Project 4

Exoplanet Composition Analysis

Greg Costa, Omar Kotrach, Matthew Williard, Dax Begeny

Introduction

- Composition of exoplanets can be found from stellar composition

- Given mass or radius of the exoplanet with stellar abundance
  - Stellar abundance found with spectra

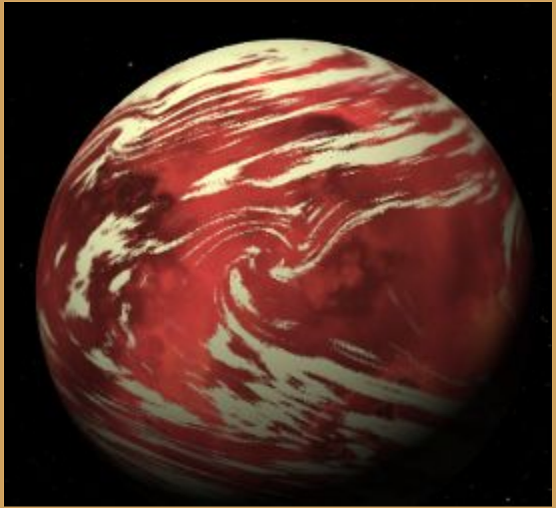
- Can calculate several parameters of the exoplanet
  - Elemental Composition
  - Core Mass Fraction
  - Radius or Mass (depending on initial parameter)

Composition of Kepler-105C

- Kepler-105 system consists of two exoplanets
  - Kepler-105b is a neptunian gas giant
  - Kepler-105c is a likely rocky super-earth

- Density varies greatly per paper
  - $11.2^{+3}_{-2.56}$ g/cm^3 (Jontof-Hutter et al. 2016)
  - $2.7^{+3.9}_{-1.8}$ g/cm^3 (Hadden & Lithwick 2017)
  - Earth density is ~5.5 g/cm^3

Kepler-105C



Hypothetical image from Nasa Exoplanet Catalog

Mass: $4.6^{+0.92}_{-0.85}\ M_\oplus$

Radius: $1.3\ R_\oplus$

Temperature: 997 K

Orbital Period: 7.126 days

ExoPlex

- Will be using a program called ExoPlex

- Input stellar compositions and exoplanet mass or radius

- Calculates many exoplanet attributes
  - Core Mass Fraction
  - Interior Mineralogy
  - Interior Pressure
  - And More

- Focus on Core mass fraction and Interior Mineralogy

Motivation

- Demonstrate the methods of using exoplanets mass with its host star's stellar abundance to calculation composition of exoplanets, such as using Exoplex
- Knowing the composition of exoplanets gives a better understanding of them and how they form
- Compare exoplanets to earth and find possible life on earth-like planets.

Methods

Review the NEA & ExoKyoto → ExoPlex radius obtained for each end of mass uncertainty

↓

Density computed for each radius (error propagated)

→ FeMg, FeO, and core composition altered

↓

Range of planetary composition for given radius and mass

Equations Used

$$V = (4/3) * \pi * R^3$$

$$\rho = M/V$$

Table 2

Sample of Well-characterized Exoplanets with Available Host-star Abundances

Planet	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Host [Fe/H]	Host [Mg/H]	Host [Si/H]	Host Fe/Mg	Host Si/Mg	$CMF_\star$	CMF_ρ	$P(H_0)$ (%)	1σ Class
Kepler-406 b	6.35 ± 1.40	1.43 ± 0.03	0.21 ± 0.04	0.20 ± 0.07	0.19 ± 0.05	0.83 ± 0.25	0.93 ± 0.26	0.33 ± 0.07	$0.76^{+0.13}_{-0.19}$	8	SM
Kepler-105 c	$4.60^{+0.92}_{-0.85}$	1.31 ± 0.07	-0.12 ± 0.04	-0.09 ± 0.07	-0.08 ± 0.05	0.76 ± 0.22	0.98 ± 0.27	0.30 ± 0.07	$0.78^{+0.18}_{-0.21}$	10	SM
Kepler-99 b	6.15 ± 1.3	1.48 ± 0.08	0.26 ± 0.04	0.25 ± 0.07	0.21 ± 0.10	0.83 ± 0.25	0.87 ± 0.24	0.33 ± 0.07	$0.65^{+0.19}_{-0.27}$	39	IHS
Kepler-102 d	2.5 ± 1.40[a]	1.18 ± 0.04	0.12 ± 0.04	0.08 ± 0.07	0.10 ± 0.05	0.88 ± 0.26	0.99 ± 0.28	0.33 ± 0.08	$0.61^{+0.31}_{>0.61}$	54	IHS
Kepler-78 b	$1.77^{+0.24}_{-0.25}$	$1.23^{+0.018}_{-0.019}$	0.00 ± 0.04	-0.07 ± 0.07	-0.03 ± 0.05	0.95 ± 0.28	1.05 ± 0.29	0.34 ± 0.08	$0.14^{+0.15}_{>0.14}$	60	IHS
Kepler-36 b	$3.83^{+0.11}_{-0.10}$	$1.50^{+0.061}_{-0.049}$	-0.18 ± 0.04	-0.18 ± 0.07	-0.19 ± 0.05	0.81 ± 0.24	0.92 ± 0.26	0.32 ± 0.07	$0.19^{+0.13}_{-0.17}$	73	IHS
Kepler-93 b	4.54 ± 0.85	1.57 ± 0.11	-0.18 ± 0.04	-0.13 ± 0.07	-0.19 ± 0.05	0.72 ± 0.21	0.83 ± 0.23	0.33 ± 0.07	$0.16^{+0.34}_{>0.16}$	93	IHS

Notes. Host star elemental ratios are expressed as molar ratios derived using the solar abundances of Lodders et al. (2009). All masses and radii are taken from the NASA Exoplanet Archive (doi:10.26133/NEA1) (Akeson et al. 2013), and the stellar abundance data are from the Hypatia Catalog. The classifications in the last column are illustrated in Figure 21, where SM = super-Mercury and IHS = indistinguishable from host star. CMF values correspond to the median values and 1σ confidence intervals.

[a] Mass value taken from Brinkman et al. (2022).

Warm Up

Let’s get familiar with ExoPlex

Input: Mass

Planet	Input: Mass	Output: Radius	Actual Radius
Earth	1	1.007	1
Mars	.107	.523	.266
Mercury	.0553	.425	.1915

Planet	Input: Fe/Mg	Output: Radius	Actual Radius
Earth	.8	1.007	1
	1 ▲	.994 ▼	
	25 ▲	.825 ▼	
	.01 ▼	1.077 ▲	
	.001 ▼	1.078 ▲	
Mars	.8	.523	.266
	1 ▲	.517 ▼	
	25 ▲	.430 ▼	
	.01 ▼	.558 ▲	
	.001 ▼	.558 ▲	
Mercury	.8	.425	.1915
	1 ▲	.420 ▼	
	25 ▲	.350 ▼	
	.01 ▼	.453 ▲	
	.001 ▼	.453 ▲	

ADDING LIGHTER ELEMENTS

Earth Mass	Input: Si in the core	Input: O in the core	Input: S in the core	Output: Radius	Mantle Composition
1	0.01	0.01	0.01	1.011	FeO=1.91
					SiO2=56.07
					MgO=34.69
					CaO=3.37
					Al2O3=3.94
	0.05	0.05	0.05	1.018	FeO=8.27 ▲
					SiO2=51.11 ▼
					MgO=33.52 ▼
					CaO=3.26 ▼
					Al2O3=3.81 ▼

ADDING LIGHTER ELEMENTS

Earth Mass	Input: Si in the core	Input: O in the core	Input: S in the core	Output: Radius	Mantle Composition
1	0.1	0.1	0.1	1.011	FeO=14.31
					SiO2=46.01
					MgO=32.75
					CaO=3.18
					Al2O3=3.72
	0.4	0.15	0.15	1.018	FeO=19.22
					SiO2=41.18
					MgO=32.68
					CaO=3.18
					Al2O3=3.72

Earth Mass	Input: Si/Mg	Output: Amount of Perovskite
1	2	53.44
	1.8	59.05
	1.5	70.19
	1.1	93.67
	1	85.08

Results

INPUT: MASS

Mass (M⊕)	Radius (R⊕)	Density (kg/m^3)	Fe/Mg	Fe in mantle	Si in core	Si/Mg	O in core	S in core
3.75	1.446	6815.27	.83	0.1	0	.98	0	0
4.6	1.53	7057.34	.83	0.1	0	.98	0	0
4.8	1.547	7124.06	.83	0.1	0	.98	0	0
>4.8	N/A	N/A	.83	0.1	0	.98	0	0

INPUT: CORE MASS FRACTION & CORE COMPOSITION

<table>
<tr><th>Mass (M⊕)</th><th>Radius (R⊕)</th><th>Fe/Mg</th><th>Si/Mg</th><th>Fe in Mantle</th><th>O in the core</th><th>S in the core</th><th>Si in the core</th><th>Mantle Composition (%)</th><th>Core Composition (%)</th></tr>
<tr><td rowspan="5">3.75</td><td rowspan="5">1.421</td><td rowspan="5">1.1</td><td rowspan="5">0.98</td><td rowspan="5">0.1</td><td rowspan="5">0</td><td rowspan="5">0</td><td rowspan="5">0.1</td><td>FeO=19.88</td><td>Fe=90</td></tr>
<tr><td>SiO2=40.03</td><td>Si=10</td></tr>
<tr><td>MgO=33.09</td><td>O=0</td></tr>
<tr><td>CaO=3.22</td><td rowspan="2">S=0</td></tr>
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</table>

Mass (M⊕)	Radius (R⊕)	Fe/Mg	Si/Mg	Fe in Mantle	O in the core	S in the core	Si in the core	Mantle Composition (%)	Core Composition (%)
3.75	▲ 1.431	1.1	0.98	0.1	▲ .02	▲ .02	0.1	FeO=19.96 ▲ SiO_2=39.79 ▼ MgO=33.22 ▲ CaO=3.23 ▲ Al_2O_3=3.78 ▲	Fe=86 ▼ Si=10 O=2 ▲ S=2 ▲
3.75	▲ 1.456	1.1	▲ 2.17	0.1	0	0	0.1	FeO=12.52 ▼ SiO_2=62.21 ▲ MgO=20.85 ▼ CaO=2.03 ▼ Al_2O_3=2.37 ▼	Fe=90 Si=10 O=0 S=0

MANTLE MINERALOGY COMPOSITION

	FeO	SiO2	MgO	CaO	Al2O3
Best fitting parameter	19.88	40.03	33.09	3.22	3.47
ExoPlex (Earth)	0.49	57.23	34.9	3.39	3.97
Allegre, et al; 1995 (Earth)	7.48	46.11	37.77	3.23	4.09

Discussion

- The mass was the most influential factor in determining the radius of a planet. With more mass, the planet has more material which leads to a greater radius
- We found an upper limit to the mass parameter at 4.8 Earth masses
- Another influential factor was the ratio between Iron and Magnesium. With a higher ratio, the radius of the planet got smaller
- When lighter elements were added to the planet, the radius increased

Conclusion

- Stellar abundances are useful for finding exoplanet composition
- ExoPlex can be used to calculate the structure of exoplanets while also allowing for experimentation of the mass parameter
- Mass and the Fe/Mg ratio had the biggest impact on radius
- ExoPlex begins to become less accurate at low and higher mass planets