Chapter 8: Magnetic structures and dynamics

Overview

- **Origin of solar magnetism:** solar model, helioseismology, solar cycle, dynamo, convection; [book: Sec. 8.2.1]
- **Solar magnetic structures:** solar atmosphere and magnetic structuring and dynamics; [book: Sec. 8.2.2]
- **Planetary magnetic fields:** geodynamo, journey through the solar system; [book: Sec. 8.3]
- **Solar wind and space weather:** solar wind, interaction with magnetospheres; [book: Sec. 8.4]
- **Astro-plasma physics:** launching collimated astrophysical jets.

Questions

Eventually, all theory has to be confronted with empirical reality. This should lead to attempt to answer the following questions:

- Is the MHD model developed so far an adequate starting point for the *description of observed plasma dynamics?*
- Are important *theoretical pieces still missing?*
- What should be the *main goals of present research* to resolve these questions?

$\Rightarrow$ Inspiration for answers to these questions to be obtained from **phenomenology of magnetic structures and associated dynamics.**

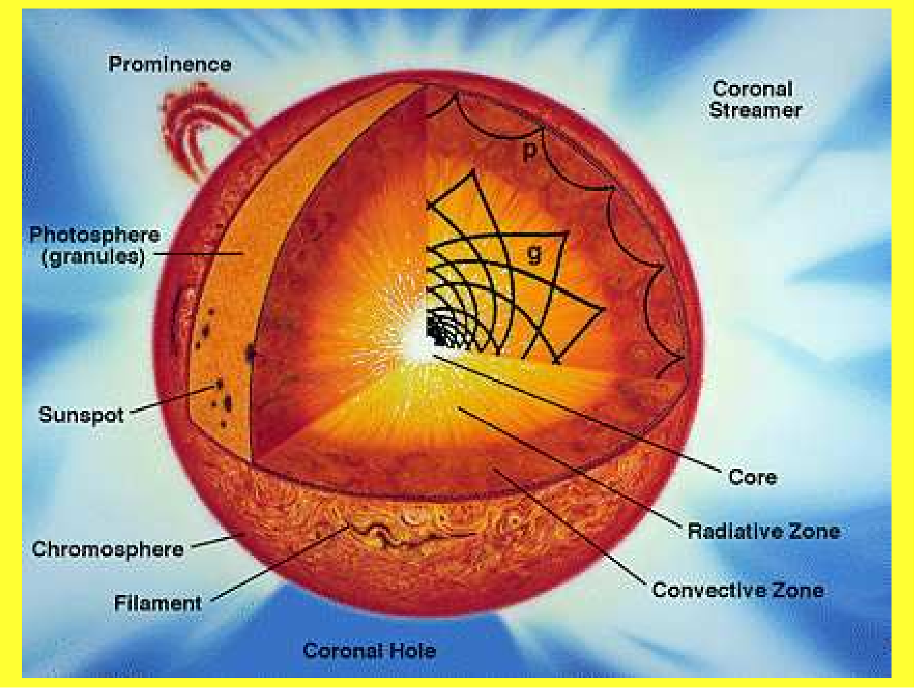
Solar magnetism

- Central question: **Where does the solar magnetism come from?**

Recall structure of the Sun:

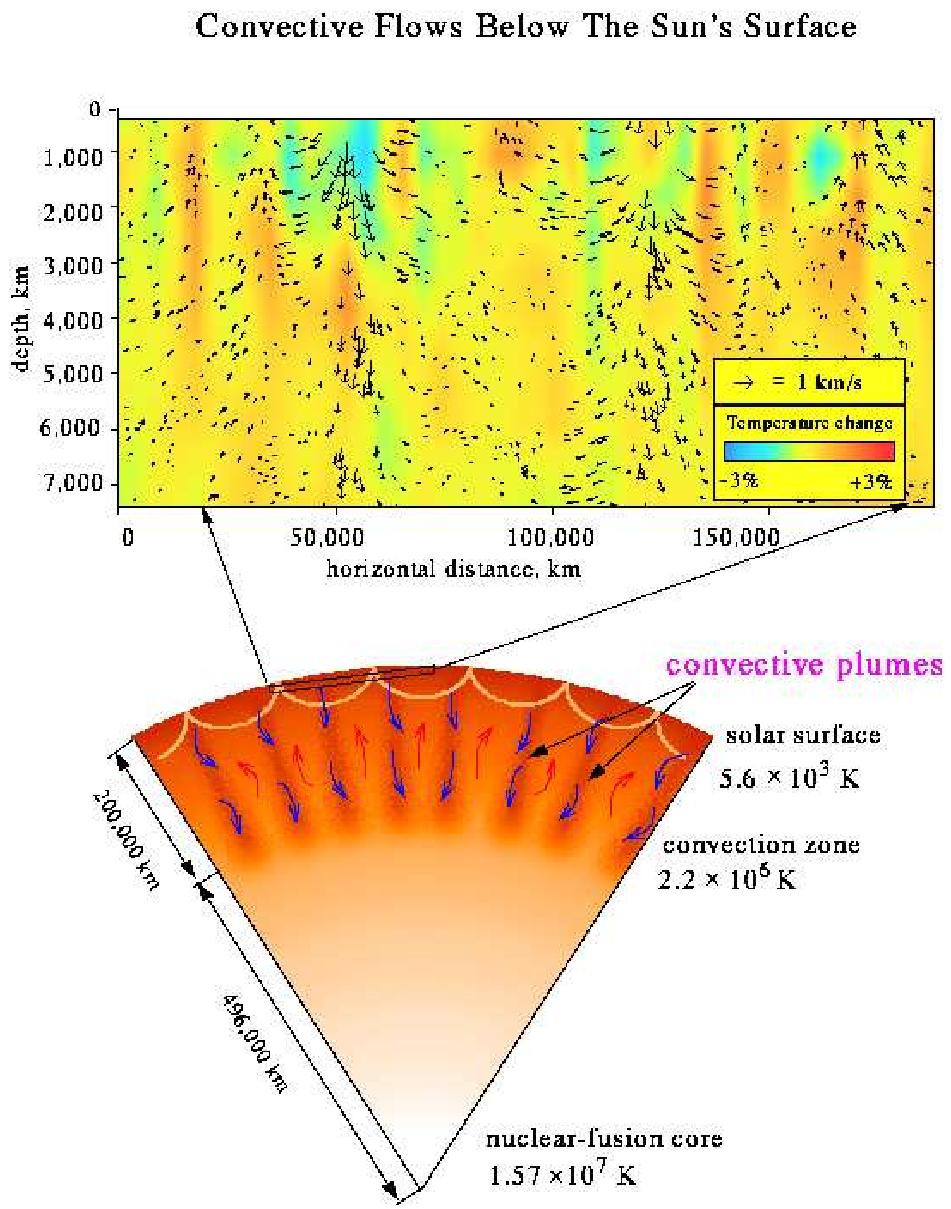
- core, $r \leq 0.25 R_\odot$: thermonuclear conversion of hydrogen into helium;
- radiative zone, $0.25 R_\odot \leq r \leq 0.71 R_\odot$: outward radiative transport of produced energy;
- **convection zone,** $0.71 R_\odot \leq r \leq R_\odot$: temperature gradient so steep that the plasma is convectively unstable

  $\Rightarrow$ **seat of the solar dynamo!**



(from SOHO web site)

Convective flows



(from SOHO web site)

Verifications of the standard solar (interior) model

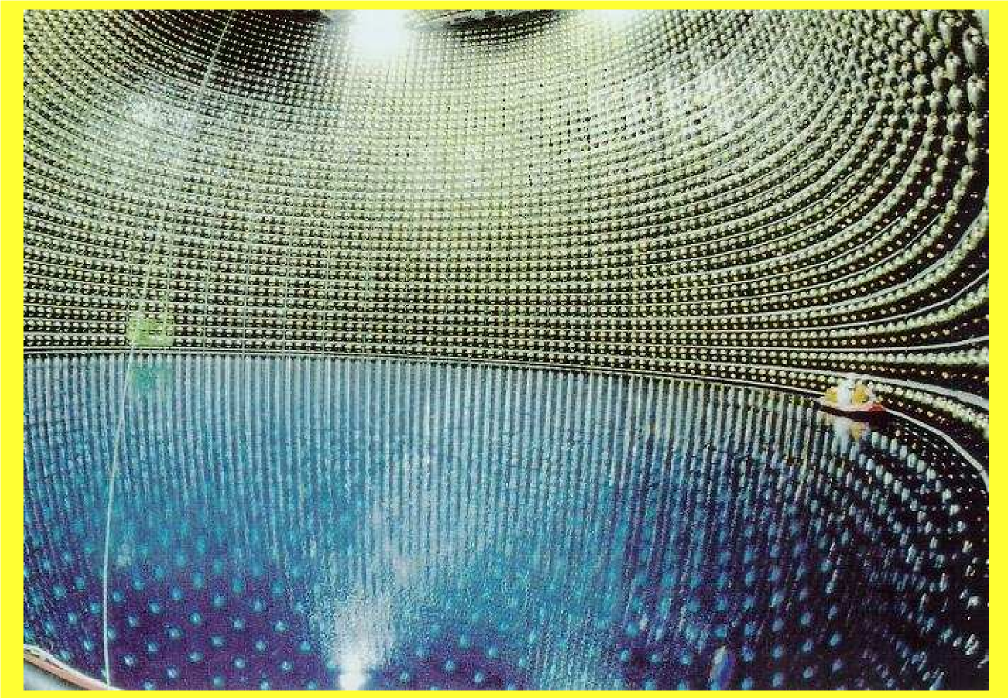
- **Helioseismology:** theory + observations;
- **Direct observation of neutrino flux** from p-p fusion reactions in the core:

– Detection by giant array of photomultipliers deep underground (scale: note the little boat with inspectors on the detector liquid!).

– This identified the *solar-neutrino problem:* the observed flux did not match the theoretical one.

– However, neutrino oscillations (non-zero mass allows conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$) would resolve it: this was actually observed.

$\Rightarrow$ *Solar-neutrino problem solved!*



http://www-sk.icrr.u-tokyo.ac.jp/sk/index_e.html (Superkamiokande)

Websites SOHO and TRACE

- SOHO (Solar and Heliospheric Observatory):
  http://sohowww.nascom.nasa.gov/

  Instruments on board SOHO:

  – Extreme UV imaging Telescope (EIT), images of Sun through solar cycle, movies of waves as running differences:
  http://sohowww.nascom.nasa.gov/ *(under EIT)*

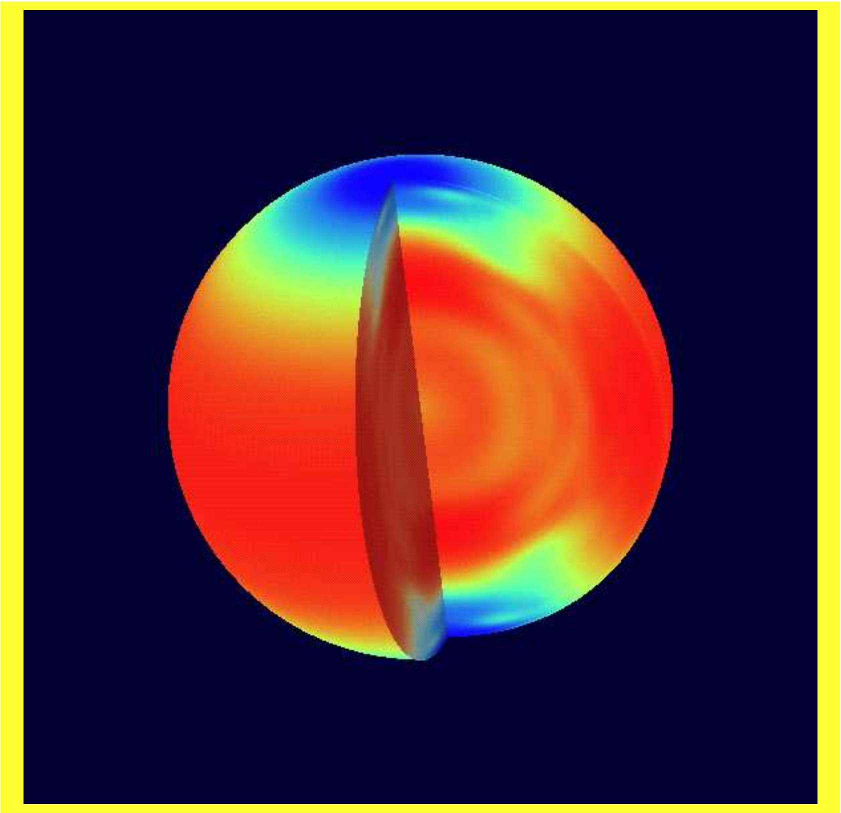
  – MDI (Michelson Doppler Imager):
  http://soi.stanford.edu/

  – MDI images (solar rotation with depth) and sunquake movie:
  http://soi.stanford.edu/results/greatest_hits.html

- TRACE (Transition Region and Coronal Explorer):
  http://trace.lmsal.com/

Helioseismology

- SOHO (Solar and Heliospheric Observatory, ESA-NASA cooperation, launched Dec. 1995):
  - continuous monitoring of the Sun,
  - http://soho.esac.esa.int/ (SOHO).
- 12 instruments, e.g. Michelson Doppler Imager (MDI), provide:
  - velocity maps of the solar surface,
  - global and local seismic inversions,
  - infer $c_\odot(r)$ and $v_\varphi(r,\theta)$.



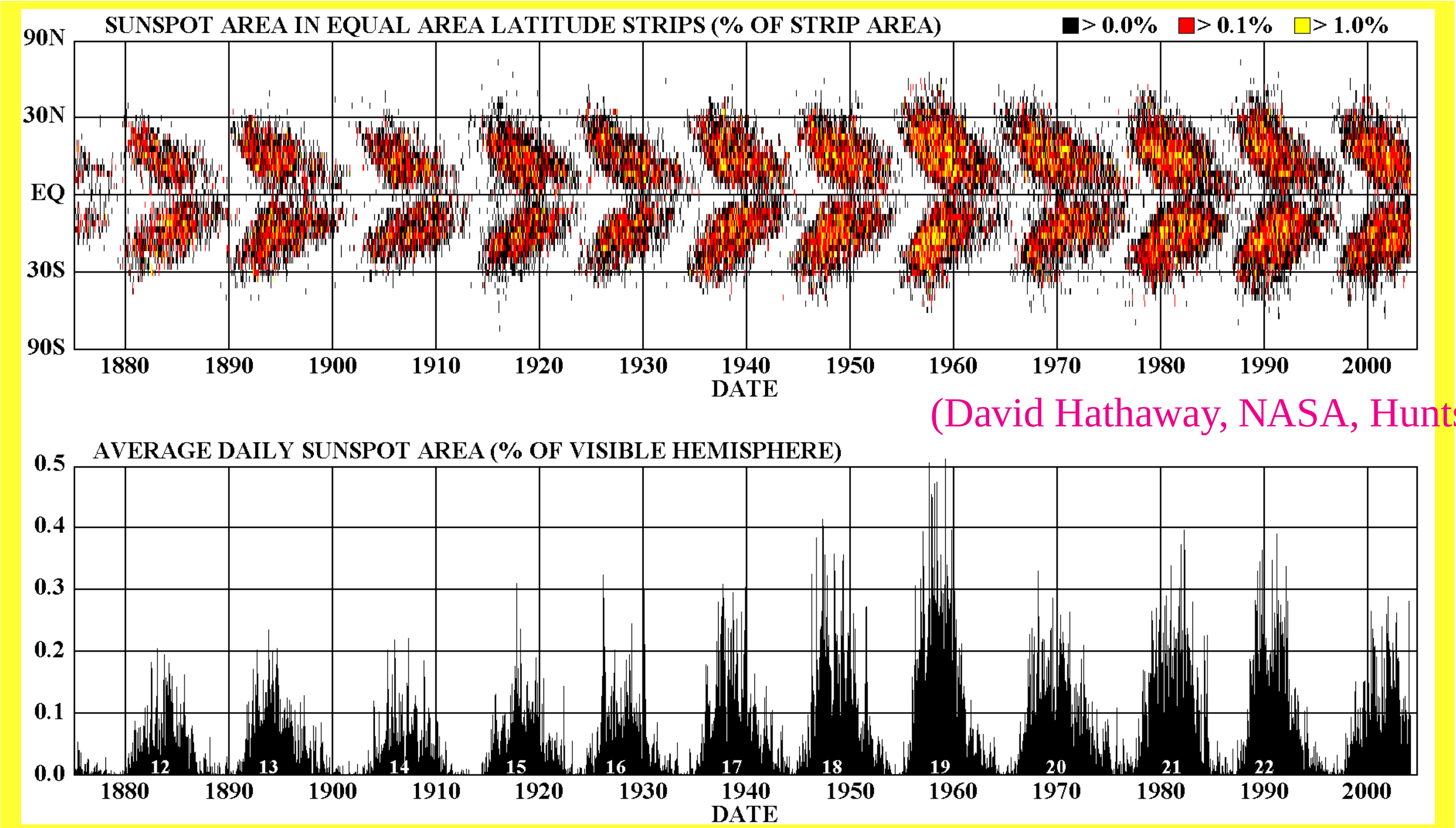
Sunspots

- Dark spots in the (visible) photosphere that cooler (darker) than surroundings.
- Can live days–month and rotate west–east across the disk in bands up to $\pm 35^\circ$ about equator.
- Reveal existence of *several 1000 Gauss magnetic field!*

(from SOHO web site)

Solar cycle

- *Butterfly diagram of the solar cycle* shows variation sunspot number with years:
  - drifting in latitude with roughly 11 year periodicity.



(David Hathaway, NASA, Huntsville)

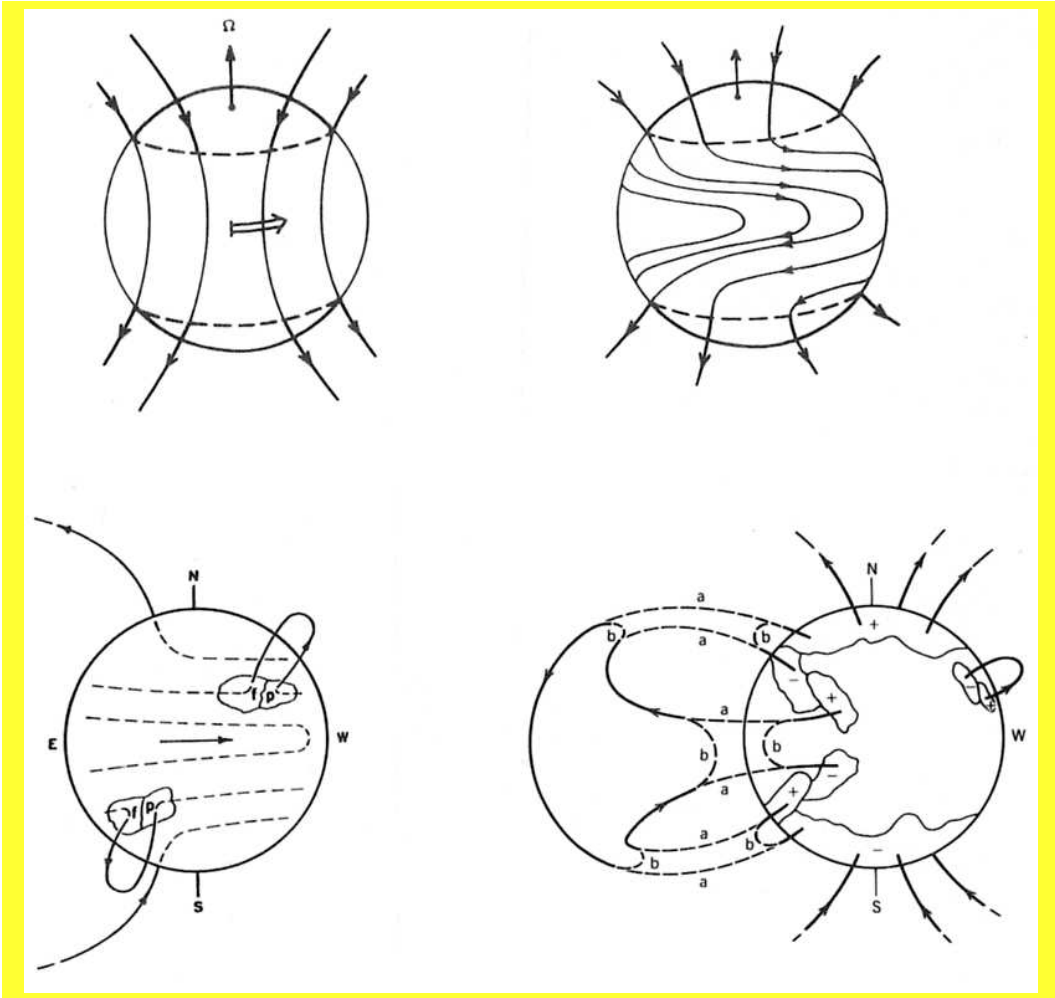
Solar dynamo

- The solar cycle (reversal of magnetic polarity every 11 years) is *a magnetic oscillation* driven by the periodic *solar dynamo:* conversion of mechanical into magnetic energy.

- Solar dynamo ingredients:

  – differential rotation,
  – convection,
  – (small) magnetic diffusivity.

- Illustrated by Babcock cartoon model (1961) of the solar cycle: [H. Babcock, Ap. J. **133**, 572 (1961)]



Crude approach:

- **Mean field dynamo**, which parameterizes the unknown diffusivity enhancement:

  – *Inhomogeneity of the magnetic field will decay* in time τ_D determined by resistivity η and length scale $l_0 \sim \nabla^{-1}$ of the inhomogeneity:

$$\tau_D = \mu_0 l_0^2/\eta = l_0^2/\tilde{\eta}\,.$$

  – Classical values for l_0 and η yield τ_D many orders of magnitude too long: reduce by factors parameterizing *turbulent vortex interactions.*

- Procedure: Split $\mathbf{v}$ and $\mathbf{B}$ in mean + fluctuations: $\mathbf{v} = \langle\mathbf{v}\rangle + \mathbf{v}'\,,\;\; \mathbf{B} = \langle\mathbf{B}\rangle + \mathbf{B}'$, which yields averaged form of induction equation:

$$\frac{\partial\langle\mathbf{B}\rangle}{\partial t} = \nabla\times\big(\langle\mathbf{v}\rangle\times\langle\mathbf{B}\rangle\big) + \nabla\times\langle\mathbf{v}'\times\mathbf{B}'\rangle - \nabla\times\big(\tilde{\eta}\nabla\times\langle\mathbf{B}\rangle\big)\;.$$

- **IF we assume**

$$\langle\mathbf{v}'\times\mathbf{B}'\rangle \approx \alpha\,\langle\mathbf{B}\rangle - \beta\,\nabla\times\langle\mathbf{B}\rangle + \ldots\,,$$

  THEN there is field amplification through α and decay through $\tilde{\eta}+\beta$ from

$$\frac{\partial\langle\mathbf{B}\rangle}{\partial t} = \nabla\times\big(\langle\mathbf{v}\rangle\times\langle\mathbf{B}\rangle\big) + \nabla\times\left(\alpha\,\langle\mathbf{B}\rangle\right) - \nabla\times\big[\,(\tilde{\eta}+\beta)\,\nabla\times\langle\mathbf{B}\rangle\,\big]\;,$$

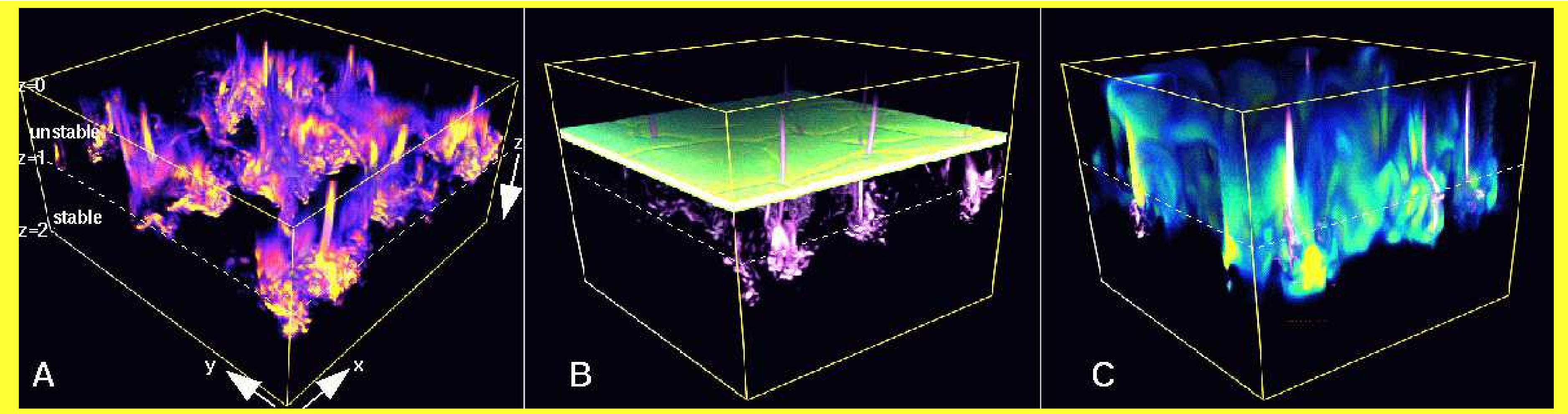
  since $\tilde{\eta}+\beta \approx \beta \approx v'l \gg \tilde{\eta}$, *using length/time scale for convective granulation.*

Improving by computational MHD:

- Since *kinematic dynamo problem* ignores backreaction on the flow,
  - need for full 3D magnetoconvection models in rotating boxes,
  - would allow for quantification of correlation coefficients α.
- Hence, ingredients **flux tube dynamo simulations**:
  - can store and amplify magnetic fields stably in overshoot region below the convection zone (tachocline),
  - will reach field strengths of order 10^5 G, forming toroidal flux tube,
  - becomes unstable to long-wavelength undular deformation (Parker instability),
  - rises without strong deformation through convection zone,
  - consistent with Joy's laws (tilt dependence on latitude of active regions due to Coriolis effects), observed asymmetries $p-f$ spots, bipole orientation w.r.t. equator,
  - expands and gets shredded just prior to photospheric emergence.

Flux tube dynamo (1)

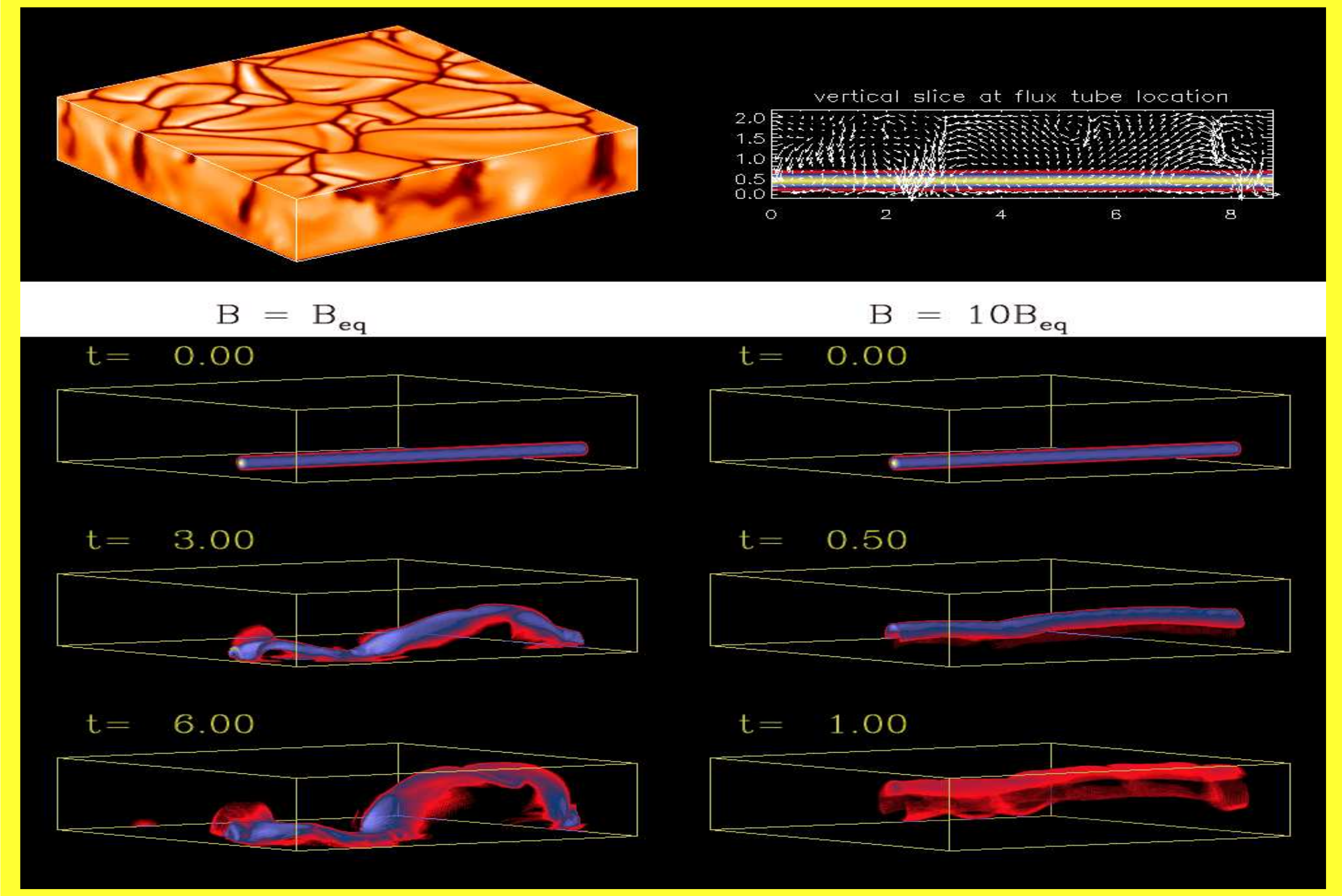
- Needs downward pumping of flux below convection zone:
  - confirmed by numerical simulations by Tobias *et al.*, ApJL **502**, L177 (1998),
  - compressible (M)HD convection on top of stable layer,
  - layer of magnetic flux, netto carried down into overshoot region,
  - there it erupts by bouyancy only when sufficiently strong.



http://lcd-www.colorado.edu/SPTP/sptp_magnet.html
(local models of turbulent compressible convection)

Flux tube dynamo (2)

- Needs coherence of boyuantly rising flux tube through convection zone (sufficient amount of twist and field strength). Simulations by Fan *et al.*, ApJL, **582**, 1206 (2003):



Now, the effects of the solar dynamo in the solar atmosphere:

Photosphere

- Photosphere is roughly 500 km thick:

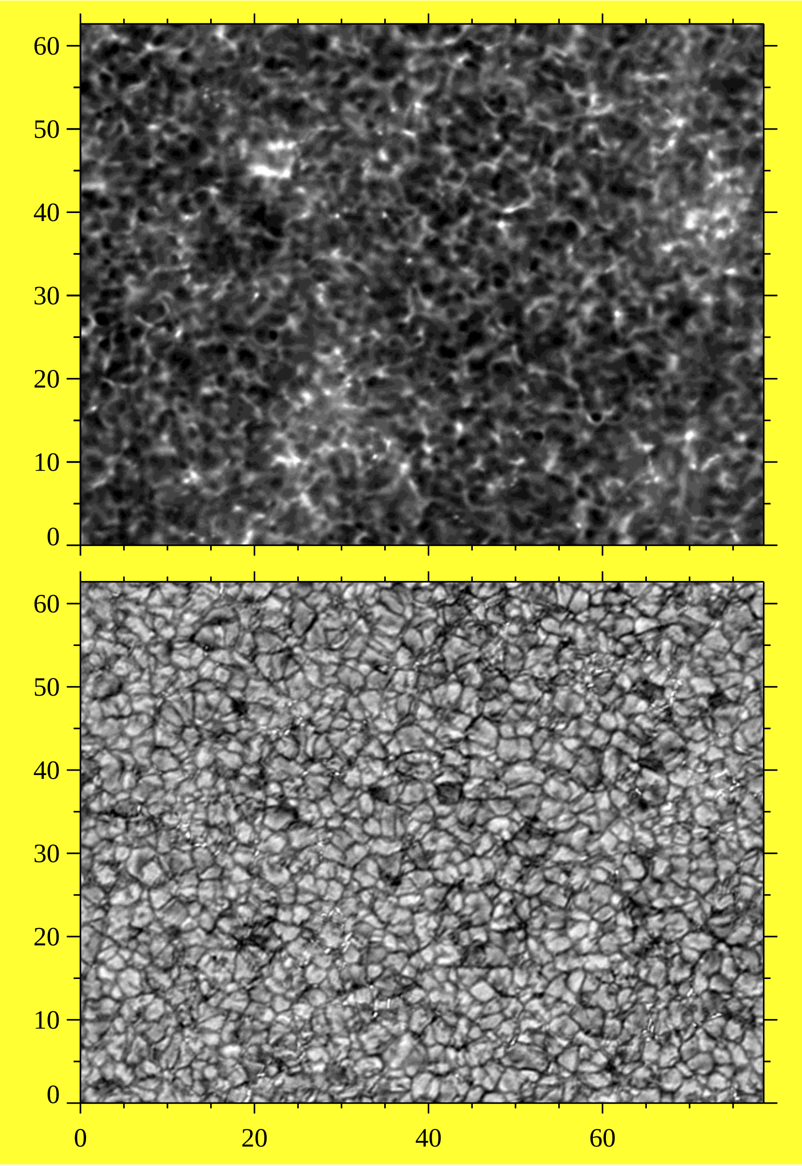
  – T drops from 6600 K to 4300 K.

- Granulation by overshooting convection cells:

  – roughly 1000 km diameter, 5 min lifetimes.

- Intense magnetic flux concentration in inter-granular lanes:

  – 1–2 kG, few 100 km (resolution limit).

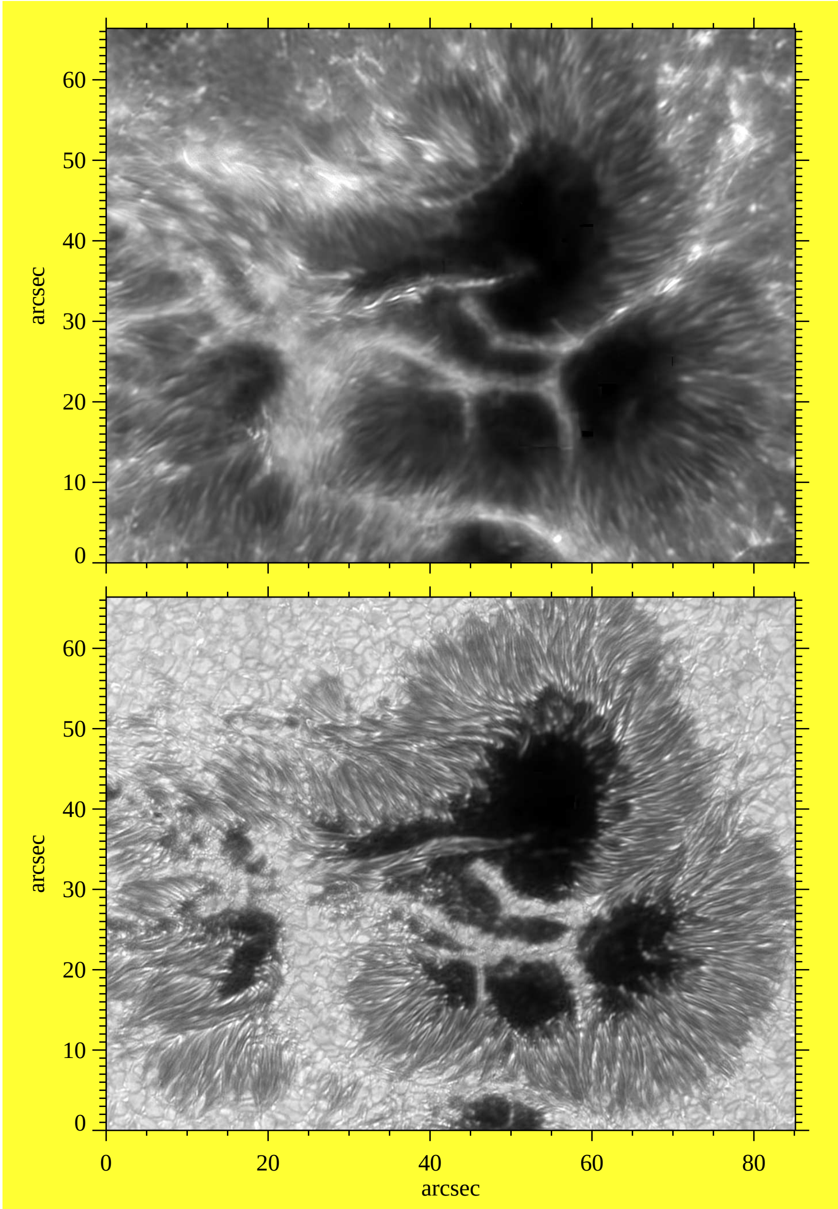


http://dot.astro.uu.nl (Rob Rutten, Utrecht)

Sunspots

- Dark umbra, at typical 3700 K, with near vertical field.
- Filamentary penumbra, intercombed dark/bright, with inclined fields.
- Subsurface structure: 'spaghetti' (umbral dots).
- Sampling sunspot with height:

  Dutch Open Telescope movie
  (dotmovie.mpeg)



⇒ *Need sunspot (local) seismology*

Active region seismology

- Interaction of p-modes with sunspots:

  – decompose in in- & outgoing waves,

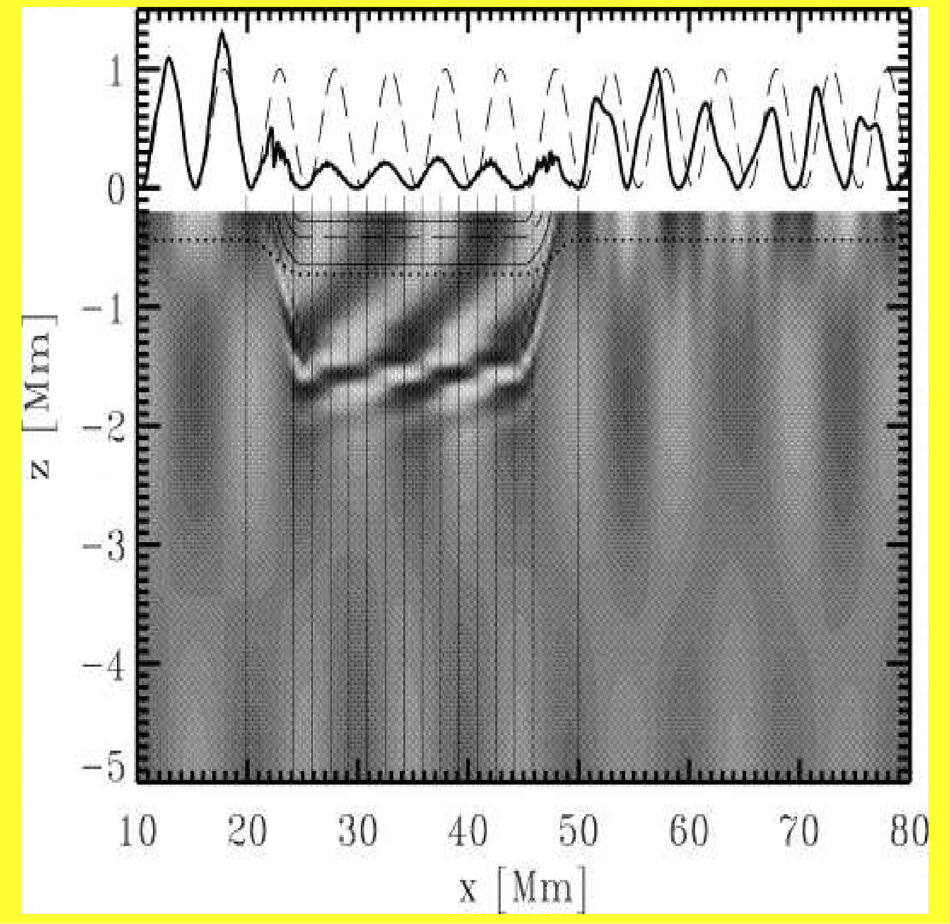
  – sunspots absorb up to 50 % of the impingent acoustic power!

- Candidate linear MHD processes:

  – driving frequencies in Alfvén continuum range causing local resonant absorption (dissipation),

- True 2D stratification:
  mode conversion (magflux.mpeg)
  to downward propagating s-modes at $\beta \approx 1$ layers.

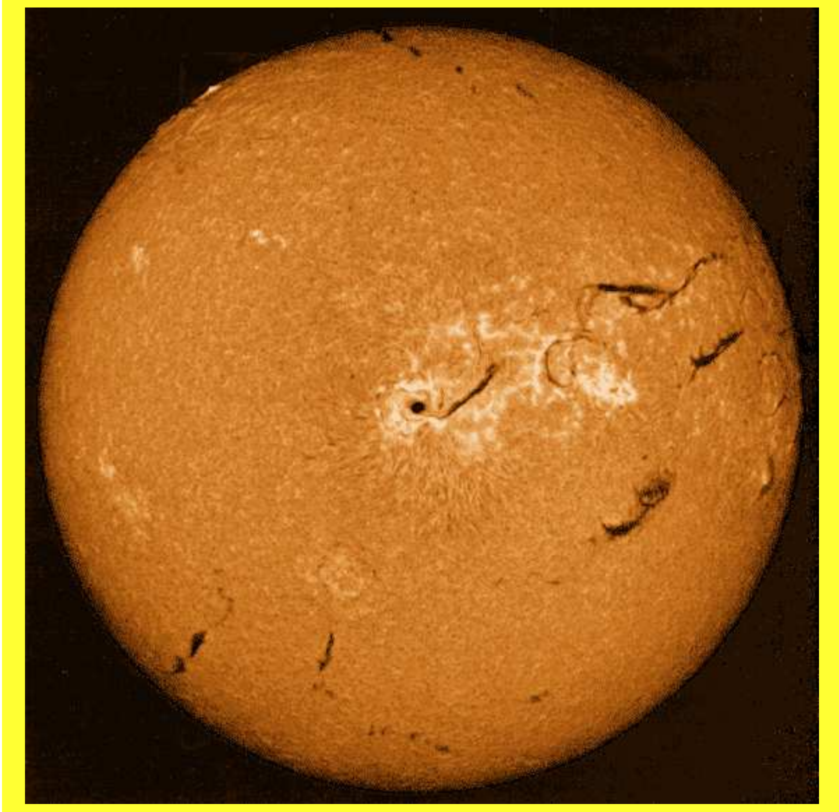
Cally and Bogdan, ApJL **486**, L67 (1997).



http://web.hao.ucar.edu/public/asr/asr96/spmf.html
(modelling interaction of p-modes with sunspots)

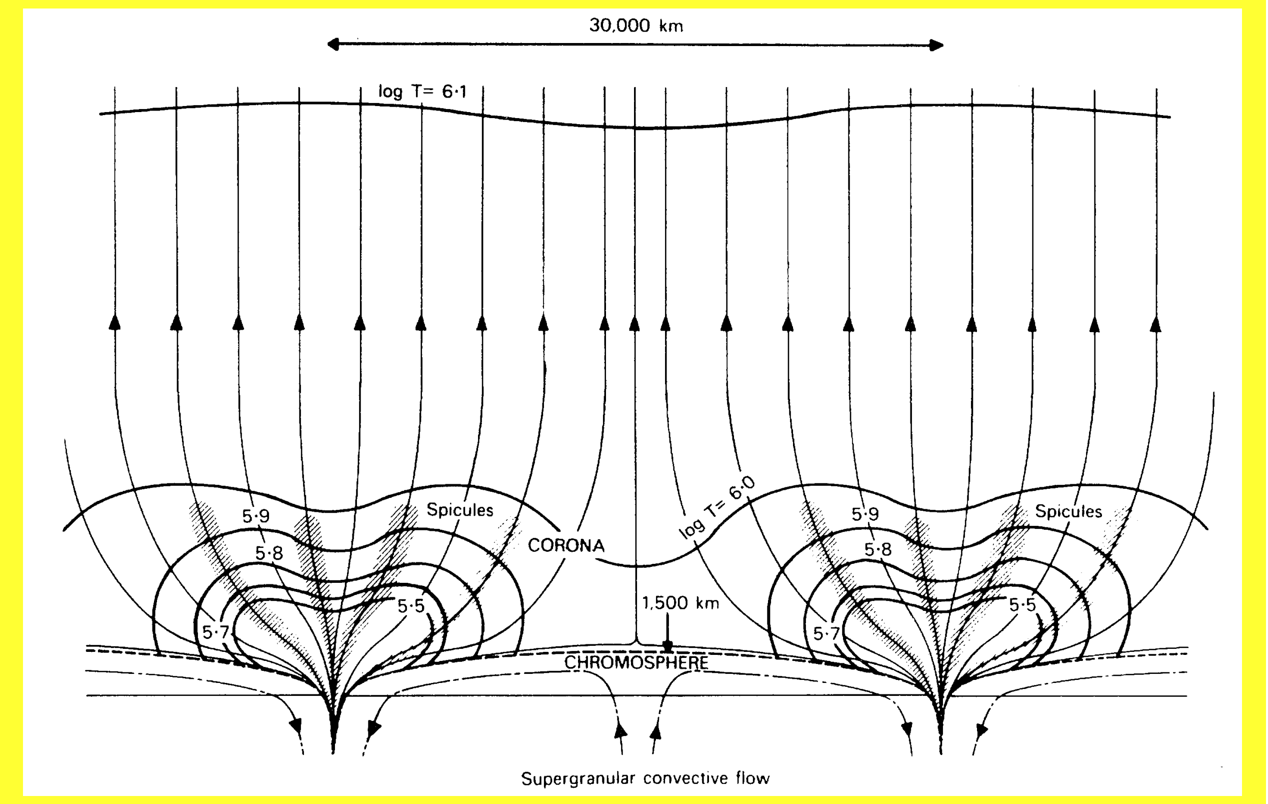
Solar chromosphere

- About 2500 km thick, T rises from 4300 K to the millions K of the corona:
  - low, middle, high chromosphere.
- Viewing sun in selected spectral lines:
  - sampling of different heights.
- Hα image at 6563 Å:
  - bright active regions and plages,
  - filaments (on disk), prominences (at the limb).



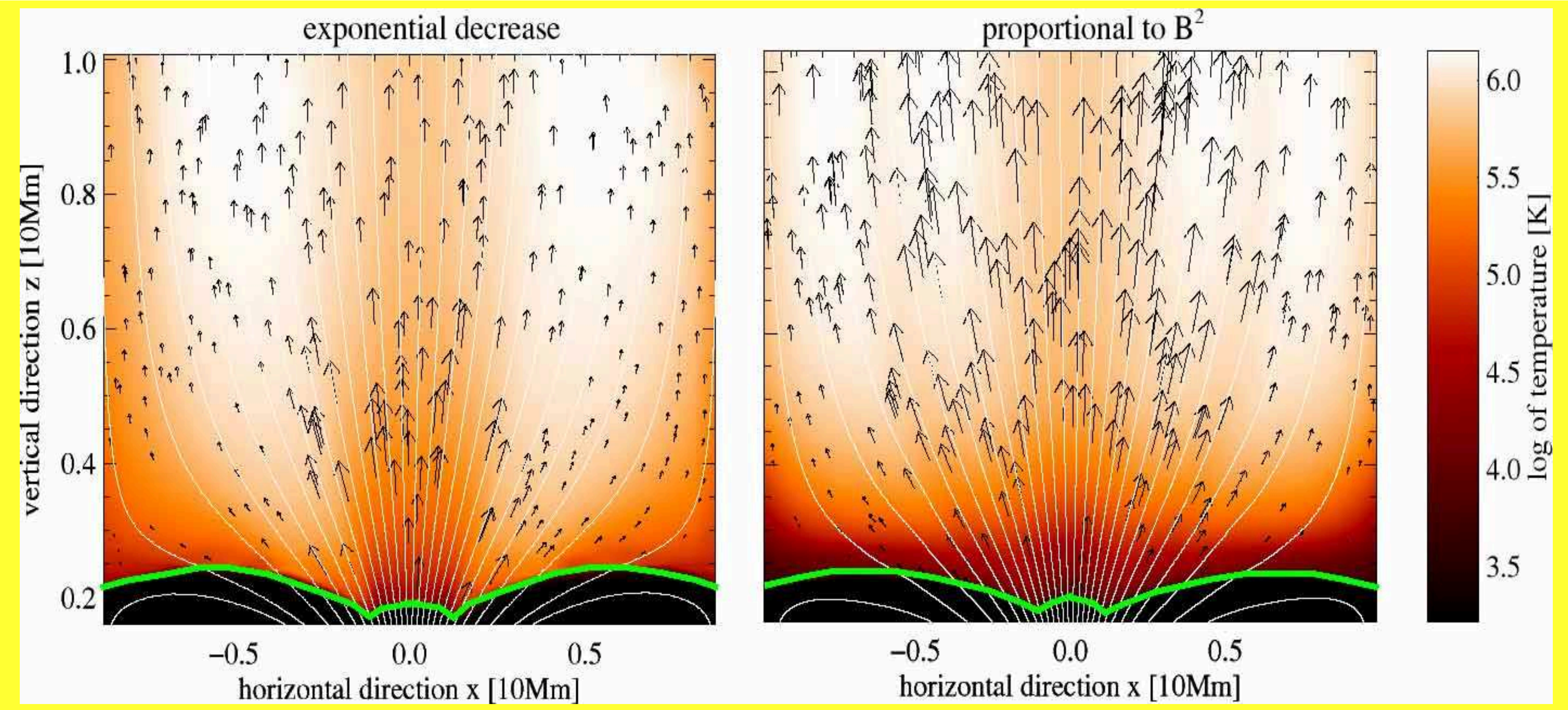
Canopy field

- Field concentrations in chromospheric network:
  - photospheric *supergranulation*,
  - several 10000 km size flow patterns,
  - *canopy field* fans out from downflow lanes.



MHD computation

- Computation of steady state from low chromosphere to corona:
  - MHD model including thermal conduction, radiative losses, heating,
  - 'realistic' funnel structure, Aiouaz *et al.*, A&A **442**, L38 (2005).
  - explore effect of ≠ coronal heating parametrization.



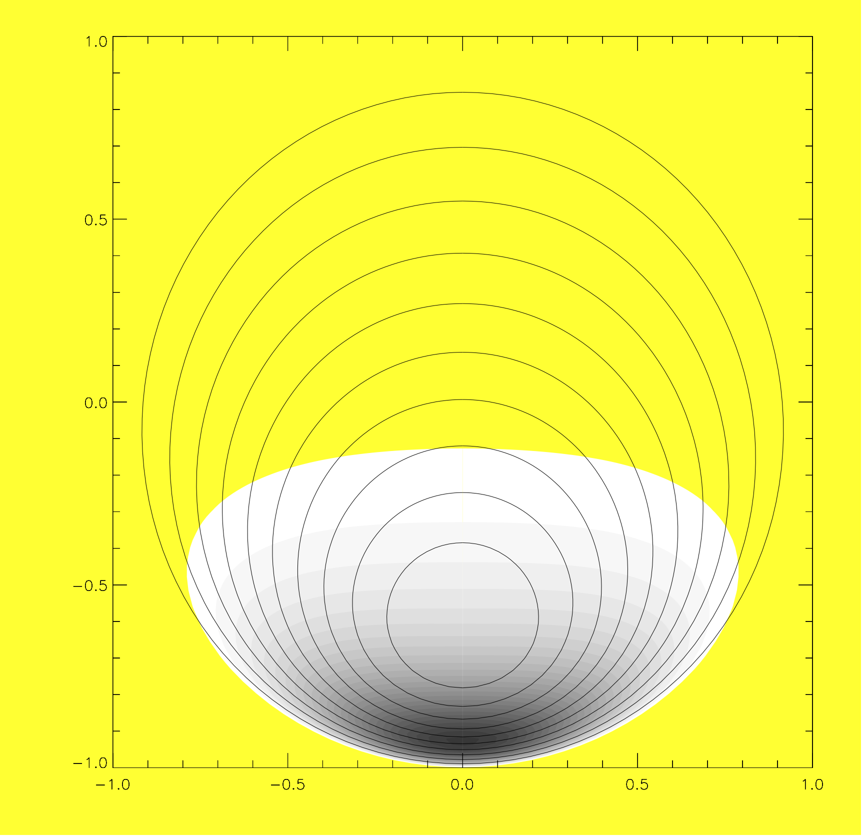
Prominences

- Prominences are suspended magnetically against gravity:
  - up in corona, 100 denser, cooler than surroundings,
  - 200 Mm long, 50 Mm high, 6 Mm wide,
  - ‘quiescent prominences’ live for months: *stable equilibria!*

MHD Prominence model

- Can (analytically and) numerically compute exact solutions to static gravitating MHD coronal loops with density enhancements (prominence) supported against gravity by hoop force (Lorentz force):

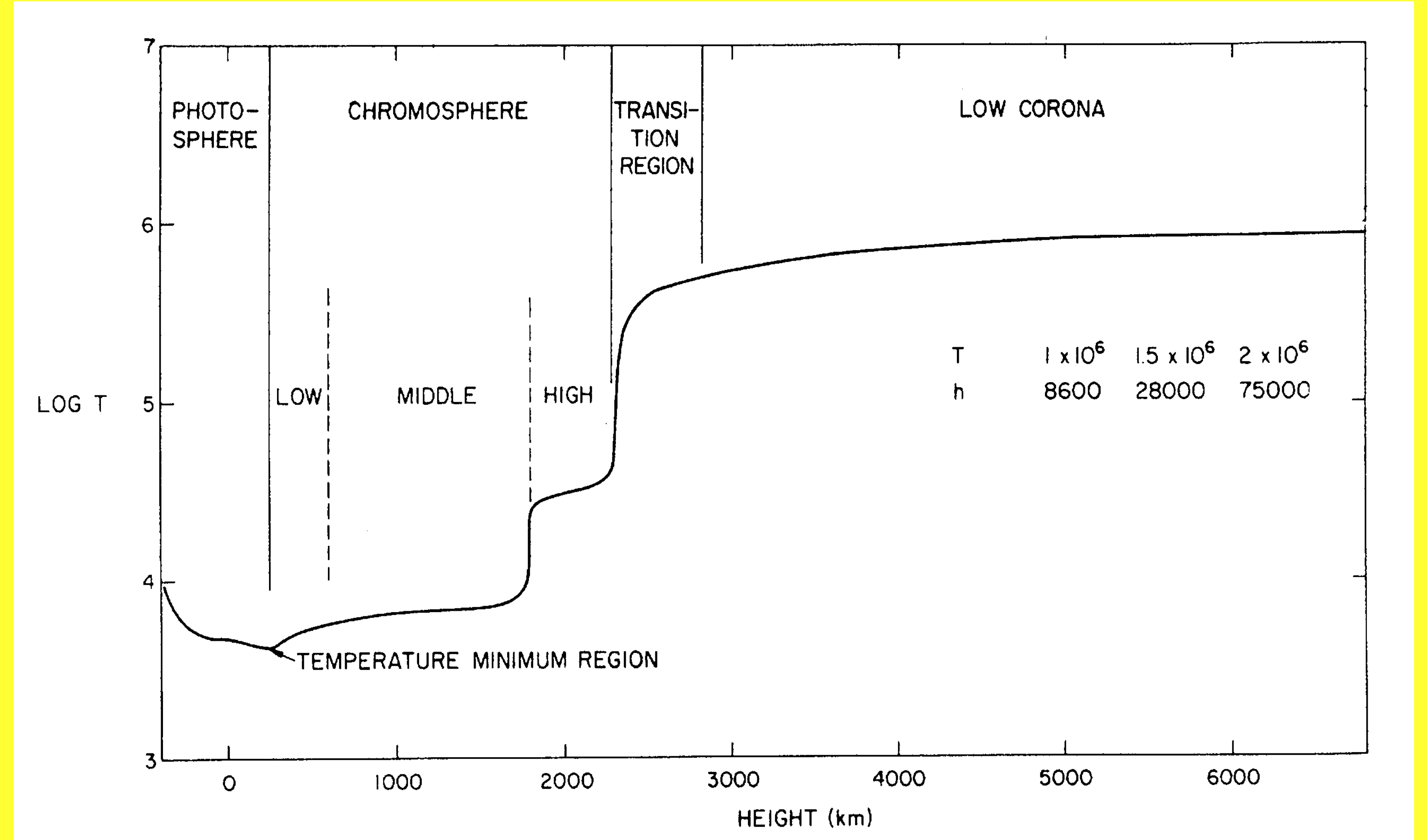
  Low & Zhang, APJ **609**, 1098 (2004).



(picture reproduced by Gordon Petrie with FINESSE code, Belien et al., JCP **182**, 91(2002))

Corona

- Temperature stratification with height:
  - rises in chromosphere, with a steep increase to 10^6 K in transition region,
  - $\Rightarrow$ *coronal heating problem.*



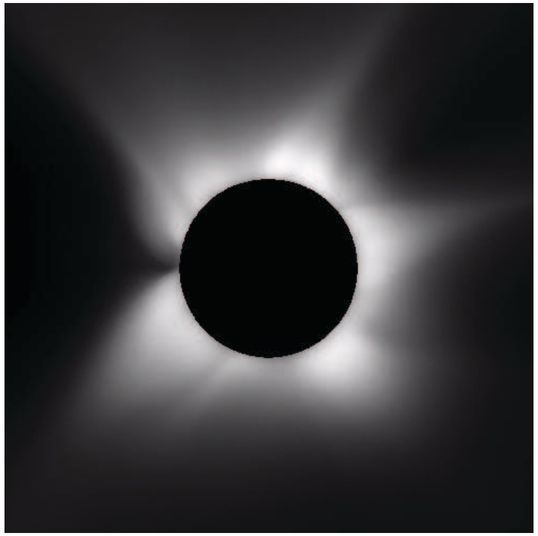
Magnetic linkage

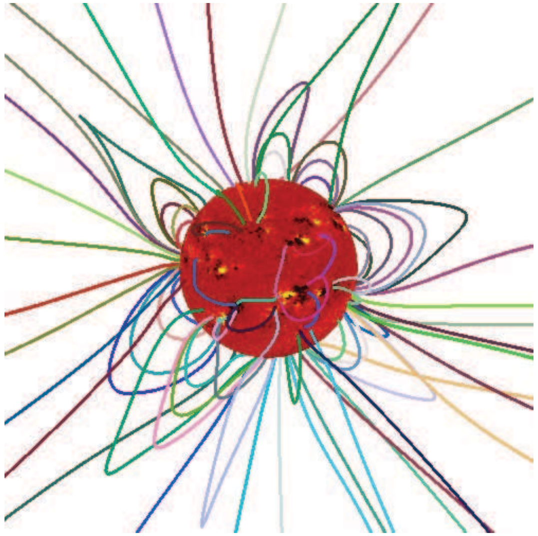
- TRACE spacecraft (NASA, launched 1998):
  - http://trace.lmsal.com/
  - explores 3D field transition region/corona,
  - unprecedented views on coronal loops:

    TRACE movie of erupting filament
    (T171-10050616-19-21-filerup.mpeg)
- Studies of MHD waves in loops:
  - coronal seismology.

Corona: eclipse images

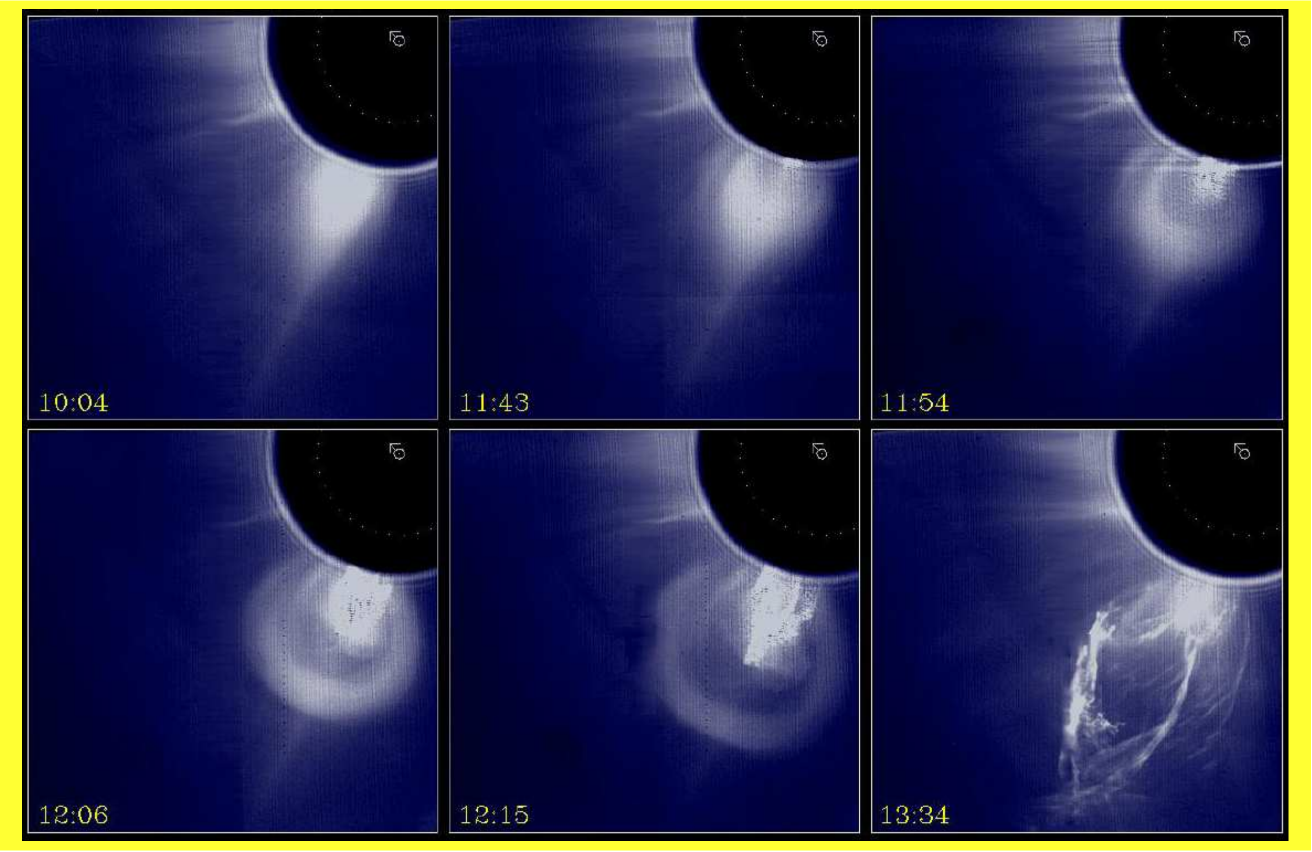
- At solar max: coronal helmet streamers.
- 3D structure can be ‘predicted’ from MHD models.





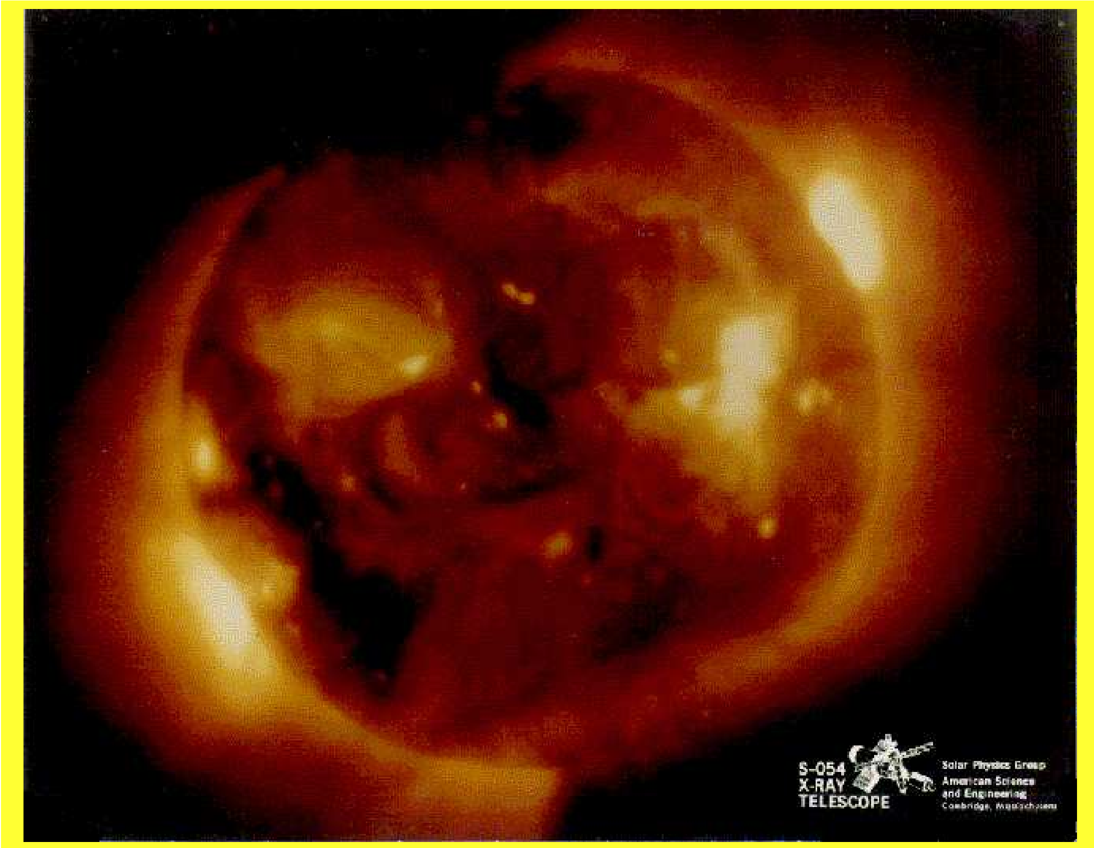
Corona: coronagraph

- Monitoring Coronal Mass Ejections (CMEs):
  - 10^{12} kg ejected, few 100–1000 km/s,
  - Solar Maximum Mission (1980–1989).



Corona: X-ray views

- **Skylab** manned space station (1973–1974):
  - continuous X-ray view (few 10 Å) of the corona.
- Rigid rotation of coronal holes.
- Transient X-ray bright points.
- **Yohkoh** satellite Japan/US/UK (1991–2005):
  - soft and hard X-ray views,
  - to be followed up by Solar-B (launch 2006).

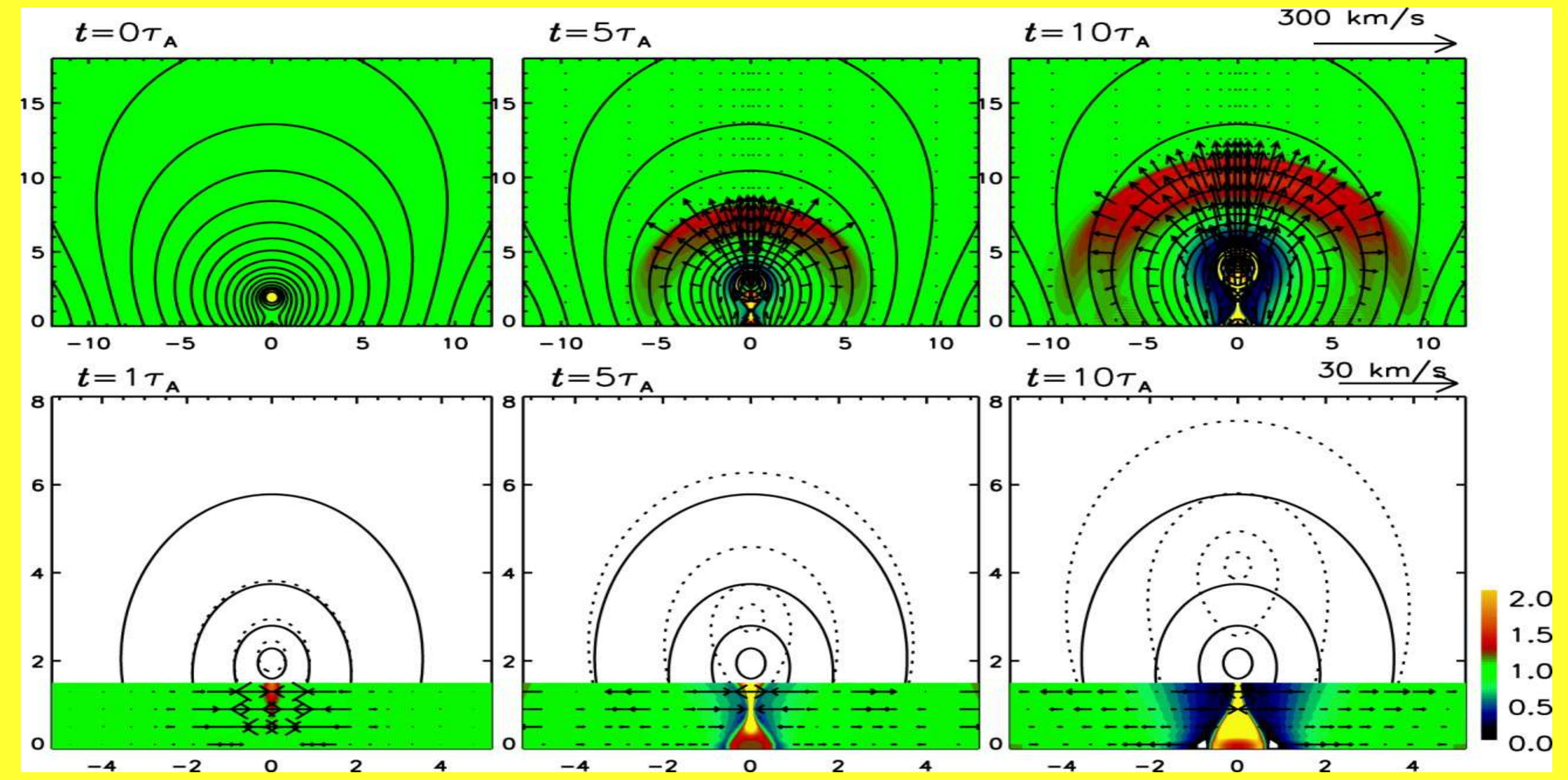


Coronal dynamics

- **SOHO** Extreme UV imaging Telescope (EIT).
  - visualizes solar cycle variations of coronal structure:

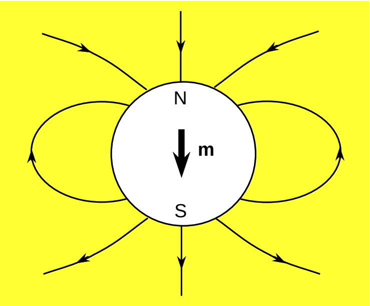
- Solar flares (10^{24} J 'explosions'):
  - reconnection, particle accelerations, associated CME.
- EIT identified **flare-associated waves** (EITrndif.mov)
  - circularly propagate away from flare site, enhanced transient coronal emission.

- MHD model for EIT waves and related chromospheric waves:
  - CME-induced due to rising flux ropes, Chen *et al.* **572**, L99 (2002);
  - Overarching shock front: ‘legs’ produce chromospheric Moreton waves;
  - EIT waves mark site of successive opening of covering field lines.

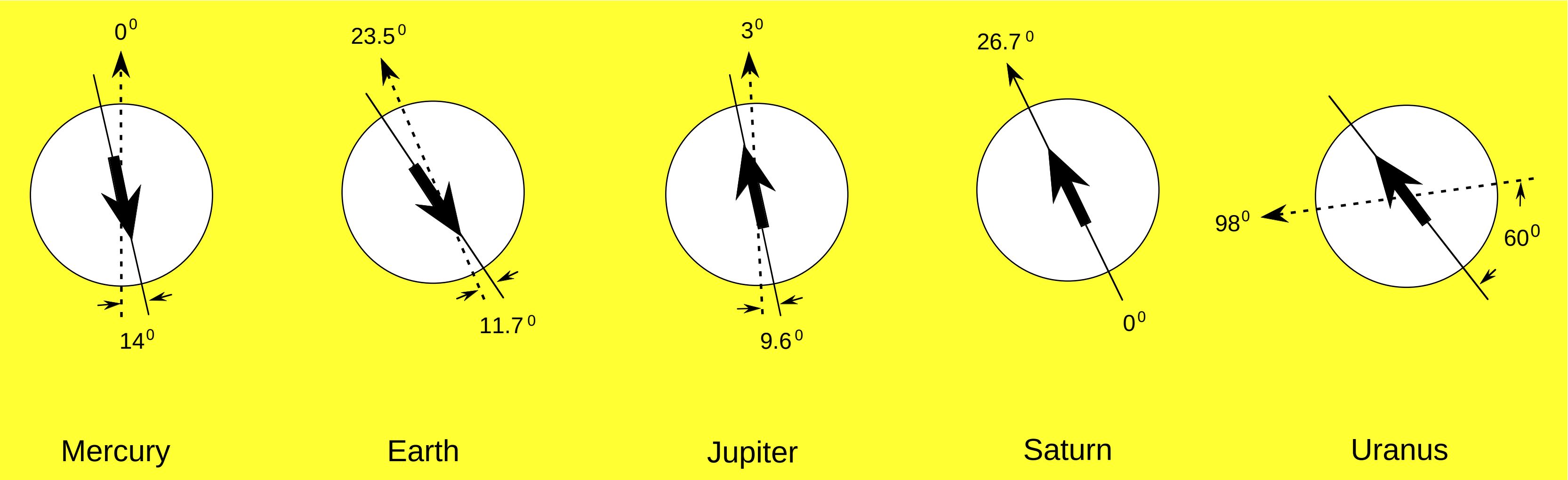


Planetary magnetic fields by themselves:

Magnetic dipole



- Dipole magnetic field: $\mathbf{B}(\mathbf{r}) = (\mu_0/(4\pi r^3))\,(3\mathbf{m}\cdot\mathbf{e}_r\,\mathbf{e}_r - \mathbf{m})$.
  - Earth: $m_{\rm E} = 8.1 \times 10^{22}\,{\rm A\,m^2}$.
- Table B.8 for values of solar system planets:
  - sizeable fields for Earth and giant planets (Jupiter, Saturn, Uranus, Neptune),
  - interesting orientation w.r.t. planetary rotation axis (preferred alignment?).

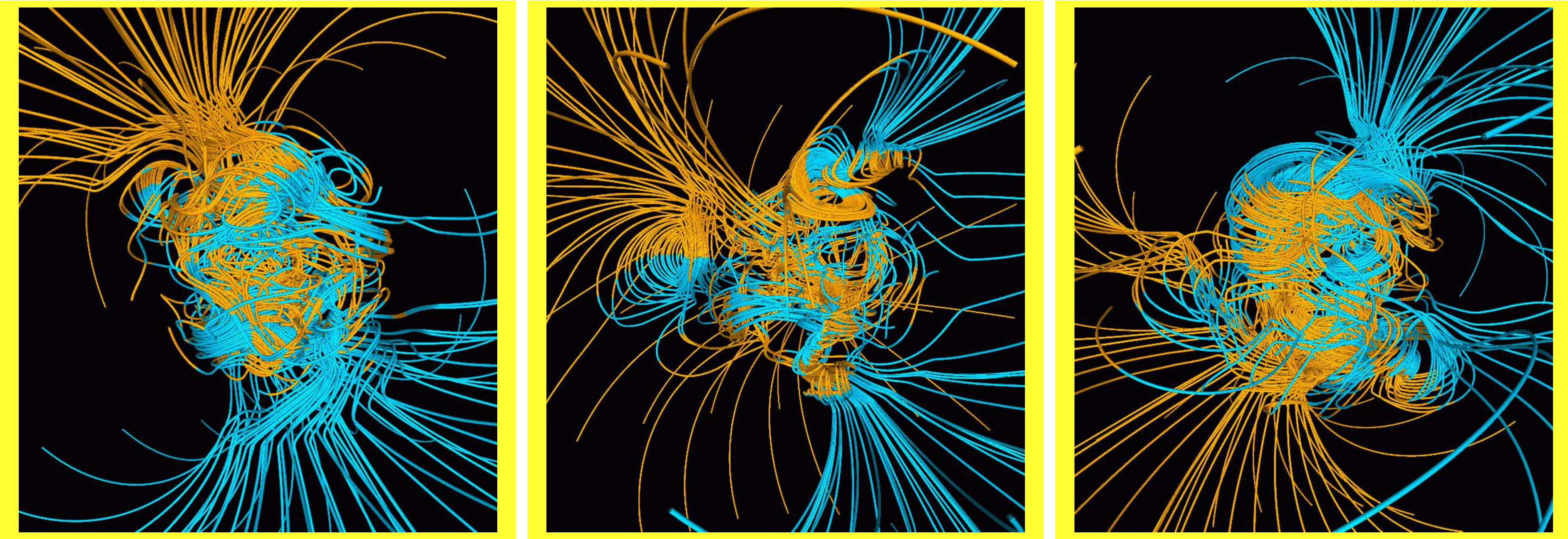


Geodynamo

- **Earth's** magnetic field is currently mostly dipolar:
  - 10 % non-dipolar (higher order multipoles),
  - evidence from magnetized rocks that orientation reverses every few 100000 years, taking a few 1000 years for full reversal.
- Earth consist of inner core, outer core, mantle, crust:
  - liquid iron outer core ($1300 < R < 3400\,\mathrm{km}$) must maintain field,
  - resistive diffusion time scale $\tau_D \sim 5 \times 10^{11}\,\mathrm{s} = 16\,000\,\mathrm{years}$,
  - need sustained (3-dimensional, non-linear) $\mathbf{B}$ generation by molten iron motion,
  - driven by heat from radioactive decay in inner solid core,
  - rotation and convection in moving conducting fluid described by Ohm's law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\,\mathbf{j}\,.$$

- *Full 3D MHD simulations* by Glatzmaier & Roberts (1995):
  - simulated several 100000 years of geodynamo activity,
  - inner core mediates randomness of reversals: its $\mathbf{B}$ can only change on diffusion time scale,
  - captured reversal event, changed dipole orientation in 1000 years:

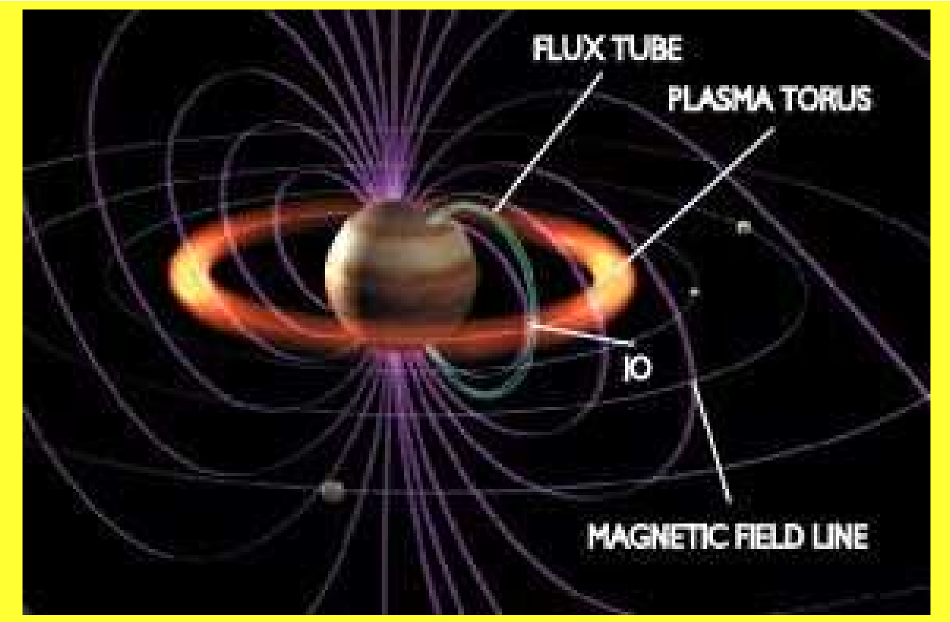


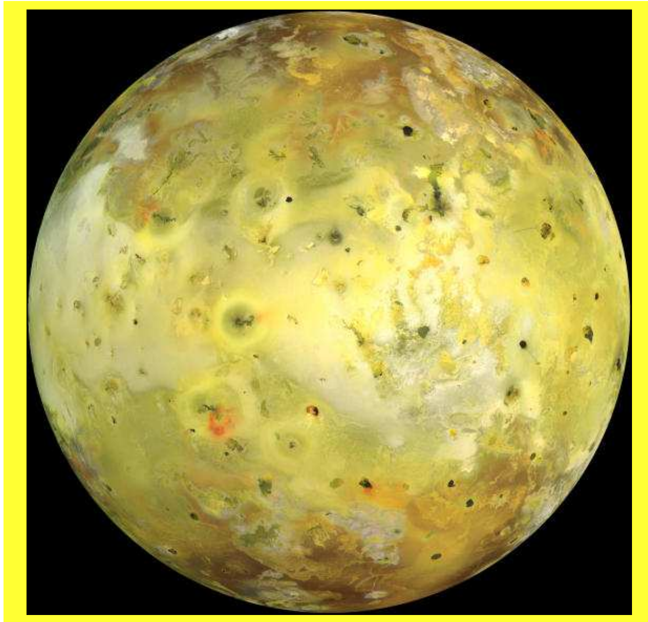
http://www.es.ucsc.edu/ glatz/ (website Gary Glatzmaier)

Jovian system

- **Jupiter** has largest magnetosphere in solar system:
  - magnetosphere extends 150 to 200 Jupiter radii,
  - magnetopause (boundary static Jovian plasma/solar wind) at $\sim 65R_{\mathrm{J}}$,
  - equatorial $\mathbf{B}$ tenfold of Earth's,
  - liquid metallic hydrogen in inner mantle drives dynamo,
  - 16 moons (Io, Ganymede, Europa, Callisto, . . .).
- NASA Galileo mission (1989–1999) arrived at Jupiter in 1995.

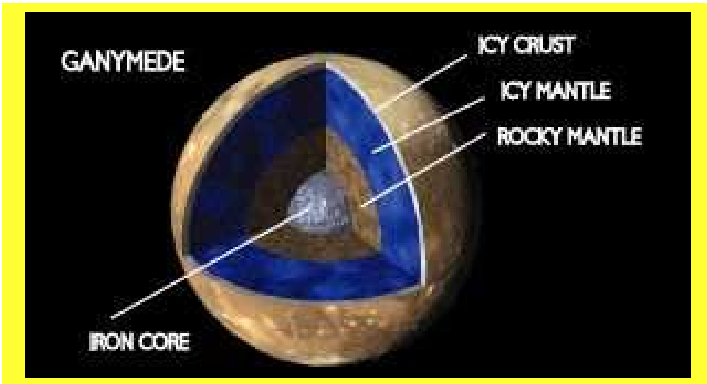
  http://home.freeuk.com/catherine-uk/
  (Galileo mission to Jupiter, pictures of Jovian system
  with 'Io plasma torus' and Ganymede on next page)





http://antwrp.gsfc.nasa.gov/apod/ap990920.html (Io)

- **Io:** strong tidal forces (eccentric orbit) induce volcanic activity,
  - injects plasma into torus about Jupiter,
  - drives auroral displays on Jupiter poles.
- **Ganymede:** dynamo in iron core (?),
  - B of 10 % Earth,
  - magnetosphere in Jovian magnetosphere.



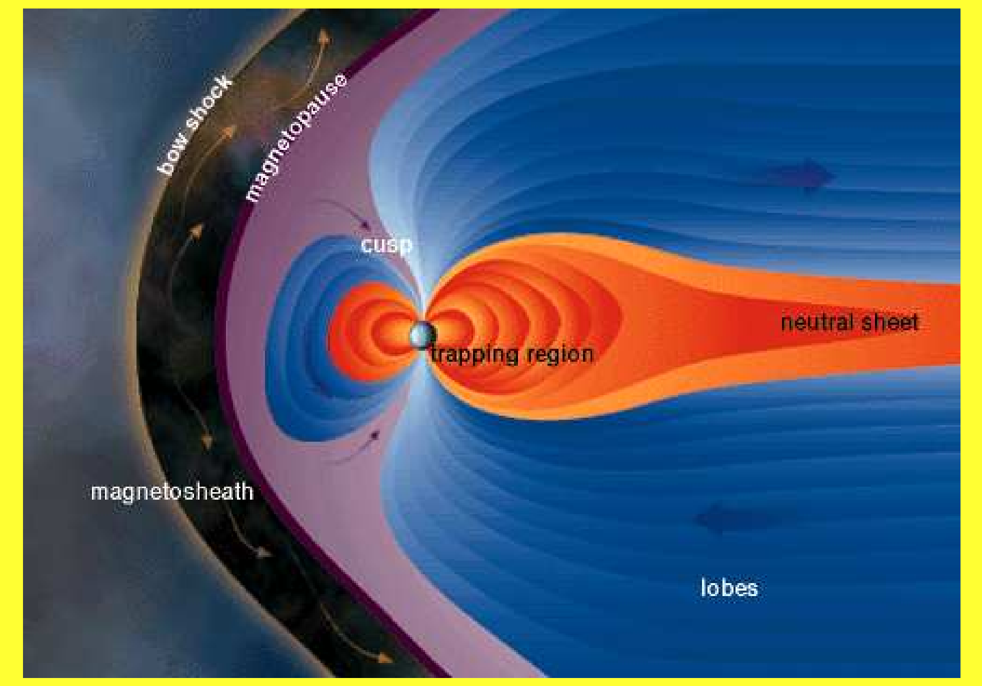
Other planets

- **Mercury:**
  - Mariner 10 (1974–75) demonstrated $\mathbf{B}$ presence,
  - future MESSENGER (NASA) and BepiColombo (ESA) missions,
  - latter includes detailed measurements of Mercury magnetosphere.
- **Venus:** $\mathbf{B}$ from interaction solar wind with ionosphere,
  - same can occur around comets.
- **Saturn:** as Jupiter, liquid metallic hydrogen outer core drives dynamo.
  - Pioneer 11 1979 discovered $\mathbf{B}$ of Saturn, later Voyager missions.
  - detailed knowledge coming from Cassini-Huygens mission, currently at Saturn (in orbit since june 2004, Huygens probe descended into Titan early 2005).
    http://saturn.jpl.nasa.gov/science/magnetosphere-formation.cfm
    (Cassini-Huygens mission)

- **Uranus:** rotation axis in the ecliptic, with angle of 60° to dipole $\mathbf{m}$.

  – Interior: rocky core, icy outer core (water ice + rock), liquid hydrogen envelope, layer of gaseous hydrogen, helium, methane.

  http://www.solarviews.com/eng/uranus.htm (Uranus)



http://www.windows.ucar.edu/tour/link=/uranus/images/uranus_magneto_gif_image.html (Uranus magnetosphere)

- **Neptune** similar to Uranus: non-aligned with rotation axis.
  - Both Uranus/Neptune off-centre (effective) dipoles.
  - Dynamo in ionized, conducting icy outer cores (?).

http://www.mira.org/fts0/planets/101/text/txt103x.htm (Neptune)

Solar wind by itself:

Solar wind: Parker model

- Coronal plasma at 10^6 K, density drops for increasing r.
  - Pressure gradient drives continuous outflow.
  - Predicted by Parker in 1958, later observed by satellites.
- Model with hydrodynamic equations, spherical symmetry:
  - Look for stationary solutions $\partial/\partial t = 0$;
  - Assume isothermal corona (fixed temperature T), include gravity:

$$\frac{d}{dr}(r^2 \rho v) = 0 \qquad \Rightarrow \qquad r^2 \rho v = \text{const}\,,$$

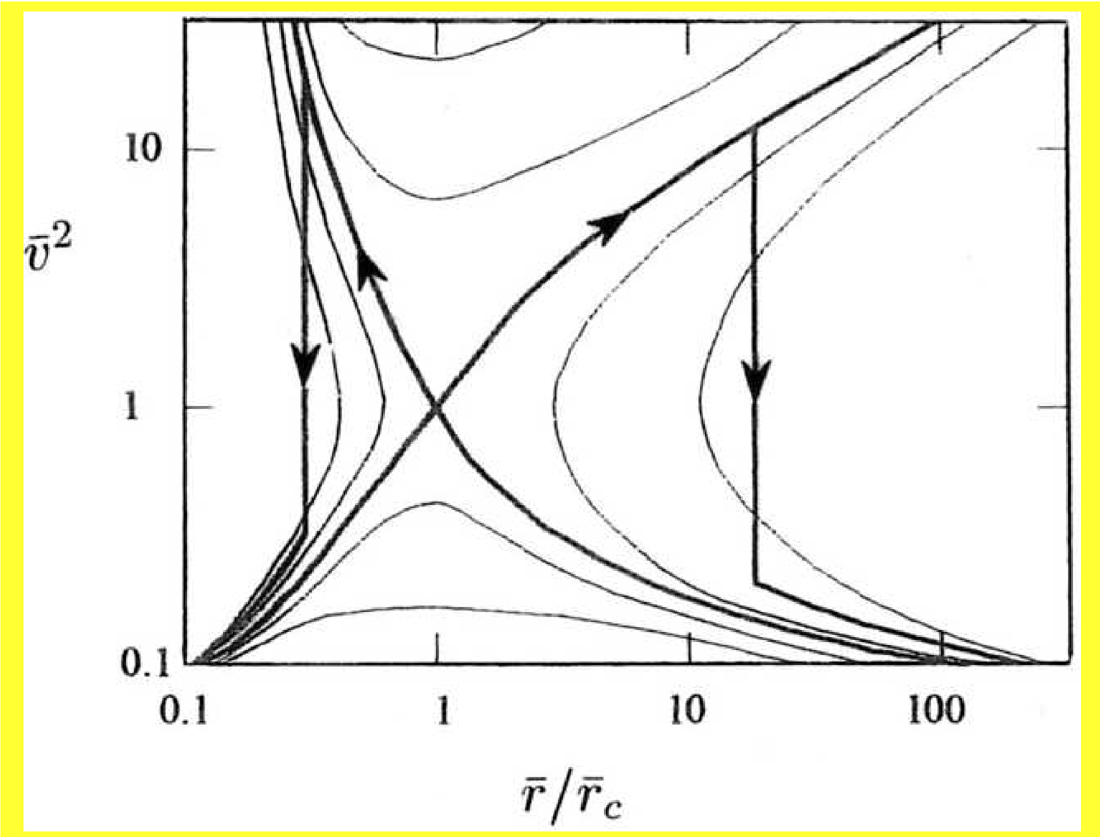
$$\rho v \frac{dv}{dr} + v_{\text{th}}^2 \frac{d\rho}{dr} + G M_{\odot} \frac{\rho}{r^2} = 0\,.$$

  - uses constant isothermal sound speed $p/\rho \equiv v_{\text{th}}^2$.

- Scale $\bar{v} \equiv v/v_{\rm th}$ (Mach number) and $\bar{r} \equiv r/R_\odot$ to get

$$F(\bar{v}, \bar{r}) \equiv \tfrac{1}{2}\bar{v}^2 - \ln \bar{v} - 2\,\ln\left(\frac{\bar{r}}{\bar{r}_c}\right) - 2\,\frac{\bar{r}_c}{\bar{r}} + \tfrac{3}{2} = C\,, \qquad \bar{r}_c \equiv \tfrac{1}{2}\frac{GM_\odot}{R_\odot v_{\rm th}^2}\,.$$

  - Implicit relation determining $\bar{v}(\bar{r})$,
  - unique solution with transonic acceleration:



Solar wind modeling

- Generalization to 1.5D magnetized wind possible analytically:

  – appropriate for equatorial plane including rotation.

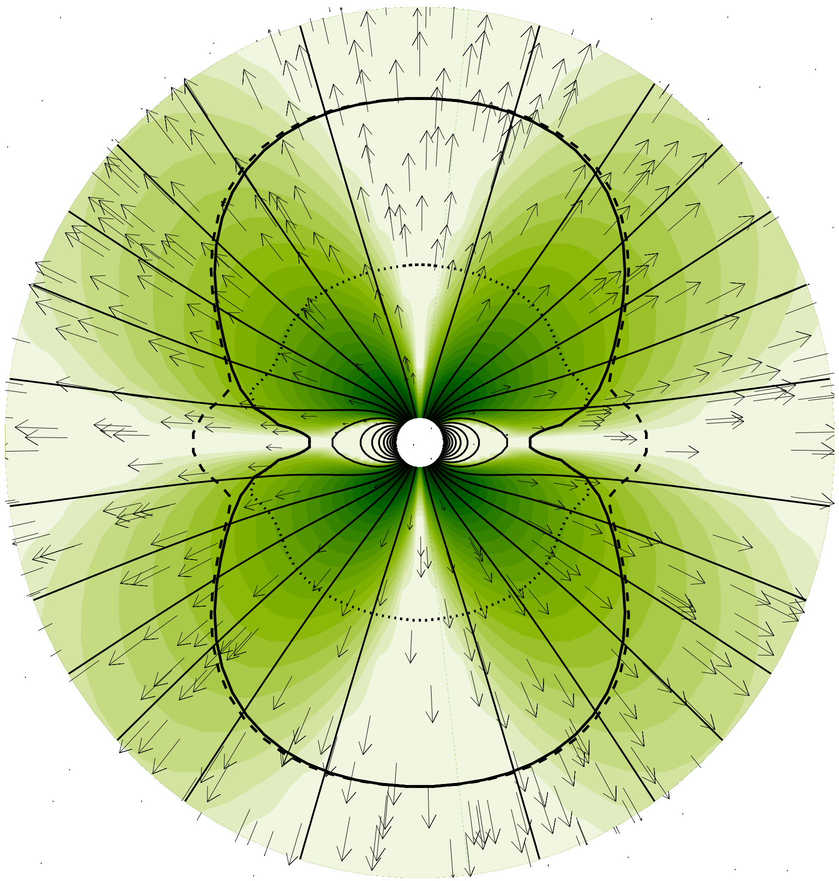
- More advanced models solve for numerical MHD steady-state:

  – MHD: 3 Mach numbers, critical transitions as hourglass curves,

  – Axisymmetric magnetized wind with a 'wind' and a 'dead' zone.

  [simulation by Keppens & Goedbloed, Ap. J. **530**, 1036 (2000) , using VAC]

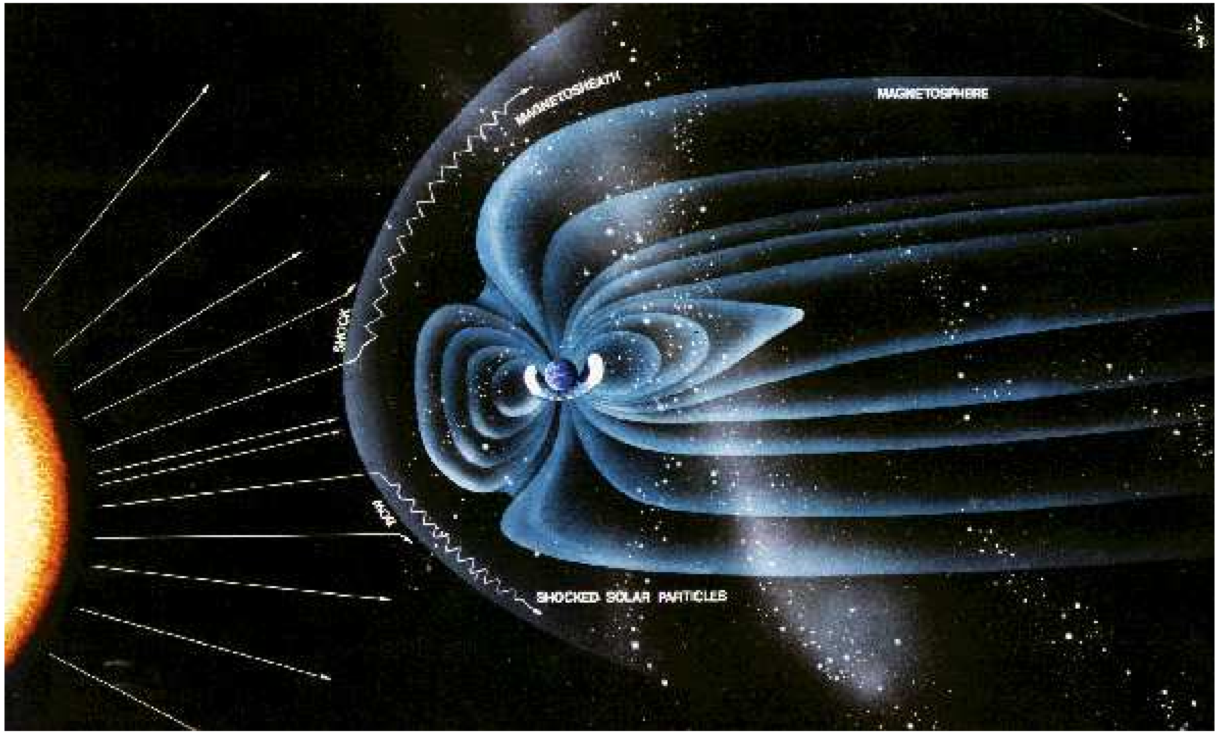
  www.rijnh.nl/n3/n2/f1234.htm



Interaction of solar wind and planetary magnetic field yields:

Magnetosphere

- Large-scale magnetic structure with
  - bow shock due to impinging supersonic solar wind (day-side),
  - magnetopause (contact discontinuity) and inner magnetosphere,
  - night-side stretched into magnetotail with equatorial current sheet.
- Size estimate from magnetic pressure $\sim (R/r)^6$ dipole field versus ram pressure $(\frac{1}{2}\rho v^2)_{\rm sw}$ wind:
  $\sim 10\,R_{\rm E}$ for Earth,
  $\sim 60\,R_{\rm J}$ for Jupiter.



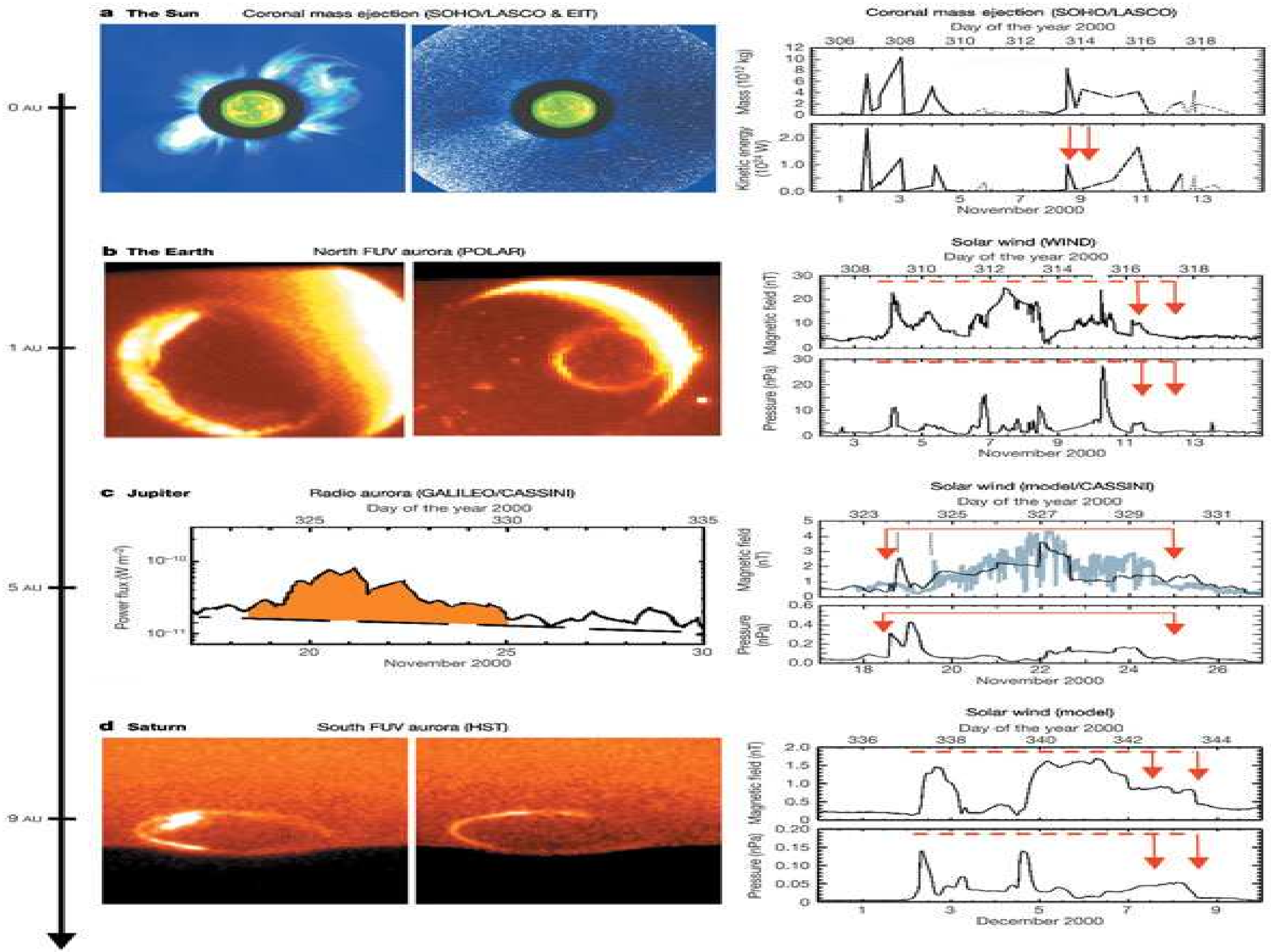
Space weather modeling

- Modern shock-capturing MHD simulations:
  - trigger (flux emergence, cancellation, shearing) + evolution of CMEs,
  - Mikic *et al.*, SAIC San Diego: **CME by flux cancellation** (Mikic-flx2d.anim.qt)
- Compute impact effect on Earth's magnetosphere *faster than real time*
  - computing challenge (few days), significant range of scales
  - Gombosi, Toth *et al.*, Univ. of Michigan:
    Centre for Space Environment movie (Toth-CSEM2004-Zoom.mov)
- **Space weather affects all planets!** Near-alignment of Earth, Jupiter, Saturn (2000)

  ⇒ *Series of CMEs (seen by SOHO) leading to interplanetary shock (overtaking and merging shocks), detected as auroral storms on Earth (Polar orbiter), observed in Jovian radio activity as measured by Cassini (fly-by on its way to Saturn), seen by Hubble as auroral activity on Saturn.*

  ⇒ *MHD model (using VAC code) used to simulate time evolution.*

- **First observation of CME event traced all the way from Sun to Saturn,**
  Prangé *et al.*, Nature, **432** (4), 78 (2004). *Right:* comparison with VAC simulations, with input from WIND spacecraft.



Sun (SOHO) LASCO & EIT

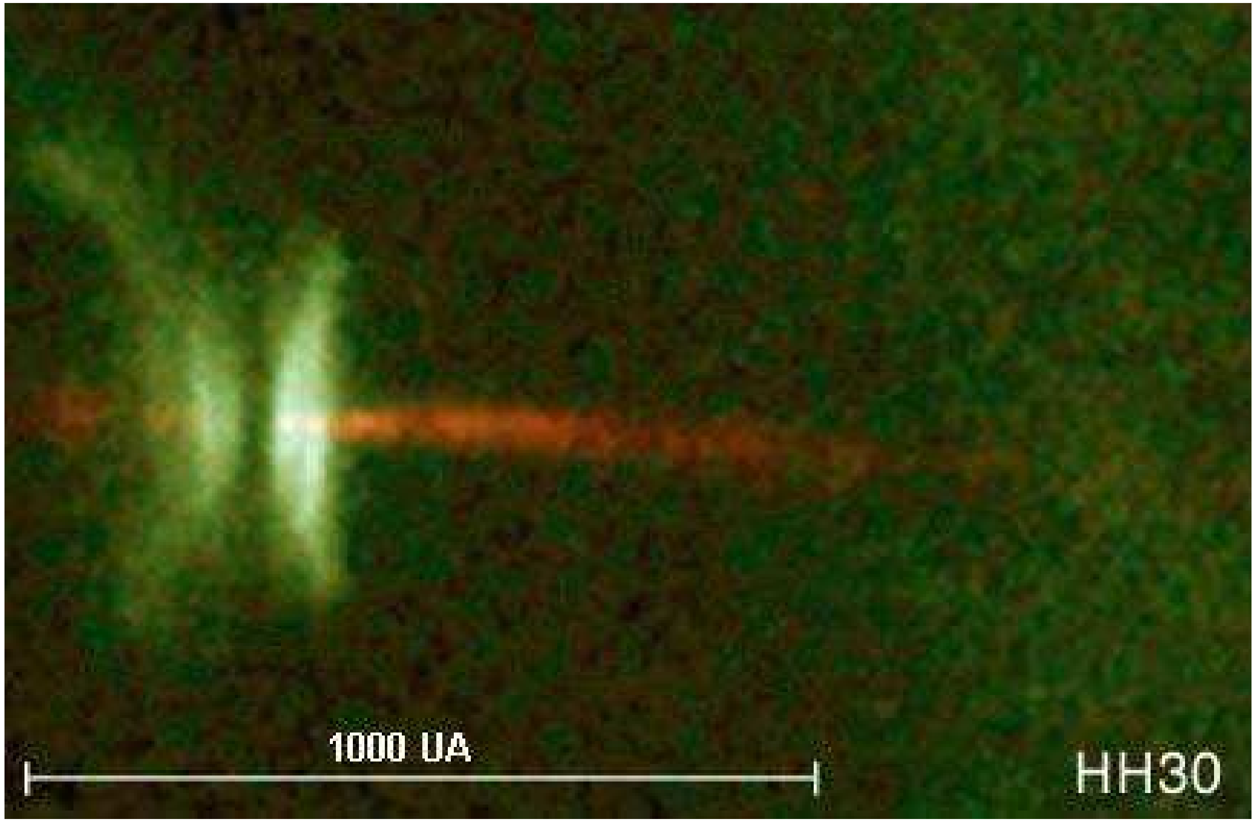
Earth (POLAR) aurora image

Jupiter (Casini) radio signal

Saturn (HST) aurora image

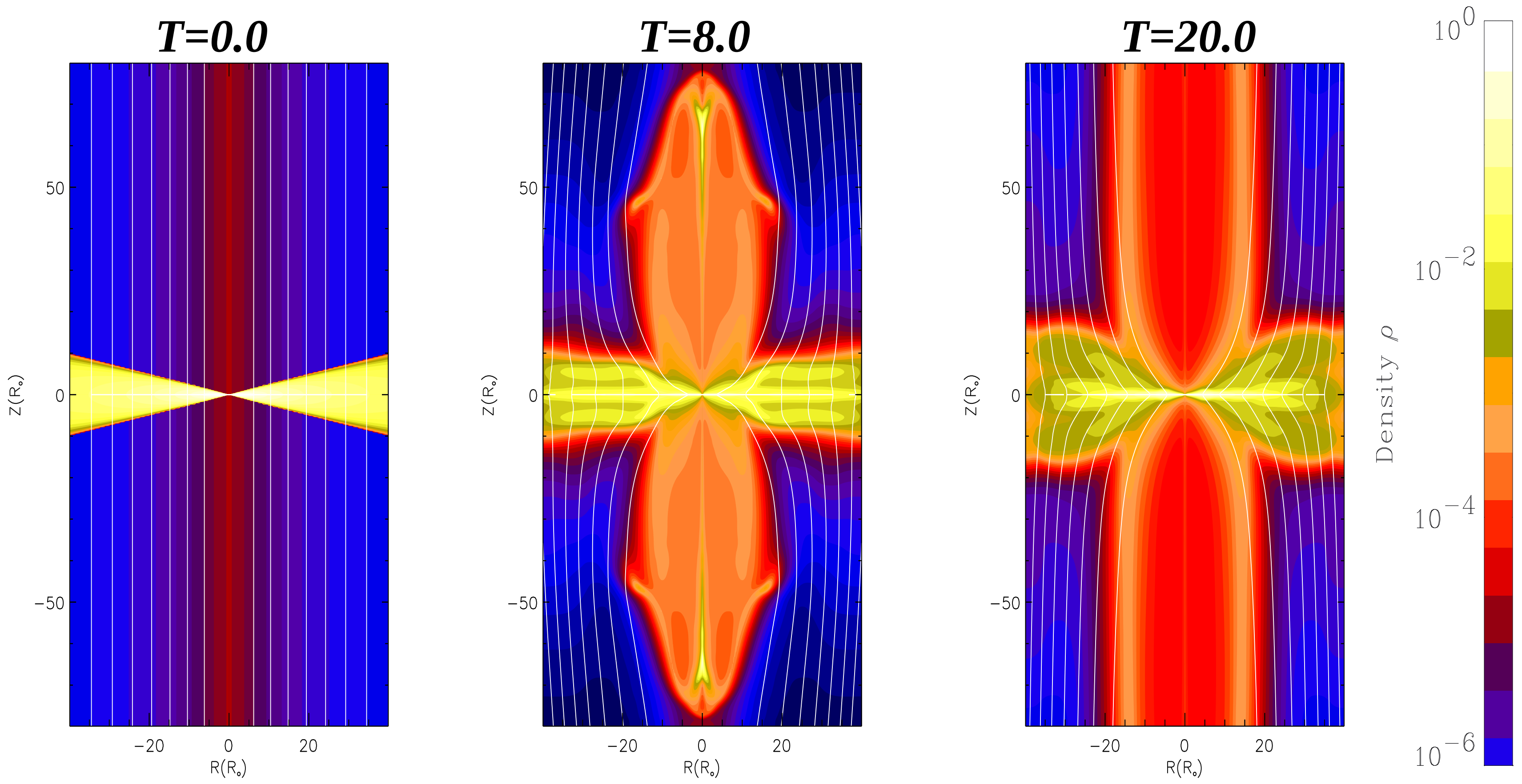
Launching astrophysical jets

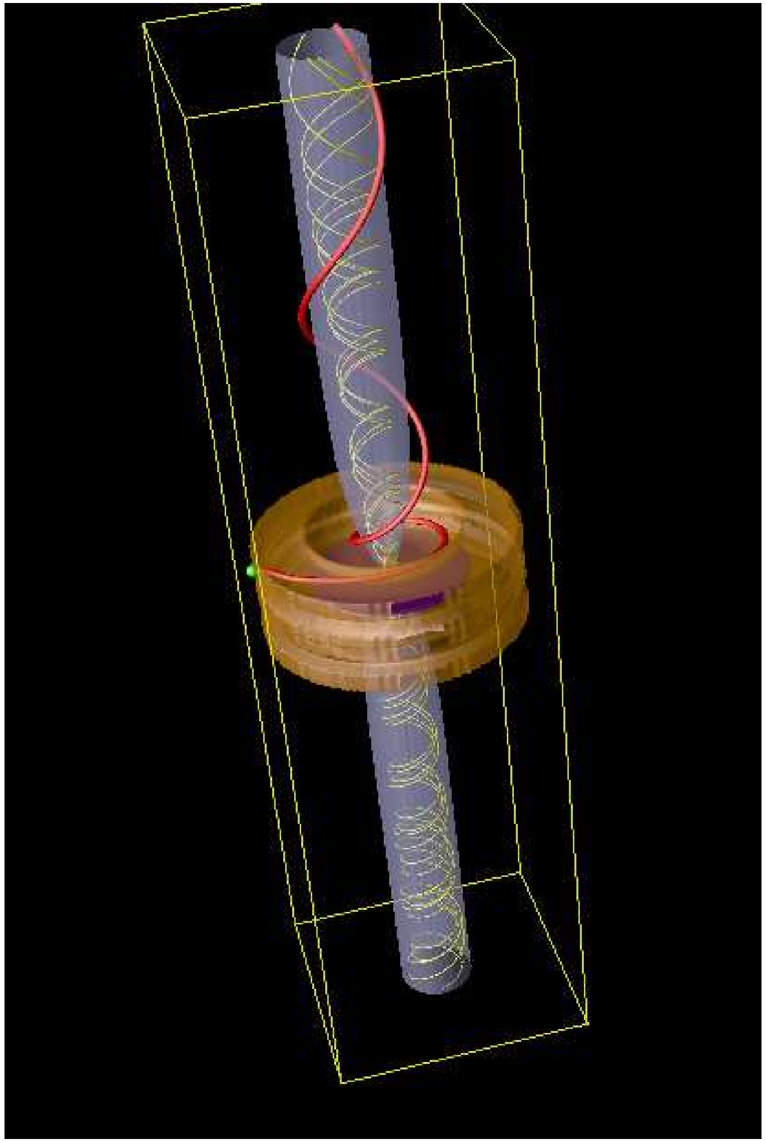
- Forming star environment (HH 30 in Taurus):
  - – optical HST image (Burrows *et al.* 1996),
  - – edge-on flaring disk, reflection nebula, jets,
  - – collimated emission-line jets from center,
  - – jet-knots move at a few hundred km/s.



- Link between accretion disk and jet?
  - observed proportionality jet/disk luminosity.
- $\mathbf{B}$ in accretion, angular momentum transport?
- Jet variability (knots):
  - internal or disk instabilities?
  - non-straight: precess or deformed helically?
- Jet collimation: magnetically?
- Jet launch: how divert order 10 % of accreting mass from inner (hottest) disk regions into outflow?
- To be studied in MHD framework!

- Axially symmetric MHD simulations with VAC by Casse & Keppens, ApJ 2002–2004:
  - disk with initial vertical $\mathbf{B}$: **self-consistently forms collimated jet** (launch.qt)
  - 15 % of accreted mass persistently ejected.





- Mechanism for launch:
  - magnetic torque brakes disk material azimuthally and spins up jet matter,
  - mass source for jet: disk,
  - B collimates,
  - B accelerates.
- **Launching jets** (MAES-AXI.qt)

Perspective

- **Space missions produce(d) numerous observations**
  - *SOHO* (1995): solar phenomena from core to beyond the Earth's orbit.
  - *Cluster satellites* (1996, 2000): 3D spatial structure of Earth's magnetosphere.
  - *Ulysses* (1990) in situ investigations of inner heliosphere.
  - *Solar Orbiter* (2012–2017) highest resolution and images of Sun's polar regions.
- **Observed dynamics demonstrates:**
  - Validity of *magnetic flux conservation* and *dynamics of magnetic flux tubes*.
  - Observed magnetic flux tubes occur in *large numbers.*
- **Many unsolved problems remain:**
  - quantitative theory of *solar dynamo,*
  - theory of *coronal heating,*
  - prediction of *solar flares,*
  - theory of *solar wind generation, heating, interaction with magnetospheres,*
  - prediction of *space weather.*