (AR 10030)





High res observations → more structure in the penumbra.
Bright filaments, dark cores.
Origin uknown.

Chromosphere



Thin layer between phot and TR.

Above phot. ~ 2000 km deep.

Density drops, less 'opaque'.

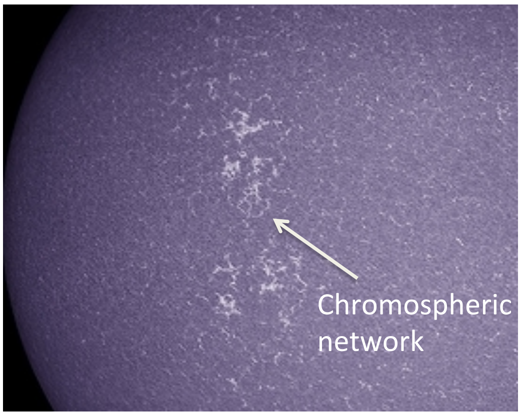
Strong Ha emission line at 656.3 nm
→ reddish colour

6000 – 3800 – 35000 K.

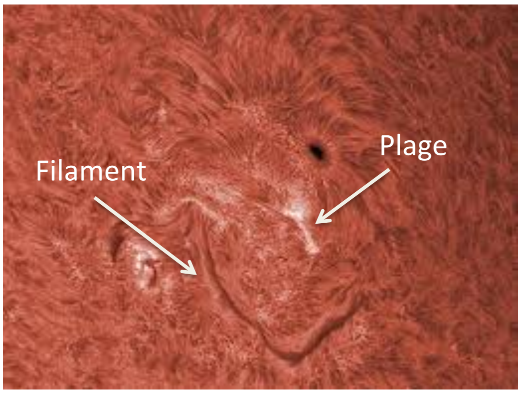
mid-top: T increases with height
→ chromospheric heating ?

Big question: what causes the chromospheric heating?
- reconnection, waves, jets (spicules), etc.

Chromosphere – Features I

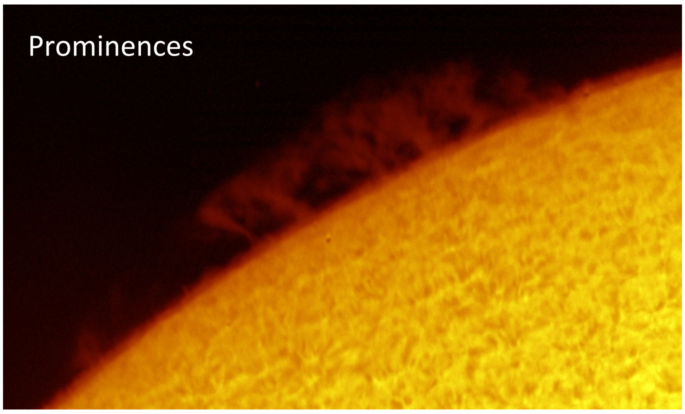


- UV – Ca II K.
- Outlines supergranule cells.
- Bright → B-fields?



- Filaments → dark (dense), cool.
- Supported by magnetic fields.
- Underlie (many) CMEs.
- Plage surround sunspots.

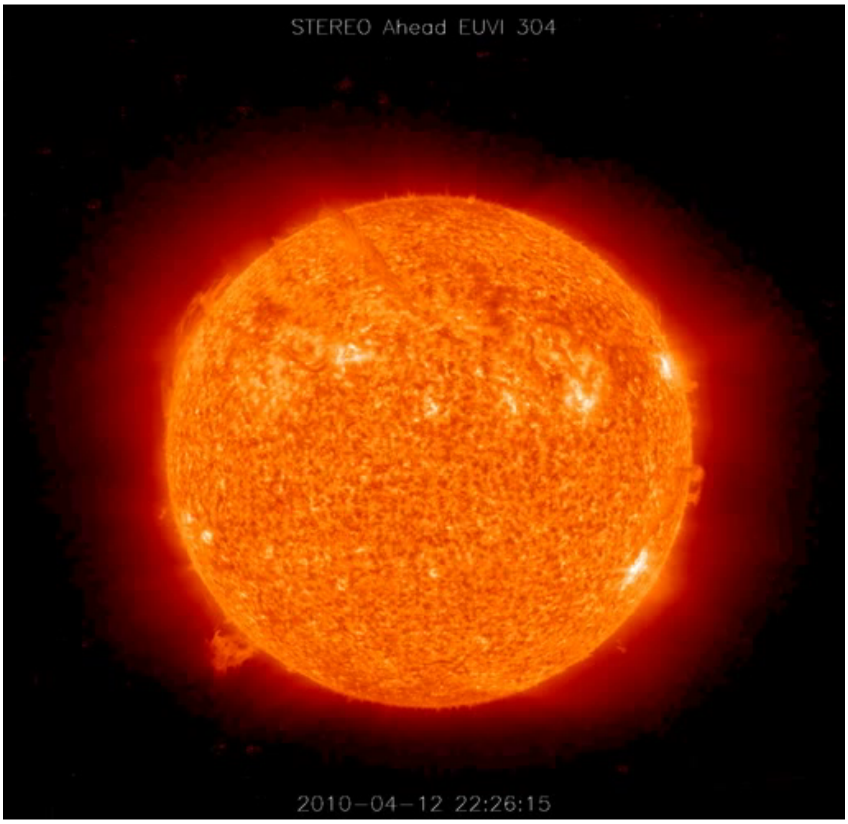
Chromosphere – Features II



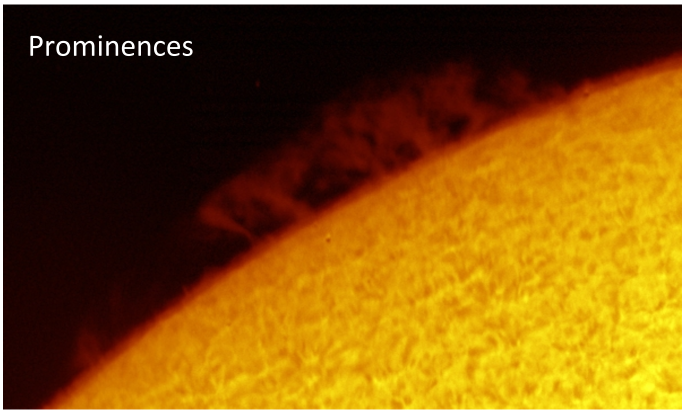
- Like filaments, but on the limb.
- Quiescent state for days/weeks.
- Unstable → erupt.

How do they form/evolve/erupt?

Filament eruption



Chromosphere – Features II



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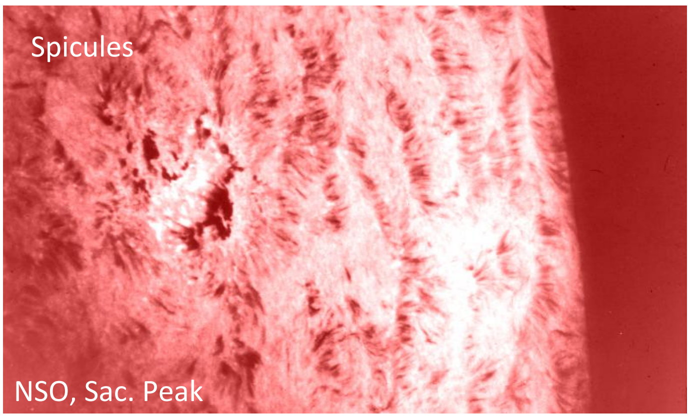
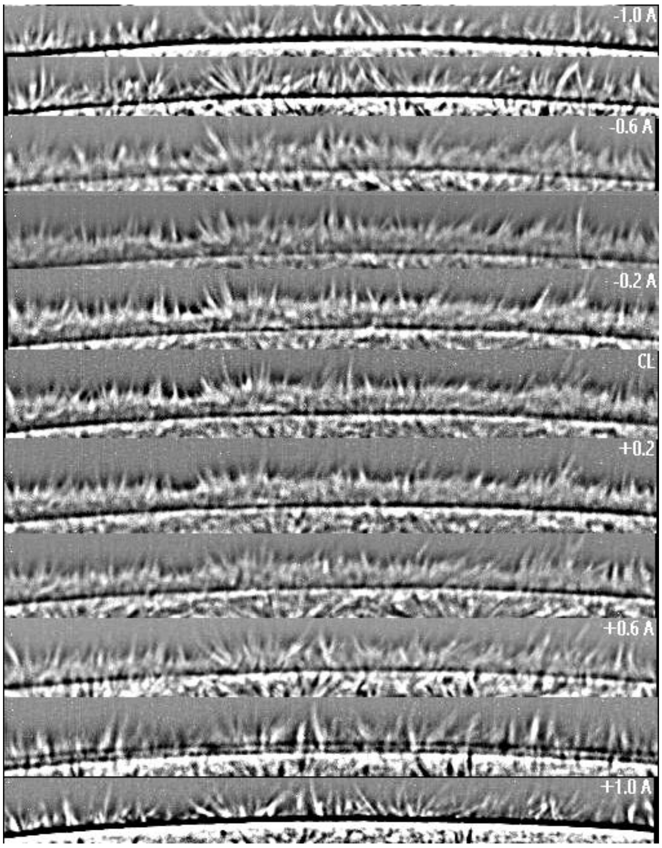


- Small, jet-like structures throughout the chromosphere.
- Dark (absorbing) streaks on the disk.
- Short – lived (max ~10 min).
- Eject material outward (20-30 km/s).

Spicules



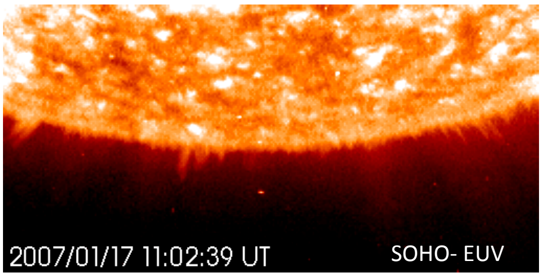
Superposition of 11 limb images taken at different wavelengths (Big Bear Solar Observatory).

Spikes of *luminous* gas on the limb (spicules).

Longest approx. 7000 km.

Speeds ~ 30 km/sec

Last only about 10 min.



Spicules

Are there two species of chromospheric spicules?
(SOT Hinode, McIntosh, De Pontieu, Hansteen, Carlsson, etc.)

Type I: driven by shock waves, lifetimes 3-7 min.

Type II: rapid formation (~ 10 sec), very thin (200 km wide), lifetimes ~ 10-150 s, rapidly heated to TR temperature, speeds 50-150 km/s.

Possible formation due to reconnection in the vicinity of magnetic flux concentrations in plage and network.

The exact process that drives and eject material in spicules is still under debate.

Spicules wiggle with 3-5mHz oscillations (carry waves?) that propagate into the corona. Speeds ~ 20 km/s in the chromosphere.
(e.g. Okamoto-De Pontieu, 2011, ApJ).

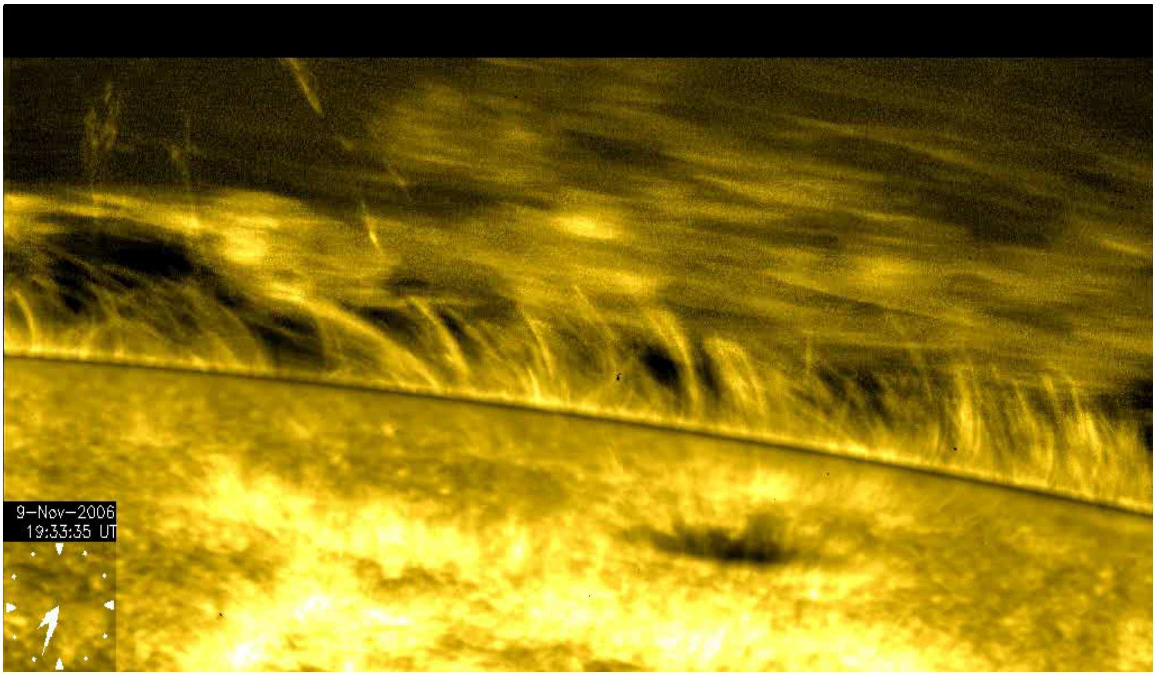
Do spicules (or associated Alfvénic waves) provide sufficient energy to heat the (quiet) corona and drive the fast solar wind ?

Yes (e.g. De Pontieu et al., 2011 Science)

No (e.g. Klimchuck 2012 JGR)

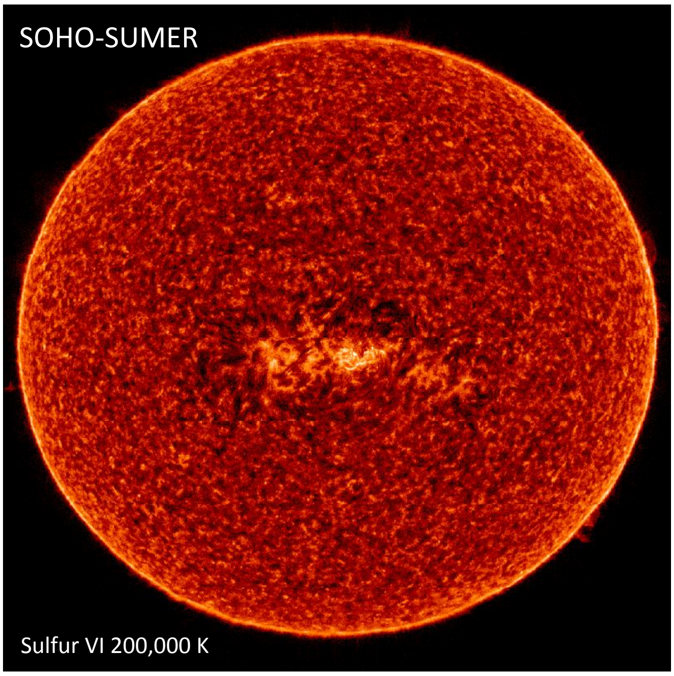
Chromosphere more dynamical than expected!

Hinode



Okamoto, et.al 2007, *Science*

Transition Region



Thin layer between Chromosphere and Corona.

Above Chrom. ~ 100 km thick.

Temp. ~ 40 x 10^3 K – 1MK.

Level of ionization is important (e.g. H,He fully ionized). Visible from space in UV, FUV, X-Rays.

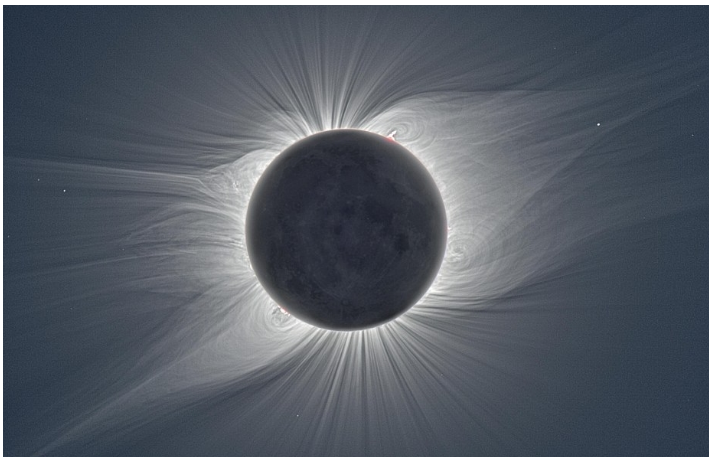
Radiative transfer within TR becomes complicated.

Magnetic forces become more effective – dominate the motion and shape of structures..

It is the site of several important transitions in the physics of the solar atmosphere.

It requires / deserves! detailed study.

Corona



Outer solar atmosphere extending into space.

T ≈ 200 x T_ph, ρ ≈ 10^(-12) x ρ_ph
→ one-millionth as much visible light.

Most of the plasma is fully ionized.
Emission from heavier elements.

Most easily seen during solar eclipse or in a coronagraph.

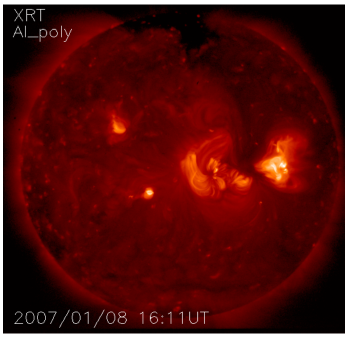
High T → usually observed in X-Rays (Skylab, Yohkoh, SOHO, TRACE, Hinode,..)

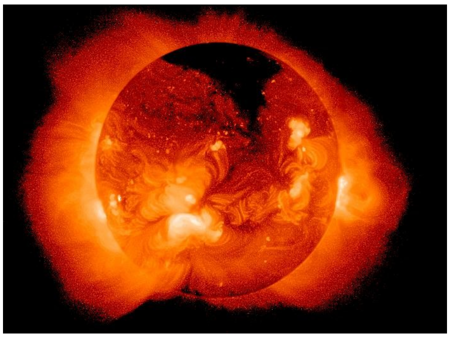
Coronal activity is magnetically driven.

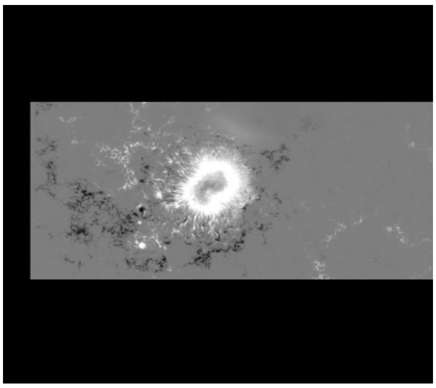
Features: Coronal loops, active regions, coronal holes, streamers, X-ray sigmoids and jets, Coronal Mass Ejections, etc.

The structure of the corona

- It is various and complex.
- In the 'quiet' periods, the corona is more or less confined to the equatorial regions, with coronal holes covering the polar regions.
- In the 'active' periods, the corona is evenly distributed over the equatorial and polar regions, though it is most prominent in areas with sunspot activity. Associated with sunspots are coronal loops.

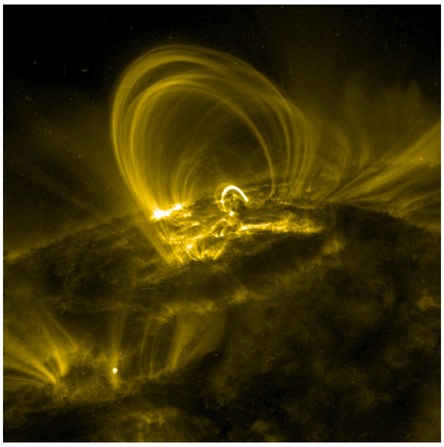


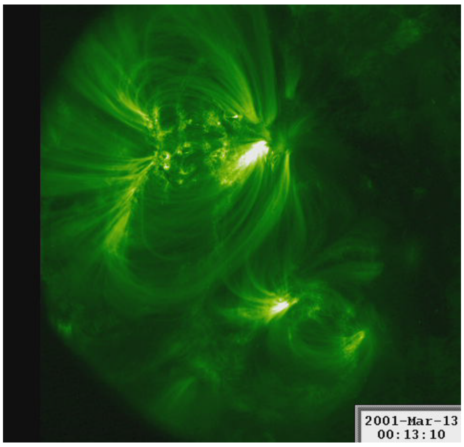




Coronal loops I

The basic structures of the solar magnetic corona.





- These structures are associated with the closed magnetic field lines that connect magnetic regions on the solar surface. They are often found with sunspots at their footpoints. They are also found in 'quiet' regions of the solar surface.
- They vary in size; wide variety of temperatures along their lengths (cool & hot loops).
- Many coronal loops last for days or weeks but most change quite rapidly.

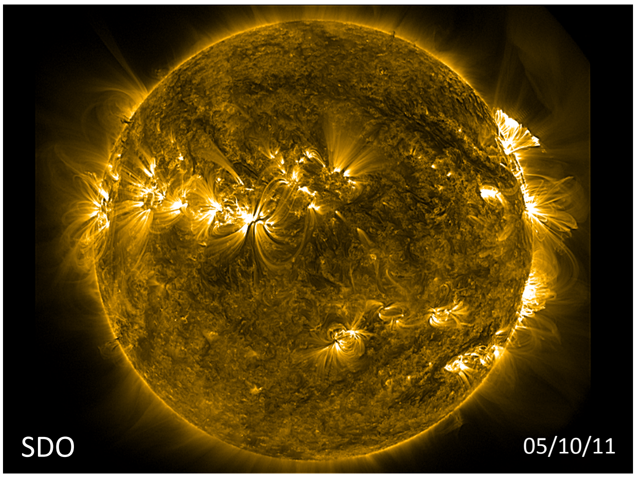
Coronal loops II

- Ideal structures to understand the transfer of energy.
- Heating of coronal loops → coronal heating problem.
- Coronal loop must be filled with plasma first.
- Is this chromospheric plasma, which is ejected from the footpoints towards the top?
- Chromospheric evaporation?
- Where is the plasma heated first?
- - corona → conduction → evaporation or
- - chromosphere → ejection/evaporation
- The mechanism(s) must be stable enough to continue to feed the corona with chromospheric(?) plasma and powerful enough to accelerate and therefore heat the plasma over 1 MK.

The exact mechanism behind plasma filling, dynamic flows and heating remains an open problem.

Active Regions

ARs are ensembles of magnetic fieldlines that connect opposite polarity fields.



They involve most (if not all) the phenomena directly linked to the magnetic field, which occur at different heights on the Sun's surface:

sunspots

spicules

filaments

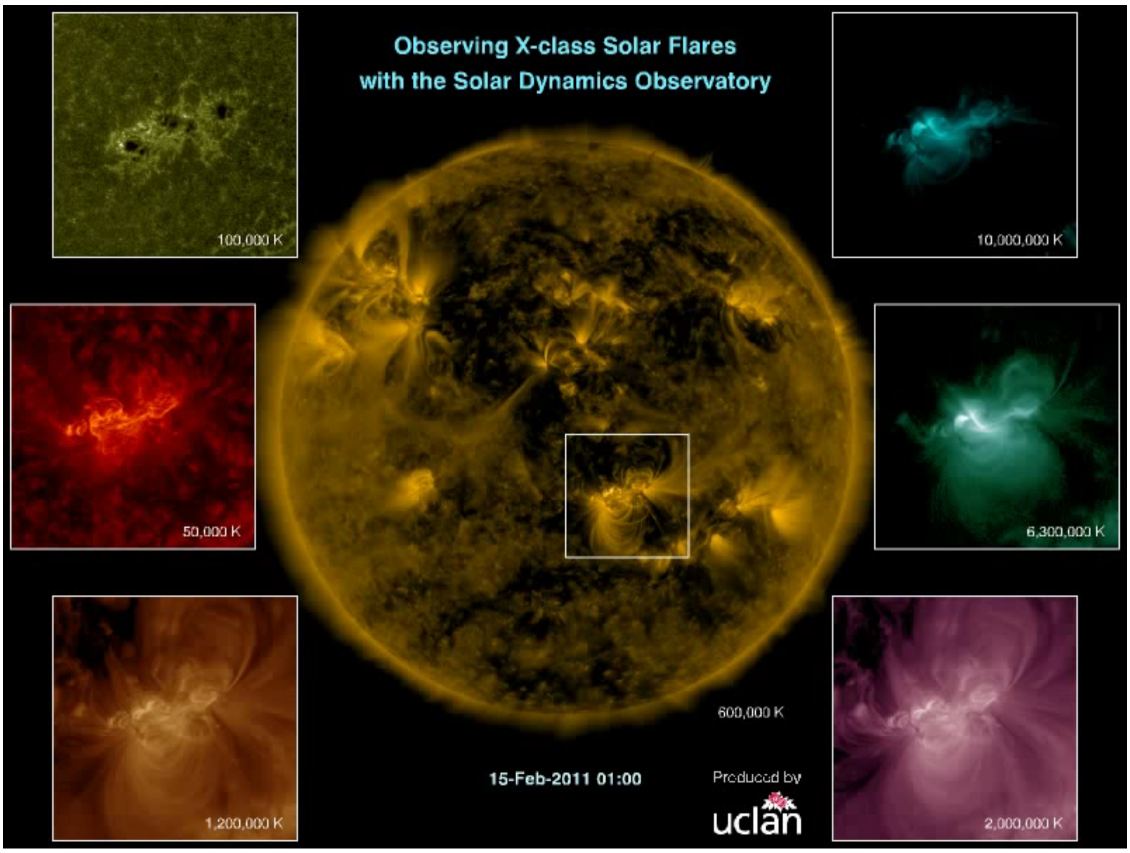
flares

CMEs

……..

ARs	Φ (Mx)	Features	Lifetime
Large	5 x 10^(21)	sunspots	Months
Ephemeral	1 x 10^(20) – 5 x 10^(21)	pores	Days/weeks
Small	3 x 10 ^(18) – 1 x 10^(20)	Pore-like, pores	Hours/days

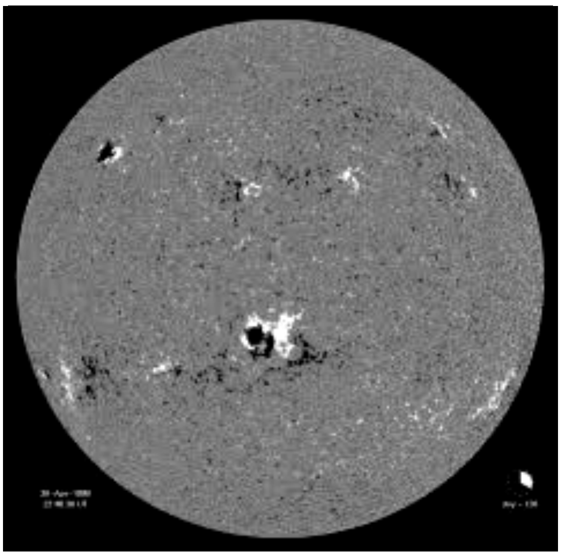
Active regions – dynamic phenomena – an example

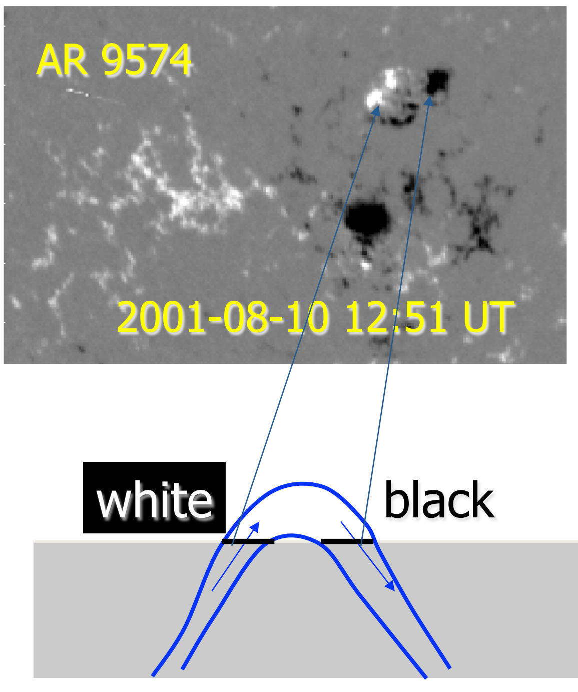


Magnetic flux emergence and associated dynamic phenomena.

Sunspots, Active Regions and Flux Emergence

Sunspots and Active Regions



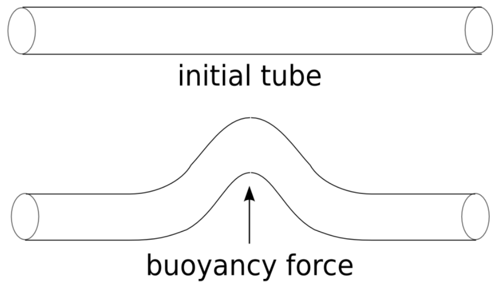


Emerging magnetic field forms sunspots

Scenario of magnetic flux emergence

Dynamo action at base of convection zone.
Magnetic buoyancy acts on the dynamo-generated magnetic field.

Total pressure continuous $P_i + (B_i)^2/2mu = P_e$
Thermal equilibrium Ti = Te
Then, since $P_i < P_e \rightarrow r_i < r_e$
B tube becomes lighter and rises (Parker 1955).

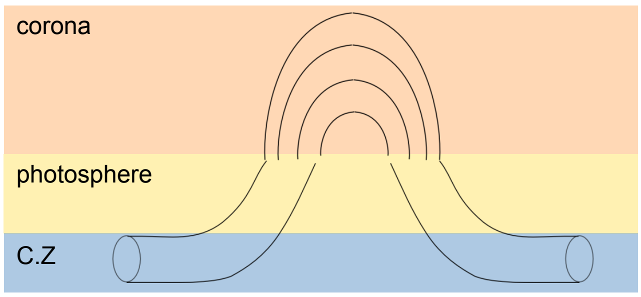


Bipolar regions appear at the photosphere (Fox, 1908).

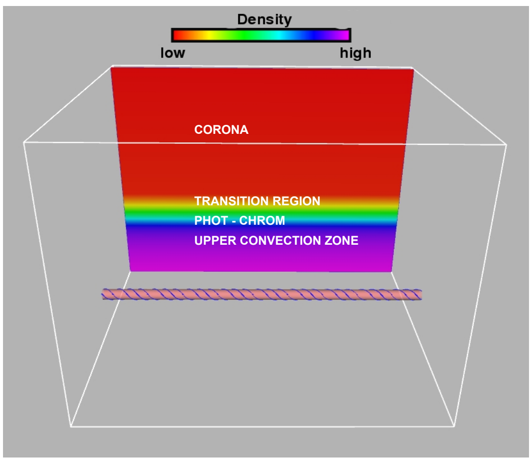
Twisted structures appear in EFR (Strous & Zwaan, 1999 – Leka et.al, 1996).

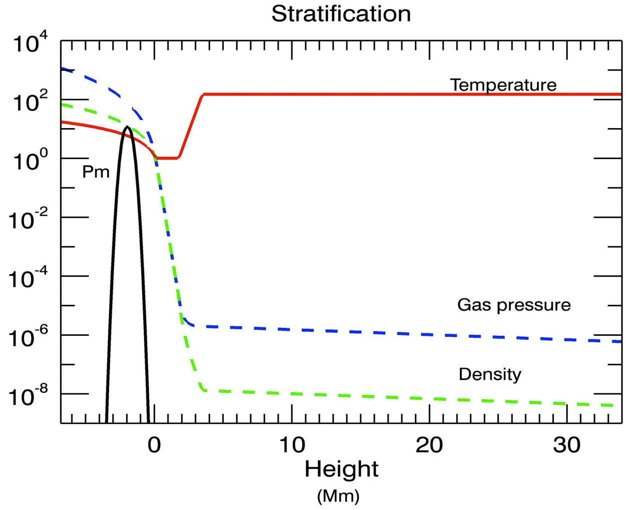
Formation of ***Ω-loops*** and arch filament systems (Bruzek, 1967).

Observations of ***eruptive*** phenomena, flares, CME's due to flux emergence (Chifor et. al, 2006, Dun et.al 2007, etc.).



Initial conditions: atmosphere and magnetic field





- Stratified (plane-parallel) atmosphere.
- Magnetic flux tube (twisted).
- Density deficit → buoyancy.
- Ambient magnetic field.

- Atmosphere, magnetic field(s).
- Large density and pressure contrast.
- Hydrostatic equilibrium.
- 3D compressible, resistive MHD (Lare3d code).

Numerical method

Three dimensional time-dependent resistive MHD equations

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{u}), \\
\frac{\partial (\rho \mathbf{u})}{\partial t} &= -\nabla \cdot (\rho\, \mathbf{u} \otimes \mathbf{u} + \underline{\tau}) - \nabla p + \rho\, \mathbf{g} + \mathbf{J} \times \mathbf{B}, \\
\frac{\partial e}{\partial t} &= -\nabla \cdot (e \mathbf{u}) - p\, \nabla \cdot \mathbf{u} + Q_{\mathrm{Joule}} + Q_{\mathrm{visc}}, \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}, \\
\mathbf{E} &= -(\mathbf{u} \times \mathbf{B}) + \eta \mathbf{J}, \\
\mathbf{J} &= \nabla \times \mathbf{B}, \\
p &= \rho T \frac{\mathcal{R}}{\tilde{\mu}},
\end{aligned}
$$

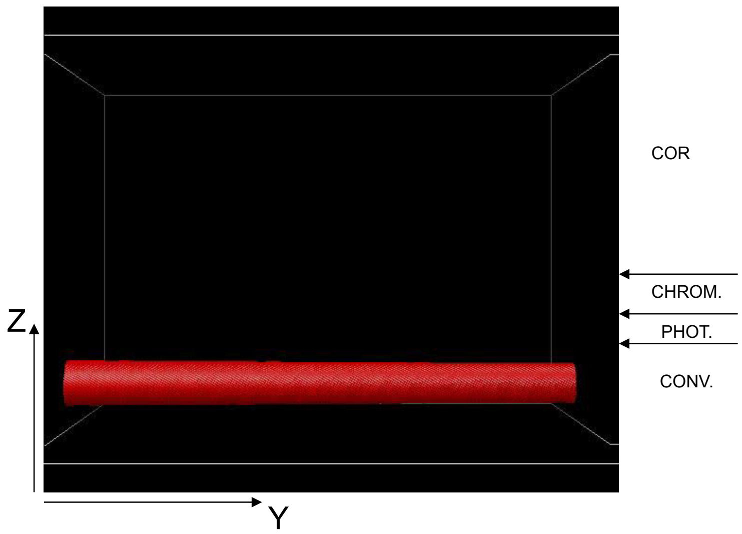
Copenhagen Stagger Code
(Galsgaard & Nordlund)

\+

Lare3D code
(Arber T.)

· 6th order - partial derivatives
· 5th order - interpolation
· 3rd order - predictor-corrector - time stepping
· Stretched staggered grid 1d, 3d
· Periodic and closed BC
· Damping zone top-bottom
. Hyperdiffusive scheme, 4th order quenced diffusion operators

Emergence and expansion into the corona



- The tube is more buoyant in the middle.
- Fieldlines expand in three directions.
- Strongly azimuthal nature at the top.
- Fan-like shape of the expanding field.

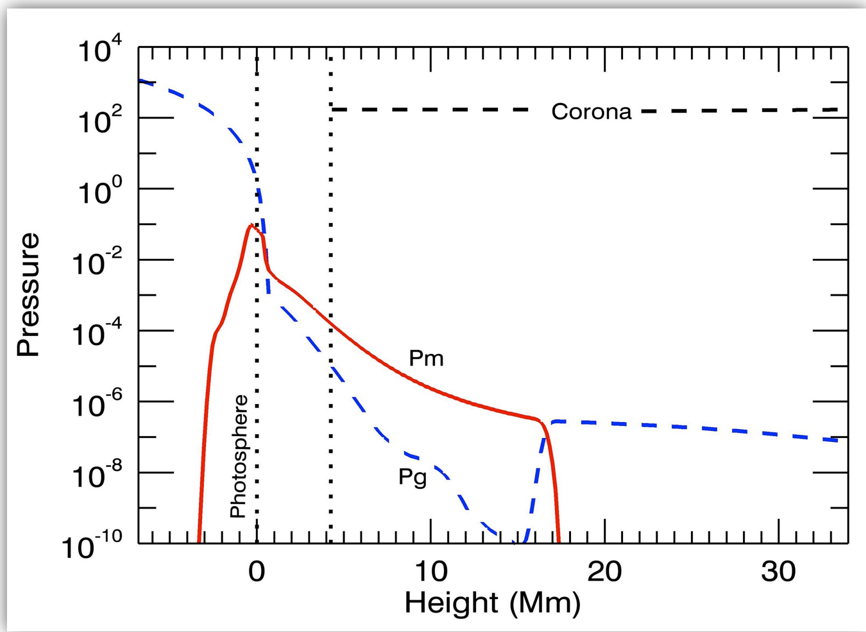
Parametric study: Murray et al. 2006

Lengthscales:
Conv. zone: 10 Mm
Phot. - Trans.: 4-6 Mm
Corona: ~15 Mm
Y-ext: 25-40 Mm
X-ext: 25-40 Mm

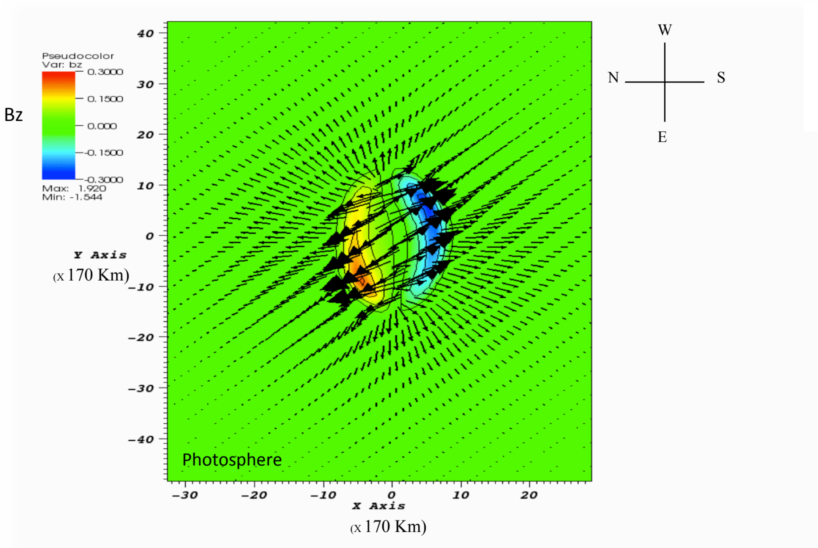
Timescales:
photosphere: t~12 min
Corona: t~30 min
top: t~50 min

Velocities:
V_{rise_init}: V_z ~ 2 km/sec
V_{max} ~ 14 km/sec
V_x ~ 47 km/sec
V_y ~ 34 km/sec
V_{downf} ~ 20 km/sec

The expansion of the field into the solar corona



Initial phase: emergence in the photosphere

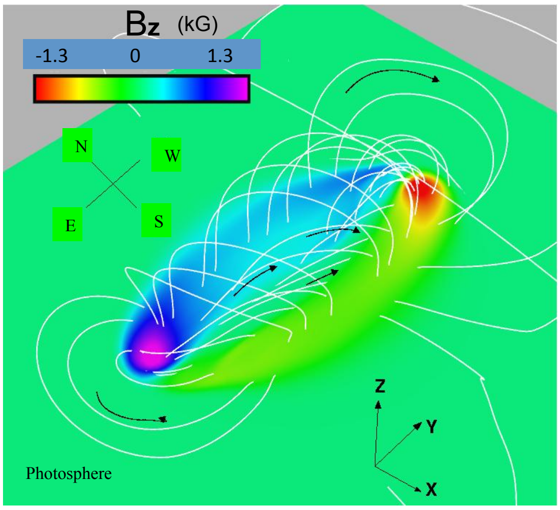


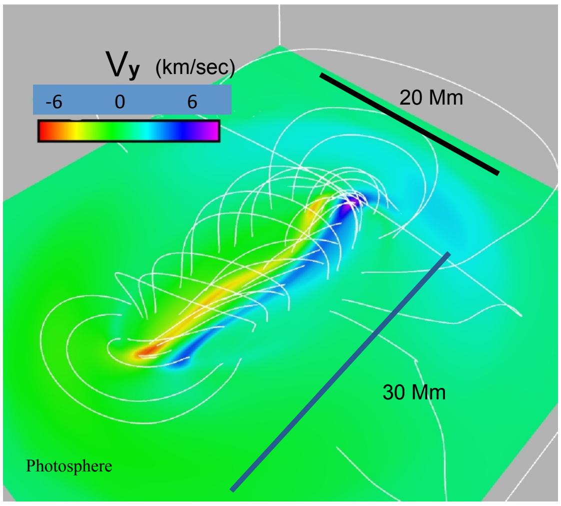
- Density deficit & buoyancy effect: tube rises to the photosphere.
- V_{rise}=1.7 km/sec, t=12.5 min.
- Formation of a bipolar region.
- B ~ 600G at the photosphere.

- Formation of *'tails'* on both sides of PIL.
- Organized *shear velocity flow* along the PIL.
- *Inflow* in the transverse direction.

Related work: Lopez Fuentes et al. 2000, Fan 2001, Canou et al. 2009.

3D topology and shearing of the field



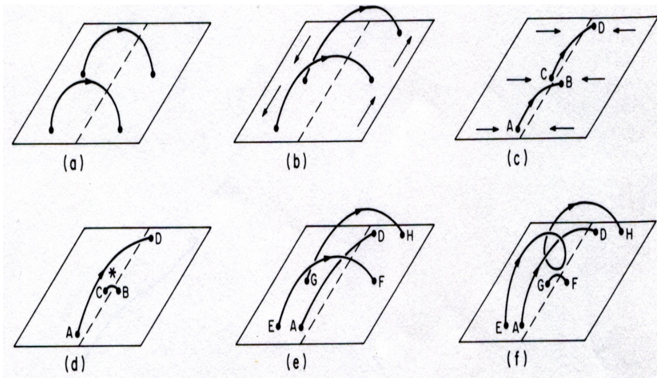


- Inner fieldlines: sheared arcade.
- Outer fieldlines: envelope field.
- Shearing: along PIL and vertical.

- Shearing: magnetically driven.
- Shear flow, aver: 3 km/sec, max 6 km/sec.

Related work: Magara & Longcope 2004, Manchester et al. 2004, Archontis et al. 2009, etc.

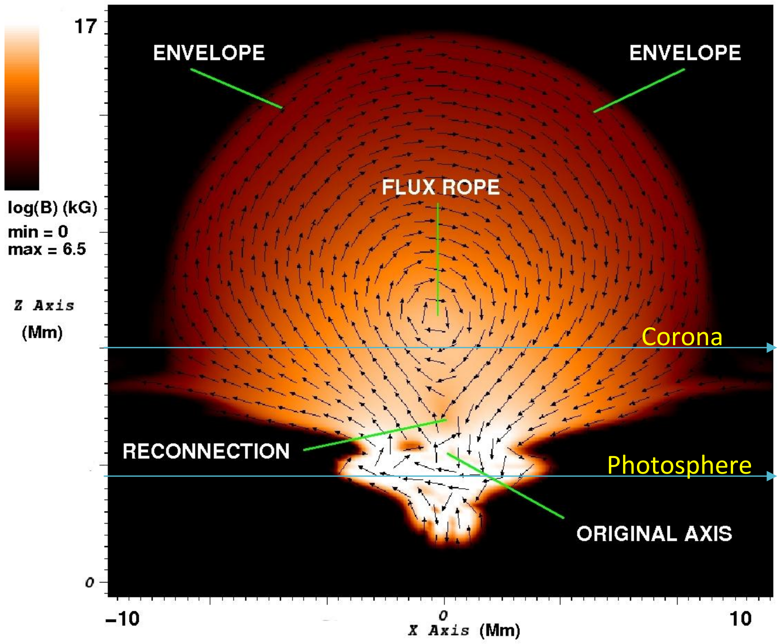
A. van Ballegooijen and P. Martens (1989)



shearing motion + convergence + reconnection

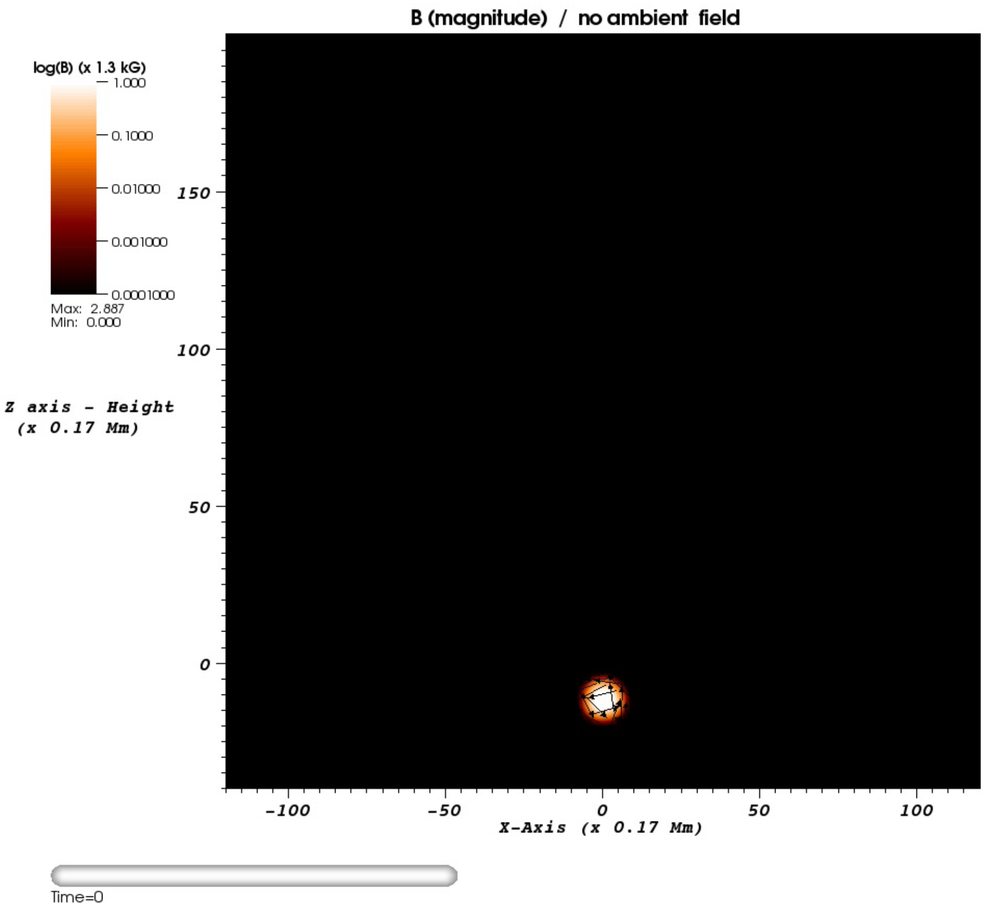
current sheets, longer loops and helical magnetic field structures that rise higher into the atmosphere.

'New' coronal magnetic flux ropes

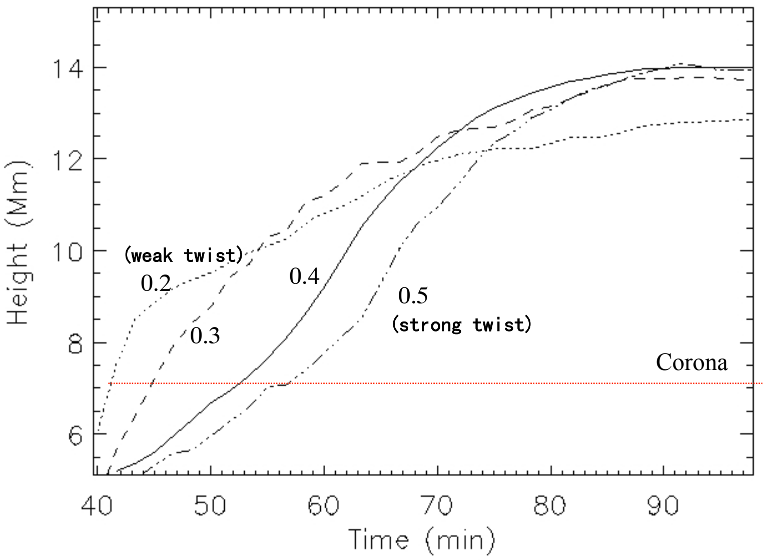


- The new rope is formed via internal reconnection.
- The expansion forms an envelope magnetic field.
- The original axis stays at photosphere.
- The new flux rope rises into the corona.
- The envelope field halts the eruption.

(In)stability /eruption of flux ropes: Torok & Kliem 2005, Demoulin & Aulanier 2010, etc.



Confined expulsion of magnetized plasma



B=6.5 kG, β=4.7, z=-1.7 Mm

The new rope *fails* to emerge into the high corona.

No break-out.

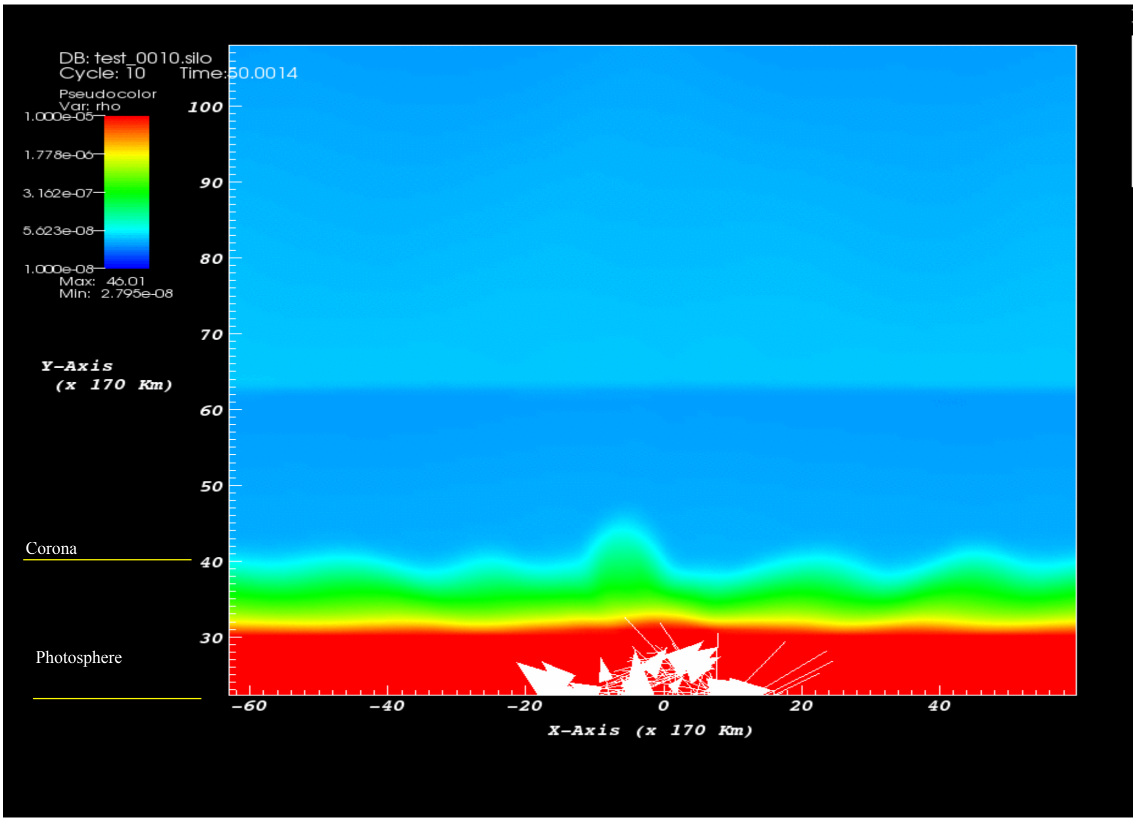
Small twist: early eruption.

Strong twist: two phases.

End: Quasi-static equilibrium.

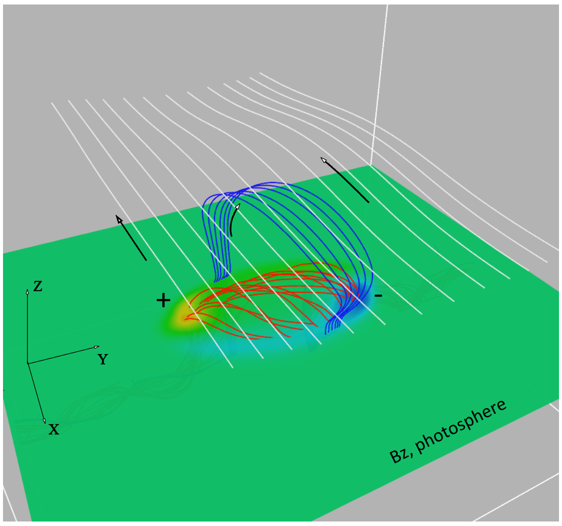
Related work: Moore, et al. 2001, Archontis & Torok 2008, Archontis & Hood 2012 .

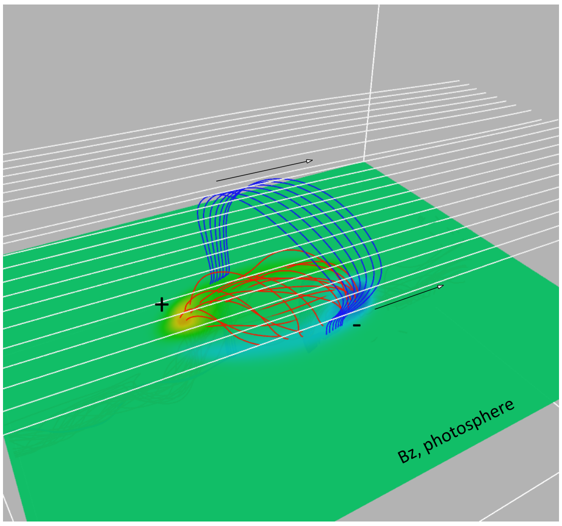
Confined expulsion of dense plasma



Emergence into an overlying coronal magnetic field

Emerging field-lines (blue, red), coronal field-lines (white).





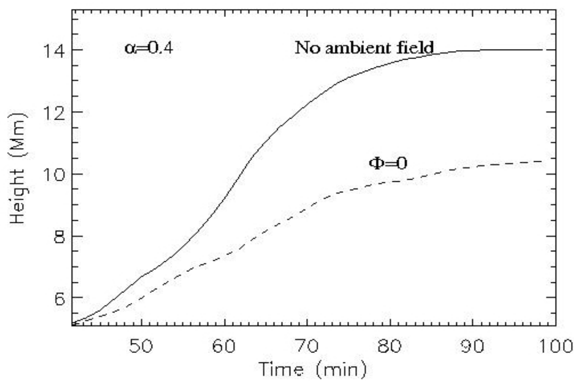
Φ is the relative contact angle.

$\Phi \approx 180$ deg. 'antiparallel' orientation

$\Phi \approx 90$ deg. 'perpendicular' orientation

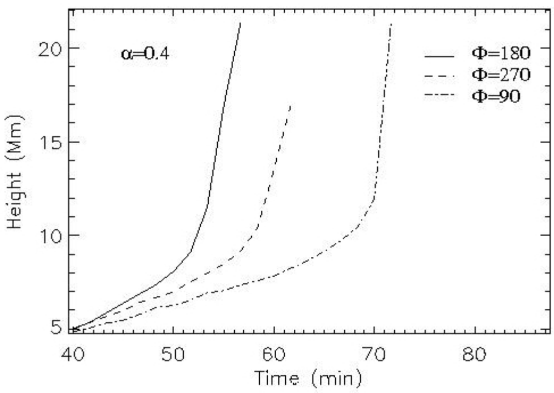
Related work: Galsgaard et al. 2007, Archontis & Hood 2012.

Why is external reconnection important?



No external reconnection

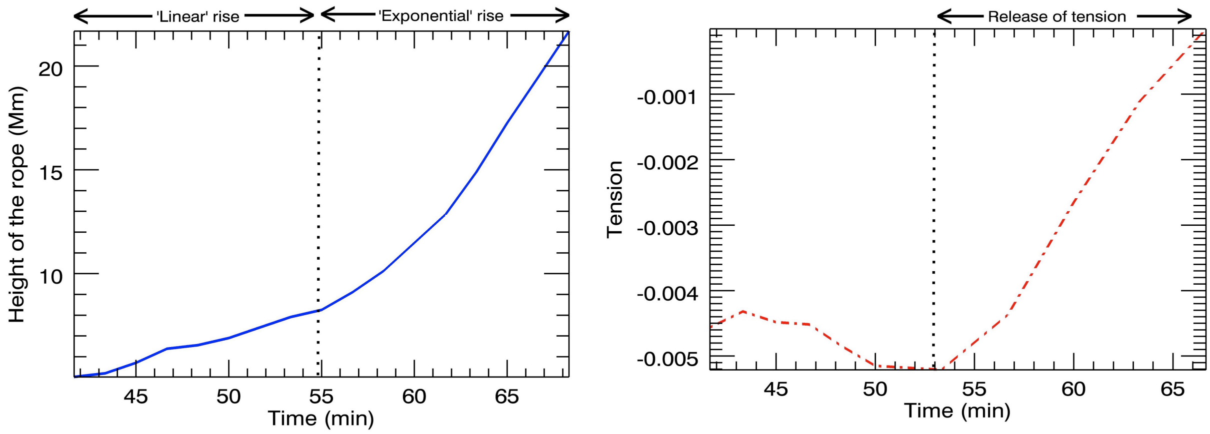
- Φ=0 (parallel ambient field).
- *Confined* expulsions.
- Weak ambient, larger expulsion heights.



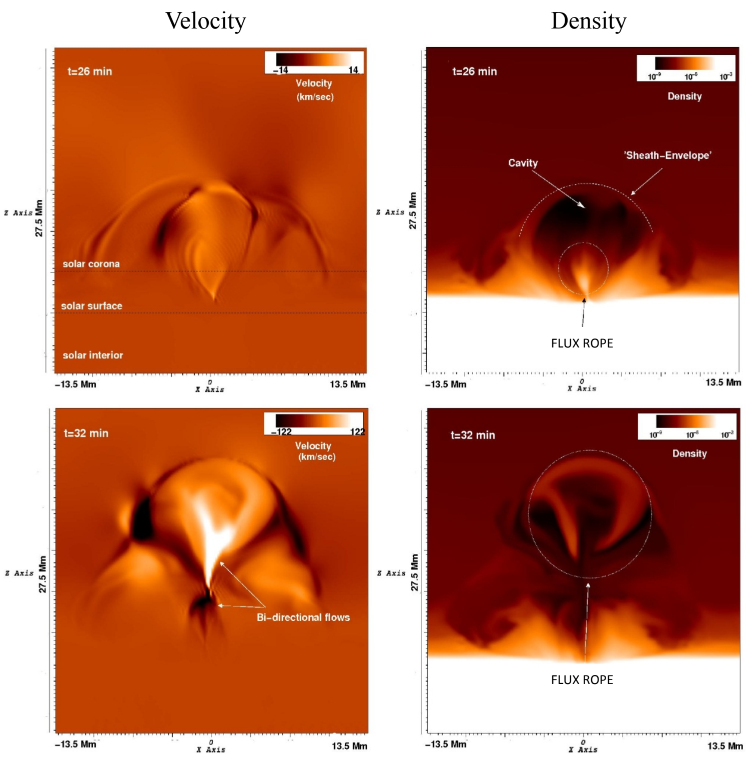
Efficient external reconnection

- Removes envelope tension.
- *Ejective* expulsions.
- More efficient → earlier eruption.
- Deformation, annihilation.

A *key process* for the plasma eruption: release of tension



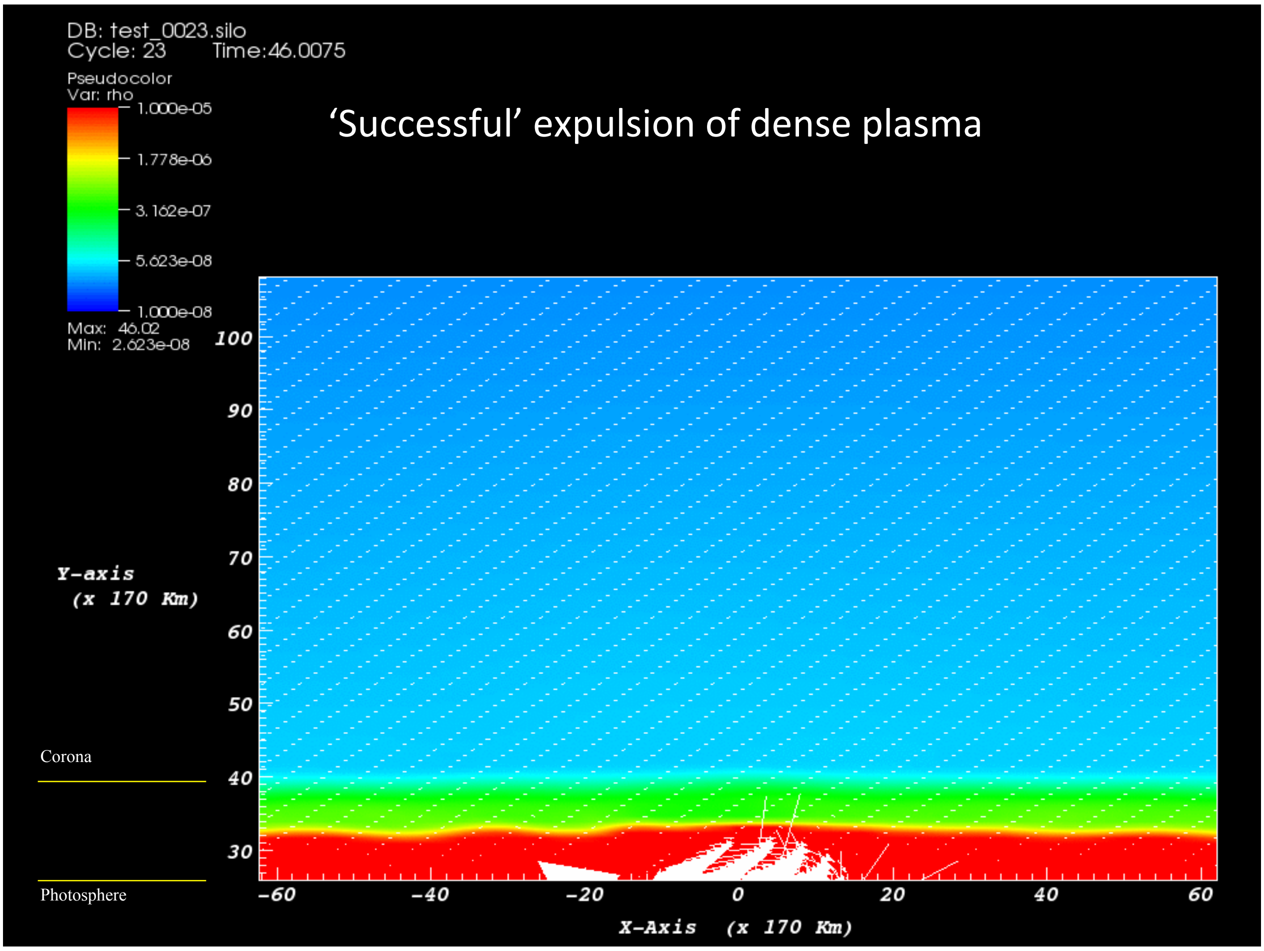
External reconnection releases the tension of the envelope field-lines and leads to the onset of the fast expulsion phase.

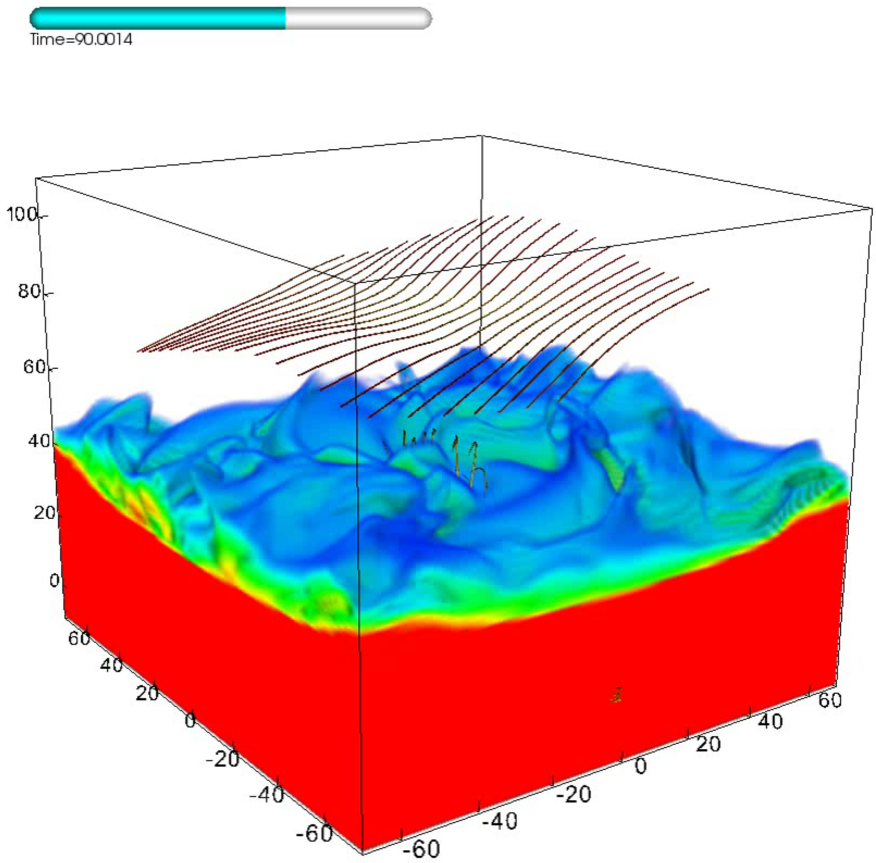


RUN-AWAY EXPULSION

- Φ=90, Vz(left), density(right).
- Upflows, front and tail.
- Profound downflows.
- Two different magnetic systems.
- Cavity-like configuration.
- Dense coronal erupting plasma.
- Draining of plasma.
- Heavier: 1-2 orders of magnitude.

Archontis & Hood A&A 2012 .


DB: test_0023.silo
Cycle: 23 Time:46.0075
Pseudocolor
Var: rho
1.000e-05
1.778e-06
3.162e-07
5.623e-08
1.000e-08
Max: 46.02
Min: 2.623e-08
'Successful' expulsion of dense plasma
Y-axis
(x 170 Km)
Corona
Photosphere
X-Axis (x 170 Km)


Time=90.0014

Open problems

- The origin of ubiquitous THMFs at the solar surface.
  - convection, local dynamo, flux emergence or…
- The heating of the chromosphere and corona.
  - reconnection
  - waves
  - spicules
  - (nano)flares, etc.
- The dynamics of magnetic flux emergence.
  - on small and large scales.
  - on the build up of active regions.
- The onset and dynamics of eruptions.
  - prominences, CMEs
  - role of flux emergence.