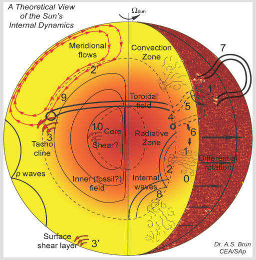
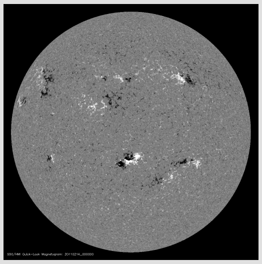
ASTR 7500: Solar & Stellar Magnetism
Hale CGEG Solar & Space Physics



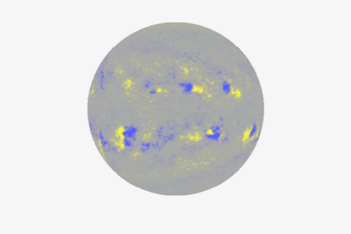


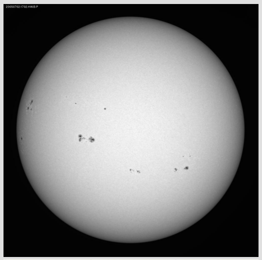
Matthias Rempel, Prof. Juri Toomre + HAO/NSO colleagues

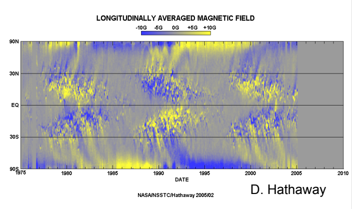
Lecture 12 Thurs 28 Feb 2013

zeus.colorado.edu/astr7500-toomre

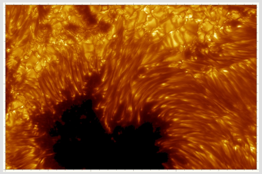
Solar magnetic field







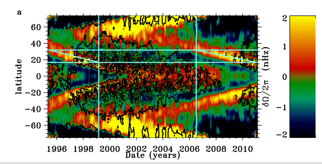
D. Hathaway

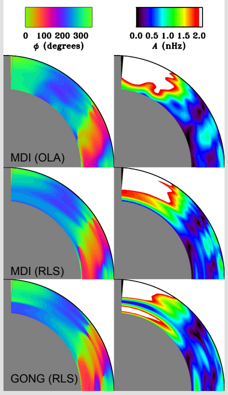


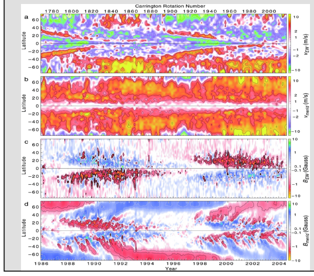
SST, La Palma

Large scale flow variations

Global Helioseismology (R. Howe)







Surface Doppler (R. Ulrich)

Solar dynamo models – what is the goal?

- What is a solar dynamo model supposed to do?
  1) Show a "solar-like" activity pattern in terms of:
     - Cyclic behavior with equator-ward propagation of activity
     - Surface flux evolution consistent with observations
     - Large scale flow variations consistent with observations
  2) Show a "solar-like" amplitude variation from cycle to cycle
  3) Allow prediction of future activity
- Most models struggle already with point 1)
  - Focus this lecture on 1)
  - 2) and 3) can provide additional constraints on dynamo models

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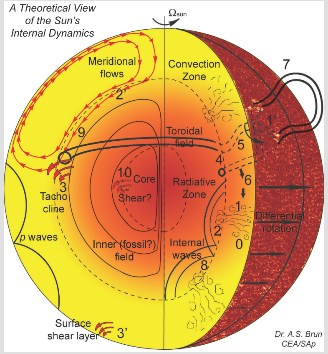
The basic dynamo ingredients



- Large-scale flows
  - Differential rotation
  - Meridional flow
  - Mean and (cyclic) variation
- Turbulent induction
  - Transport
    - Advective
    - Diffusive
  - α-Effects
    - Key terms that enable dynamo action
- Flux emergence
  - Links dynamo to photospheric field observations
  - Might play role in dynamo process itself
    - Babcock-Leighton mechanism

Numerical modeling approaches

- Meanfield models
  - Solve equations for mean flows, mean magnetic field only
  - Inexpensive, but need good model for correlations of small scale quantities (e.g. turbulent angular momentum transport), see extensive work by Rüdiger & Kitchatinov)
  - Can address the full problem, but not from first principles (models have many degrees of freedom and tunable parameters)
- 3D numerical simulations
  - Solve the full set of equations (including small and large scale flows, magnetic field) from first principles
  - Very expensive:
    - Low resolution runs for long periods >10 years
    - High resolution for short periods
  - Good understanding of differential rotation, ingredients of solar dynamo, no complete model yet
- Advances in computing infrastructure shift balance toward 3D simulations, but we need both!

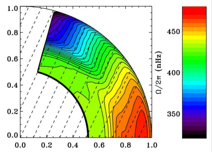
Mean field models

- Mean field models consider only average quantities
  - Sunspots are a key feature of the solar cycle, but they are averaged away
- Mean field models make strong assumptions that are not well justified from first principles
- Too many degrees of freedom require “educated guesses”

$$(\overline{v' \times B'})_i = a_{ik}\overline{B}_k + b_{ijk}\frac{\partial \overline{B}_j}{\partial x_k}$$

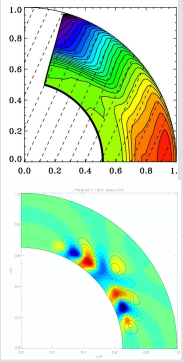
  - Contains 36!!! (mostly unknown) functions of r and ϑ, in most models only 2 are considered and even that allows for a lot of freedom
  - Computing mean field coefficients from 3D simulations (Schrinner et al. 2007, Ghizaru etal. 2011) shows that in general almost all of them are important!
- Mean field models allow us to study certain scenarios or they allow to analyze a complicated 3D simulation, but one has to be very lucky to find the “correct” model for the solar cycle without additional knowledge
- Non-linear feedback difficult to implement

Solar dynamo models



- Mean field models
  - Convection zone dynamos
  - Tachocline/interface dynamos
  - Near surface shear layer dynamos
  - Flux transport dynamos
- Main uncertainties
  - Location of dynamo
  - Poloidal field regeneration (B_r, B_ϑ from B_φ: α-effect)
  - Turbulent transport (magnetic pumping, turbulent diffusion vs. magnetic buoyancy)
  - Role of meridional flow (propagation of activity belt)

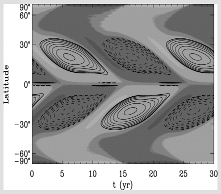
Mean field dynamos



- Thin layer dynamos
  - Overshoot/tachocline dynamos
    - Radial shear, αΩ-type dynamos, latitudinal propagating dynamo wave
    - Negative α in northern hemisphere for equatorward propagation
  - Surface shear layer?
  - Main problem:
    - Typically very short latitudinal wave length (several overlapping cycles)
- Distributed dynamos
  - Interface dynamos
    - Ω-effect in tachocline, α-effect in CZ, introduced to avoid problems with strong α-quenching
    - Solutions very sensitive to details

Mean field dynamos

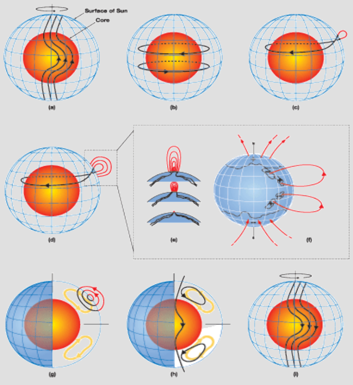
- Distributed dynamos
  - Flux transport dynamo
    - Advective transport of field by meridional flow
    - Propagation of AR belt advection effect
    - Cycle length linked to overturning time scale of meridional flow
  - Central assumption:
    - Proper meridional flow profile (mostly single flow cell poleward at top, equatorward near bottom of CZ)
    - Weak turbulent transport processes
    - Babcock-Leighton α-effect
  - Overall:
    - Most successful in reproducing solar like behavior



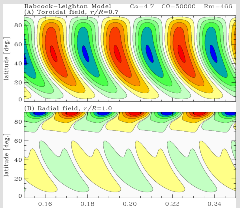
Dikpati et al. 2004

Schematic of a Babcock-Leighton flux transport model
(Durney,Choudhuri,Schüssler,Dikpati,Nandi,Charbonneau,Gilman,Rempel,Hotta)

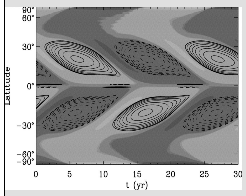
- Differential rotation
  - Toroidal field production
  - Stored at base of CZ
  - Rising flux tubes
- Babcock-Leighton effect
  - Tilt angle of AR
  - Leading spots have higher probability to reconnect across equator
- Transport of magnetic field by meridional flow



Solution properties flux transport dynamos



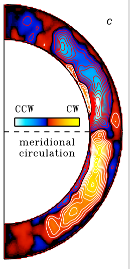
Dikpati & Charbonneau (1999)



Dikpati et al. (2004)

- Good agreement with basic cycle properties
  - Equatorward propagation
  - Weak cycle overlap
  - Correct phase relation between poloidal and toroidal field
- Less good agreement
  - Poleward extension of butterfly diagram?
  - Polar surface field typically too strong
  - Symmetry of solution (quadrupole preferred)
- More complicated ingredients can improve agreement
  - Strong variation of magnetic diffusivity in CZ
  - Additional α-effect at base of CZ
- Expense: Strong sensitivity to many not well known ingredients

Meridional flow structure, assumptions flux transport dynamo

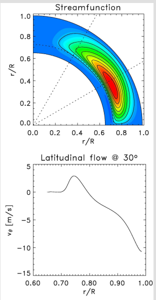


3D simulation
Miesch et al. (2008)

- Observations
  - Poleward near surface (surface Doppler and local helioseismology agree well)
  - Recent results indicate shallow return flow (Hathaway 2011)?
- Theory
  - Mean field models: single flow cell, related to inward transport of angular momentum
  - 3D: low res runs multi cellular, recent high res single cell, results not yet converged
- Advection dominated regime difficult to realize:

$$\eta_{turb} \propto H_p V_{rms}$$

$$V_{merid} \propto V_{rms}^2 / V_{rot}$$



Mean field model
Rempel (2005)

3D simulations

- Solve the full set of equations (including small and large scale flows, magnetic field) from first principles
  - No shortcuts, have to solve for the full problem including differential rotation and meridional flow
  - Non-linear effects automatically included
- Intrinsic limitations
  - Boundary conditions (radial direction)
    - Tachocline at base of CZ
    - Top boundary typically 20 Mm beneath photosphere
  - Cannot capture solar Re and Rm, how to treat small scales
    - DNS: resolve dissipation range with artificially increased diffusivities
    - (I)LES: do only the minimum required to maintain numerical stability
- Very expensive
  - Low resolution runs for long periods >10 years
  - High resolution for short periods
- Good understanding of differential rotation, ingredients of solar dynamo, no complete model yet

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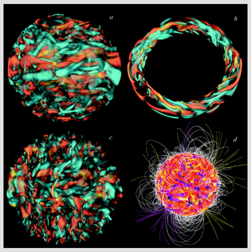
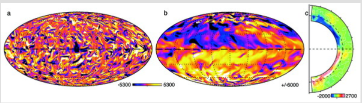
3D dynamo simulations

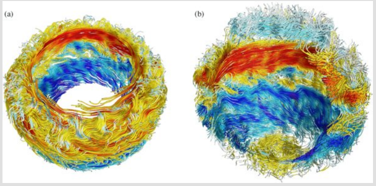
- 1981 Gilman & Miller
  - First 3D convective dynamos in a spherical shell (Boussinesq)
- 1983 Gilman
  - Dynamo simulations with reduced diffusivities
    - large scale field and periodic field reversal
    - poleward propagation
- 1985+ Glatzmaier …
  - Mostly 3D geodynamo models
- 2004 Brun, Miesch, Toomre
  - Turbulent dynamo (anelastic)
    - 800 G peak toroidal field
    - Mean field 2% of energy
    - No cyclic behavior



3D dynamo simulations

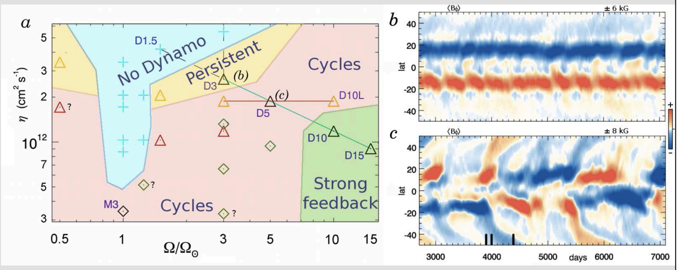
- 2006 Browning et al.
  - Addition of tachocline
  - Organized ~5 kG field in stably stratified region
- 2008+ Brown et al.
  - Faster rotating stars
  - Strong field (~10 kG) maintained within CZ
  - Cyclic behavior for certain parameter choices (faster rotation)





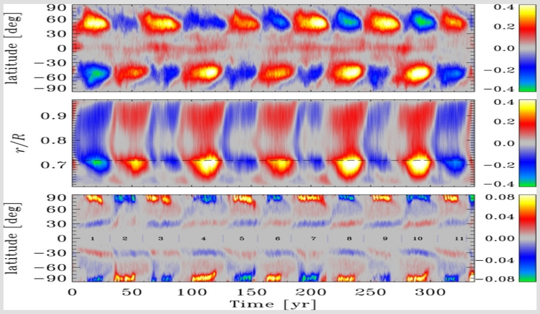
Cyclic dynamo regimes

- 2011 Brown et al.
  - Cyclic behavior typically found for sufficiently high Rm
    - Small diffusivity
    - Fast rotation

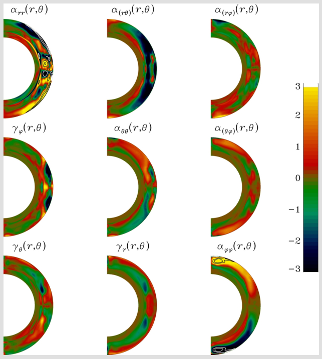


3D dynamo simulations

- 2010 Ghizaru et al., 2011 Racine et al.
  - Cyclic αΩ-type dynamo 60 yr period
  - Magnetic field generated near base of CZ



Characterization of large-scale dynamo (Ghizaru etal. 2011)

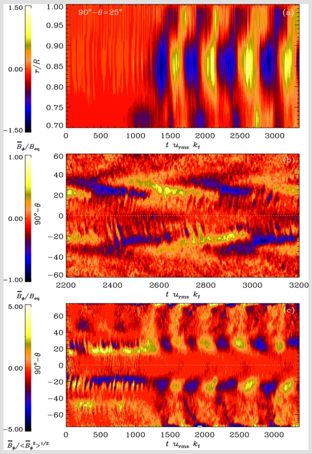


$$(\overline{v' \times B'})_i = (\alpha_{ik} + \varepsilon_{ijk}\gamma_j)\overline{B}_k$$

- ➢ All components have comparable amplitude
- ➢ Strongest effect present in diagonal elements, but substantial deviation from isotropy
  - αϑϑ and αφφ show pattern that reflects expectation from helicity profiles, but not αrr
- ➢ Turbulent pumping
  - Down- and equatorward in bulk on convection zone
  - Poleward near surface in high latitudes
  - Mimics /competes with meridional flow

3D dynamo simulations

- ➢ Kapyla et al. (2012)
  - 33 year period
  - Field generated in bulk of CZ
  - Equatorward propagation below 40 deg latitude
  - Cycle length non-linear effect
    - Much shorter cycles during kinematic growth phase
    - “Phase transition” due to non-linear feedback



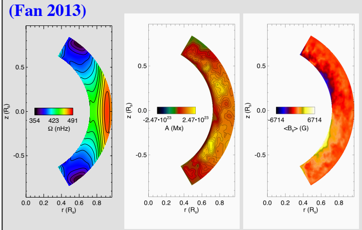
Simulations of convective dynamo in the solar convective envelope with the FSAM code (Fan 2013)

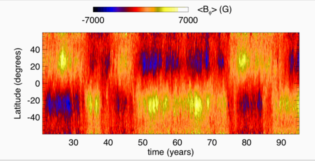
domain: $r \in (0.722R_s, 0.971R_s)$, $\theta \in (\pi/2 - \pi/3, \pi/2 + \pi/3)$, $\phi \in (0, 2\pi)$

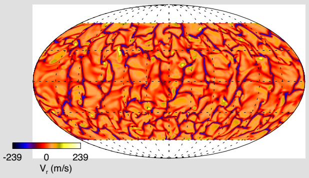
grid: $96 \times 512 \times 768$

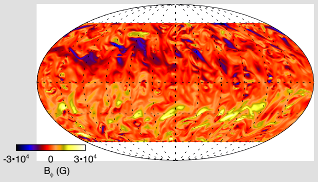
$\kappa = 3\times10^{13}\ cm^2s^{-1}$, $\nu = 1.5\times10^{12}\ cm^2s^{-1}$, $\eta = 1.5\times10^{12}\ cm^2s^{-1}$,

at top and all decrease with depth as $1/\sqrt{\rho}$









3D dynamo simulations

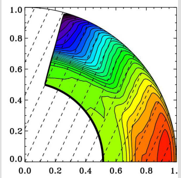
- ➢ Recent developments:
  - Several independent groups find cyclic dynamos with periods in the 10-60 year range
  - Some models with equatorward propagation of activity
  - No simple explanation for cycle length and magnetic field patterns
    - Cycle length non-linear effect (longer cycles in saturated phase)
    - Not obvious if different models get similar solutions for the same reason
- ➢ Contrast to meanfield models:
  - In general no single dominant turbulent induction term (like a scalar α-effect) that could capture the behavior
  - Non-linear feedback more than just saturation effect (i.e. long cycle length only found in non-linear regime)

What are the main uncertainties?

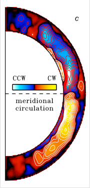
- ➢ Large scale flows:
  - Differential rotation well known
    - Role of latitudinal vs. radial shear not clear

$$\Omega-\text{effect}:\ B_p \bullet \nabla\Omega$$

$$\frac{\partial\Omega}{\partial r} > \frac{1}{r}\frac{\partial\Omega}{\partial\vartheta},\ \text{but typically}:\ B_r\ <\ B_\vartheta$$



    - Role of tachocline (essential or does it just shape activity)
      - Fully convective stars show strong activity!
    - Variation of Ω (torsional oscillations) very small
      - Weak magnetic feedback or DR strongly driven?
      - What does this tell us about saturation?
  - Meridional flow
    - Poleward at surface
    - Flow structure in CZ?
    - Shallow return flow (Hathaway 2011)?



Miesch et al. 2008

What are the main uncertainties?

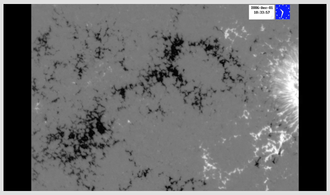
- ➢ Turbulent induction/transport
  - In most 3D simulations turbulence is more complicated than a combination of diffusion, advection and α-effects
  - Flux transport dynamos assume weak (< 10% of MLT estimates) turbulent transport processes - is that reasonable?
    - η has to be small, but not ν and κ (need to transport energy and maintain DR)?
    - no clear indication from numerical experiments for asymmetric magnetic quenching of η, ν and κ
  - More general problem
    - Diffusivities of the order $\eta_{turb} \propto H_p V_{rms}$ give too short cycles
    - Are longer cycles an intrinsically non-linear effect?
  - How is the poloidal magnetic field maintained?
    - kinematic (turbulent) α-effect?
    - magnetic saturation, role of magnetic helicity?
    - driven by magnetic instabilities?

What are the main uncertainties?

- Flux emergence process
  - By-product of dynamo or essential part of dynamo process?
    - 10^{24} Mx is a lot of flux: 10 kG x 100 Mm^2
  - Poloidal field in photosphere consequence of AR tilt angle
    - Babcock-Leighton α-effect
    - Is that enough to drive the dynamo?
      - Polar flux ~ 0.1% of toroidal flux
      - How to get back from 0.1% to 100%
      - DR can do ~100!
      - Babcock-Leighton flux transport dynamos have typically too strong polar field!
- What determines field amplitude
  - Feedback on DR, meridional flow?
  - Quenching of turbulent induction (magnetic helicity) ?

Flux emergence and sunspot formation

- General accepted view
  - Magnetic flux rising toward surface from deep convection zone
  - Observations show at first strong horizontal expansion of emerging flux
- Key question
  - Transport of flux through convection zone and re-amplification in photosphere:
    - Density contrast of 10^6
      - $B \sim \rho^{\varepsilon}$ $\varepsilon = 1/2 \ldots 2/3$
      - 100 kG -> 100 G
      - 100 G -> 3kG ???
    - Vigorous convection



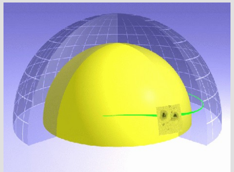
Flux emergence event observed with Hinode SOT

Modeling of flux emergence

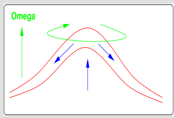
- Lower convection zone (up to ~ 20 Mm depth beneath photosphere)
  - Strongly subsonic velocities
  - Ideal gas equation of state sufficient
  - Size of flux tubes smaller than Hp and typical scale of convection
    - Flux tubes travel several times their diameter
    - Interaction with ambient flows (including flows created by rising flux) key to dynamics
    - Density contrast of 100 (out of 10^6)
  - Modeling approaches
    - Thin flux tube approximation
    - 3D anelastic MHD models
    - Both with and without background convection

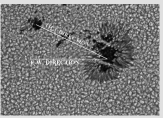
Flux emergence in lower convection zone

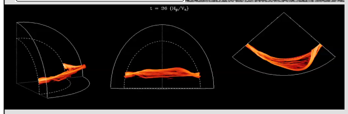
(Caligari, Fan, Fisher, Moreno-Insertis, Schüssler …)



Thin flux tube simulation: Caligari et al. (1995)





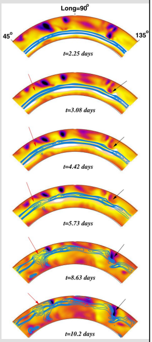


3D simulation: Fan (2008)

- Consistent results from thin tube and 3D simulations
- Coriolis force causes tilt of the top part of tube
- Explains asymmetry between leading/following spot
- Works best with ~ 100 kG flux tubes
  - Consistent with stability considerations in overshoot region
  - Too strong for dynamo models
- Twist required for 2D/3D simulations
  - Prevents fragmentation
  - Induces additional tilt (opposing that from Coriolis force)
  - Trade off between stability and tilt

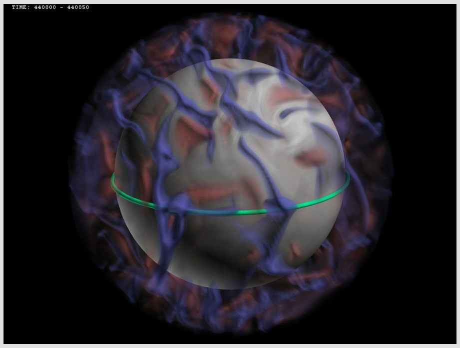
Interaction with convection

- 3D anelastic MHD (Jouve & Brun 2009)
  - Self consistent interaction with convection, differential rotation and meridional flow (Global convection zone simulation)
  - Convective motions additional source of tilt, substantially shape tube during rise
  - Challenge: Focus on global picture limits resolution on the scale of flux tube, requires tubes with $>>10^{22}$ Mx flux
- Thin flux-tubes rising in convective background
  - Take velocity from global CZ simulation
  - Treat flux tube as thin tube
  - Weber, Fan & Miesch 2011



Jouve & Brun (2009)

Interaction with convection



Weber, Fan & Miesch (2011)

- Thin flux tube rising in convective envelope (taken from global 3D simulation)
- Flux tube evolution mostly dominated by convective time scales
- Less dependence on initial field strength
  - Best results for 40-50 kG (100-150 kG without convection)

Flux emergence in upper most 20 Mm

- Upper convection zone
  - Subsonic/supersonic transition velocities
  - Partial ionization, 3D radiative transfer important
  - Size of flux tubes larger than Hp and typical scale of convection
    - Flux 'tubes' travel about their diameter
    - Density contrast of 10^4 (out of 10^6)
    - Dynamics dominated by strong expansion
    - Most weakening of field strength near surface
  - Modeling approaches
    - Fully compressible MHD (with RT and realistic EOS)
- Currently treated independent from deep convection zone (computational constraints)

Flux emergence, sunspot formation

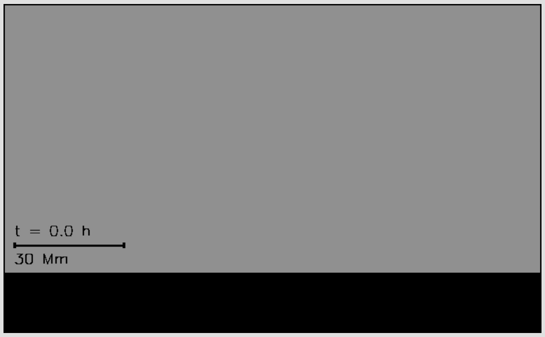
Magnetogram

(tau=1)

Domain size:

150x75x16 Mm

|B|
(vertical slice)



Rempel & Cheung 2013

Sunspot fine structure

highest resolution, short time scales, shallow domains

Resolution:
16x16x12 km
(3072x3072x512)

Computing resource:
NSF-Teragrid
Cray-XT5 (Kraken, NICS)
3072-12288 cores
1 solar hour
~ 3 days (on 12288 CPUs)
~ 800,000 CPU hours
~ 10 TB data (3 TB/day !)

Data handling major challenge!
Achieved data rates larger than
SDO mission!