Mantle convection and plate tectonics on rocky exoplanets

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Already a number of rocky exoplanets have been discovered, ranging in size from sub-Earth mass to super-Earths of up to ~10 Earth masses (~2 Earth radii). Obvious and linked questions to ask are: Do they have plate tectonics, and what are their interior dynamics? Simple scaling relationships predict that larger versions of the Earth (same composition, surface temperature and surface water) are more likely to have plate tectonics than an Earth-size planet (van Heck and Tackley, 2011). However, there are a number of ways in which exoplanets differ from Earth, and these present challenges to our understanding. Here I focus on three differences. Firstly, pressure: deep super-Earth mantles reach much higher (up to 10 times) pressure than the Earth's deep mantle, implying large differences in physical properties, particularly viscosity. If conventional creep mechanisms (diffusion/dislocation-creep) are dominant, a huge viscosity increase with pressure along an adiabat is expected, which simulations predict would lead to a strongly super-adiabatic temperature gradient in their deep mantles (Tackley et al., 2013). However, it has alternatively been proposed that interstitial diffusion may become the dominant creep mechanism at high pressure (Karato, 2011 Icarus), which would lead to a roughly constant viscosity with pressure and thus a quite different temperature profile and more vigorous deep-mantle dynamics. Some phase transitions have also been proposed to take place at the very high pressures reached. Secondly, composition: Exoplanets may differ substantially in composition from Earth, leading to differences in their physical properties and melting behaviour, which can influence their long-term evolution (Spaargaren et al. 2020). Ongoing work is investigating the plausible range in compositions (Spaargaren et al., in press) and their influence on dynamics. Thirdly, surface temperature. Of special interest here is tidally-locked planets, on which the equilibrium surface temperature varies greatly from the star-facing side to the dark side. Simulations indicate strong differences in dynamics between the two sides for planet LHS 3844b (Meier et al., 2021). Some exoplanets may even be molten on their star-facing side, and are the focus of ongoing investigation.

Meier, T. G., D. J. Bower, T. Lichtenberg, P. J. Tackley and B.-O. Demory (2021) Hemispheric tectonics on super-Earth LHS 3844b, Astronomical Journal Letter, 908:L48, https://doi.org/10.3847/2041-8213/abe40013.

Spaargaren, R. J., M. D. Ballmer, D. J. Bower, C. Dorn, and P. J. Tackley (2020), The influence of bulk composition on the long-term interior-atmosphere evolution of terrestrial exoplanets, Astronomy & Astrophysics, 643, doi:10.1051/0004-6361/202037632.

Spaargaren, R., H. Wang, S. Mojzsis, M. Ballmer and Tackley, P. J., Plausible constraints on the range of bulk terrestrial exoplanet compositions in the Solar neighbourhood. ApJ., in press.

Tackley, P. J., M. Ammann, J. P. Brodholt, D. P. Dobson, and D. Valencia (2013), Mantle dynamics in super-Earths: Post-perovskite rheology and self-regulation of viscosity, Icarus, 225(1), 50-61, doi:http://dx.doi.org/10.1016/j.icarus.2013.03.0

van Heck, H., and P. J. Tackley (2011), Plate tectonics on super-Earths: Equally or more likely than on Earth, Earth Planet. Sci. Lett., 310(3-4), 252-261.