Silicate Atmospheres, Clouds, and Fractional Vaporization of Hot Earth-like Exoplanets

Laura Schaefer and Bruce Fegley, Jr.

Planetary Chemistry Laboratory
Department of Earth and Planetary Sciences
Washington University, St. Louis, MO

Introduction

- Exoplanets on short orbits around their stars will be hot due to both stellar and tidal heating
- Extreme heating over a planet's lifetime may lead to loss of volatiles
  - Venus is in a closer orbit than the Earth and has lost its water content due to stellar heating
  - Jupiter's moon Io is dominated by S, and may have lost lighter volatiles such as H, C, and N due to intense tidal heating
- If a hot Earth-like exoplanet loses its volatile content, a silicate atmosphere may form
- We model the formation of a silicate atmosphere of a hot Earth-like exoplanet

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Super-Earth Exoplanets

- There are currently 26 known planets with $M < 20\ M_{Earth}$
- Recently discovered transiting exoplanet CoRoT-7b has:
  - $M < 11\ M_{Earth}$
  - a = 0.017 AU (orbital period of 0.854 days)
- Models (Léger et al. 2009, A&A) suggest the planet is tidally-locked
  - T_{day} = 1800 – 2600 K, T_{night} ~ 150 K
- Dayside temperature is high enough to melt and vaporize rock
  - Planet may have a partial magma ocean
- Volatiles could have been blown away from the atmosphere or condensed on the cold nightside
  - Results in a net loss of elements from the magma ocean
  - Atmosphere may be composed of rock-forming elements

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Methods

- We used the MAGMA code to calculate the composition of a silicate atmosphere formed by heating of different terrestrial planet analog materials
  - calculates vaporization of systems containing Si, Mg, Fe, Ca, Al, Ti, Na, K, and O
    - As a function of temperature (1500 – 3000 K) and mass-loss by isothermal fractional vaporization
    - Results give the composition of the atmosphere and total pressure
- Fractional vaporization may simulate
  1. removal of material from dayside to nightside on CoRot-7b or
  2. Loss of material from the atmosphere
- We also calculate the composition of clouds, which may alter the atmospheric composition

5 Model Planet Compositions

Oxide Wt%	Continental crust[a]	Oceanic crust[b]	BSE[c]	Moon[d]
SiO_2	62.93	50.36	45.97	47.17
MgO	3.79	7.61	36.66	36.29
Al_2O_3	15.45	15.85	4.77	3.90
TiO_2	0.70	1.48	0.18	0.18
FeO	5.78	9.56	8.24	9.31
CaO	5.63	12.24	3.78	3.08
Na_2O	3.27	2.77	0.35	0.05
K_2O	2.45	0.13	0.04	0.005
Total	100.00	100.00	99.99	99.985

[a]Wedepohl (1995). [b]Klein (2005). [c]BSE=Bulk Silicate Earth. O'Neill & Palme (1998). [d]Warren (2005).

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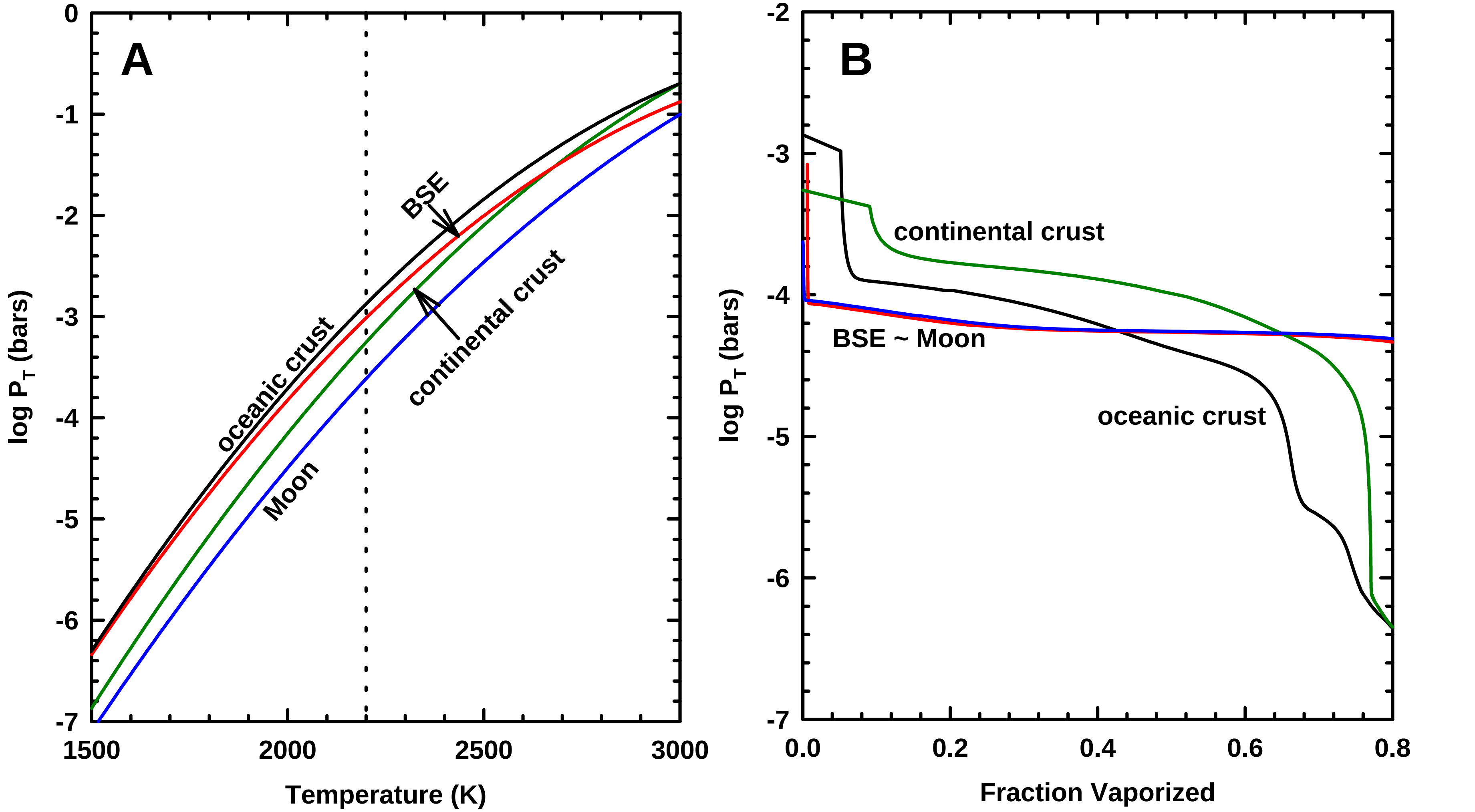
Total Pressure (1)



A. Initial total pressure for the model materials as a function of T (dashed line indicates F_{vap} = 0.0 on right graph B).

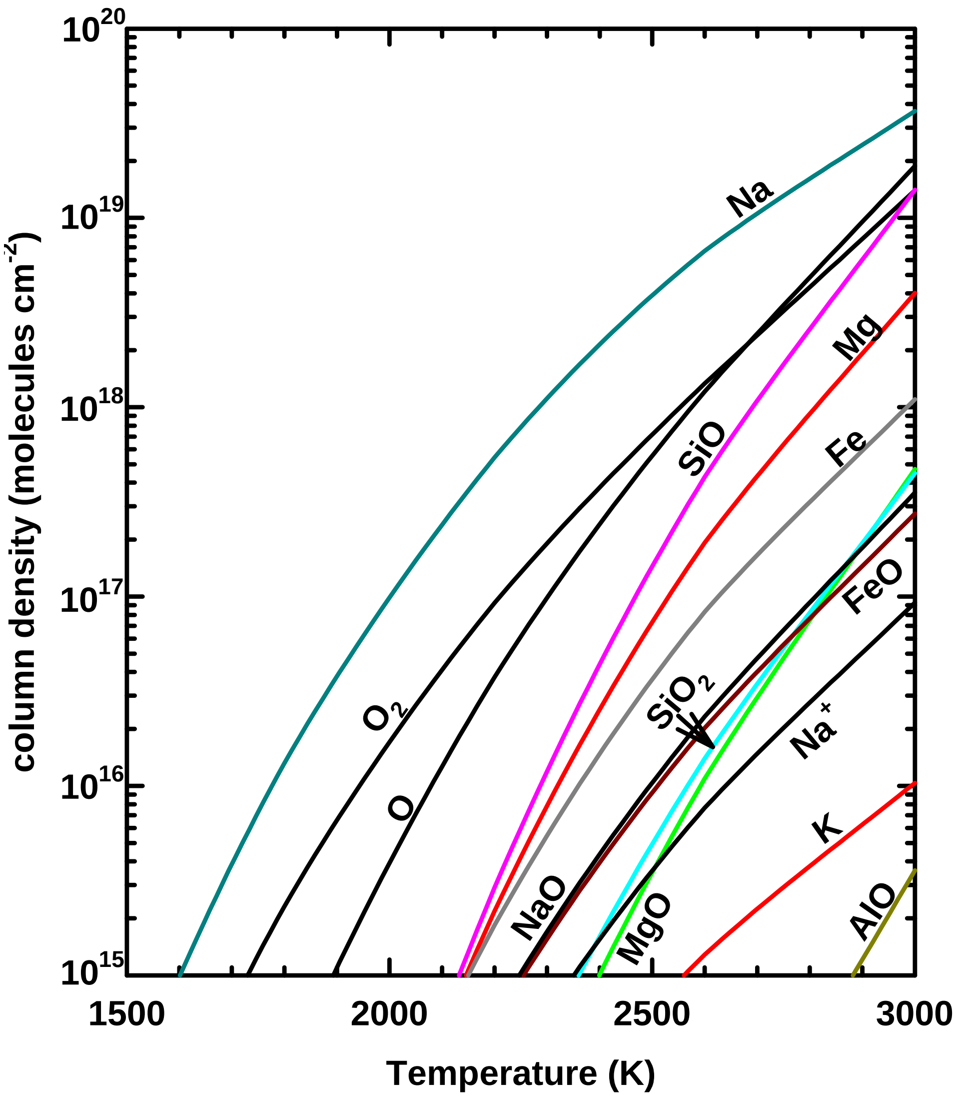
B. Total pressure for the model materials as a function of fraction vaporized at a constant temperature of 2200 K.

Total Pressure (2)

Material	$\log_{10} P_T = a + b/T + c/T^2$ a	b	c
Cont. crust	7.91	-29,390	10.729×10^6
Oceanic crust	6.02	-21,614	4.567×10^6
BSE	5.77	-21,524	0.494×10^6
Moon	8.17	-32,114	13.735×10^6

- Equations are for initial pressures shown in graph A on previous slide
- Initial pressures are unrelated to planet composition
- Pressure drops during fractional vaporization due to loss of material from the magma ocean

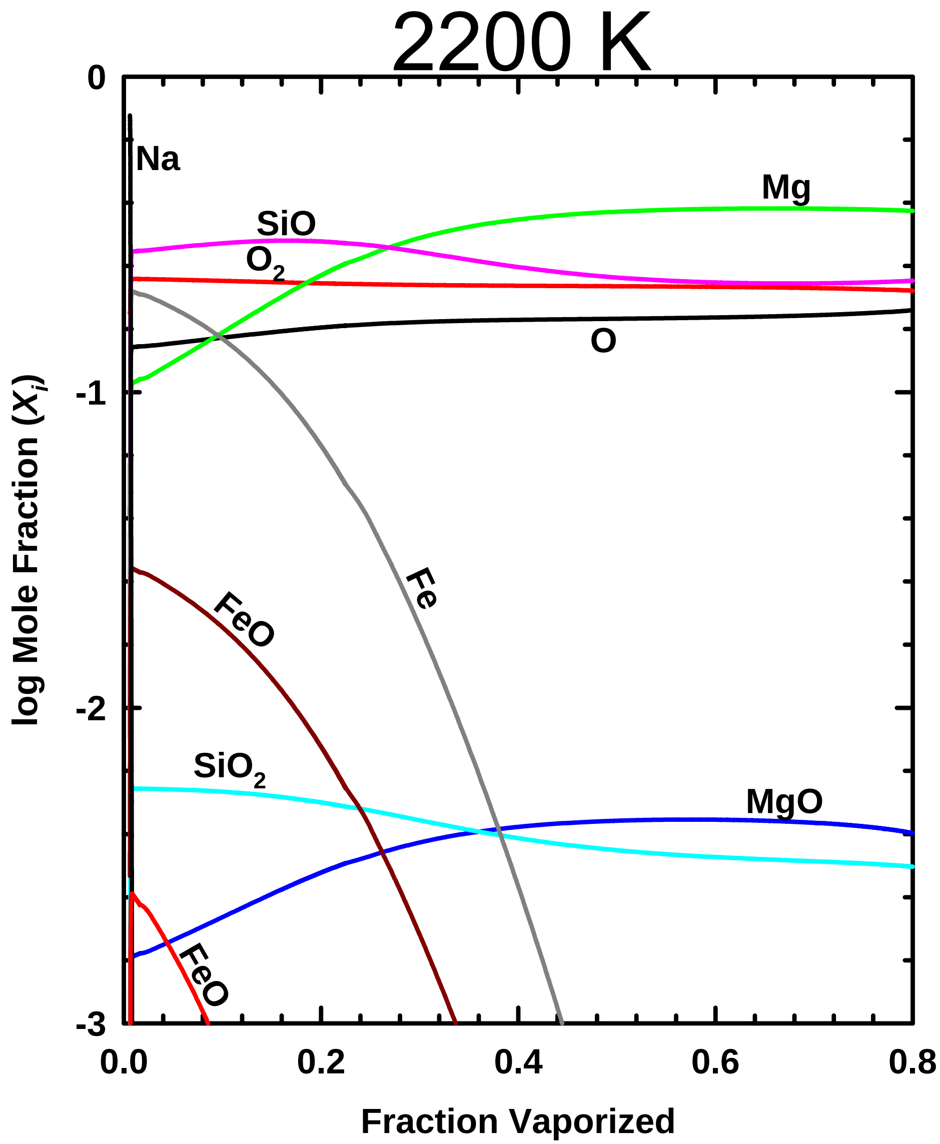
8 Temperature-dependent results



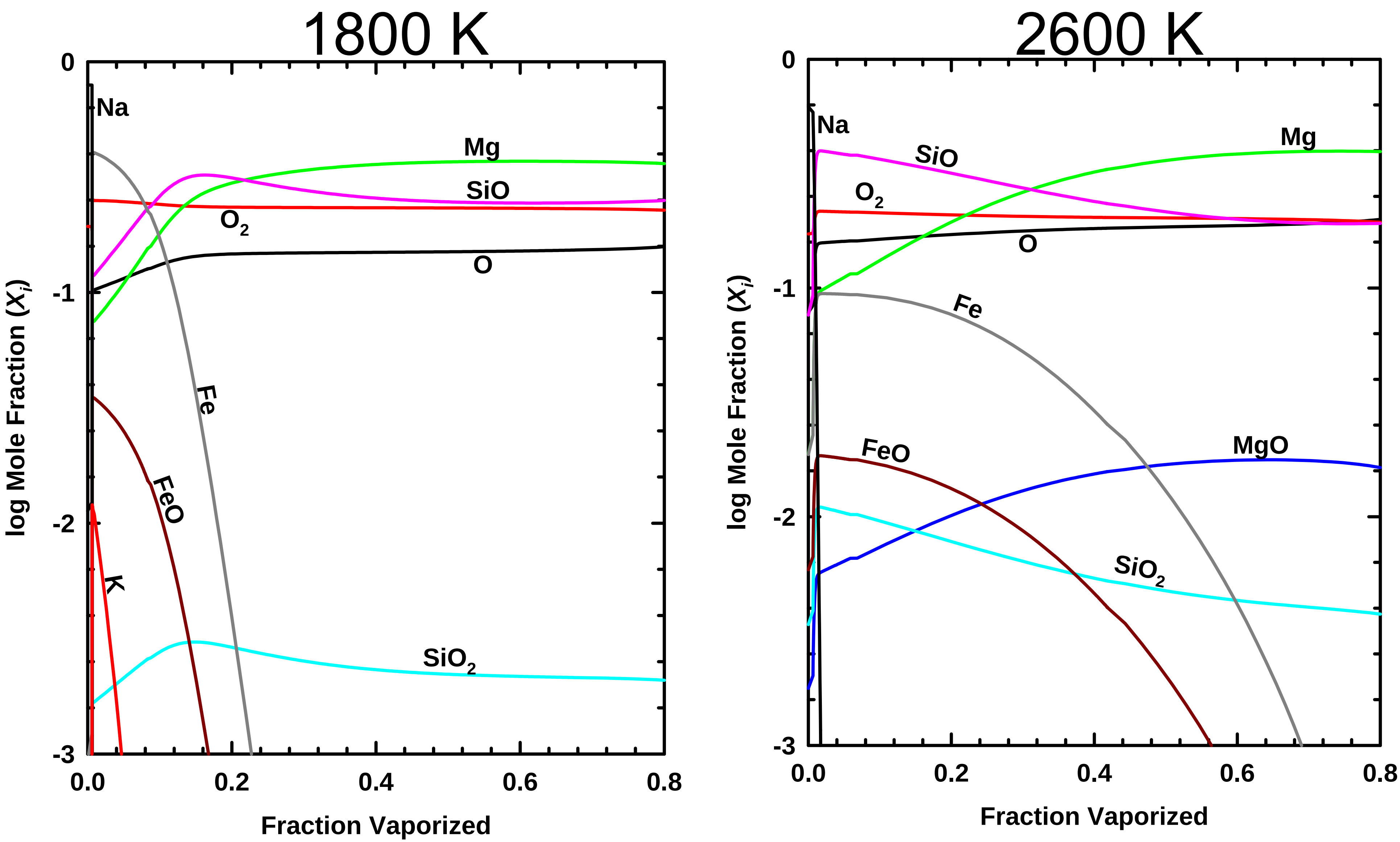
- Graph shows initial results for the BSE (F_{vap} = 0)
- Column density ($P_i N_A / \mu g$) is calculated for a planet the size of CoRoT-7b (g~36m/s^2)
- Na is the major gas at all temperatures
  - O_2, O, and SiO are also very abundant
- Results for other model planets are similar, but:
  - K gas is much more abundant for the continental crust material
  - Fe is more abundant for the lunar material

9 Fractional Vaporization of the BSE (1)

- Graphs (here and following slide) show atmospheric composition as a function of fraction vaporized at constant temperature
- Na is lost from system first, then K and Fe
- SiO becomes major gas
- Mg becomes more abundant than SiO at higher fractions vaporized
- O and O_2 maintain fairly constant abundance
- Elements are lost more quickly as temperature increases
  - e.g., see Fe(g) at 1800 K vs. 2600 K
- Results for the Moon are very similar

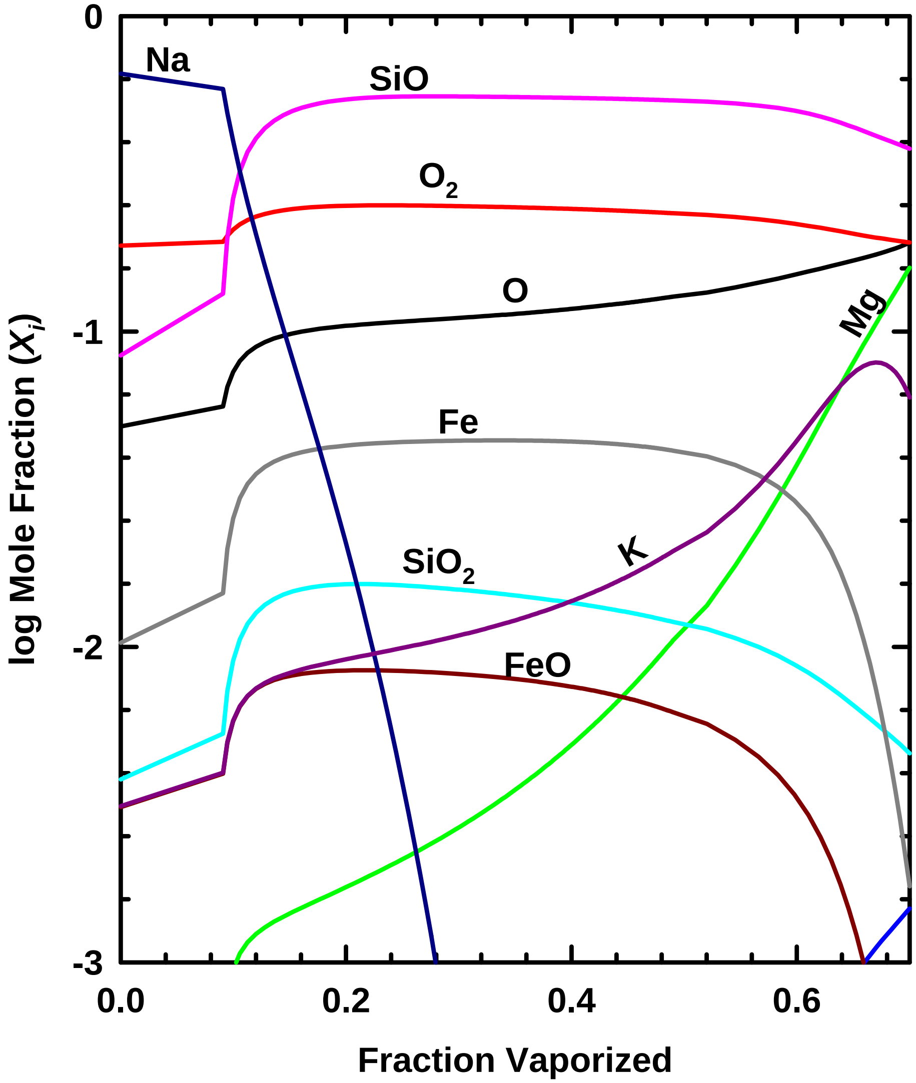


10 Fractional Vaporization of the BSE (2)



Continental Crust

2200 K



- Graph shows atmospheric composition as a function of fraction vaporized at 2200 K
- Na is present to much higher F_{vap} than for the BSE
- SiO is major gas, and Mg is less important than for the BSE
- K is abundant at high F_{vap}
- Atmospheric composition is less dependent on F_{vap} than BSE
- Results for the oceanic crust are similar

12 Clouds in BSE atmosphere

cloud	T_{cond} (K)	Z (km)	cloud	T_{cond} (K)	Z (km)
$MgSiO_3$	2125	2	"FeO"	2000	5.5
$MgAl_2O_4$	2075	3.5	$CaTiO_3$	1775	12
Al_2O_3	2025	5	$MgTiO_3$	1750	12.5
$CaSiO_3$	2025	5	Na_2O	1225	27.5
SiO_2	2025	5	K	400	50

- We calculated cloud condensation temperatures (T_{cond}) for the atmosphere generated at 2200 K for the BSE model
- Assumes dry adiabat and $g \sim 36$ m/s^2
- Mg, Al, Si, Ca, and Fe may fall back to surface and be reincorporated in the magma ocean
- Ti, Na, and K remain in atmosphere to high enough altitudes that they may either be transported to nightside or removed from atmosphere by stellar wind

Extended Na cloud

- Large clouds of Na exist around Mercury and Jupiter's moon Io
  - At Mercury, the Na cloud (~10^{11} cm^{-2}) extends to ~23$R_{Mercury}$
  - At Io, the Na cloud (10^{10} - 10^{12} cm^{-2}) extends to ~500$R_{Jupiter}$ (~19,600R_{Io})
  - These clouds are very bright spectral features
- An Earth-like exoplanet with a silicate atmosphere may have an extended Na cloud
  - Na is present in the atmosphere to high altitudes
    - may interact with stellar wind
  - A large Na cloud around a transiting planet like CoRoT-7b will occult more of the stellar disk than a closely bound atmosphere
    - Increases the probability of detection for a super-Earth
- Na has already been detected in the atmospheres of several giant exoplanets (HD209458b, HD189733b)

Silicon Monoxide (SiO)

- SiO gas has strong IR bands at 4 and 9 μm and lines throughout mm wavelengths
- Possible SiO gas masers
  - SiO masers are observed in circumstellar shells, molecular clouds, star-forming regions, and supernovae
  - SiO has column densities from 10^{11} to 10^{15} cm^{-2} in these regions
    - The BSE has SiO column densities $>10^{11}$ cm^{-2} for T >1650 K
- Photochemical destruction of SiO occurs by absorption of UV light (λ < 300 nm)
  - However, silicate vapor is very opaque for high temperatures and pressures, so photochemical destruction of SiO may not be very efficient
- Condensation of SiO as $MgSiO_3$ or SiO_2 is plausibly the most important loss process for SiO gas

Conclusions

- The major gas of silicate atmospheres formed by heating of Earth-like planets is Na(g)
  - Na stays in atmosphere to high altitudes and may interact strongly with the stellar wind
    - May form large extended clouds similar to those seen around Mercury and Io
  - Extended Na clouds would occult more of the stellar disk than a closely bound atmosphere and may be observable using current techniques
- We recommend searching for the gases Na, O_2, O, and SiO in the atmospheres of super-Earth exoplanets