Exoplanet Dynamo Simulations

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We learn about planetary magnetic fields from observations, laboratory experiments, and numerical simulations.

Dynamo simulations: fluid flows in a rotating electrically-conducting density-stratified fluid maintain differential rotation and helical flows, which generate a 3D time-dependent magnetic field according to the magnetohydrodynamic equations.

2D differential rotation shears poloidal magnetic field into toroidal field.
3D helical flows twist toroidal magnetic field into poloidal field.

Before starting a 3D dynamo simulation of an exoplanet one would need to identify (or assume and approximate) the material properties of the fluid and the dominant processes that drive and influence fluid flow and magnetic induction. (Also the equations, numerical methods, …)

Radial profiles of the mean density, temperature, pressure, composition, thermodynamic derivatives, and viscous, thermal, compositional and magnetic diffusivities.

Heating: gravitational contraction, radiogenic, ohmic, stellar.

Cooling: progression through a series of nearly adiabatic stratifications.

Fluid shell thickness.

External gravitational fields (precession, tides).

Thermal and compositional stratifications:
unstable (convection), stable (gravity waves), double diffusive (both), phase transitions (latent heat flux).

Dynamo action requires fluid flow that has sufficiently vigorous shear and helicity.

Dynamos for which the effects of rotation dominate over convection tend to have magnetic polarities that reverse infrequently (or not at all).

Dynamos for which the effects of convection dominate over rotation tend to have polarities that reverse more frequently than the geodynamo.

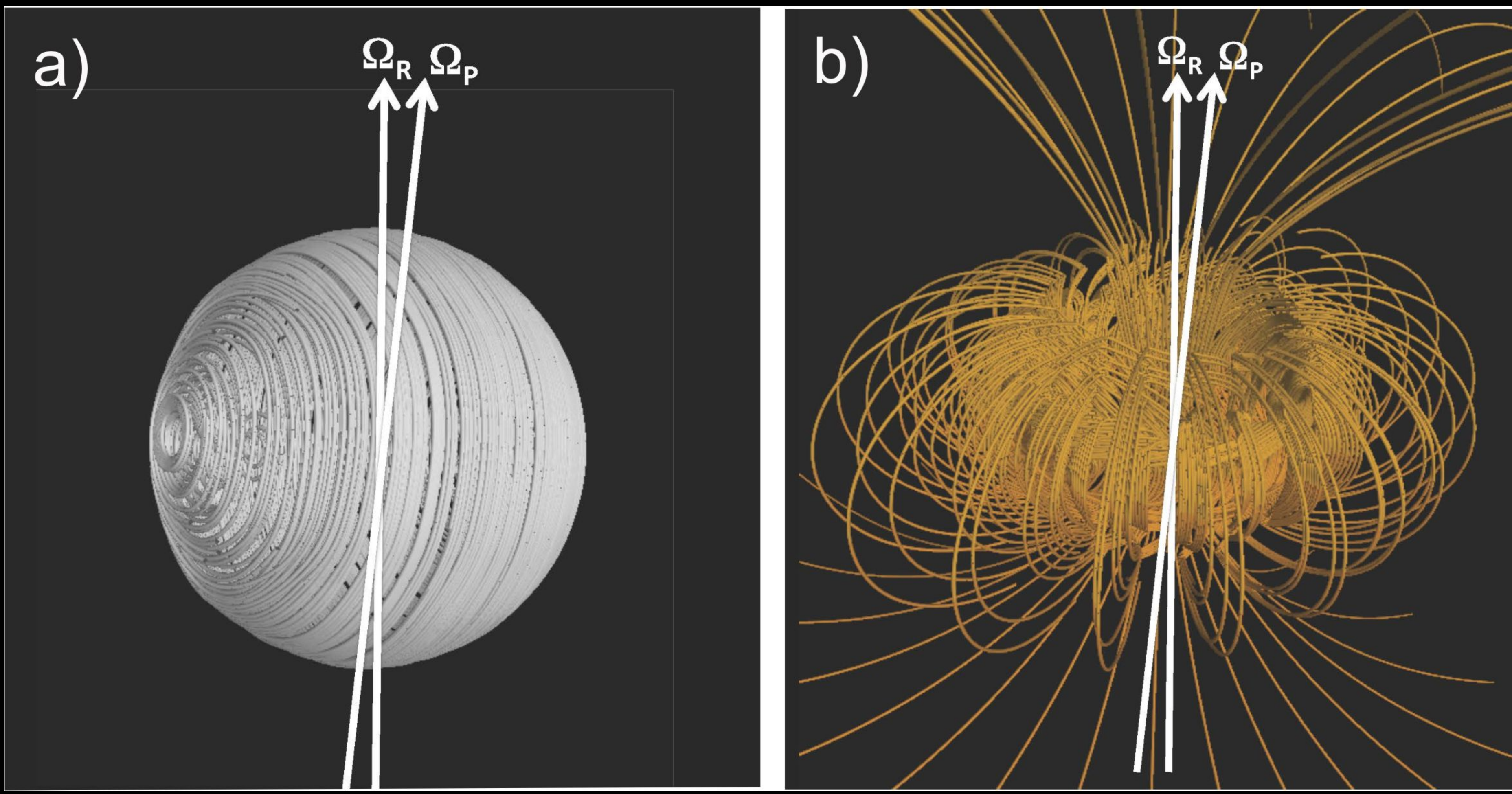
Convection of a silicate mantle above a fluid iron core:

the more vigorous the mantle convection and plate tectonics,
the greater the heat flow and the more vigorous the core convection,
the more frequent the magnetic polarity reversals,
and the shorter the dynamo lifetime.

Boundary conditions:

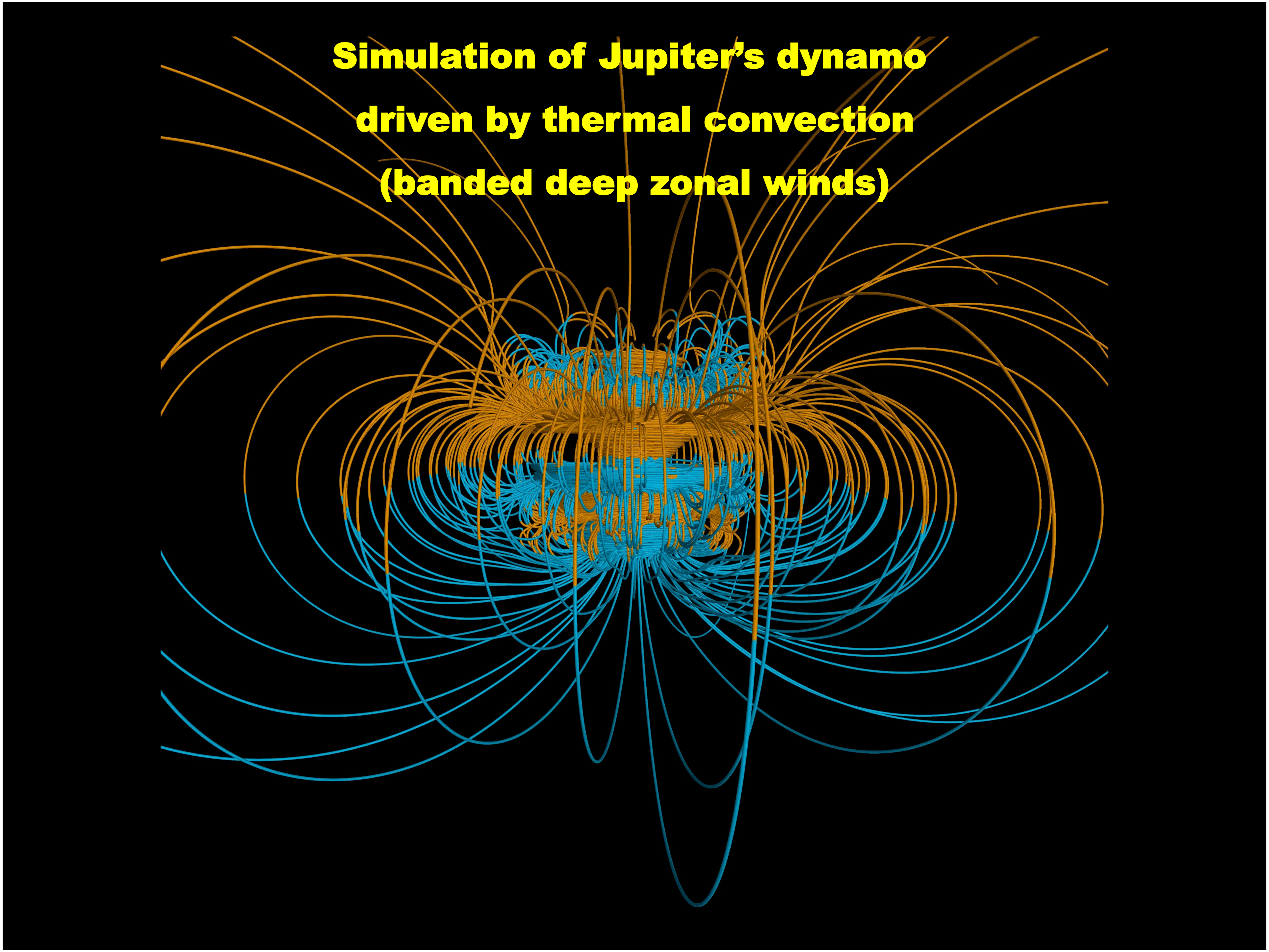
Non-slip or free-slip, impermeable or permeable (free surface),
heterogeneous heat flux, chemical reactions, phase transitions,
"hot Neptunes" and "hot Earths" (tidally locked, day / night sides,
time-dependent external magnetic and gravity fields and stellar radiation).

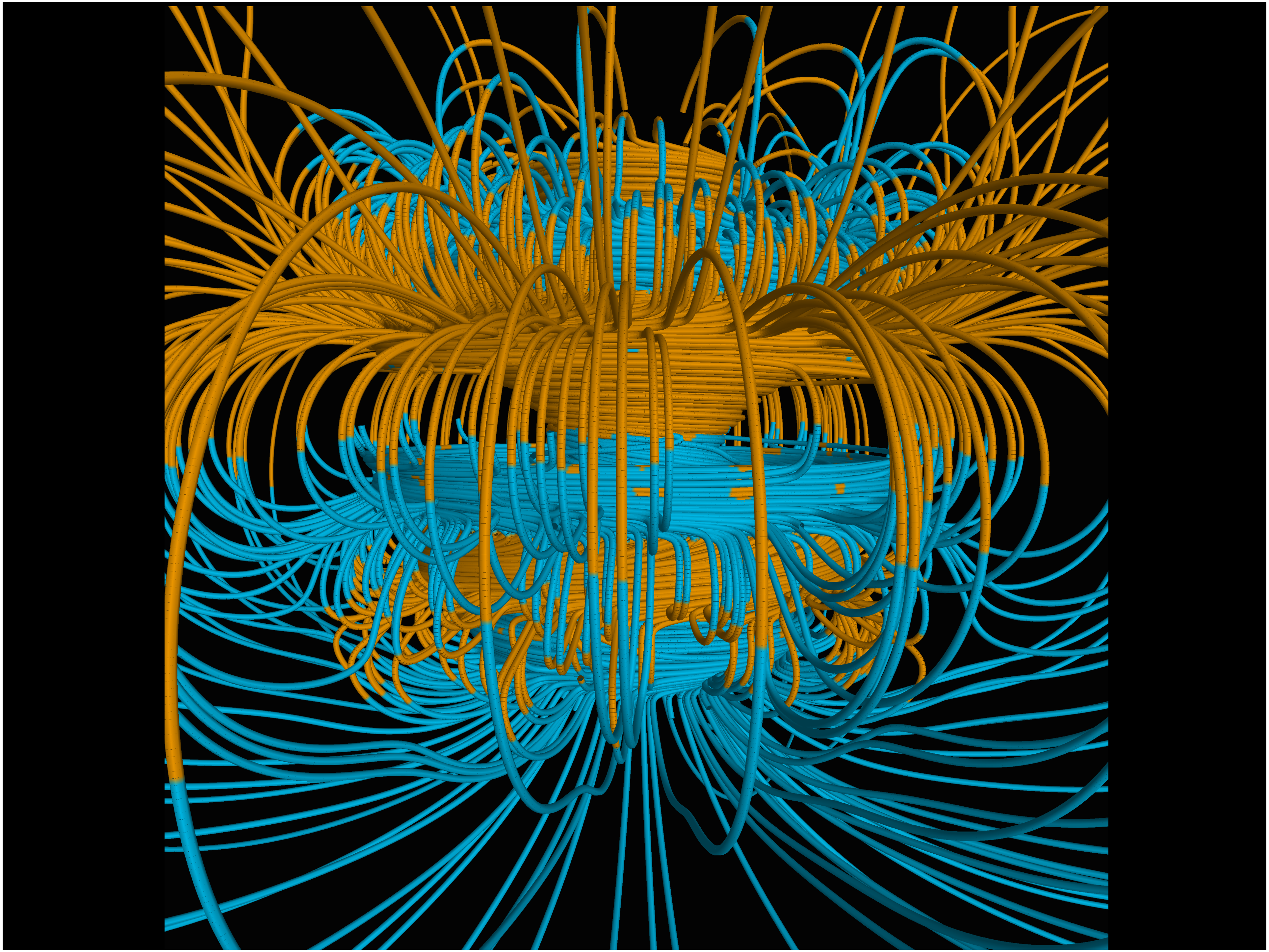
Simulation of the ancient lunar dynamo driven by precession



"tilt-over" fluid flow pattern

magnetic field lines

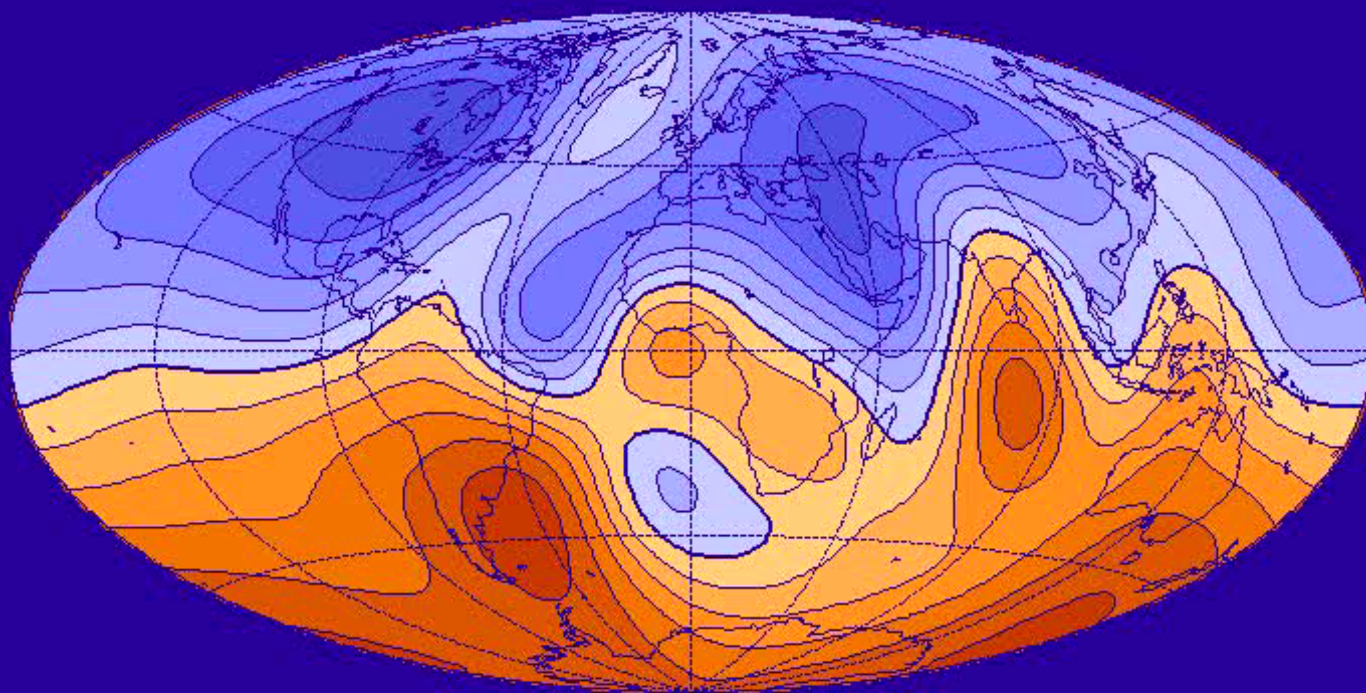

Simulation of Jupiter's dynamo
driven by thermal convection
(banded deep zonal winds)



The Earth's magnetic field

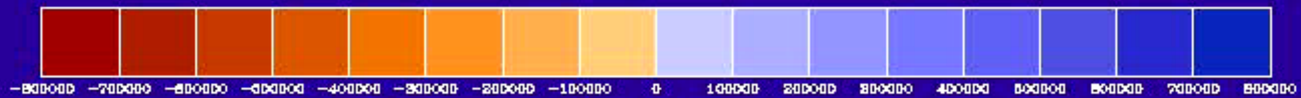
(radial component at the CMB)

1590



Contour interval = 10^5

Andy Jackson



Simulation of the geodynamo

driven by thermal and compositional convection

(radial component at the CMB)