Interior Structure And Habitability Of Super-Europas And Super-Ganymedes

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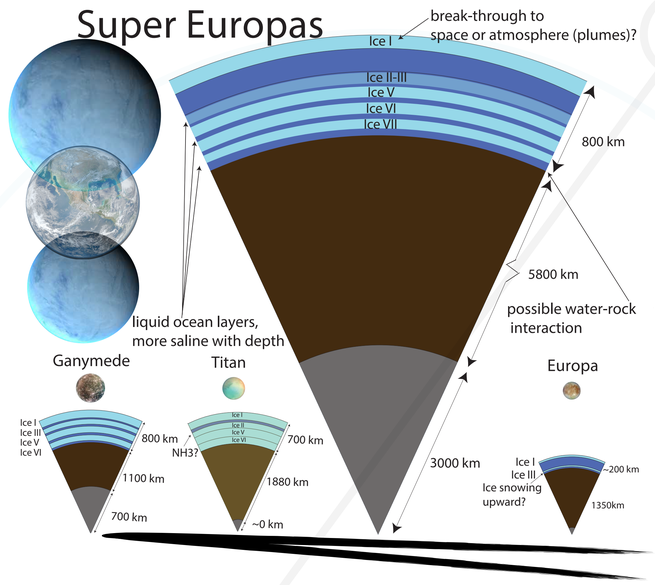
SUMMARY

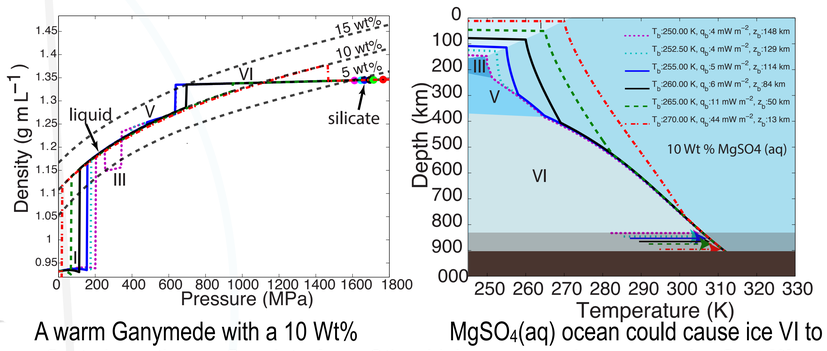
- Fluid-rock interactions in super Earth oceans are regarded as limited by negatively buoyant high pressure ices V, VI, VII, and VIII.
- Analogous assumption made for large icy worlds Ganymede and Titan: ocean depths up to 800 km create >GPa pressures (>10katm). Applying accurate fluid thermodynamics to planetary interiors challenges these assumptions.
- Increased density in highly saline oceans implies possible oceans perched under and between high pressure ices.
- In some model oceans, high-pressure ices become buoyant, implying frazil-like upward snows, interlayered liquids and fluids in direct contact with rock.



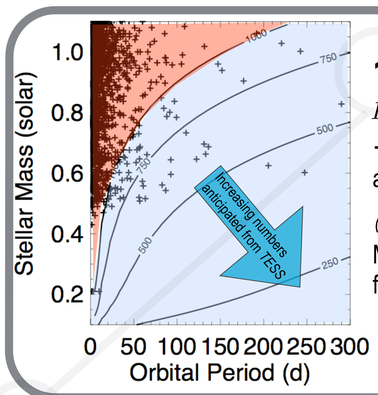
4. Watery exoplanets will resemble larger icy satellites in the solar system, with high-pressure ices and salty oceans.

Application of detailed thermodynamics to icy satellites [5,6] reveals strong density and temperature gradients.

How do deep salty oceans affect geodynamic evolution?



A warm Ganymede with a 10 Wt% $MgSO_4$(aq) ocean could cause ice VI to float above the seafloor interface, Other high pressure phases can also float [6].



1. Confirmed and candidate Kepler planets with $R < 2.5R_\oplus$.

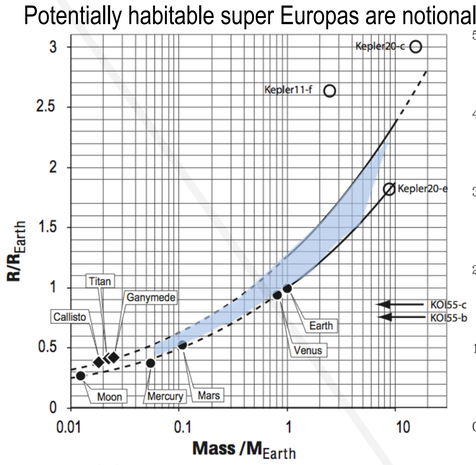
→Watery Earth-like planets are probably common around other stars.

(contours: temperature in Kelvin).

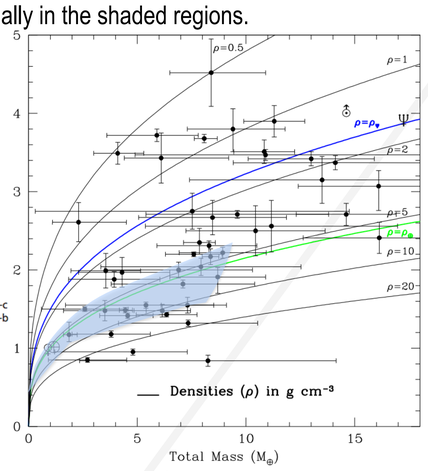
More small, cool worlds will be discovered as facilities such as *TESS* come into operation [1].

2. Mass-radius, planet density vs composition, etc., provide information about internal structure related to habitability.

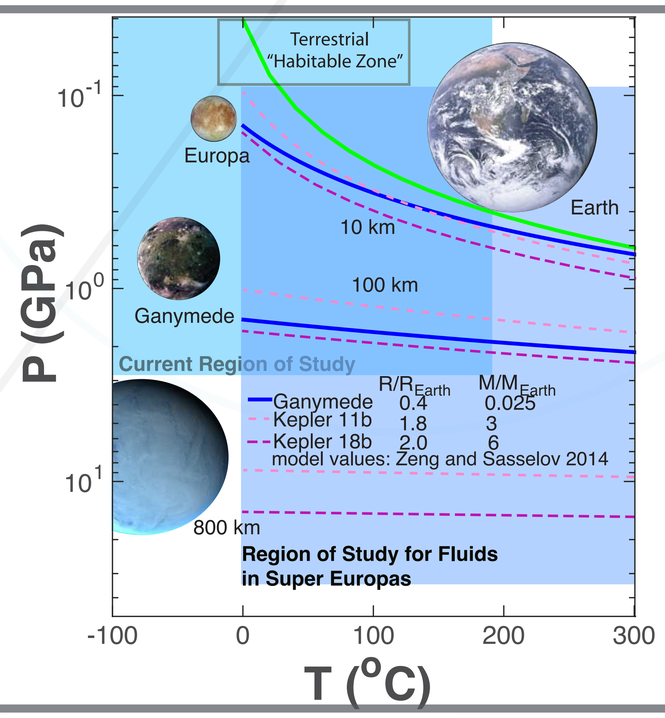
Potentially habitable super Europas are notionally in the shaded regions.



530 model planets [2].
curves separate wet (upper) and dry (lower) worlds.
Jupiter's moon Europa at the same position as the Moon.



Known exoplanets [3] of relevant size.
Constant density curves (Neptune in blue and Earth in green).

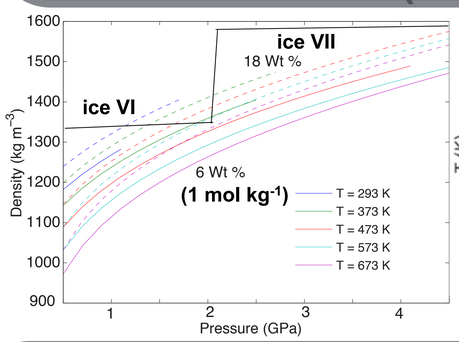


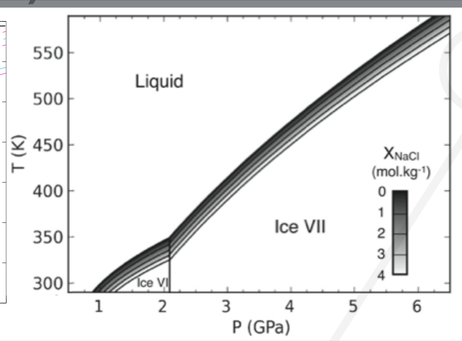
5. Pressures in exoplanet oceans span the multi-GPa range of pressures where liquids are possible.

Pressure (GPa), temperature (°C) profiles in upper mantles of selected objects
[as per Ref. 7], beginning at presumed seafloor depth.

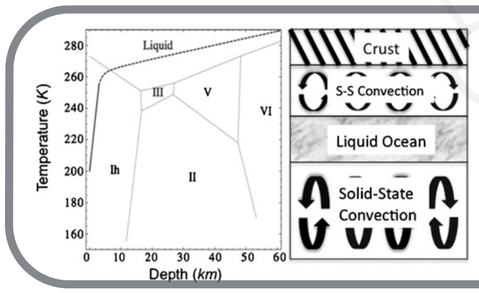
Overlying ocean assumed at a constant temperature.

Known exoplanets, albeit very hot ones, modeled as super Europas with seafloor depths like Earth's (10 km), Europa's (100 km, and Ganymede's (800 km; [6]).

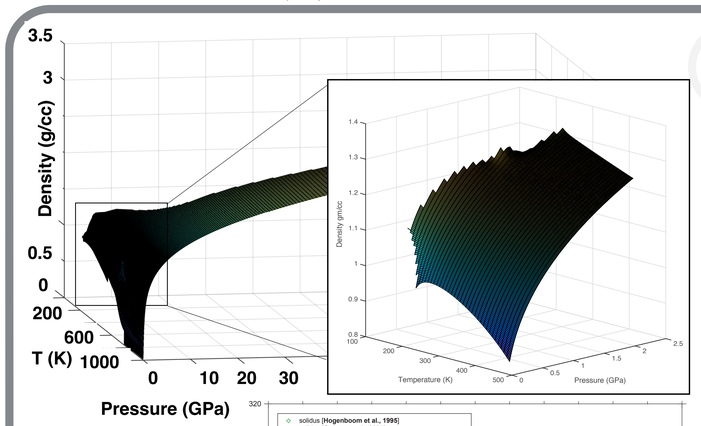




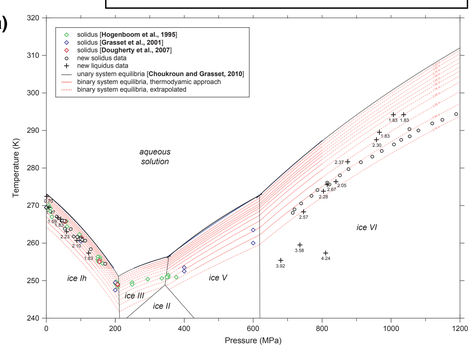
6. Recent EOS and phase measurements for NaCl (aq) indicate ice VII floats at P >5 GPa.



3. Interior models for $5M_\oplus$ water planets [4], with water oceans with NH_3 neglect effects of dissolved species (salts).



Gibbs free energies of $MgSO_4$ allow computation of ice equilibrium under super Earth pressures.
(Bollengier et al., *in prep*)



7. Modern computer processing allows us to apply geophysical methods of regularization to construct optimized "local" fits of thermodynamic properties that easily accommodate new data.

$$\left(\frac{\partial \rho}{\partial P}\right)_T = \frac{1}{c^2} + \frac{\alpha^2 T}{C_P} \qquad \left(\frac{\partial C_P}{\partial P}\right)_T = -T\left(\frac{\partial^2 V_{sp}}{\partial T^2}\right)_P \quad \rightarrow \quad \rho = \left(\frac{\partial G}{\partial P}\right)^{-1}_{T,n} \qquad C_P = \left(\frac{\partial^2 G}{\partial T^2}\right)_{P,n}$$

We constructed Gibbs free energies for water [13, 14, Brown et al., in prep.; left].
We are using G to develop general thermodynamics of aqueous solutions:

$$G = G^{water} + G^{ex}$$

Aqueous chemistry separable by contributions from:

- water (G°)
- interaction of water with ions
- interaction of ions with each other
- interaction of ions with each other and water

$$G^{ex}/(w_w RT) = f(I) + 2\sum_c\sum_a m_c m_a [B_{ca} + (\sum_c m_c z_c) C_{ca}]$$
$$+ \sum\sum_{c<c'} m_c m_{c'} [2\Phi_{cc'} + \sum_a m_a \psi_{cc'a}] + \sum\sum_{a<a'} m_a m_{a'} [2\Phi_{aa'} + \sum_c m_c \psi_{caa'}]$$
$$+ 2\sum_n\sum_c m_n m_c \lambda_{nc} + 2\sum_n\sum_a m_n m_a \lambda_{na} + 2\sum_{n<n'}\sum m_n m_{n'} \lambda_{nn'} + \sum_n m_n^2 \lambda_{nn} + \ldots$$

Pitzer formulation[15]

Mostly unavailable and unimportant at low concentration

We are beginning to estimate Pitzer parameters under planetary conditions.

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