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NICS

Simulations of Solar Active Regions

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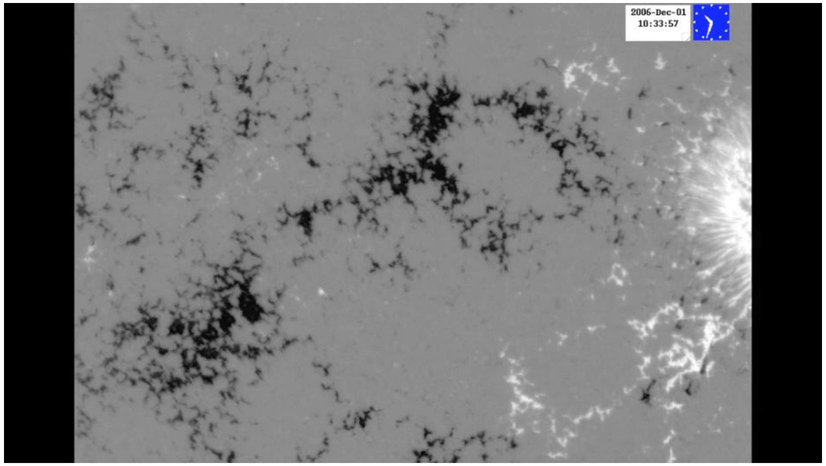
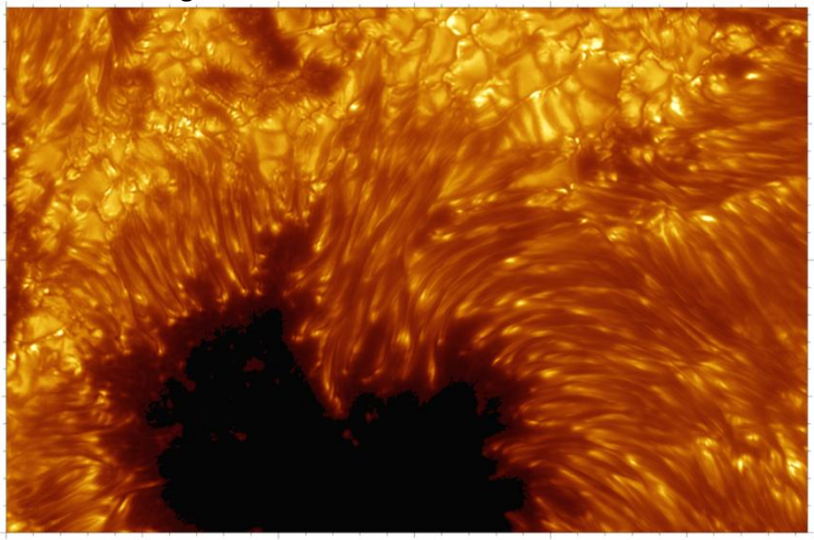
Sunspot formation and fine structure

- Sunspots are the most prominent concentrations of strong (about 3 kG) magnetic field on the sun
- They form from a magnetic field emerging into the photosphere from beneath
- Sunspots exhibit fine structure (umbral dots, penumbral filaments) on the smallest scales currently observable
- Project focuses on simulations of active region formation (large domains and long time scales) and sunspot fine structure (high resolution for shorter time periods)



Flux emergence event observed with Hinode SOT



Sunspot fine structure observed with Swedish Solar Telescope (SST)

Simulation setup (flux emergence)

- Radiative MHD equations—grey approximation for radiative transfer; OPAL equation of state for a solar mixture
- Cartesian domain
  - 92,000 x 49,000 x 8300 km^3
  - Bottom boundary at z = -7500 km (10 pressure scale heights to base of photosphere)
  - 960 x 512 x 256 grid cells
- Initial condition: convection without magnetic field
- Periodic side boundaries
- Potential field at top boundary
- Following Rempel, Schüssler, and Knölker (2009), artificially limit Alfvén speed (through reduction of Lorentz force where plasma-beta < 0.05)

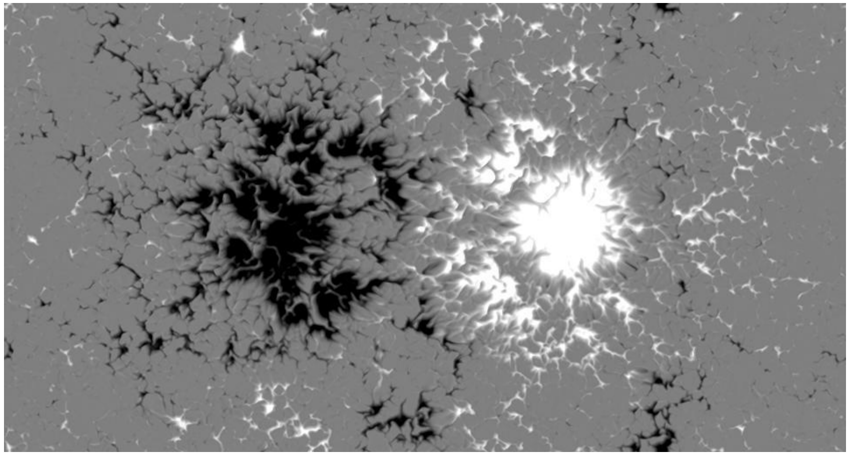
Introduction of magnetic tube

- **Kinematically advect a twisted semi-torus into the domain with an upflow speed of 1 km/s (Mach number approx. 0.03)**
- **Semi-major axis: R = 16,000 km**
- **Semi-minor axis: a = 3600 km**
- **B = 21 kiloGauss (at tube axis), plasma β = Gas Pressure/Mag Pressure = 26**
- **Toroidal flux = 7 x 10^{21} Mx**
- **The dimensionless twist parameter λ was varied to examine the effect of magnetic twist on the formation of the active region**

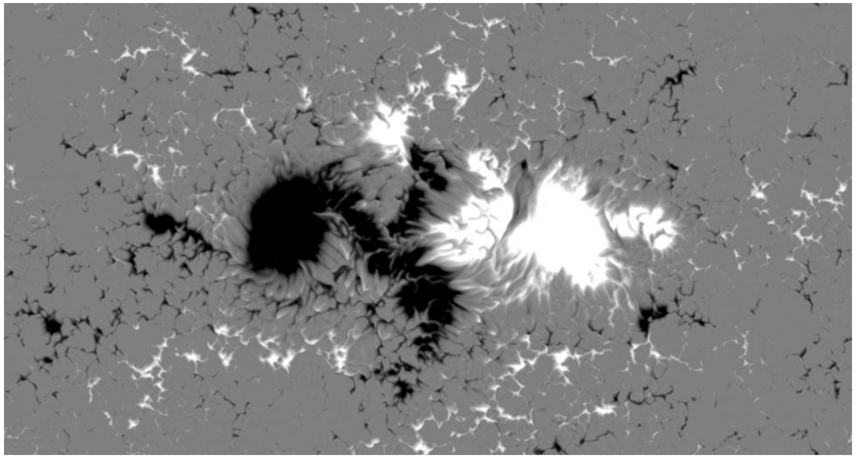
$$\begin{aligned}
\mathbf{B} &= \nabla \times [A_\phi(r,\theta)\hat{\phi}] + B_\phi(r,\theta)\hat{\phi}, \\
A_\phi(r,\theta) &= \frac{\lambda a^2 B_t}{2r\sin\theta} \exp\left\{\frac{-\varpi^2}{a^2}\right\}, \\
B_\phi(r,\theta) &= \frac{a B_t}{r\sin\theta} \exp\left\{\frac{-\varpi^2}{a^2}\right\}, \\
\varpi &= \sqrt{r^2 + R^2 - 2rR\sin\theta}.
\end{aligned}$$

Following Fan and Gibson 2004

Effect of twist on active region formation



Simulation without magnetic twist



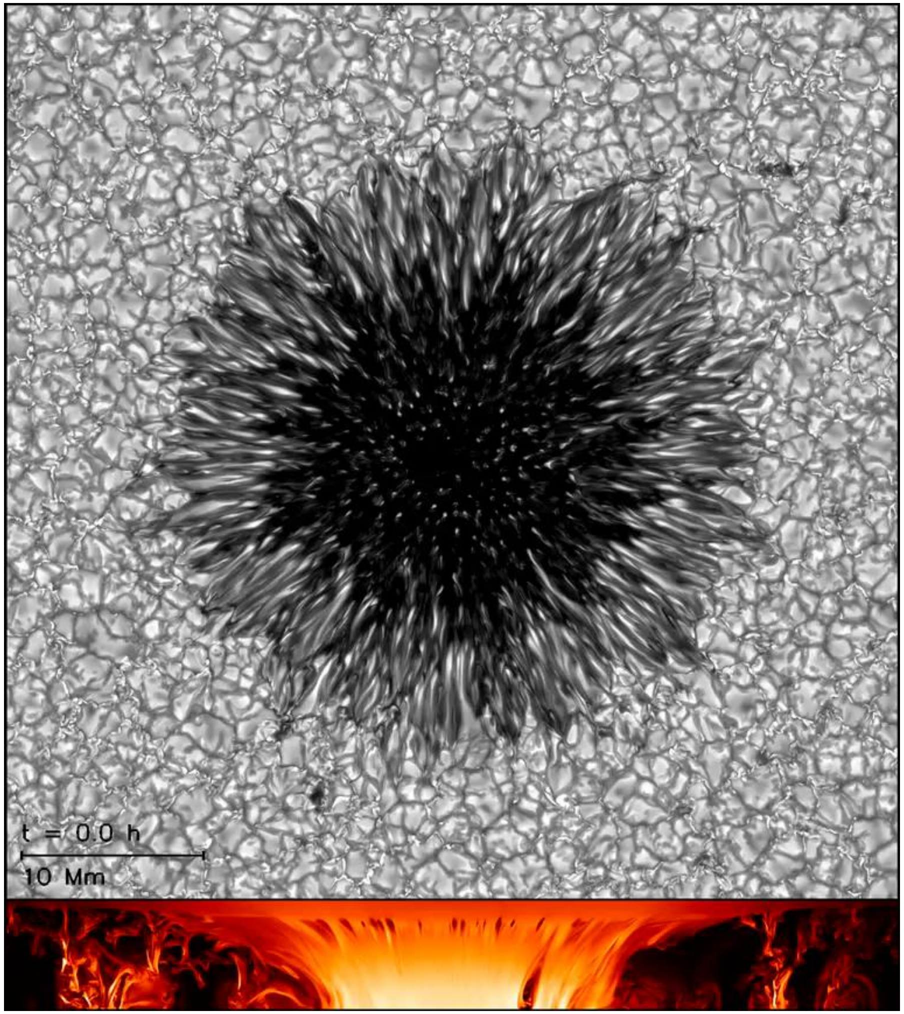
Simulation with $\lambda = 0.25$

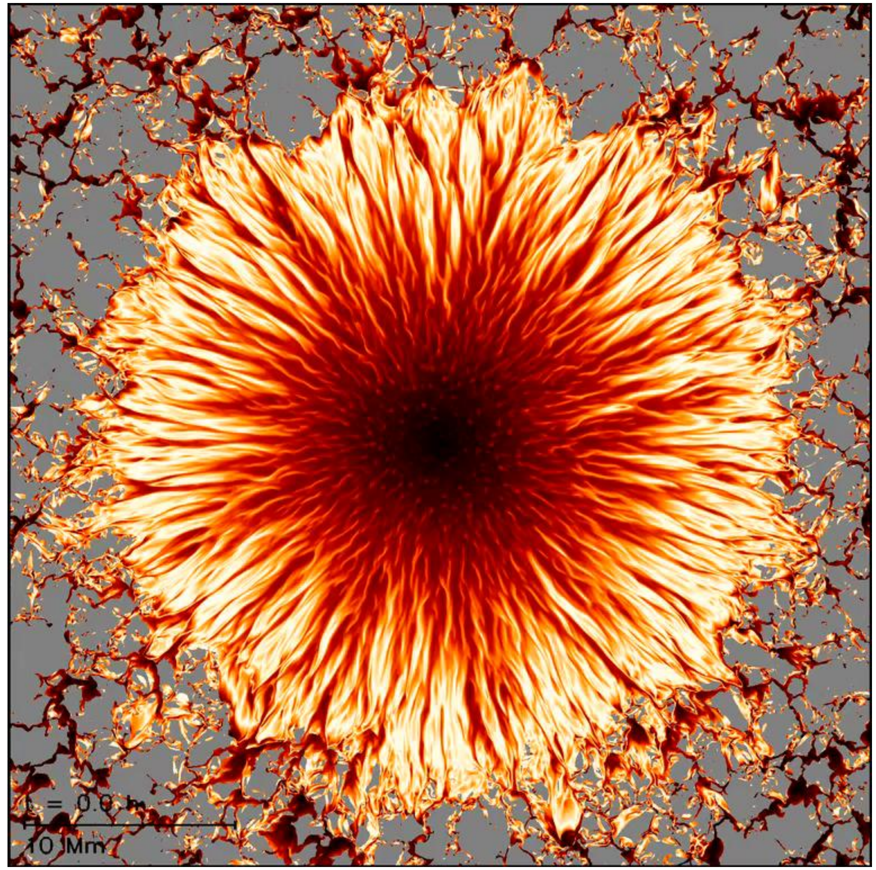
The simulation of the emergence of an untwisted torus demonstrates that magnetic twist is not necessary for the coalescence of the emerged magnetic flux into coherent spots. This is consistent with the varying degrees of twist inferred in observed active regions

When magnetic twist is present, Lorentz forces lead to a systematic torque that drives rotating surface flows

Simulation setup (fine structure)

- Cartesian Domain
  - 49 x 49 x 6.1 Mm
  - Resolution from 96 x 96 x 32 to 16 x 16 x 12 km
  - Up to 3072 x 3072 x 512 grid points
  - Simulation ran on up to 12288 cores on Kraken
- Initial condition
  - Axisymmetric field structure added into thermally relaxed convection simulation (full flux emergence process is too expensive at the resolution required here)
- Focus of simulation
  - Investigate robustness of previously found results with respect to grid resolution



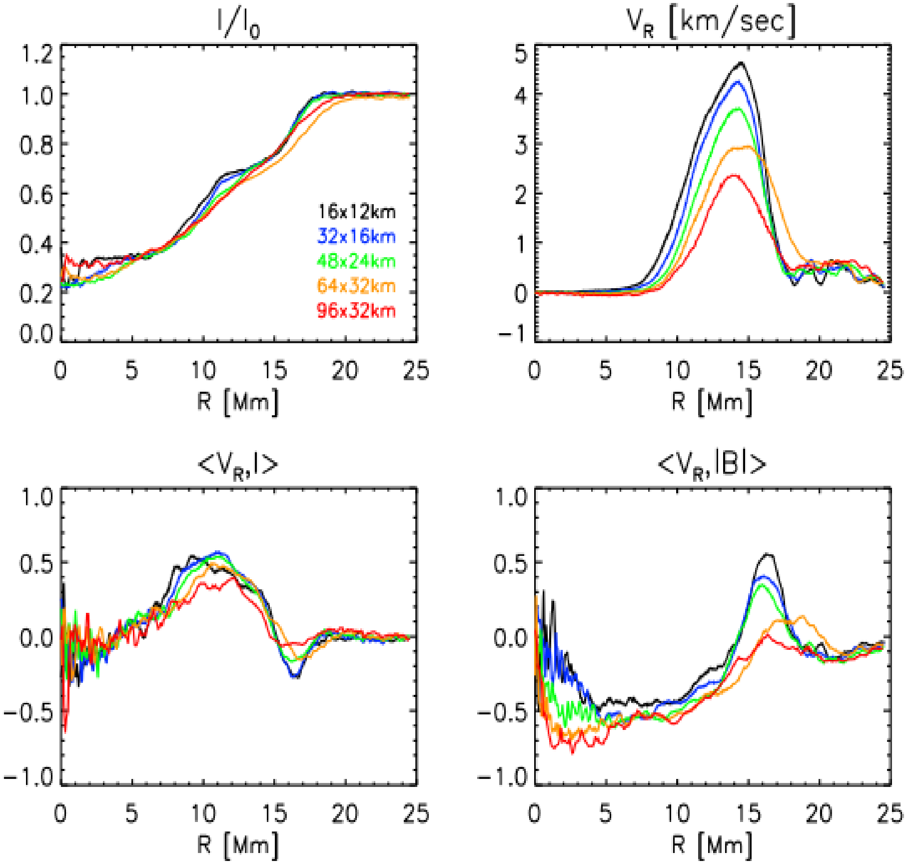


Left: Intensity and subsurface field strength
Right: Inclination angle of field (vertical, black; horizontal, bright yellow; regions with |B| < 200 G, grey)

Numerical simulation explains sunspot fine structure as consequence of magneto-convective energy transport in umbra and penumbra. Large scale horizontal outflows of up to 5 km/s average velocity are driven by magnetic forces

Convergence study and robustness of results

- **High resolution runs on Kraken allowed for a thorough convergence study**
- **Most properties of sunspot fine structure and amplitude of large scale outflows are well captured with a grid resolution of 48 x 24 km**



Convergence of properties in photosphere with grid resolution. **Top:** mean intensity and outflow velocity as function of distance from spot center
Bottom: Correlations between outflow and intensity as well as field strength

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