ASU Arizona State University
School of Earth and Space Exploration

NExSS

ExoPlex Mass-Radius Code

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Sagan Summer Workshop
7-17-2019

First things first:

1. This is an actively developing code
2. This may not be the best tool for your specific job
3. It’s in python, so we’ll be coding!

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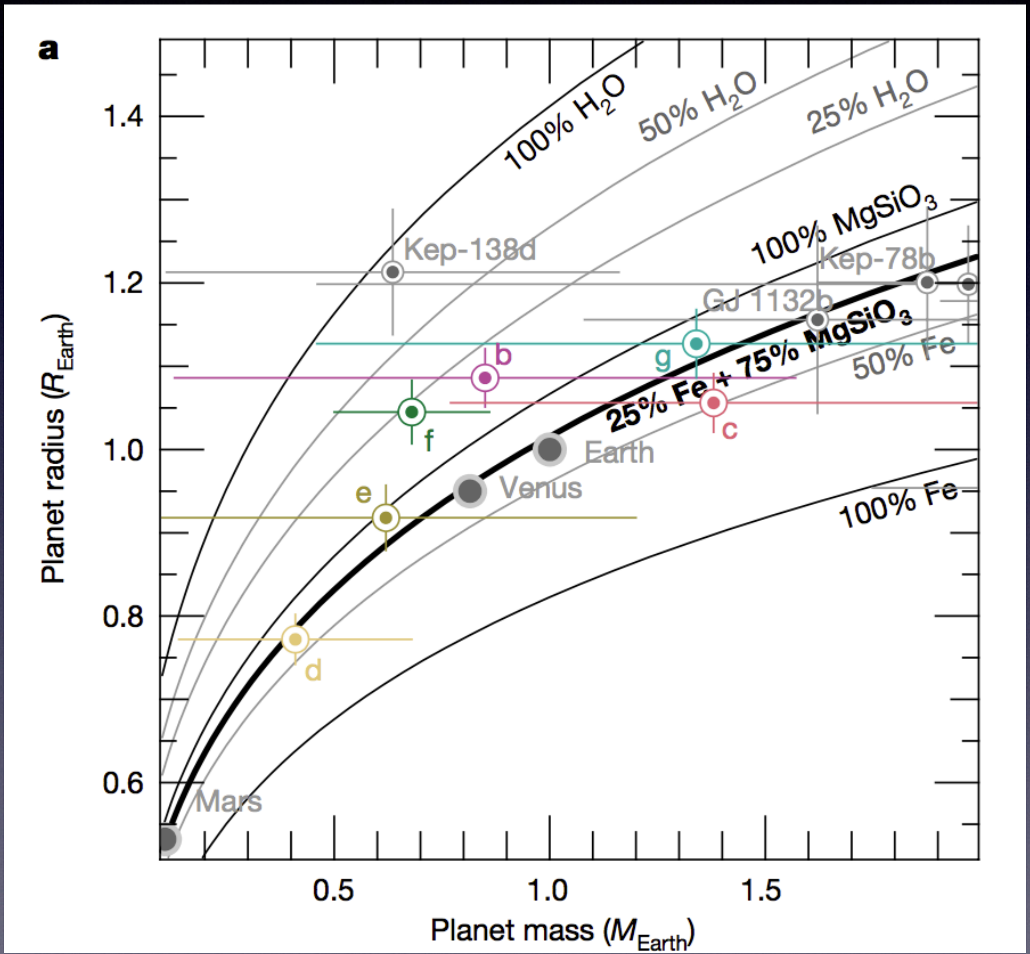
How do we "measure" *composition?*



Gillon et al., 2017

Mass in a sphere

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r),$$

Hydrostatic Equil.

$$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2},$$

Equation of State of material

$$\rho(r) = f(P(r), T(r), X(r))$$

Adiabatic temperature gradient

$$\frac{dT(r)}{dr} = \frac{\alpha(r)g(r)}{C_P(r)},$$

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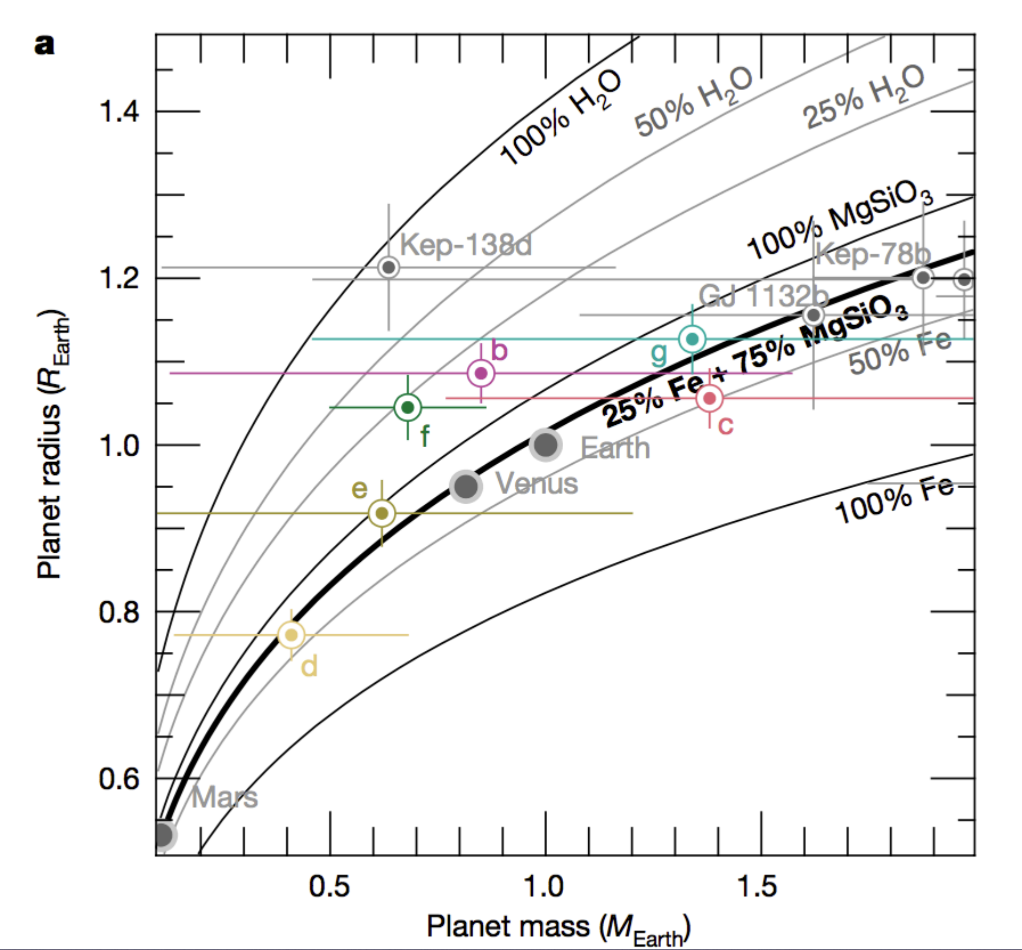

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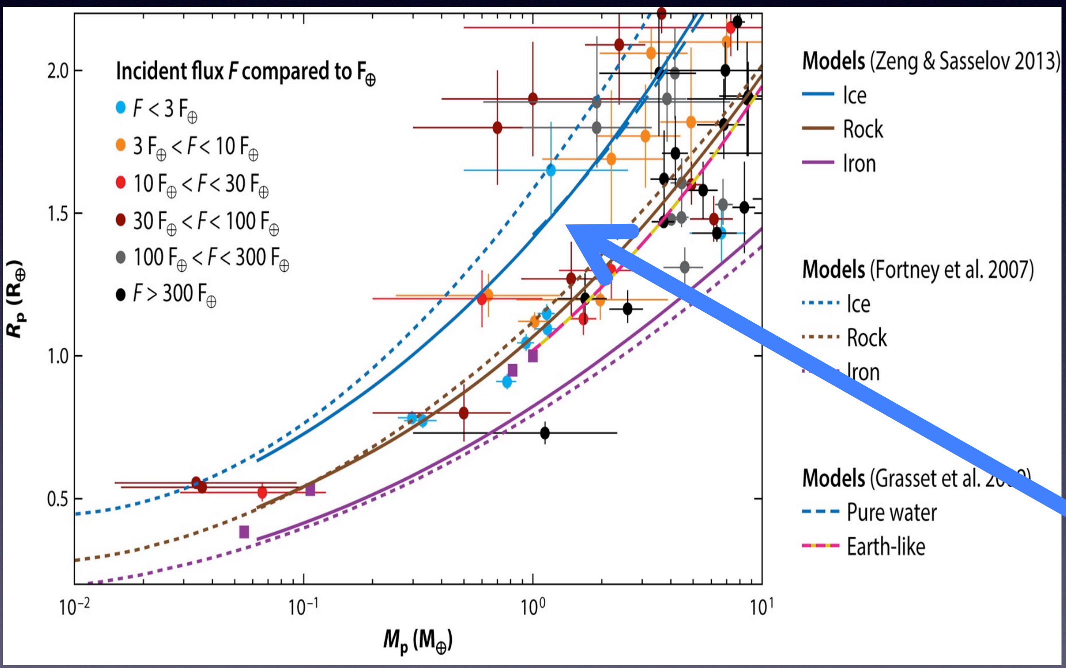

Jontof-Hutter, 2019, Ann. Rev.

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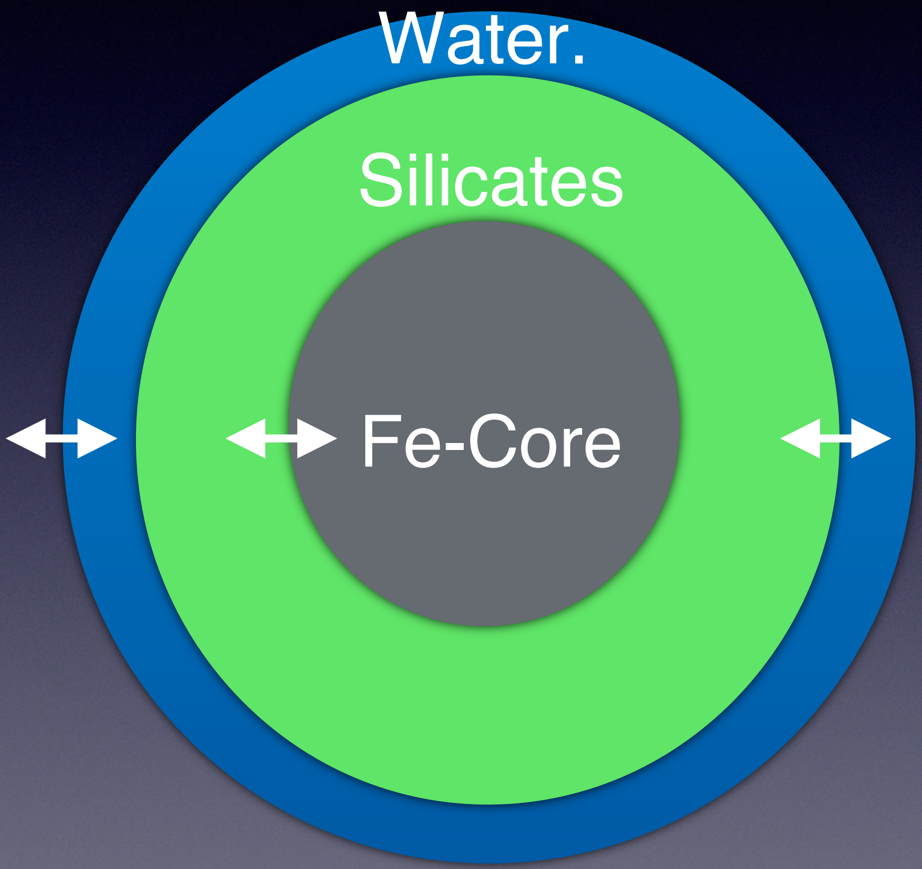
Let's Build a Planet!



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Let's Build a Planet! M Earth Mass

Comp.	Mass
Water	M
Silicate	dM
Silicate	dM
Silicate	dM
Silicate	dM
Core	dM
Core	dM
Core	0

Mass in a sphere

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r),$$

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$$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2},$$

Equation of State of material

$$\rho(r) = f\left(P(r), T(r), X(r)\right)$$

Adiabatic temperature gradient

$$\frac{dT(r)}{dr} = \frac{\alpha(r)g(r)}{C_P(r)},$$

Let's Build a Planet! M Earth Mass

Comp.	Mass	Rad.	Pres.
Water	M	dr_7	1 bar
Silicate	dM	dr_6	dP
Silicate	dM	dr_5	dP_2
Silicate	dM	dr_4	dP_3
Silicate	dM	dr_3	dP_4
Core	dM	dr_2	dP_5
Core	dM	dr	dP_6
Core	0	0	dP_7

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$$\frac{dT(r)}{dr} = \frac{\alpha(r) g(r)}{C_P(r)},$$

Let's Build a Planet! M Earth Mass

Comp.	Mass	Rad.	Pres.	Temp.
Water	M	dr_7	P_0 =1 bar	T_P
Silicate	dM	dr_6	P_0+dP	T_P+dT_1
Silicate	dM	dr_5	$P_0+dP_1+dP_2$	$T_P+dT_1+dT_2$
Silicate	dM	dr_4	… + dP_3	…+dT_3
Silicate	dM	dr_3	…+dP_4	dT_4
Core	dM	dr_2	…+dP_5	300 K
Core	dM	dr	…+dP_6	300 K
Core	0	0	…+dP_7	300 K

Let's Build a Planet! M Earth Mass

Comp.	Mass	Rad.	Pres.	Temp.	Grav.
Water	M	dr_7	$P_0 = 1$ bar	T_P	$\ldots + dg_7$
Silicate	dM	dr_6	$P_0 + dP$	$T_P + dT_1$	$\ldots + dg_6$
Silicate	dM	dr_5	$P_0 + dP_1 + dP_2$	$T_P + dT_1 + dT_2$	$\ldots + dg_5$
Silicate	dM	dr_4	$\ldots + dP_3$	$\ldots + dT_3$	$\ldots + dg_4$
Silicate	dM	dr_3	$\ldots + dP_4$	dT_4	$\ldots + dg_3$
Core	dM	dr_2	$\ldots + dP_5$	300 K	$dg + dg_2$
Core	dM	dr	$\ldots + dP_6$	300 K	dg
Core	0	0	$\ldots + dP_7$	300 K	0

Let's Build a Planet! M Earth Mass

Comp.	Mass	Rad.	Pres.	Temp.	Grav.	Density
Water	M	dr_7	$P_0 = 1$ bar	T_P	$\ldots + dg_7$	ρ_1
Silicate	dM	dr_6	$P_0 + dP$	$T_P + dT_1$	$\ldots + dg_6$	ρ_2
Silicate	dM	dr_5	$P_0 + dP_1 + dP_2$	$T_P + dT_1 + dT_2$	$\ldots + dg_5$	ρ_3
Silicate	dM	dr_4	$\ldots + dP_3$	$\ldots + dT_3$	$\ldots + dg_4$	ρ_4
Silicate	dM	dr_3	$\ldots + dP_4$	dT_4	$\ldots + dg_3$	ρ_5
Core	dM	dr_2	$\ldots + dP_5$	300 K	$dg + dg_2$	ρ_6
Core	dM	dr	$\ldots + dP_6$	300 K	dg	ρ_7
Core	0	0	$\ldots + dP_7$	300 K	0	ρ_8

Let's Build a Planet! M Earth Mass

Comp.	Mass	Rad.	Pres.	Temp.	Grav.	Density	Rad.
Water	M	dr_7	P_0 =1 bar	T_P	…+dg_7	ρ_1	dr_7
Silicate	dM	dr_6	P_0+dP	T_P+dT_1	…+dg_6	ρ_2	dr_6
Silicate	dM	dr_5	P_0+dP_1 +dP_2	T_P+dT_1 +dT_2	…+dg_5	ρ_3	dr_5
Silicate	dM	dr_4	… + dP_3	…+dT_3	…+dg_4	ρ_4	dr_4
Silicate	dM	dr_3	…+dP_4	dT_4	…+dg_3	ρ_5	dr_3
Core	dM	dr_2	…+dP_5	300 K	dg+dg_2	ρ_6	dr_2
Core	dM	dr	…+dP_6	300 K	dg	ρ_7	dr
Core	dM	0	…+dP_7	300 K	0	ρ_8	0

Let's Build a Planet! M Earth Mass

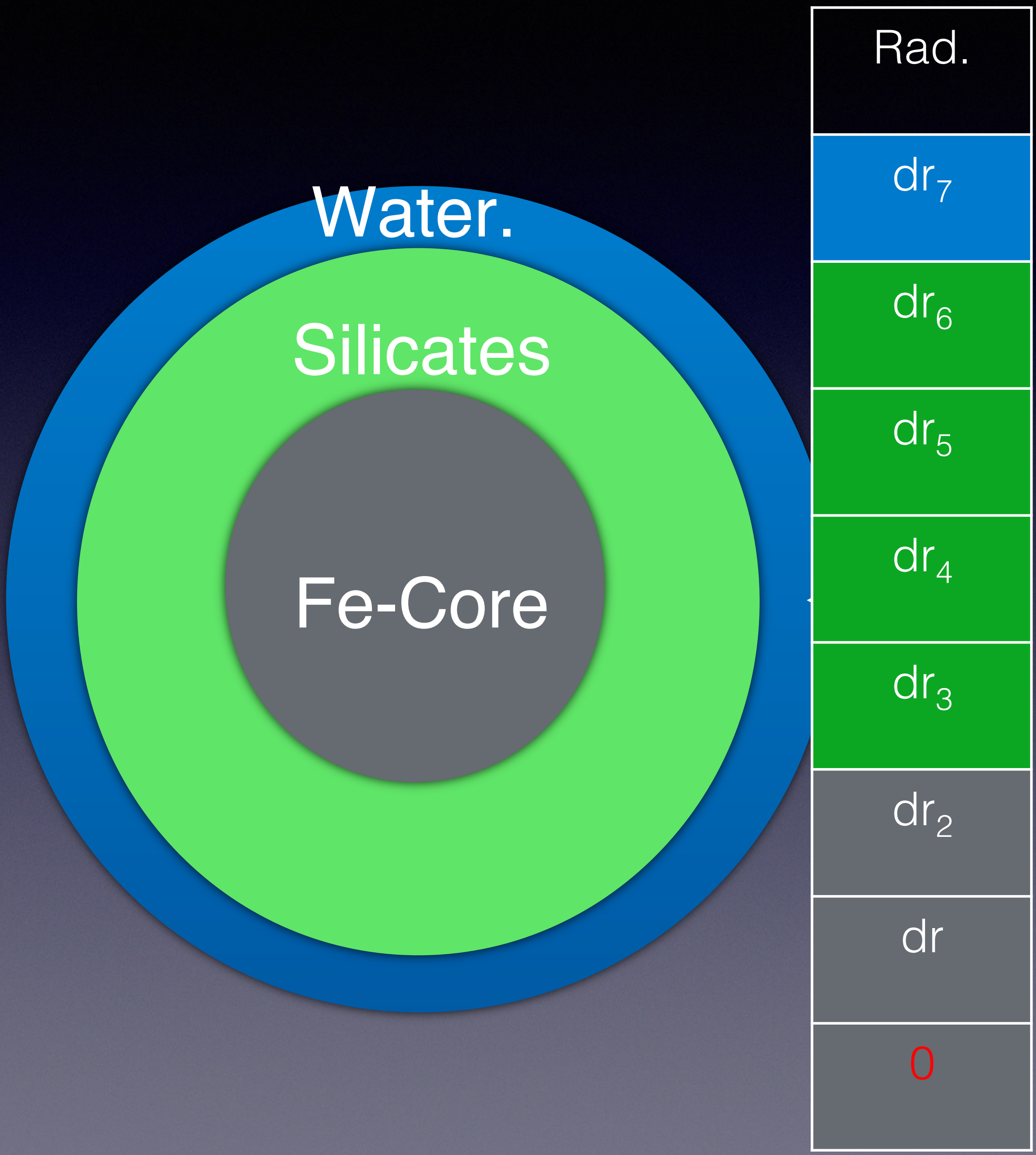
Comp.	Mass	Rad.	Pres.	Temp.	Grav.	Density	Rad.
Water	M	dr_7	$P_0 = 1$ bar	T_P	$\ldots+dg_7$	ρ_1	dr_7
Silicate	dM	dr_6	P_0+dP	T_P+dT_1	$\ldots+dg_6$	ρ_2	dr_6
Silicate	dM	dr_5	$P_0+dP_1+dP_2$	$T_P+dT_1+dT_2$	$\ldots+dg_5$	ρ_3	dr_5
Silicate	dM	dr_4	$\ldots + dP_3$	$\ldots+dT_3$	$\ldots+dg_4$	ρ_4	dr_4
Silicate	dM	dr_3	…+d[illegible]	[illegible] dT_4	$\ldots+dg_3$	ρ_5	dr_3
Core	dM	dr_2	…+d[illegible]	[illegible]300 K	$dg+dg_2$	[illegible]	dr_2
Core	dM	dr	$\ldots+dP_6$	[illegible]	[illegible]	[illegible]	dr
Core	dM	0	$\ldots+dP_7$	300 K	0	ρ_8	0

$\Delta\rho < 10^{-6}$

Equations of State

$$\rho(r) = f(P(r), T(r), X(r))$$

$$\frac{dT(r)}{dr} = \frac{\alpha(r) g(r)}{C_P(r)},$$

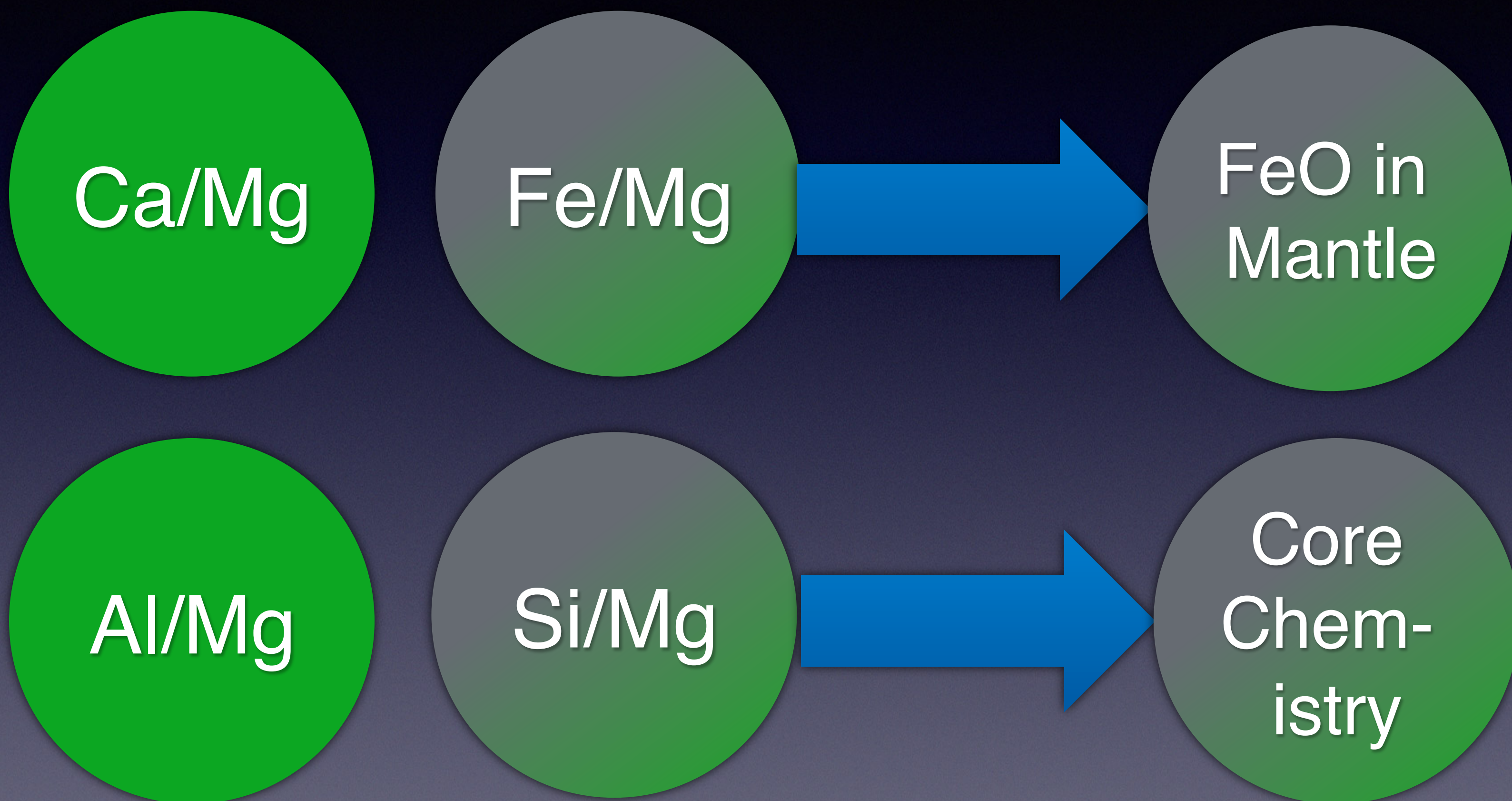


IAPWS

PerPlex or Grids

EoS from Shock experiments

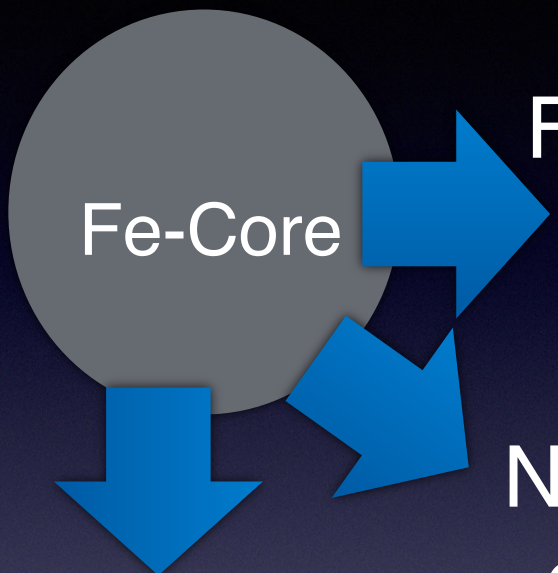
Calculating Composition



Core Chemistry

$$\rho(r) = f(P(r), T(r), X(r))$$

P = Mass/ Volume



Fe – 55 g/mol

Ni – 58 g/mol

X– < 55 g/mol

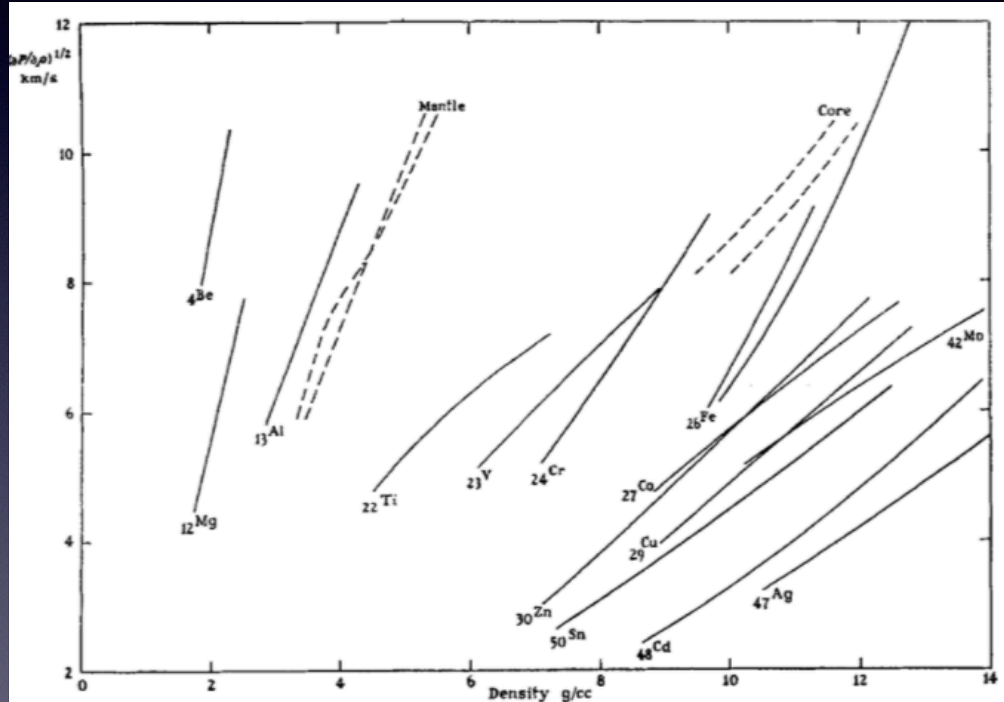


FIG. 5.—Hydrodynamical sound velocity as function of density for metals and for the Earth's mantle and core.

Birch, 1964 JGR

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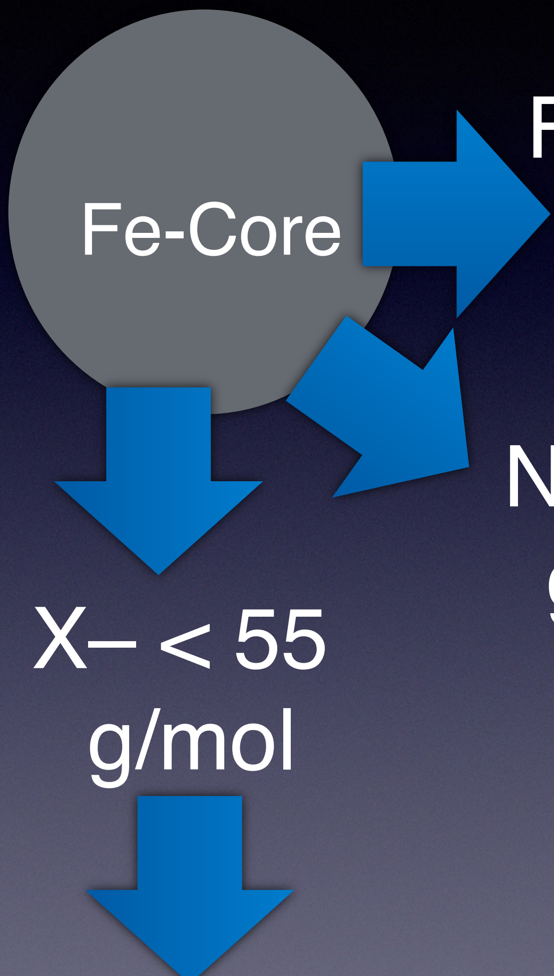


Fe – 55 g/mol

Ni – 58 g/mol

X– < 55 g/mol

X= Si (28), S (32), O (16)

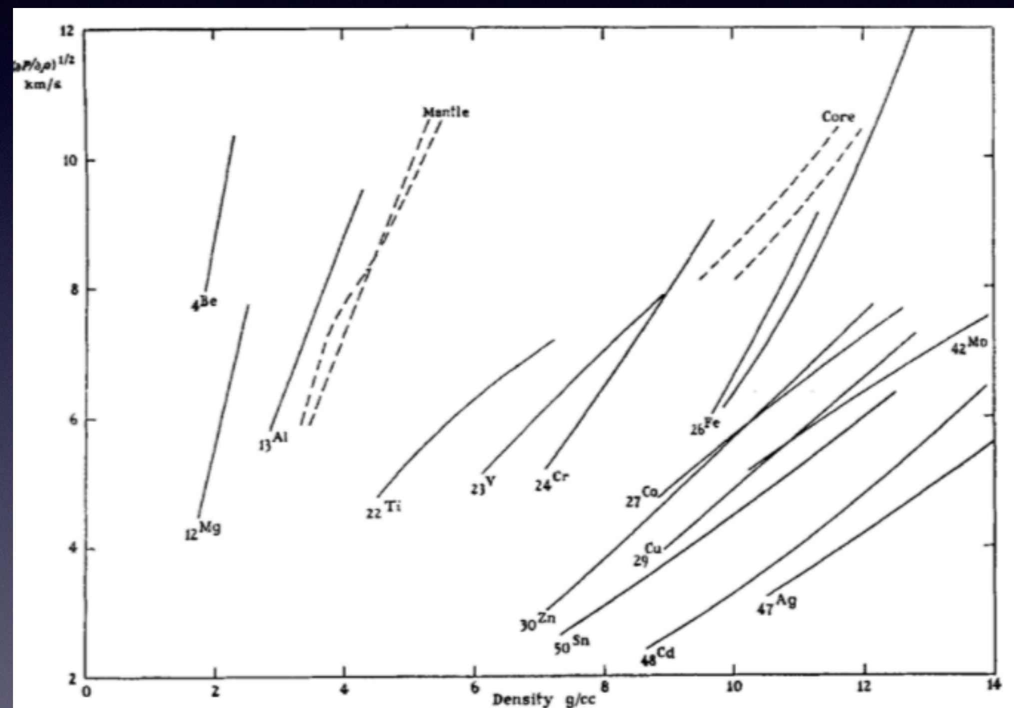
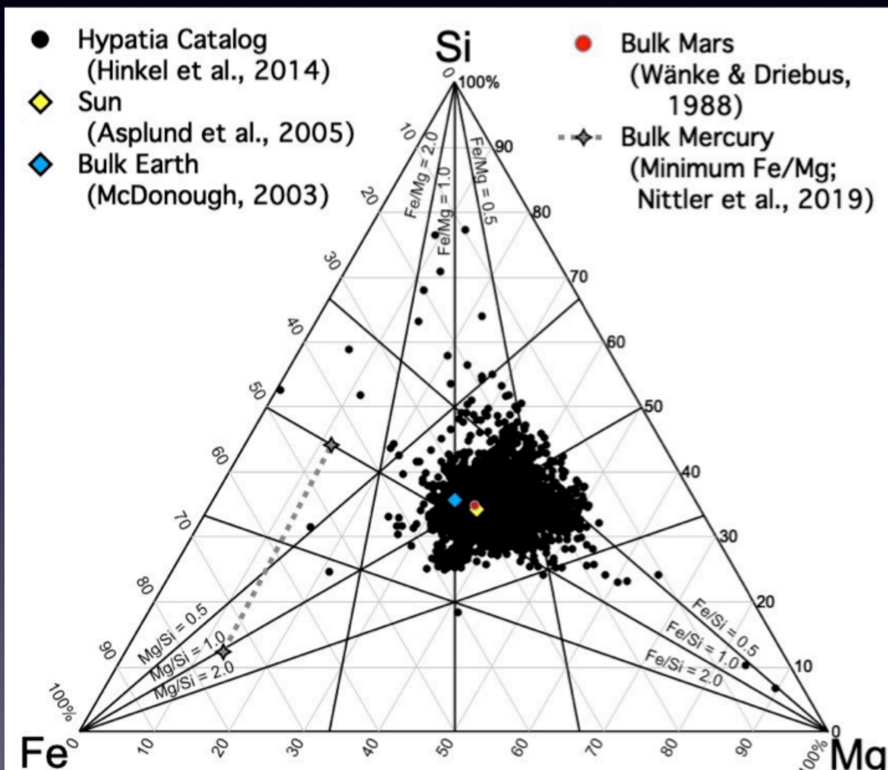


FIG. 5.—Hydrodynamical sound velocity as function of density for metals and for the Earth's mantle and core.

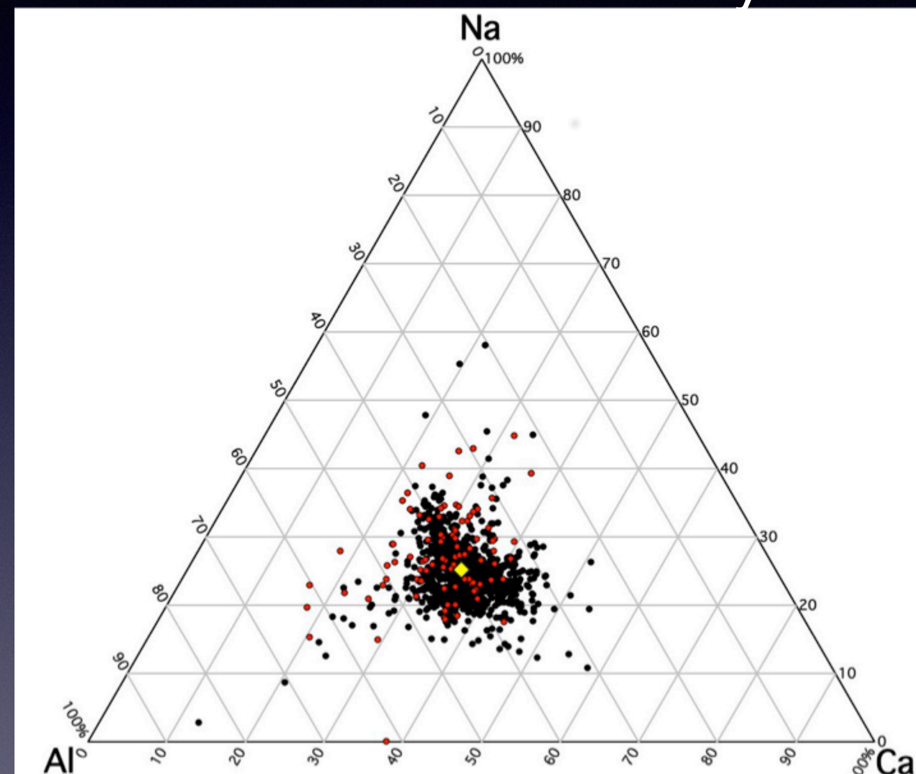
Birch, 1964 JGR

Stellar diversity~Planet diversity

Refractory: 1-to-1-ish



Moderately Volatile
Ultra-refractory



Earth: 40%⇧+50% O
+ 10% everything else

Unterborn et al., *2019*

Stellar diversity~Planet diversity

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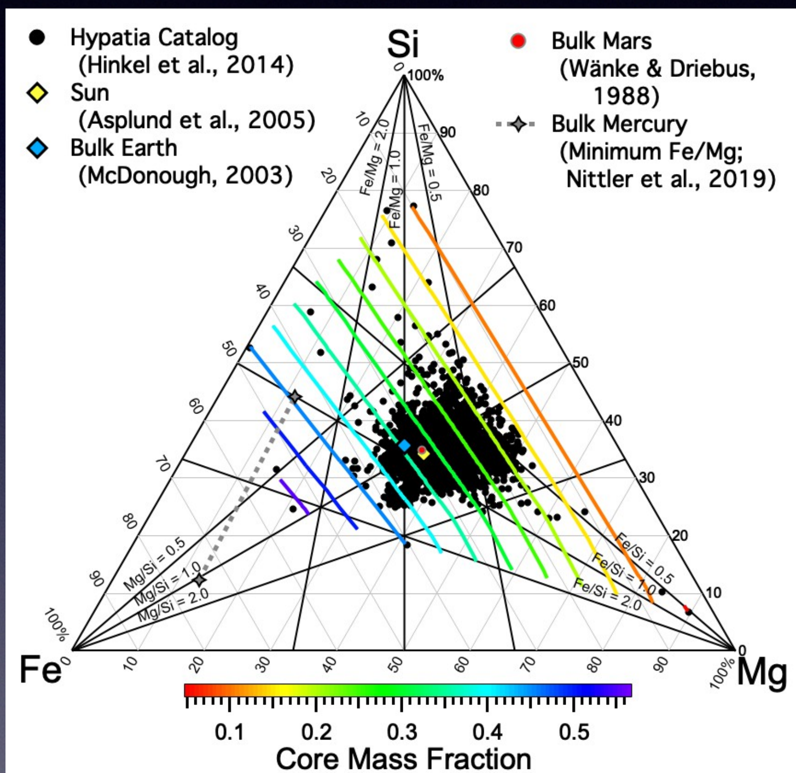

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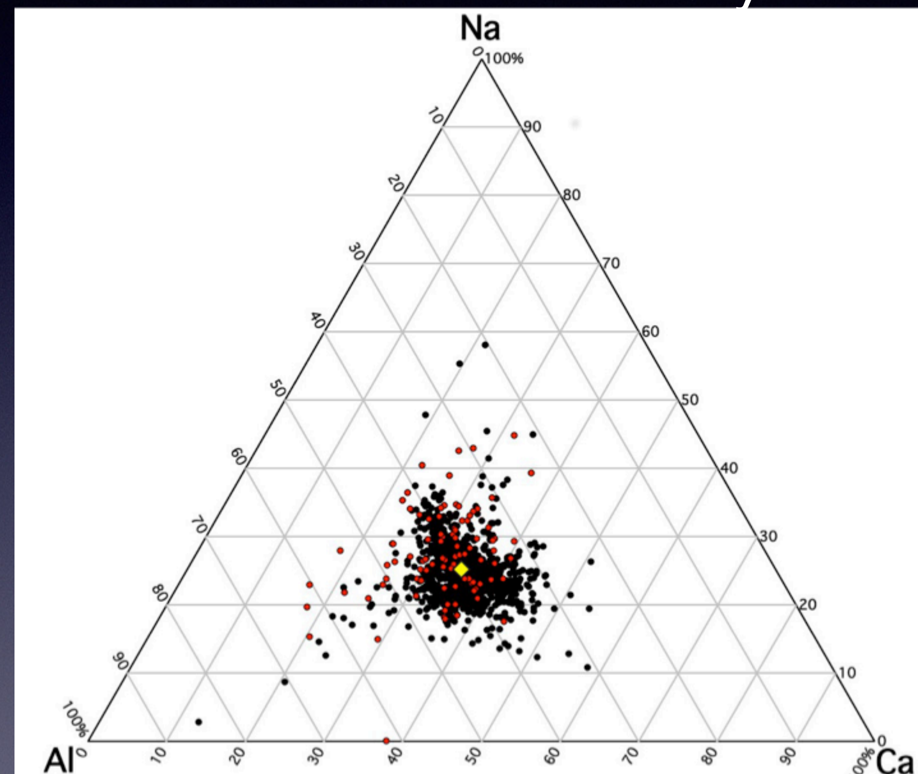

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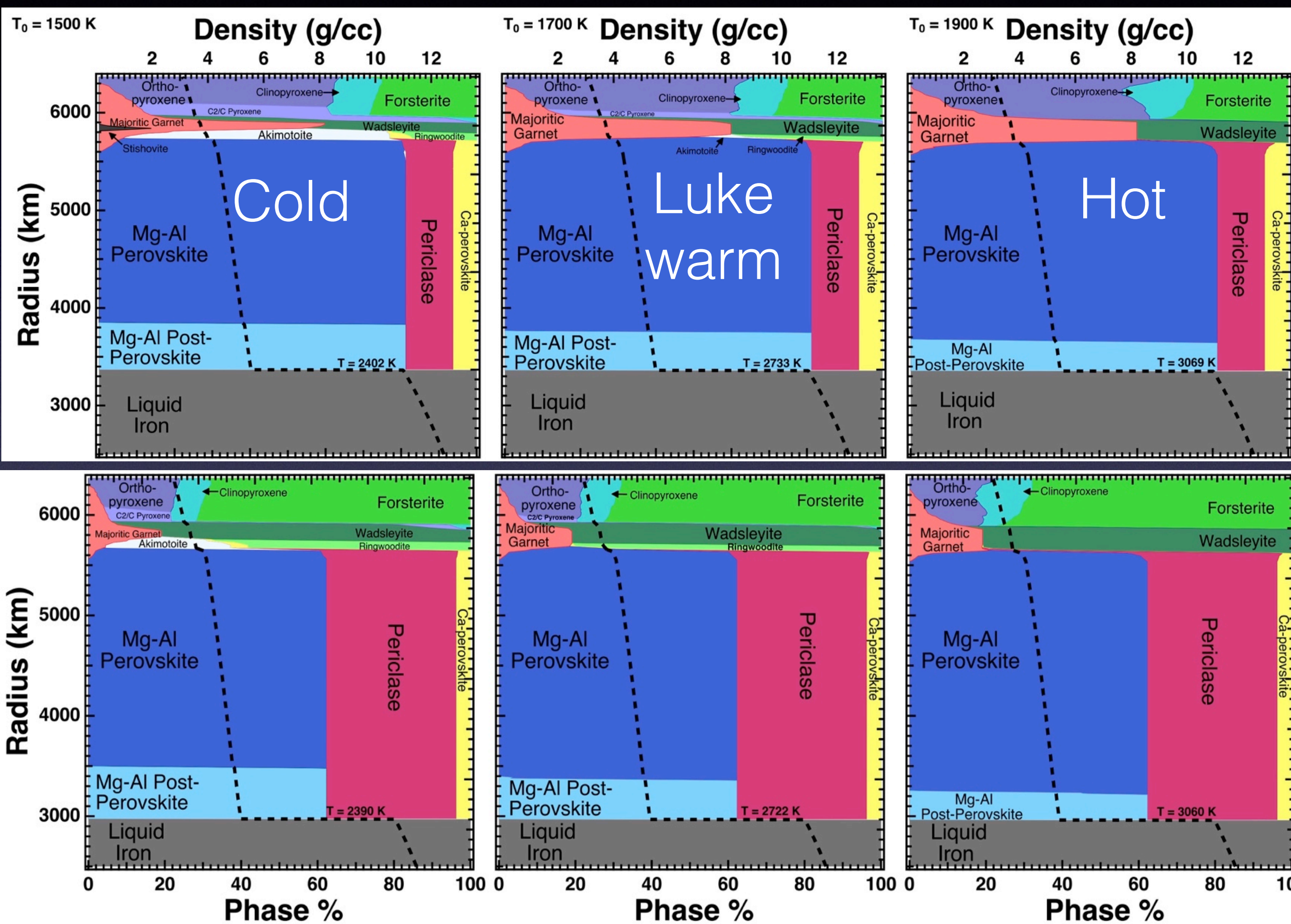
ExoPlex



<u>Earth</u>

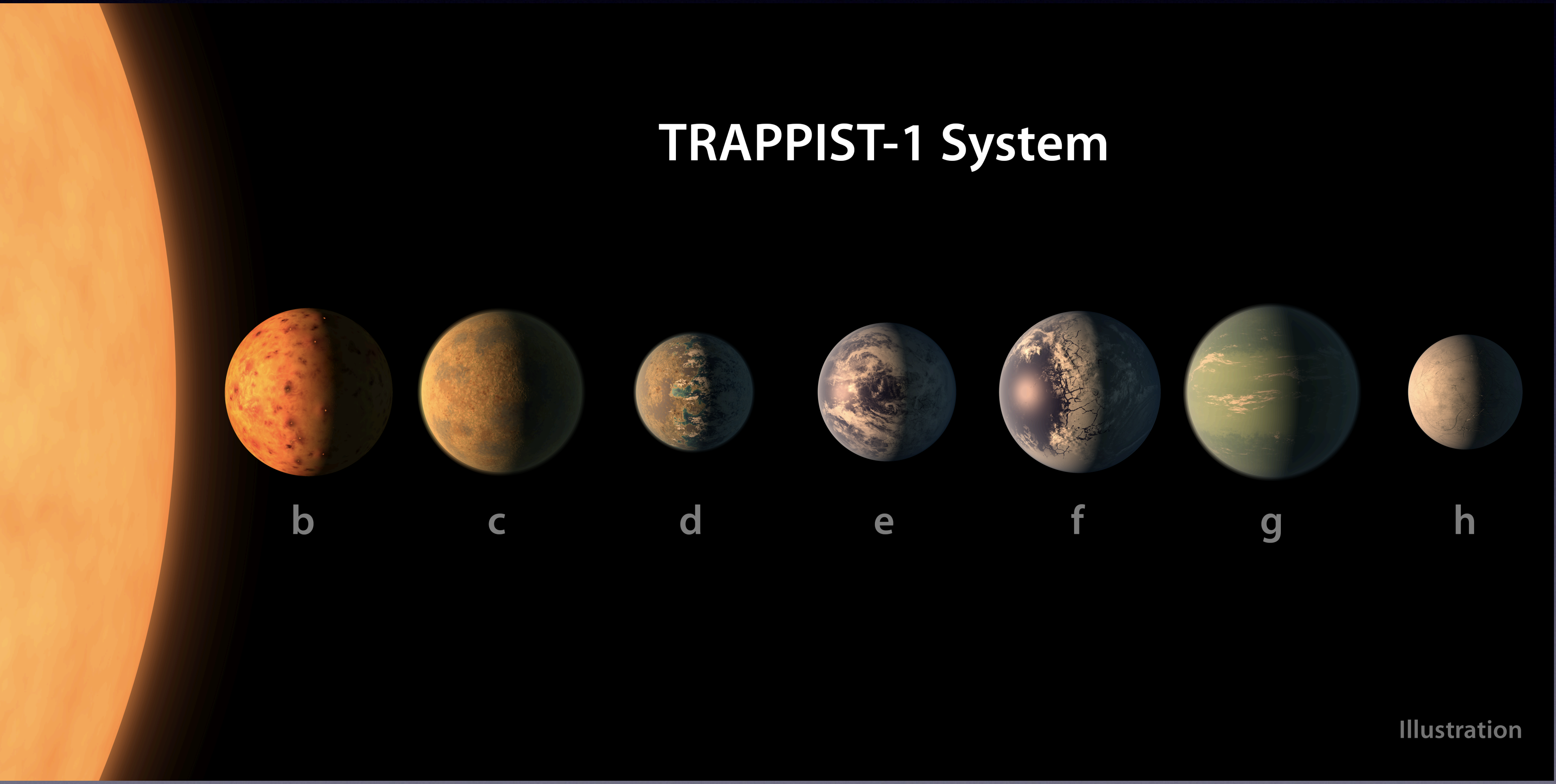
Mg/Si = 1.1
Fe/Mg = 0.9
Al/Mg = 0.1
Ca/Mg = 0.07

<u>Random Star</u>

Mg/Si = 1.5
Fe/Mg = 0.5
Al/Mg = 0.04
Ca/Mg = 0.04

Hinkel & Unterborn, 2018 *ApJ*

Hands-on Session: Characterizing TRAPPIST-1



NASA