Accumulation and evolution of primordial atmospheres around terrestrial planets

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Alexander Stökl

The Astrophysics of Planetary Habitability

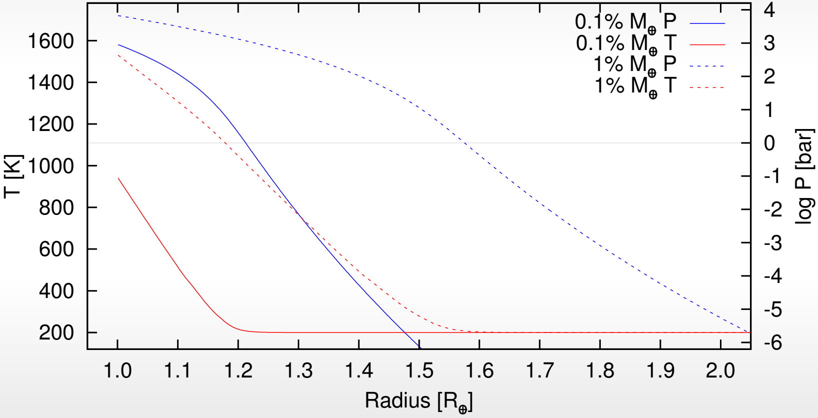
Vienna, February 2016

University of Vienna, Department of Astrophysics

Motivation

- Observed small radius planets appear to have low average densities.
    - Indicative of extended envelopes
    - Primordial envelopes
- An Earth-mass planetary core with 1% persistent primordial envelope is not habitable in the conventional sense.

Examples of atmosphere structures



Scope

- Consider cores of terrestrial planets embedded in the gas of the protoplanetary disk
- Formation of planetary core essentially completed; core mass 0.1 $M_\oplus$ – 5 $M_\oplus$
- Earth-like orbit around Solar-type star (habitable zone)
- Ambient conditions (i.e. ρ, T @ 1AU) from disk model
- Not focusing on formation of giant planets – though massive cores experience runaway accretion

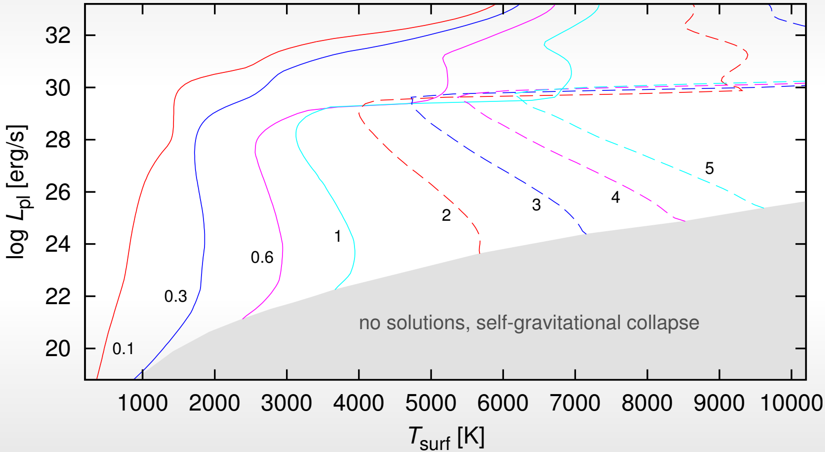
Numerical description and setup

- 1D-spherical symmetry (for $R < R_{\mathrm{Hill}}$ and $R < H_P$)
- Model from surface of planetary core to Hill radius
- Hydrodynamics (Eqs. of continuity, energy and motion)
- Radiation (Moment description: J, $\vec{H}$)
- Convective transport (Eq. for turbulent convective energy)
- Adaptive grid equation
- Realistic gas: EOS (Saumon et al. 1995); Opacity (Freedman et al. 2008)
- Dust with constant dust depletion factor $f = 0.01$ and opacity data from Semenov et al. 2003

Stationary models

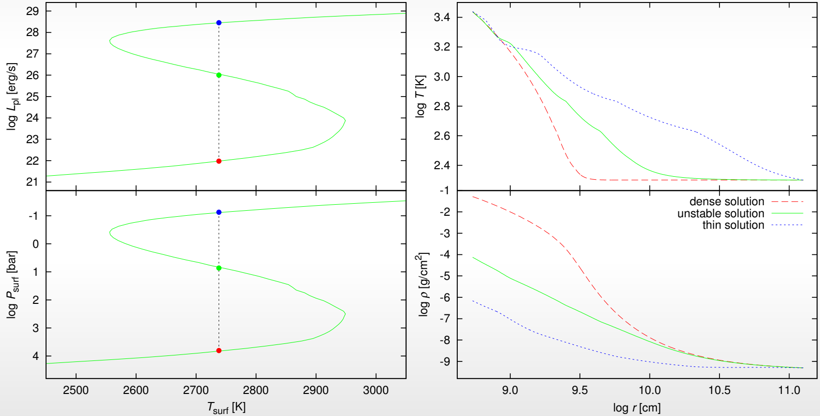
- Stationary limit of the set of time-dependent equations
- Usually characterized by planetary luminosity – associated with a stream of accreted planetesimals
- Replace luminosity with surface temperature of the planetary core

Stationary models



Non-unique solutions

Focus on core mass $0.6M_\oplus$



Dynamical stability

- Change from $L_{\mathrm{pl}} = \mathrm{const.}$ to $T_{\mathrm{surf}} = \mathrm{const.}$
- Solution for T_{surf} is not unique, multiple stationary solutions for one T_{surf}
- Calculate time-dependent models with constant T_{surf} (IBC) to investigate stability
- Models on negative slope ($\frac{\mathrm{d}L_{\mathrm{pl}}}{\mathrm{d}T_{\mathrm{surf}}} < 0$) are dynamically unstable (for a fixed T_{surf})
- Evolve to one of the stable solutions

Time-dependent models

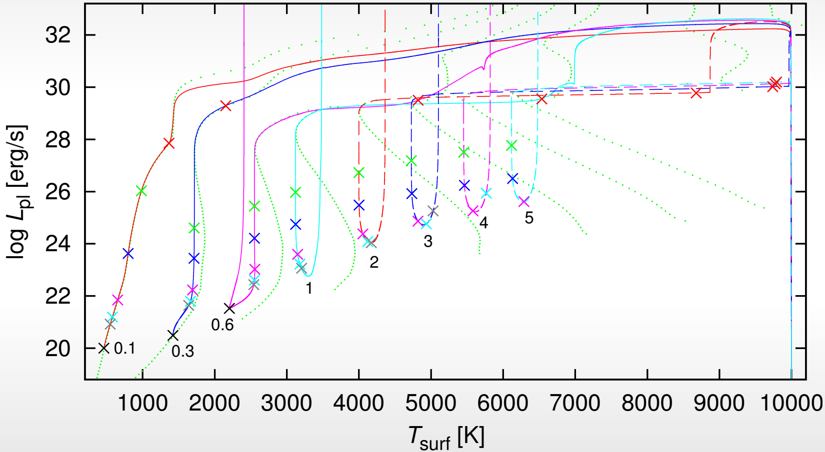
- Implicit time integration scheme
- Not affected by the CFL-limit
- Allows hydrodynamics simulations over evolutionary time-scales

Accumulation of planetary atmospheres

Description of the scenario:

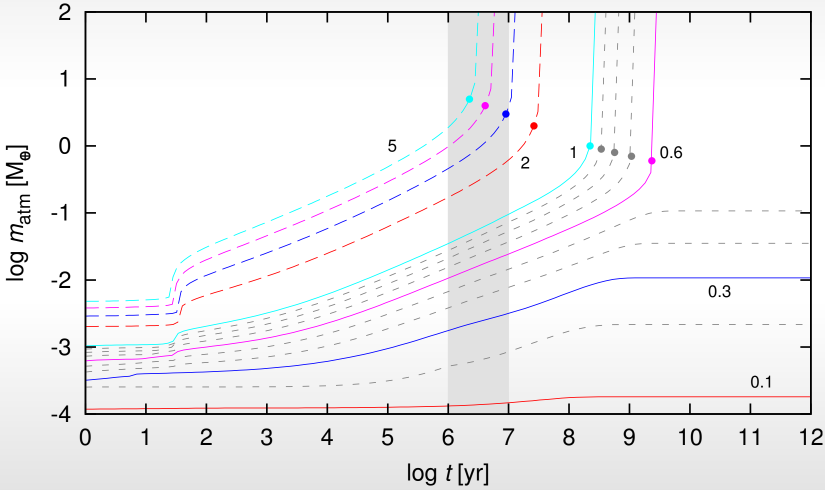
- Start with bare and hot planetary core in unperturbed disk environment
- (Indefinitely) Constant outer boundary conditions (ρ, T)
- Planetary luminosity results from core temperature and atmosphere structure
- Atmosphere forms through inflow and accumulation of disk gas
- Atmosphere characterization by T_{surf} instead of L_{pl}
- Internal energy budget of the core (constant integral heat capacity) including radiogenic heat production

Accumulation of planetary atmospheres



Crosses are model times [yrs] of 1 (red), 10^2 (green), 10^4 (blue), 10^6 (violet), 5×10^6 (cyan), 10^7 (gray) and 10^9 (black)

Mass evolution



Amount of atmosphere

$M_{\rm core}$ $[M_\oplus]$		$f_{\rm env}$ in % for	
	$t_{\rm disk} = 10^4$ yr	$t_{\rm disk} = 10^5$ yr	$t_{\rm disk} = 10^6$ yr
0.1	0.12 (0)	0.13 (0)	0.13 (0)
0.2	0.13 (0)	0.16 (0)	0.26 (0)
0.3	0.21 (0)	0.32 (0)	0.58 (0)
0.4	0.26 (0)	0.47 (0)	0.96 (0)
0.5	0.32 (0)	0.62 (0)	1.3 (0)
0.6	0.38 (0)	0.77 (0)	1.8 (0)
0.7	0.44 (0)	0.93 (0)	2.2 (0.38)
0.8	0.49 (0)	1.1 (0)	2.6 (1.1)
0.9	0.55 (0)	1.2 (0.29)	3.0 (1.8)
1	0.61 (0)	1.4 (0.57)	3.4 (2.4)
2	1.2 (1.0)	3.0 (2.8)	7.9 (7.6)
3	1.9 (1.8)	4.8 (4.7)	13 (13)
4	2.7 (2.6)	6.8 (6.7)	20 (20)
5	3.4 (3.4)	8.9 (8.8)	27 (27)

Johnstone et al. 2015

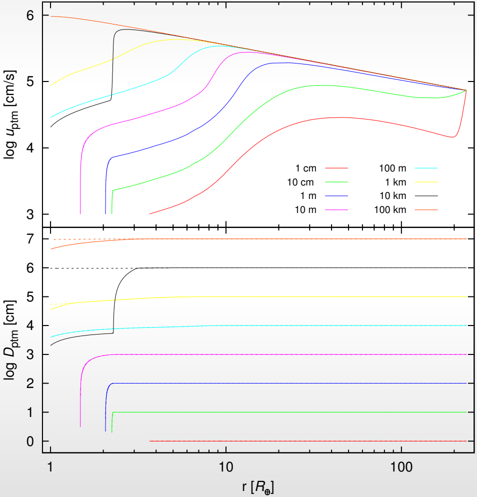
Envelope mass fractions $f_{\rm env}$ defined as $f_{\rm env} = M_{\rm atm}/(M_{\rm atm} + M_{\rm core})$.

Numbers in brackets give surviving atmosphere after 1 Gyr escape.

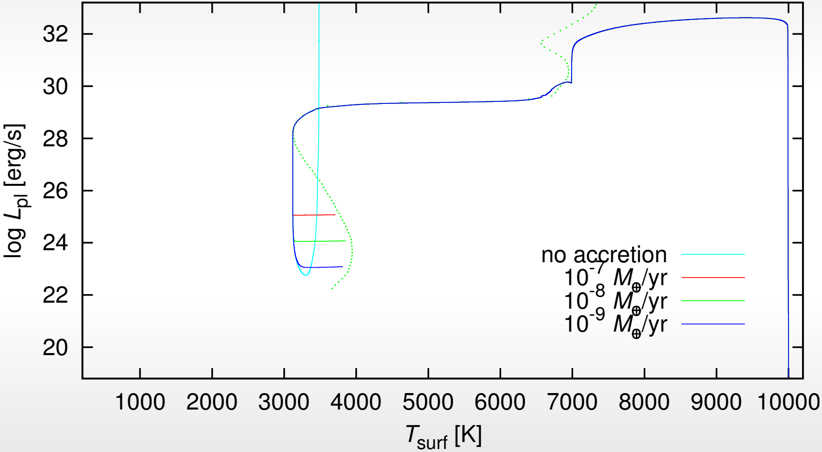
Motion and breakup of planetesimals

- Assuming constant and continuous stream of infalling planetesimals of uniform (average) size
- Equation of motion of the planetesimals:
  - Gas drag
  - Gravitational acceleration
- Equation for the size of the planetesimals:
  - Surface melting
    - w/ fraction of dissipated energy
    - Ambient temperature in the atmosphere
  - Breakup (ram pressure vs. compressive strength)
- Solved together with the system of dynamic equations

Motion and breakup of planetesimals

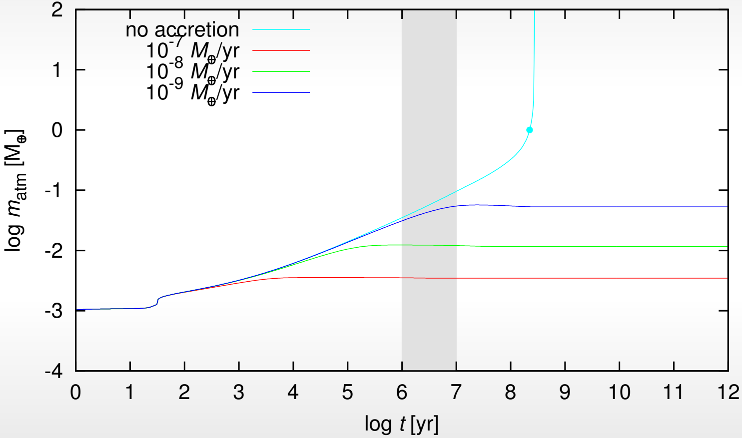


Evolution w/ accretion of planetesimals



$$L_{acc} \simeq GM_{pl}\dot{M}/R_{pl} = 1.2 \times 10^{23/24/25}$$

Evolution w/ accretion of planetesimals



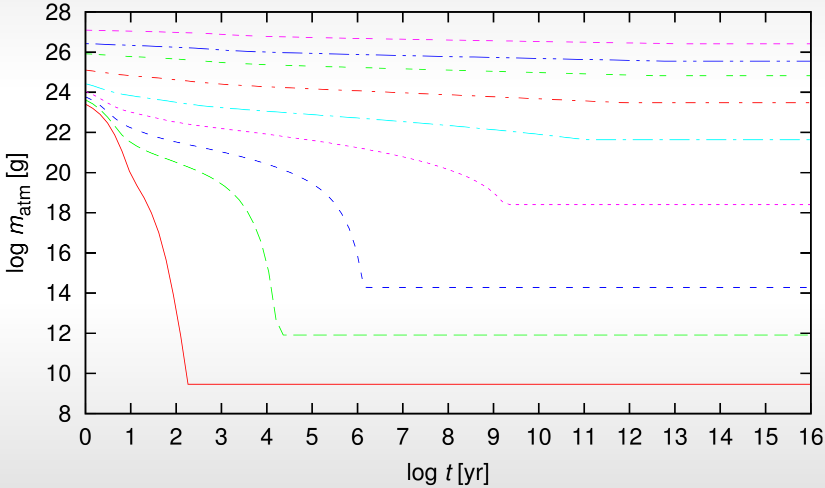
Accretion rate of planetesimals gives upper limit of atmosphere mass – yet cannot be maintained indefinitly

The Grand Scheme

Putting together various mechanisms and phases into one consistent model:

- Dynamic accumulation of atmospheres
- Atmospheric evolution with infalling planetesimals
- Consistent growth of core from accretion of planetesimals
- More detailed (radially resolved) model for the interior of the core
- Include losses driven by extreme ultraviolet and soft X-ray stellar irradiation
- Follow through dynamic reaction (outflow) when disk evaporates

Dynamic outflow after disk dispersal



Stoekl et al. 2015

Conclusions

- The structure and properties of embedded planetary atmospheres are a time-dependent problem
- A comparatively short duration embedded phase is sufficient for the accumulation of a significant primordial atmosphere
- For cores more massive than about one Earth mass the atmosphere is unlikely to get removed by later processes