Modeling the albedo of magma ocean planets

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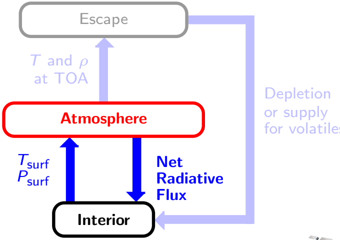
- Atmospheric submodel designed for coupling in order to study a generic telluric planet early evolution.
    - Interior – **Atmosphere** – Escape
    - Atmospheric module *[Marcq, 2012; Marcq et al., 2017]* is operational.
- Inputs
    - Surface temperature
    - Surface pressures (H_2O, CO_2, N_2).
- Outputs
    - Spectral reflectance how much energy is absorbed from the host star?
    - OLR how fast does the magma ocean cool? Which **thermal spectrum** can be observed?
    - TOA Z, T, ρ and composition at 0.1 Pa level: lower boundary condition for future escape submodel.



Escape

T and ρ at TOA

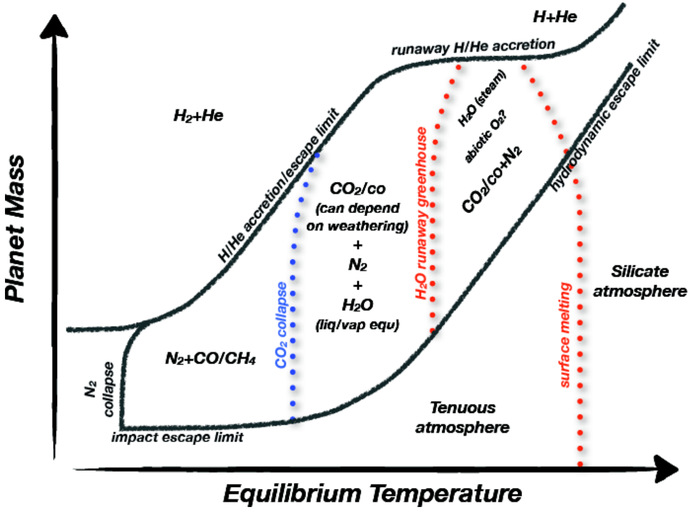
Depletion or supply for volatile

Atmosphere

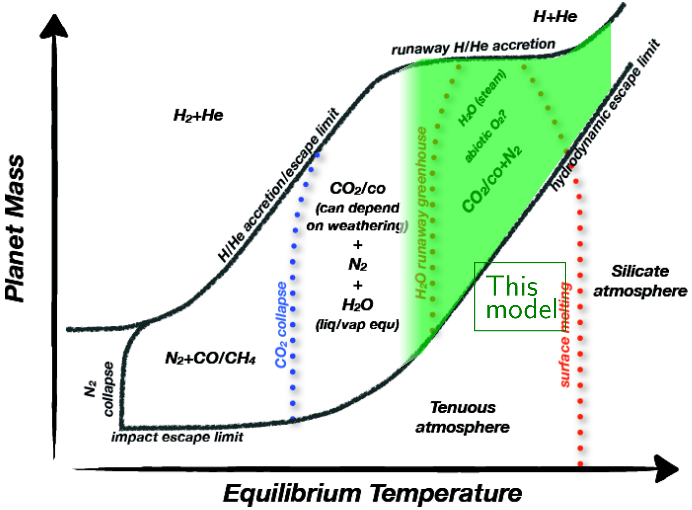
T_{surf}
P_{surf}

Net Radiative Flux

Interior



From *Forget & Leconte (2013)*



From *Forget & Leconte (2013)*

- Radiative–convective 1D model
  - Inspired from *Abe & Matsui (1988)* and *Kasting (1988)*
  - Main difference **no mandatory radiative balance ($\boldsymbol{T_{\mathrm{eff}} \geq T_{\mathrm{eq}}}$)!**
    - Surface temperature prescribed by interior submodel.
- Algorithm
  1. Prescribed P grid up to 0.1 Pa.
  2. Prescribed $T(P)$ profile.
  3. Computation of $Z(P)$ et $\rho_i(P)$ according to equations of state and hydrostatic equilibrium.
     - CO_2 and N_2 considered as ideal gases.
     - H_2O is **not** ! $P > P_c$ and/or $T > T_c$ common.
  4. Computation of gaseous absorption (k-correlated LUT) and Rayleigh opacities from 0 to $3.5 \cdot 10^5$ cm^{-1}
  5. Computation of radiative properties of possible clouds.
  6. Computation of IR and SW radiative fluxes with DISORT (4 streams).

- 3 layers from surface up to mesopause

  Dry Troposphere follows a dry adiabat.

  Moist Troposphere follows a moist adiabat. Clouds are located there.

  Mesosphere considered isothermal.

- Boundaries

  Dry/Moist where H_2O reaches saturation (if already occuring at surface ⇒ no dry troposphere and formation of a H_2O ocean).

  Moist/Mesosphere where $T < T_0 =$ TOA temperature, fixed here at 200 K.

- $\alpha_v = \rho_{H_2O}/(\rho_{CO_2} + \rho_{N_2})$
  - Vertically uniform within dry troposphere and mesosphere.
  - Decreasing with increasing height within moist troposphere.

- Rayleigh
  - Simple $\propto \lambda^{-4}$ dependency for CO_2, N_2 and H_2O *[Kopparapu et al., 2013; Sneep & Ubachs, 2005]*.
- Clouds (optional)
  - Present throughout the moist troposphere
  - Mass loading from *Kasting (1988)* for Earth-like clouds.
  - Optical properties (Q_{ext}, ϖ_0, g) similar to present day Earth-like clouds.
  - Henyey-Greenstein phase function

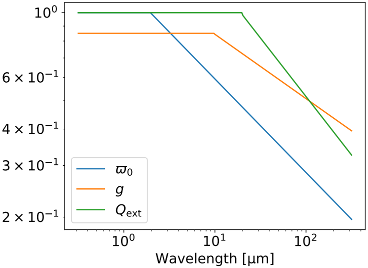


Figure: Cloud optical properties

- Spectral Lines
  - High-resolution spectra computed with KSPECTRUM *[Eymet 2009]*.
  - Yields a (α_v, T, P) grid of 16 k-coefficients *[Wordsworth et al., 2010]*.
  - Reverting to “grey” opacities possible
    - if approximate, fast computations are needed with no need for any spectral output.
- Continuum opacities

CO_2-CO_2: derived from Venus measurements *[Bézard, priv. comm.]*

H_2O-H_2O: from MT_CKD v2.5 *[Clough et al., 2005]*

CO_2-H_2O: not taken into account yet.

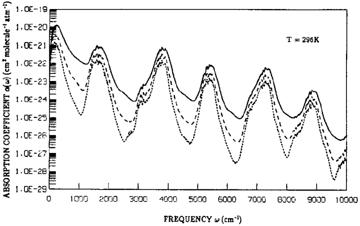


Figure: Continua for H_2O-H_2O (solid) and H_2O-CO_2 (dashed) from *Ma & Tipping (1992)*

- NIR windows open up for $T_{\text{surf}} > T_{\varepsilon}$
  - **Detectability** and magma ocean **cooling rate** decrease strongly for $T_{\text{surf}} < T_{\varepsilon}$
  - T_{ε} depends on H_2O and CO_2 atmospheric inventory

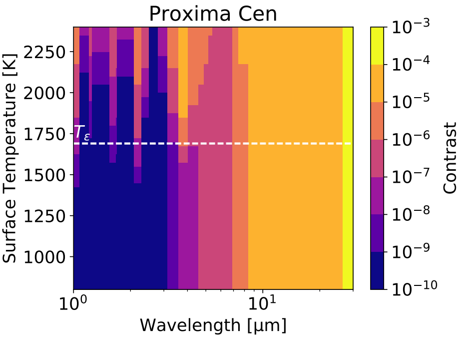


Figure: OLR Contrast for a 300 bar H_2O, 100 bar CO_2 Earth-like planet around Proxima Centauri

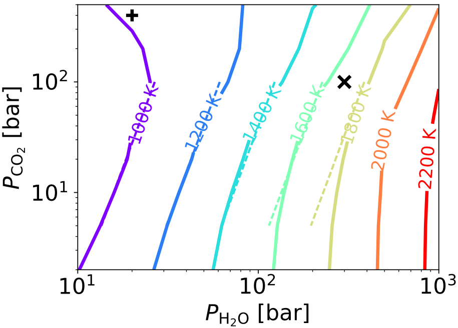


Figure: T_{ε} contours wrt. H_2O and CO_2 surface pressures

- Clouds become optically thinner with increasing T_{surf}
  - Vertical extent decreases.
  - Integrated mass loading much more so.

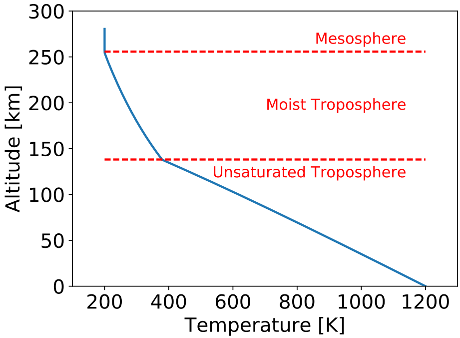


Figure: $T(z)$ profile for $T_{\mathrm{surf}} = 1200$ K, 300 bar H_2O, 100 bar CO_2

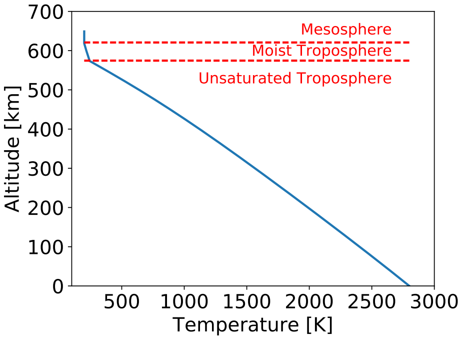


Figure: $T(z)$ profile for $T_{\mathrm{surf}} = 2800$ K, 300 bar H_2O, 100 bar CO_2

- With clouds
  - Overall visible/NIR reflectance dominated by clouds.
  - Loss of spectral constrast at higher T_{surf}
- Without clouds
  - Higher atmospheric temperatures lead to decrease in continuum opacity $\Rightarrow$ increasing reflectance with increasing T_{surf}?

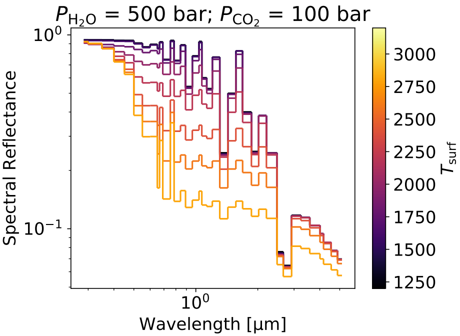


Figure: With clouds

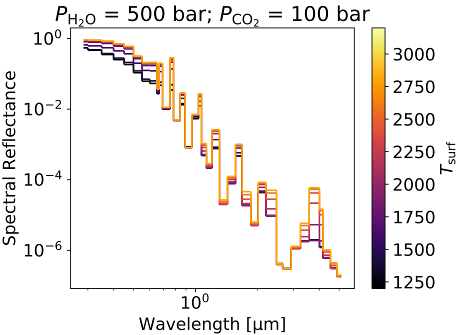


Figure: Without clouds

- Spectral reflectance decreases with increasing wavelength
  $\Rightarrow$ Lower albedo around M-stars compared to G-stars
- Two regimes for albedo depending on T_{surf} wrt. $T_A = T_\varepsilon + 240\,\mathrm{K}$
  $T_{\mathrm{surf}} \ll T_A$ High albedo, dominated by cloud scattering
  $T_{\mathrm{surf}} \gg T_A$ Low albedo, dominated by Rayleigh scattering
- Broadly speaking, albedo increases with CO_2 content, decreases with H_2O content

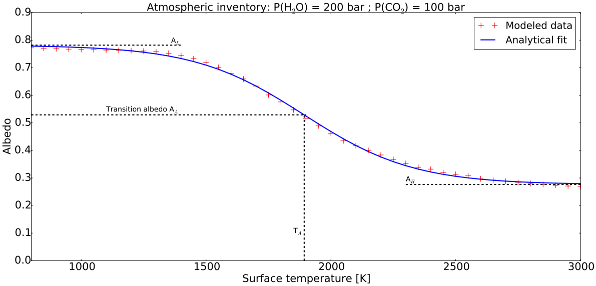


Figure: Albedo wrt. T_{surf}

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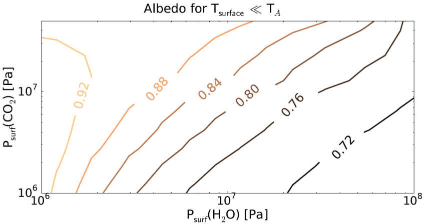

Figure: Low T_{surf} albedo around the Sun

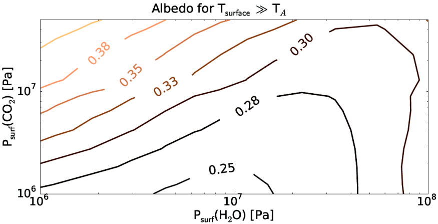

Figure: High T_{surf} albedo around the Sun

- Summary
  - Simple coupled atmospheric 1D model already operational *[Lebrun et al., 2013; Salvador et al., 2017]*
    - Like *Hamano et al. (2013,2015)*, can be made more complex than atmospheric parametrizations usually embedded in coupled magma ocean cooling studies *[Elkins-Tanton 2008]*
  - **Very high albedo** until water ocean condenses
    - **unless very young** (less than 10^5 yr)
  - Albedo **decreases with star temperature**.
- To do
  - Publish SW model results – *Marcq et al. (2017)* already published for thermal IR.
  - Smoothing the mesospheric temperature profile $T(z)$ – important for self-consistent TOA temperature.
  - Implement corrections to plane-parallel geometry for small planets and very hot atmospheres.
  - Longer simulations possible once coupled with an escape model.