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Super-Earth lava planet from birth to observation: photochemistry, tidal heating, and volatile-rich formation

Harrison Nicholls[1], Tim Lichtenberg[2], Richard D. Chatterjee[1], Claire Marie Guimond[1], Emma Postolec[2], and Raymond T. Pierrehumbert[1]
[1]Atmospheric, Oceanic, and Planetary Physics, University of Oxford, Oxford, United Kingdom (harrison.nicholls@physics.ox.ac.uk)
[2]Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands

Larger-than-Earth exoplanets are sculpted by strong stellar irradiation, but it is unknown whence they originate. Two propositions are that they formed with rocky interiors and hydrogen-rich envelopes ('gas-dwarfs'), or with bulk compositions rich in water-ices ('water-worlds') . Multiple observations of super-Earth L 98-59 d have revealed its low bulk-density, consistent with substantial volatile content alongside a rocky/metallic interior, and recent JWST spectroscopy evidences a high mean molecular weight atmosphere. Its density and composition make it a waymarker for disentangling the processes which separate super-Earths and sub-Neptunes across geological timescales. We simulate the possible pathways for L 98-59 d from birth up to the present day using a comprehensive evolutionary modelling framework. Emerging from our calculations is a novel self-limiting mechanism between radiative cooling, tidal heating, and mantle rheology, which we term the 'radiation-tide-rheology feedback'. Coupled numerical modelling yields self-limiting tidal heating estimates that are up to two orders of magnitude lower than previous calculations, and yet are still large enough to enable the extension of primordial magma oceans to Gyr timescales. Our analysis indicates that the planet formed with a large amount (>1.8 mass%) of sulfur and hydrogen, and a chemically-reducing mantle; inconsistent with both the canonical gas-dwarf and water-world scenarios. A thick atmosphere and tidal heating sustain a permanent deep magma ocean, allowing the dissolution and retention of volatiles within its mantle. Transmission features can be explained by in-situ photochemical production of SO2 in a high-molecular weight H2-H2S background. These results subvert the emerging gas-dwarf vs. water-world dichotomy of small planet categorisation, inviting a more nuanced classification framework. We show that interactions between planetary interiors and atmospheres shape their observable characteristics over billions of years.