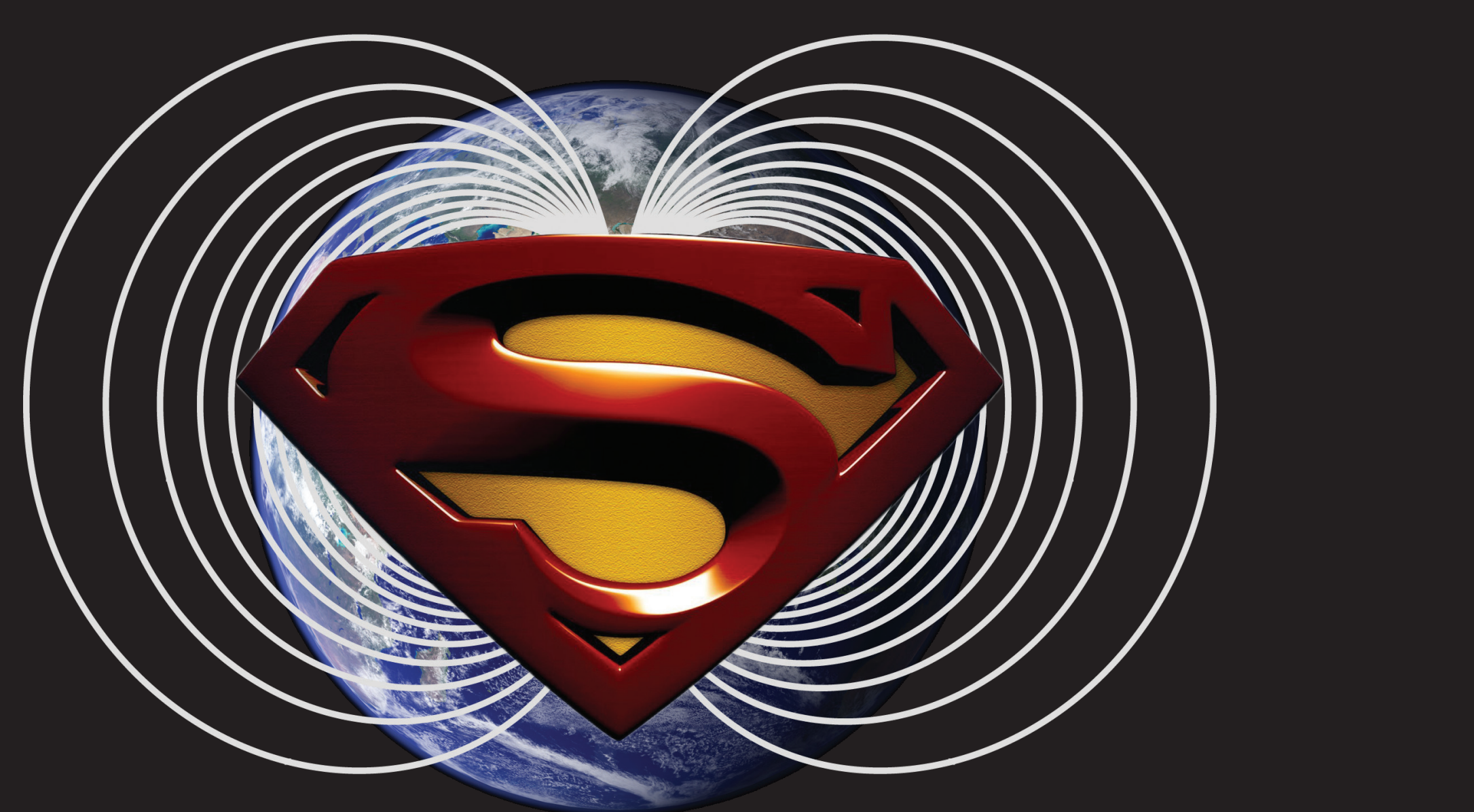
The Effect of Lower Mantle Metallisation on the Dynamo Generated Magnetic Fields of Super-Earths

Ryan Vilim[a], Sabine Stanley[a], Linda T. Elkins-Tanton[b]
[a] Department of Physics, University of Toronto
[b] Department of Terrestrial Magnetism, Carnegie Institution of Washington



Motivation

The ever increasing number of exoplanets that have been discovered has prompted research into the possible internal structure of these planets. In the deep interiors of large terrestrial exoplanets (super-Earths), much higher pressures and temperatures will be present than occur in the Earth, leading to interesting new material properties. These novel material properties could have a significant impact on the dynamics of planetary evolution in these planets.

Recent work[1,2,3] has shown that at the pressures which are expected to exist within super-Earths, some silicates should dissociate and metallise, conducting electricity with a conductivity near that of iron. This should have an effect on the dynamics of both the mantle[4] and the core. Here we use a numerical dynamo model which incorporates a conducting lower mantle to determine the effect of this metallisation on magnetic field generation in terrestrial exoplanets.

Implementation

We use the Kuang-Bloxham numerical dynamo model[5] to simulate magnetic field generation in the core of a super-Earth with a conducting mantle. The equations this model solves are in Box 1.

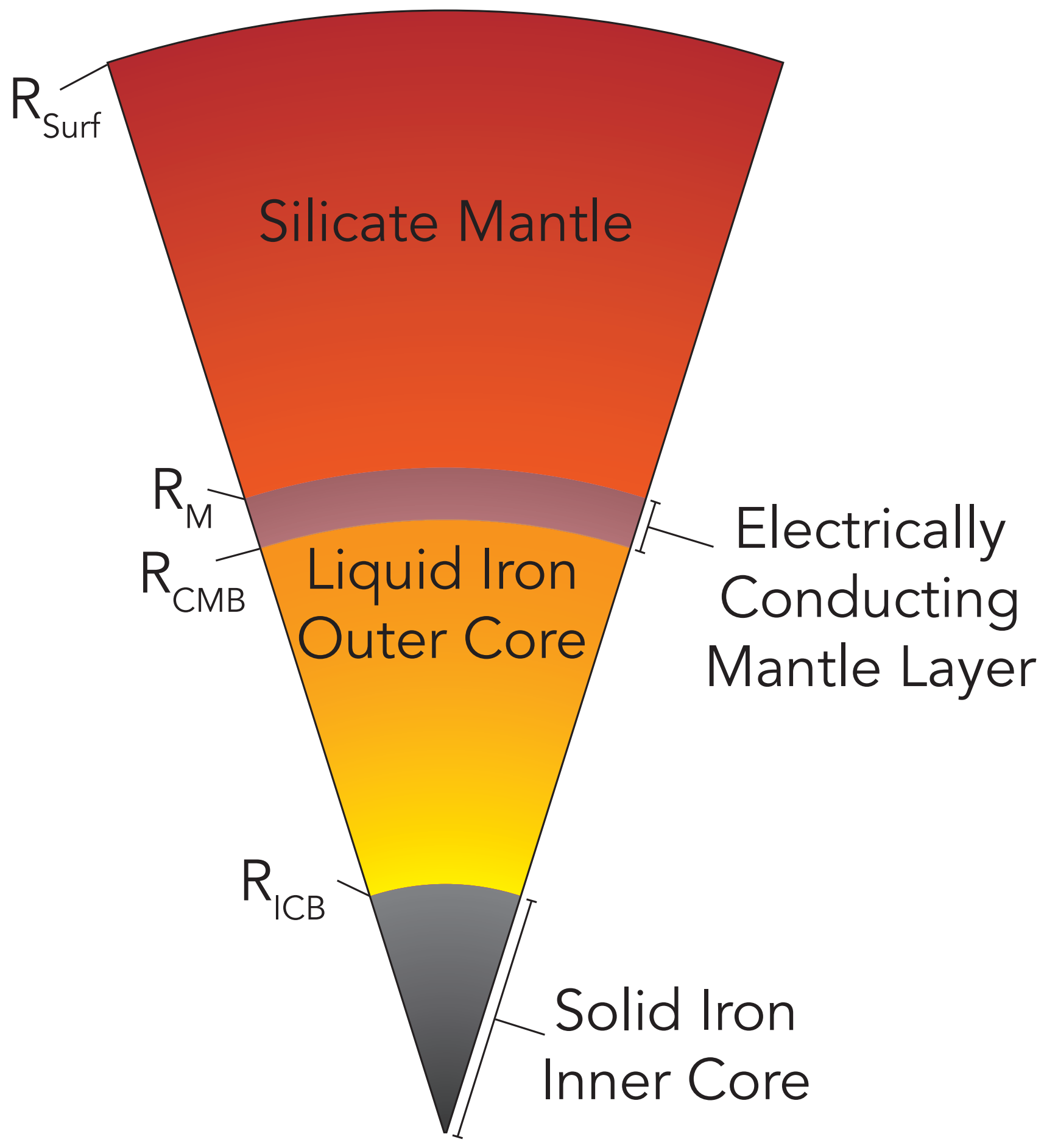


Figure 1: A schematic diagram of a planet with an electrically conducting mantle. Our model solves for the region below R_M.

In our models we choose a conducting mantle layer that extends from R_{CMB} to 1.07 R_{CMB} (where R_{CMB} is the core mantle boundary radius) (Fig. 1). The relative conductivity of the mantle layer is given by $^{\sigma_M}/_{\sigma_o}$ which varies from 0.0025 ($^1/_{400}$) to 1 in our simulations. We also choose three inner core sizes (0.35R_{CMB}, 0.5R_{CMB}, 0.7R_{CMB}), to represent terrestrial exoplanets in various stages of their thermal evolution. All other parameters are kept constant and are listed in Box 1.

$$Ro\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}+\hat{\mathbf{z}}\times\mathbf{u}=-\nabla p+\mathbf{J}\times\mathbf{B}+Ra\Theta\mathbf{r}+E\nabla^2\mathbf{u}$$

$$\frac{\partial T}{\partial t}+\mathbf{u}\cdot\nabla T=q_\kappa\nabla^2 T$$

$$\frac{\partial\mathbf{B}}{\partial t}=\nabla\times(\mathbf{u}\times\mathbf{B})+\nabla^2\mathbf{B}$$

Ra = Rayleigh # = $\frac{\alpha_C g_o h_C r_o^2}{2\Omega\eta}$ = 12000
E = Ekman # = $\frac{\nu}{2\Omega r_o^2}$ = 2.112x10^{-5}
Ro = Magnetic Rossby # = $\frac{\eta}{2\Omega r_o^2}$ = 4.225x10^{-6}
q_κ = Roberts # = $\frac{\kappa}{\eta}$ = 5

$\mathbf{B}$ Magnetic Field
$\mathbf{u}$ Velocity
T Temperature
$\mathbf{\Theta}$ Temperature perturbation

Screening Effect

The addition of a conducting mantle layer should attenuate the external field by a factor proportional to $e^{-\sqrt{\omega\mu_o\sigma_M r/2}}$. Where r is the size of the conducting layer, ω is the characteristic timescale of the field, and μ_o is the magnetic permeability of free space. Because small scale field components typically vary faster than large scale field components, this will have the effect of preferentially damping any observed small scale components.

Lorentz Force Coupling

In addition to the screening effect, the dynamo can also be affected by magnetic coupling to the mantle. A consequence of magnetic flux conservation is the frozen flux theorem, where magnetic field lines are frozen into conductors. This means that if the mantle conducts electricity, the magnetic field lines coming from the dynamo region will become stuck in the mantle. As they are simultaneously frozen into the liquid outer core, the large zonal flows that typically form in dynamo simulations will shear these magnetic field lines.

Results

We find that the addition of an electrically conducting mantle to a dynamo increases the strength of both the internal field, and the field at the CMB. This is due to the ease with which the dynamo is able to shear magnetic field which is anchored into a conducting mantle. In Fig. 2 we plot the axisymmetric ϕ component of the magnetic field for a case where $^{\sigma_M}/_{\sigma_o}$ =0.0025 ($^1/_{400}$) (non-conducting mantle, left) and $^{\sigma_M}/_{\sigma_o}$=1 (highly conducting mantle, right). Note that in the highly conducting case, a large amount of toroidal field is sheared out at a radius coincident with the CMB.

As the dynamo mechanism converts toroidal field into poloidal field, we find that the poloidal field is stronger after the addition of an electrically conducting mantle (Fig. 3a). We find that the increase in the poloidal energy at the CMB occurs mostly in the non-axisymmetric parts of the field (Fig. 3c,d). However, these non-axisymmetric components are preferentially screened by the conducting mantle layer.

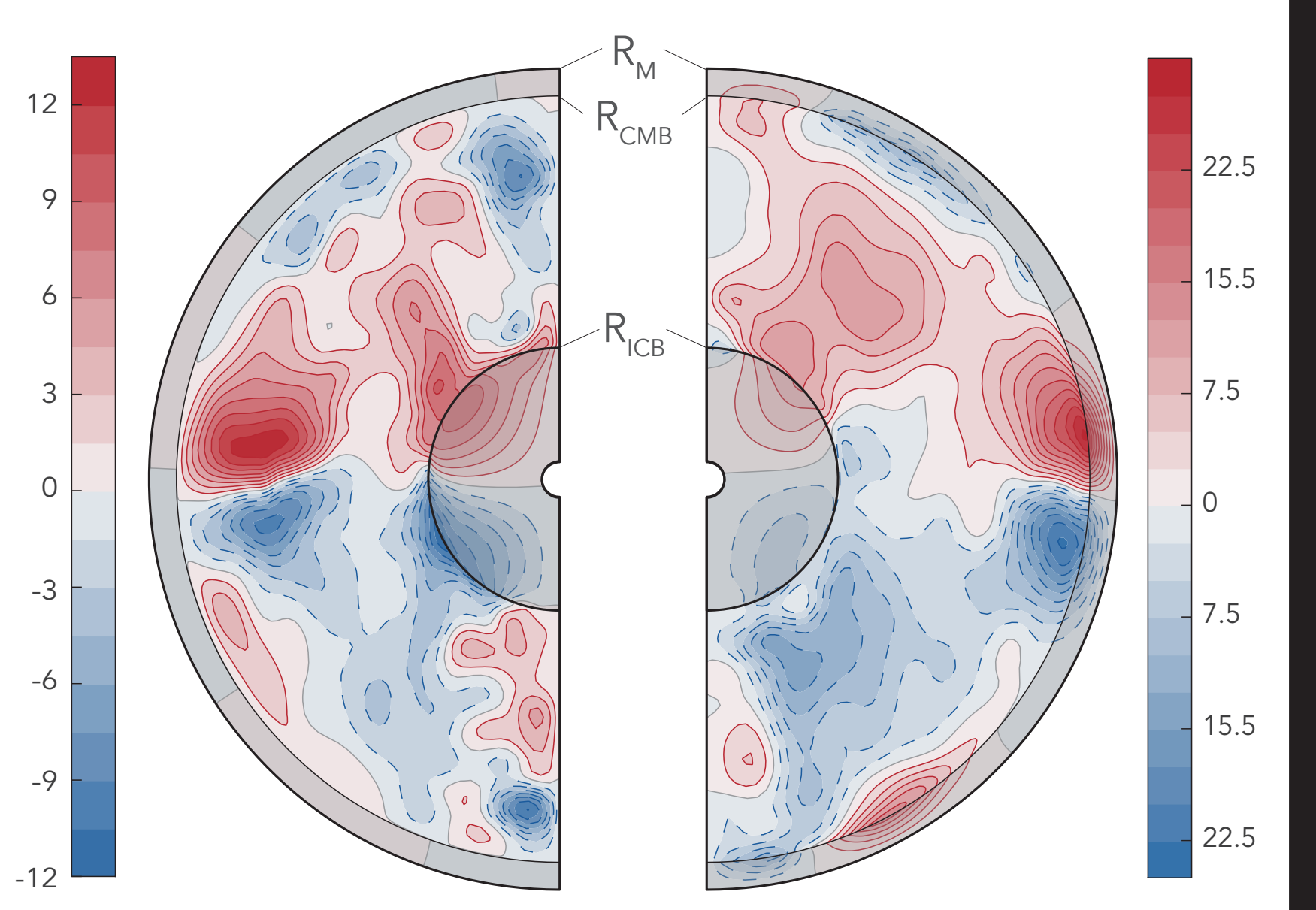


Figure 2: Snapshots of the axisymmetric ϕ component of the magnetic field for R_{IO}=0.35. Left: A simulation without an electrically conducting mantle, Right: A simulation with an electrically conducting mantle. Note the differing scales in each plot.

This means that above the conducting mantle layer the poloidal field increases only marginally, or decreases (Fig. 3b). We conclude that terrestrial exoplanets with metallised mantles should be more difficult to detect than planets without metallised mantles despite generating stronger poloidal magnetic fields at the top of the dynamo region.

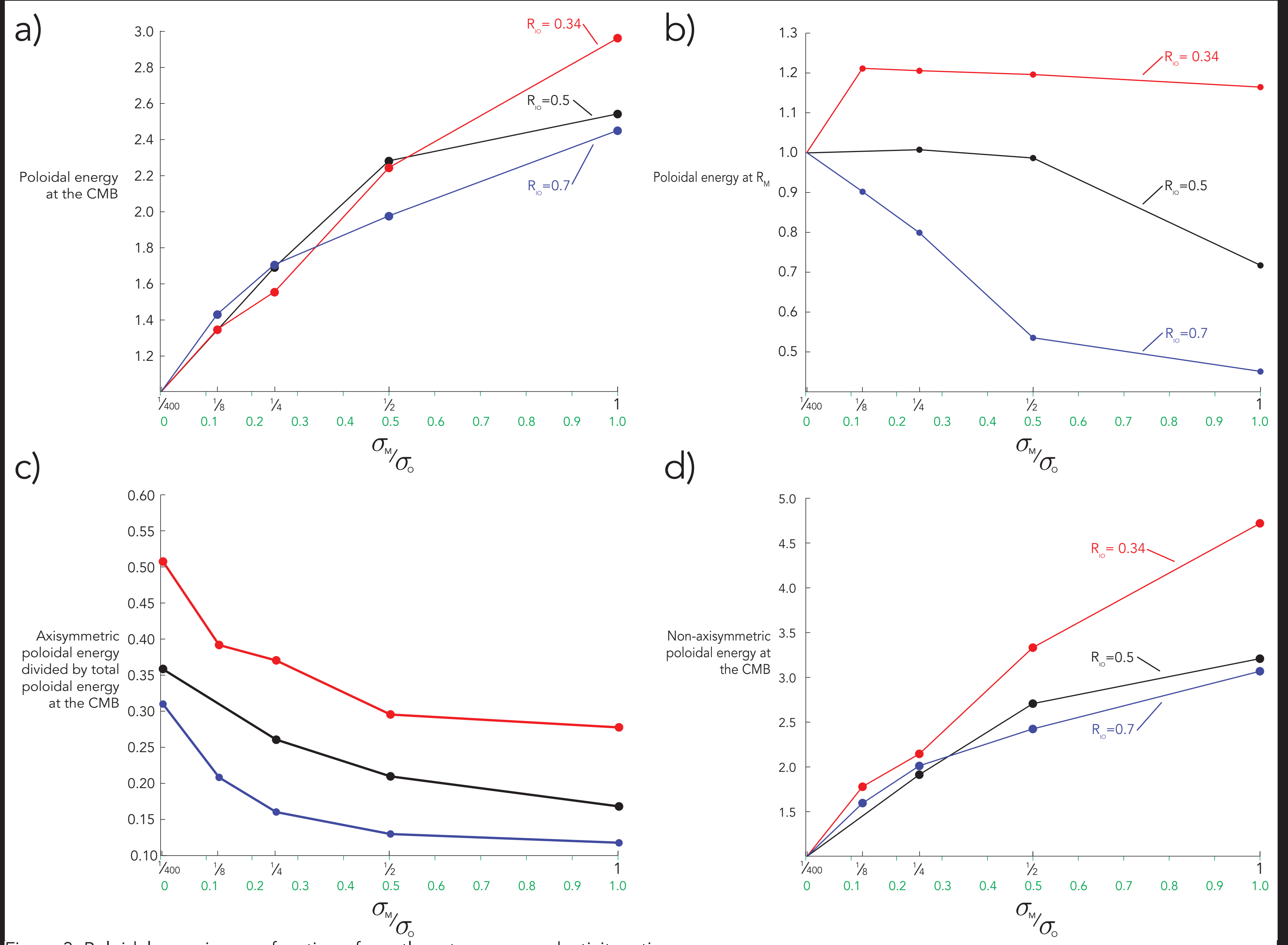


Figure 3: Poloidal energies as a function of mantle outer core conductivity ratio.

References

1. Tsuchiya, T. and Tsuchiya, J. (2011). PNAS, 108, 1252-1255
2. Nellis, W. J. (2011). The European Physical Journal Special Topics. 196, 121–130
3. Ohta, K., Cohen, R.E., Hirose, K., Haule, K., Shimiu, K., and Ohishi, Y. (2012). PRL, 108, 026403
4. van den Berg, A. P., Yuen, D. A., Beebe, G. L., & Christiansen, M. D. (2010). Physics of the Earth and Planetary Interiors. 178, 136–154
5. Kuang, W., & Bloxham, J. (1999). Journal of Computational Physics, 153, 51–81