Data Analysis 2: Stars and Exoplanets (75 points)

Please read the general instructions in the separate envelope before you start this problem.

In this problem, we will explore the connection between the physical properties of exoplanets and their host stars and will use the observational data to discover as much as possible about these systems. You may neglect interstellar extinction.

Part 1 (20 points).

Name of planet	Name of star	$T_{eff}\,(K)$	$g\,(ms^{-2})$	m_v (magnitudes)	parallax (milliarcsec)
$Gorgona$	$HD\,209458$	5980	347	7.63	20.67

Table 1: Observational data for exoplanet Gorgona and its parent star *HD 209458*

The effective temperature (T_{eff}) and the gravitational acceleration in the surface of the star (g) can be measured from the shape of the spectrum and its absorption lines. The visual apparent magnitude (m_v) and parallax are measured by doing photometry and astrometry, respectively.

Additionally, it has been observed that every 3.52 days the brightness of the star drops due to the transit of the planet in front of it, as it is represented in this lightcurve:

1.1 20.0pt

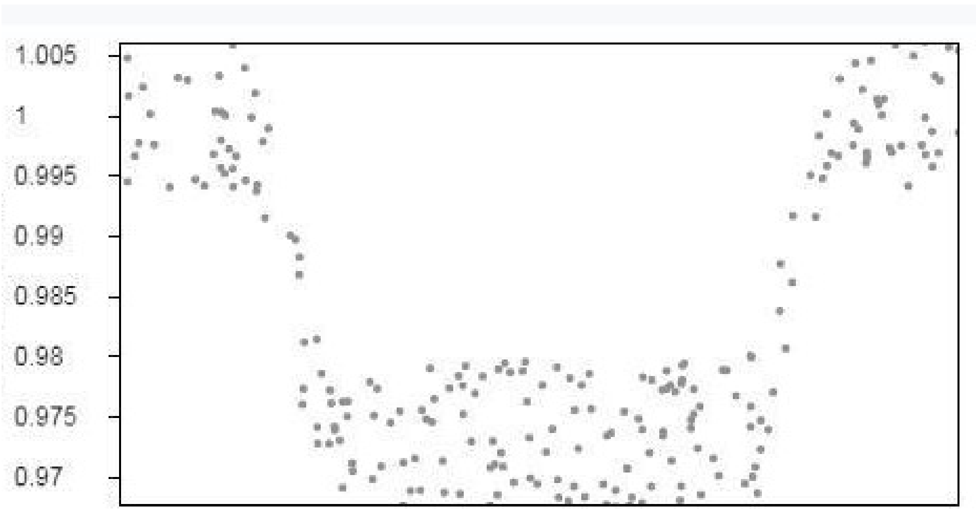


Figure 1: Normalized Flux (y-axis) against time (x-axis) for the parent star *HD 209458*

Use the given information to calculate the following quantities for the *HD 209458* system:

Luminosity of the star	Radius of the star	Mass of the star	Mean planet's orbital radius	Radius of the planet in Jupiter's radius
$L_\star$ $[L_\odot]$	$R_\star$ $[R_\odot]$	$M_\star$ $[M_\odot]$	a $[au]$	R_p $[R_J]$

Note: Assume that the bolometric correction for all F and G type stars is the same.

Part 2 (25 points).

The habitable zone is defined as the region in which a planet may have liquid water on its surface. This is mainly related to the amount of radiation received from the host star, which must be within some limits to ensure a favorable range of planet surface temperatures.

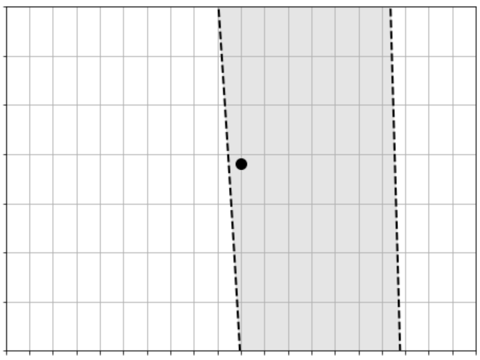
We define the effective flux received by a planet as $S_{eff} = \frac{L}{a^2}$, where L is the star luminosity in solar units, and a is the mean orbital radius in au. The minimum flux in the habitable zone can be approximated by $S_{min} = S_{eff_\odot} + n \cdot T_\star + b \cdot T_\star^2 + c \cdot T_\star^3 + d \cdot T_\star^4$, where $T_\star = (T_{eff} - T_{eff_\odot})$, and $S_{eff_\odot}$ is the equivalent flux for the case of the Sun, which along with the coefficients $n,\ b,\ c,\ d$ is given in the following table. The maximum flux for habitability, S_{max}, is found with the same equation but different constants:

Constant	S_{max}	S_{min}
$S_{eff_\odot}$	1.0512	0.3438
n	1.3242×10^{-4}	5.8942×10^{-5}
b	1.5418×10^{-8}	1.6558×10^{-9}
c	-7.9895×10^{-12}	-3.0045×10^{-12}
d	-1.8328×10^{-15}	-5.2983×10^{-16}

The table below gives real data for 7 different star-planet systems. However planet names have been changed to honour some natural sanctuaries in Colombia:

Stellar Parameters		Planet Parameters	
$T_{eff}\ [K]$	$M_V\ [mag]$	Name	$a[au]$
6180	3.68	Tayrona	0.04
5730	3.87	Iguaque	0.04
5980	4.21	Gorgona	0.04
5480	6.04	Amacayacu	0.08
5770	3.48	Malpelo	0.05
6130	3.07	Pisba	0.03
6140	3.85	Tatamá	0.06

2.1 In the following figure, the vertical axis represents the effective temperature of stars, and the horizontal axis represents the effective flux received by orbiting planets. The dot marked on the graph represents planet Earth, and dashed lines mark the limits of the habitable zone. 15.0pt



Put numerical labels at tickmark position on both axes. Draw on the same figure the exact position where Gorgona and Amacayacu would be, as if they were also located at 1 au from their corresponding stars.

2.2 Now considering the real orbital radius given in the table for each planet, indicate with YES or NO which of them are in the habitable zone. Show your quantitative reasoning on the working sheets. 10.0pt

Planet's Name	In habitable zone? YES / NO
Tayrona	
Iguaque	
Gorgona	
Amacayacu	
Malpelo	
Pisba	
Tatamá	

Part 3 (30 points).

In the last page you find a list of 38 exoplanets, and the goal is to find out if low-mass exoplanets (LME) and high-mass exoplanets (HME) tend to orbit around stars with different characteristics.

3.1 To get a robust low-mass subsample one can apply a technique called "iterative sigma-clipping". The idea is to compute the mean (μ) and the standard deviation (σ) of the masses and to exclude from the sample, those planets with masses above $\mu + \sigma$. Then repeat the same steps with the remaining subsample two more times. We will say that planets in the final subsample are the low-mass ones, and those excluded during the iterations, the high-mass ones. Fill the following table with the numbers you find in the process: 10.0pt

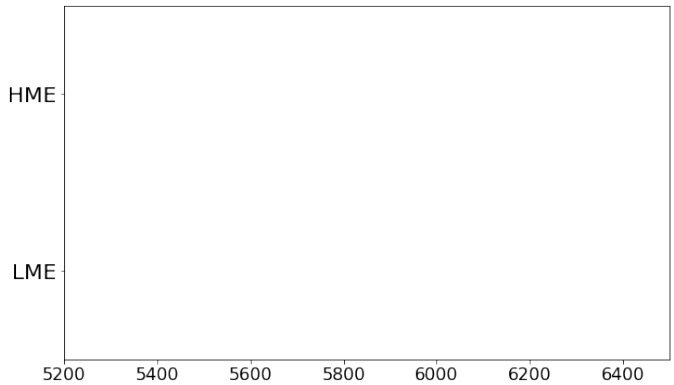
Low-mass sample	Sample size	μ	σ	$\mu + \sigma$	No. of planets to exclude
Full / Original	38				
subsample after 1st iteration					
subsample after 2nd iteration					
subsample after final iteration		---	---	---	---

3.2 Make a plot using the X-axis for the serial number of the planets in the list $(1, 2, 3, \ldots)$, and the Y-axis for the mass of the planets. Mark 3 horizontal lines at the $\mu + \sigma$ thresholds you found in the iterations: 5.0pt

3.3 Let's investigate the possible difference in the effective temperatures of host stars in both groups, computing some descriptive statistics: 10.0pt

	Min.	1st Quartile	Median 2nd quartile	3rd Quartile	Max
LME					
HME					

3.4 Draw boxplots summarizing the numbers you just computed. Do you see a clear difference in the temperatures of the stars orbited by low-mass and high-mass planets? Write YES or NO. 5.0pt



Planetary type vs host star temperature (K)

No.	Name of Planet	Planet Mass $[M_J]$	T_{eff} of the Host Star
1	KEPLER-37 b	0.01	5520
2	KEPLER-21 b	0.02	6256
3	HD 97658 b	0.02	5468
4	HD 46375 b	0.23	5345
5	HD 219134 h	0.28	5209
6	HD 88133 b	0.30	5582
7	HD33283 b	0.33	5877
8	HD 149026 b	0.36	6096
9	BD-10 3166 b	0.46	5578
10	HD 75289 b	0.47	6196
11	HD 217014 b	0.47	5755
12	HD 2638 b	0.48	5564
13	WASP-13 b	0.49	6025
14	WASP-34 b	0.59	5771
15	HD 209458 b	0.69	5988
16	HAT-P-30 b	0.71	6177
17	WASP-76 b	0.92	6133
18	WASP-74 b	0.97	5727
19	HAT-P-6 b	1.06	6442
20	HD189733 b	1.14	5374
21	WASP-82 b	1.24	6257
22	KELT-7 b	1.29	6460
23	HD 149143 b	1.33	6067
24	KELT-3 b	1.42	6404
25	KELT-2A b	1.49	6164
26	HD86081 b	1.50	6015
27	HAT-P-7 b	1.74	6270
28	HD 118203 b	2.14	5847
29	HAT-P-14 b	2.20	6490
30	WASP-38 b	2.71	6178
31	HD17156 b	3.20	5985
32	KELT-6 c	3.71	6176
33	HD 75732 d	3.86	5548
34	HD 115383 b	4.00	5891
35	HD 120136 b	5.84	6210
36	WASP-14 b	7.34	6195
37	HAT-P-2 b	8.74	6439
38	XO-3 b	11.79	6281