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DETECTION OF EXOMOONS BY DECAMETRIC RADIO EMISSIONS AND DETERMINATION OF THEIR HABITABILITY THROUGH TIDAL HEATING

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DETECTION OF EXOMOONS BY DECAMETRIC RADIO EMISSIONS AND DETERMINATION OF THEIR HABITABILITY THROUGH TIDAL HEATING

by

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ABSTRACT

DETECTION OF EXOMOONS BY DECAMETRIC RADIO EMISSIONS

AND DETERMINATION OF THEIR HABITABILITY

THROUGH TIDAL HEATING

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Over 4000 exoplanets have been discovered but most of them are unsuitable for life. With organic compounds being discovered on Saturn's moon Enceladus, exomoons have become hotspots for extra-terrestrial life. The strong tidal force of Jupiter have various effects on its moons. Large heat dissipation in Io creates an ionic atmosphere, which interacts with Jupiter electromagnetically. As a result, Io emits characteristic radio emissions. Subsurface ocean is also created in Europa due to heat dissipation in its interior. Tidal dissipation is calculated for different cases for Galilean moons. Habitable zones for Io and Europa are determined by varying the semi-major axis of their orbits. Four exoplanets similar to Jupiter are selected. Io-like, Europa-like and Enceladus-like exomoons are simulated around each exoplanet and tidal dissipation is calculated. Based on these calculations habitable zones are estimated for these exomoons. Two candidates are also proposed for future detection of exomoons.

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CHAPTER 1

INTRODUCTION

1.1 What is Tidal Heating?

Tidal heating occurs when the orbital gravitational energy and rotational energy of a heavenly body is dissipated as heat. This is caused by Tidal force. When an object orbits around another object, it experiences different gravitational pull on nearest and farthest side. The tidal force can be calculated using Newton's law of Gravitation. For example, on a moon of mass m and radius r, the tidal force by the planet of mass M and radius R is given by:

$$F = \pm \frac{2Gmr}{R^3}$$

If the moon is in a synchronous orbit around the planet, then one side of moon always distorts. This is known as Tidal Locking. (Laughlin, 2019)

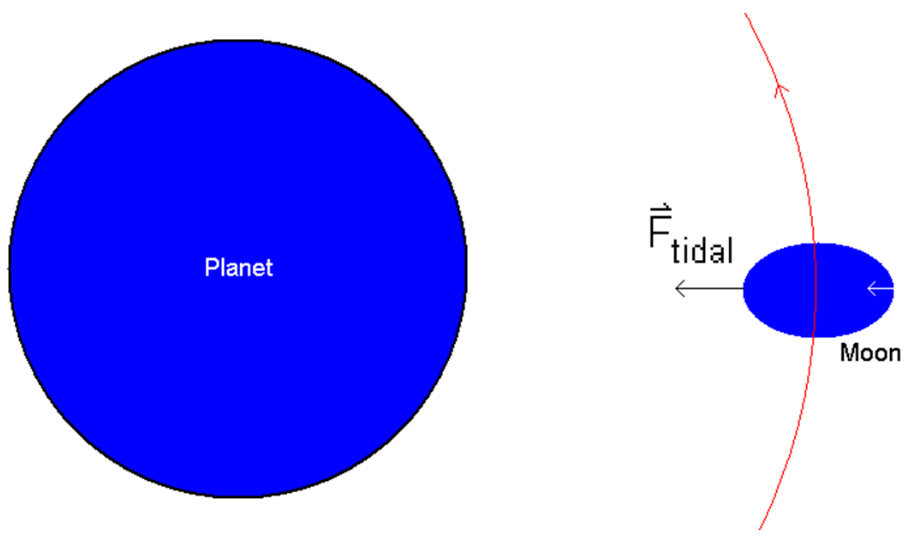

Figure 1.1: Tidal forces acting on a moon

1.1.1 Equations of Tidal Heating

Let a moon of radius r, dissipation factor Q and love numbers h_2 and k_2 revolve around a planet of mass M in an orbit of eccentricity e, semi major axis a and obliquity I. Let n be the mean motion of the satellite. The equations of tidal heating in such a moon is derived by (Wisdom, 2008) for four different cases. These equations are given in Table 1.1. In these equations, $\zeta(e)$, $\zeta(e, I)$ and $\zeta_L(e, x)$ are different functions of eccentricity and obliquity. In this study, tidal heating for only case 1 and case 2 are calculated as factors such as obliquity are difficult to assume and measure astronomically.

Case	Assumptions	Equation
Case 1	synchronous orbit low e and zero obliquity $h_2 = 5k_2/3$ satellite is an incompressible homogeneous sphere	$e^2 \frac{21}{2} \frac{k_2}{Q} \frac{G\, M^2\, r^5\, n}{a^6}$
Case 2	moderate to high e uniform density satellite $k_2 = 3h_2/5$ $\sin \Lambda = 1/Q$ (for small 1/Q)	$\zeta(e) \frac{21}{2} \frac{k_2}{Q} \frac{G\, M^2\, r^5\, n}{a^6}$
Case 3	for eccentricity and non zero obliquity	$\zeta(e, I) \frac{21}{2} \frac{k_2}{Q} \frac{G\, M^2\, r^5\, n}{a^6}$
Case 4	asymptotic nonsynchronous rotation	$\zeta_L(e, x) \frac{21}{2} \frac{k_2}{Q} \frac{G\, M^2\, r^5\, n}{a^6}$

Table 1.1: Equations of Tidal Heating for different cases

1.1.2 Tidal Heating in Galilean and Saturnian Moons

The four Galilean moons – Io, Europa, Ganymede and Calisto revolve around the Jupiter in orbits of small eccentricity. These moons experiences large amount of tidal forces due to humongous size of Jupiter. As a result of large tidal heating, Io is the most volcanically active celestial body in the solar system. Also, icy satellite Europa is theorized to have a subsurface ocean! Similarly, Saturn's icy moon Enceladus may have subsurface ocean. Recently, organic molecules were discovered from jets of Enceladus. (Postberg et al., 2018)

1.2 Habitable Zones

A habitable zone is defined as the zone where a heavenly body can have liquid water. Commonly, stellar habitable zones are used to calculate whether the planet is in the habitable zone of its star. Stellar habitable zones are dependent on luminosity and irradiance from the star. In the solar system, Earth is in the stellar habitable zone of the Sun, whereas Jupiter is very far away from the zone.

1.2.1 Planetary Habitable Zones

In this study, planetary habitable zones are defined as zones around a Jupiter-like planet or any other planet where a moon around the planet can become habitable due to tidal heating. This planetary habitable zone has no dependence on star's luminosity.

CHAPTER 2

METHODOLOGY

2.1 Tidal Heating in Solar System

Using the formulae given by Wisdom (2007), tidal heating in Galilean moons - Io, Europa, Ganymede and Calisto is calculated for case 1 and case 2. Tidal heating in Saturn's moon Enceladus is also calculated. These calculations are analyzed and compared with other published data. A new python code is created to do these calculations. The dissipation factor for Io was taken from (Lainey et al., 2009). The dissipation factor for Europa, Enceladus is taken as 100 as they are icy satellites (Goldreich and Soter, 1966). The dissipation factor for Ganymede and Calisto is also taken as 100. Other parameters such as love numbers for the moons are taken from other journals (Chen et al., 2014).

Hill's radius for Jupiter and Roche's limit for Io and Europa are calculated. These values are given in Table 2.1. Then, the semi-major axis of Io and Europa are varied to estimate planetary habitable zone for Jupiter.

2.2 Tidal Heating in Exoplanets

From various exoplanet catalogs, a list of Jupiter-like exoplanets is created. These exoplanets have masses in range of 0.8 to 2.4 Jupiter masses. The semi major axis of their orbits are also between 4.2 to 6.2 AU. This is because Jupiter is at a distance of 5 AU from the Sun. The list of such exoplanets are given in Table 2.3. These exoplanets are also plotted on the night sky. This plot is given in Figure 2.1.

Out of the 17 Jupiter-like exoplanets, 4 exoplanets are selected on the basis of spectral type of their stars. The stars are selected whose spectral types are closest to the Sun. These exoplanets are listed in Table 2.2. Then, Io-like, Europa-like and Enceladus-like exomoons are simulated around each of the selected exoplanets. The simulated exomoons have the same parameters as that of Io, Europa and Enceladus respectively. Tidal heating for Case 1 and Case 2 is calculated for each exomoon in Watts and W/m^2.

Roche's radius for	Io (AU)	Europa (AU)
Rigid satellite	6.750601×10^{-4}	7.118882×10^{-4}
Fluid satellite	8.235733×10^{-4}	8.685036×10^{-4}

Table 2.1: Roche's radius for Io and Europa

Planet Name	a (AU)	e	ω (degrees)	Orbital Period (days)	Mass of Star (M_{Sun})	Planetary System
ups And e	5.2456	0.00536	7.3	3848.86	1.27	4 planets
HIP 11915	4.8	0.1	155	3830	1	1 planet
HD 220773 b	4.94	0.51	226	3724.7	1.16	1 planet
HD 222155 b	5.1	0.16	137	3999.0	1.13	1 planet

Table 2.2: List of selected exoplanets where a is semi major axis of planet, e is eccentricity and ω is orbital angle

Exoplanet	Spectral type	Distance from star (AU)	Jupiter Mass	Distance from Earth (light-year)	Coordinates RA and Dec
BD+49 828 b	KO	4.2	1.6	n/a	03 02 33.7375 +49 43 47.963
HD 154345 b	G8V	4.3	1.3	58.904	17 02 36.4037 +47 04 54.764
HD 162004 b	G0V	4.43	1.53	72.276	17 41 58.1031 +72 09 24.851
HIP 11915	G5V	4.8	0.99	186.887	02 33 49.0262 -19 36 42.500
HD 187123 c	G5	4.89	1.99	163.078	19 46 58.11299 +34 25 10.2810
HD 220773 b	F9	4.94	1.45	159.816	23 26 27.4448 +08 38 37.842
HD 7449 c	F8V	4.96	2.00	127.201	01 14 29.32198 -05 02 50.5942
HD 222155 b	G2V	5.1	1.9	160.143	23 38 00.30741 +48 59 47.4907
HD 13931 b	G0	5.15	1.88	144.161	02 16 47.37946 +43 46 22.7907
HD 98800B	K5	5.2	1.00	150	11 22 05.288 -24 46 39.05
mu Ara e	G3 IV-V	5.235	1.814	49.901	17 44 08.70114 -51 50 02.5853
ups And e	F8 V	5.2456	1.059	43.933	01 36 47.84216 +41 24 19.6443
HD 134987 c	G5 V	5.8	0.82	72.406	15 13 28.66706 -25 18 33.6468
GJ 328 b	K7	4.5	2.3	64.579	08 55 07.597 +01 32 56.44
HD 145934 b	K0	4.6	2.28	-	16 13 09.88 +13 14 22.0
HD 4732 c	K0 IV	4.6	2.37	184.278	00 49 13.94862 -24 08 12.0224
#NN SER c	- WD+M	6.155 5.38	2.24 6.91	1630 -	15 52 56.131 +12 54 44.68
#mu Ara c	- G3 IV-V	5.34 0.091	1.89 0.033	49.901 -	17 44 08.70114 -51 50 02.5853

Table 2.3: List of Jupiter-like exoplanets. Exoplanets with # have different parameters on different catalogs

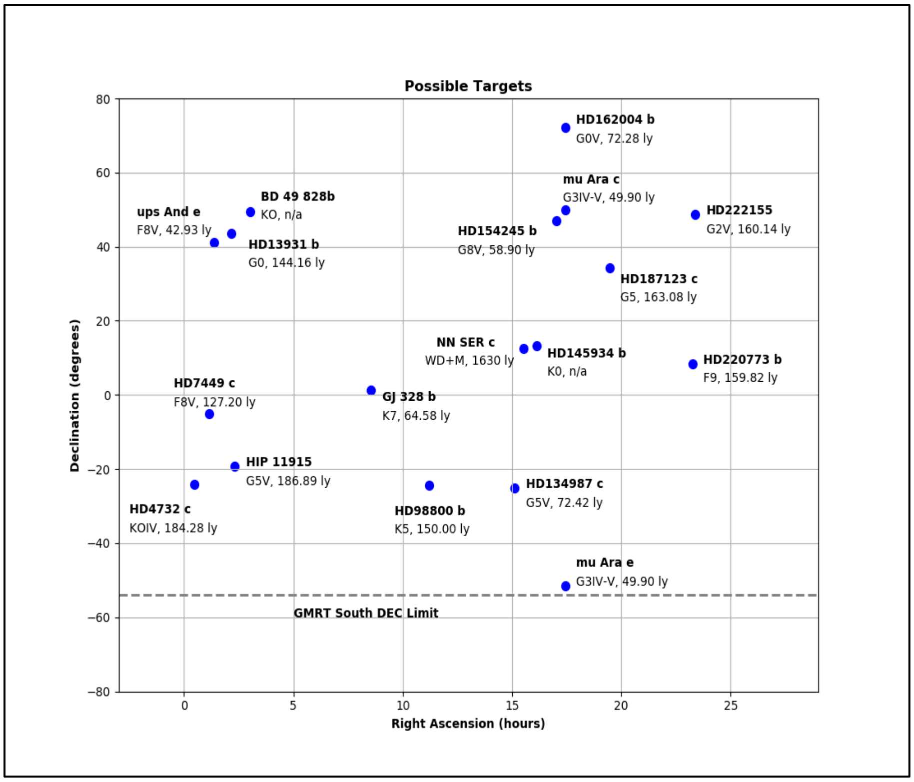

Figure 2.1: Jupiter-like exoplanets plotted in the night sky

2.2.1 Exoplanets near Solar System

The Jupiter-like exoplanets are located far away and thus cannot be observed for radio emissions. Hence, more exoplanets are selected which are within 20 light years distance from the Sun. These systems are listed in Table 2.3. Out of these, two star systems are proposed for future observations. Tidal heating is calculated for Io-like and Europa-like exomoons around these two systems.

Star Name	Spectral type	Distance (light years)	Solar Mass
Alpha Centauri A	G2 V	4.4	1.09-1.10
Tau Ceti	G8 Vp	11.9	0.81-82
Sigma Draconis	G9 V	18.8	0.89
Eta Cassiopeiae A	G3 V	19.4	0.9-1.1
82 Eridani	G5 V	19.8	0.97
Delta Pavonis	G5-8 V-IV	19.9	1.1

Table 2.4: Star systems near Earth

CHAPTER 3

RESULTS

The tidal heating in Galilean and Saturnian moons is calculated for all the four cases. The results are shown in Table 3.1. It can be observed that there is not much difference in the heat dissipation for four cases. The earlier reported value for tidal heating in Io is very similar to calculations done in this study. However, there is a discrepancy in the calculations and reported values for Europa and Enceladus. The tidal heating in all these moons are also converted to W/m^2 for Case 2 and is given in Table 3.2.

Name	True Value (W)	Case 1 (W)	Case 2 (W)	Case 3 (W)	Case 4 (W)
Io	$9.33 \pm 1.87 \times 10^{13}$ (Lainey et al., 2009)	9.310×10^{13}	9.313×10^{13}	9.63×10^{13}	9.63×10^{13}
Ganymede	None (Cassen, Peale and Reynolds, 1980)	4.73×10^{9}	4.73×10^{9}	4.40×10^{11}	4.40×10^{11}
Calisto	None (Cassen, Peale and Reynolds, 1980)	1.10×10^{9}	1.10×10^{9}	1.68×10^{11}	1.68×10^{11}
Europa	5.7×10^{11} (Cassen, Peale and Reynolds, 1980)	3.426×10^{11}	3.431×10^{11}	1.902×10^{12}	1.902×10^{12}
Enceladus	1.58×10^{10} (Howett et al., 2011)	2.653×10^{8}	2.654×10^{8}	2.80×10^{8}	2.80×10^{8}

Table 3.1: Tidal heating in Galilean moons and Enceladus

Moon	Tidal Heating (W/m^2)
Io	2.23
Europa	0.011
Enceladus	0.012
Ganymede	0.0000544
Calisto	0.0000151

Table 3.2: Tidal heating in Galilean moons and Enceladus in W/m^2

3.1 Habitable Zone of Jupiter

The Hill's radius for Jupiter is calculated to be 0.35501 AU. The semi major axis of Io and Europa is varied and variations of tidal heating with semi major axis are calculated. A plot of these results is created using a python code and is shown in Figure 3.1. From Table 3.2, it can be observed that both Europa and Enceladus have tidal heating of around 0.011 W/m^2. Thus, for a moon to possess a subsurface ocean, the tidal heating should be around 0.011 W/m^2. From the graph, the habitable planetary zone for Jupiter is estimated to be in between 5.375×10^8 m and 8.981×10^8 m as the tidal heating for moons like Io and Europa lies between 0.06 and 0.0082 W/m^2.

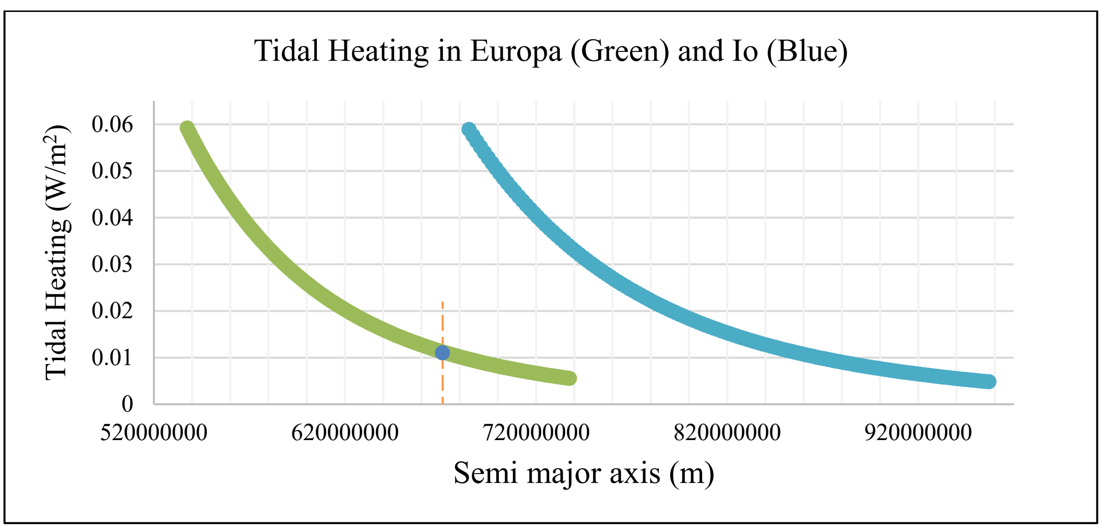

Figure 3.1: Semi major axis v/s Tidal Heating. The orange line depicts actual position of Europa and its true value of tidal heating

3.2 Tidal Heating in Exomoons

Tidal heating in Io-like, Europa like and Enceladus like exomoons is calculated for the 4 selected Jupiter-like exoplanets and are also converted to W/m^2. These calculations are given in Table 3.3.

Exoplanet	Exomoon	Tidal Heating Case 1	Tidal Heating Case 2
ups and e	Io-like	1.0751×10^{14} W 2.5783 W/m^2	1.0754×10^{14} W 2.5791 W/m^2
	Europa-like	3.9106×10^{11} W 0.0127 W/m^2	3.9078×10^{11} W 0.0128 W/m^2
	Enceladus-like	3.4919×10^{8} W 0.0004 W/m^2	3.4933×10^{8} W 0.0004 W/m^2
HIP 11915	Io-like	9.0845×10^{13} W 2.1786 W/m^2	9.0872×10^{13} W 2.1793 W/m^2
	Europa-like	3.2968×10^{11} W 0.0108 W/m^2	3.3020×10^{11} W 0.0108 W/m^2
	Enceladus-like	2.9506×10^{14} W 0.0004 W/m^2	2.9518×10^{14} W 0.0004 W/m^2
HD 220773 b	Io-like	2.3585×10^{14} W 5.6561 W/m^2	2.3592×10^{14} W 5.6578 W/m^2
	Europa-like	8.5591×10^{11} W 0.0280 W/m^2	8.5727×10^{11} W 0.0280 W/m^2
	Enceladus-like	7.6602×10^{8} W 0.001 W/m^2	7.6633×10^{8} W 0.001 W/m^2
HD 222155 b	Io-like	4.6356×10^{14} W 11.1172 W/m^2	4.6370×10^{14} W 11.1205 W/m^2
	Europa-like	1.6823×10^{12} W 0.0550 W/m^2	1.6850×10^{12} W 0.0550 W/m^2
	Enceladus-like	1.5056×10^{9} 0.0019 W/m^2	1.5062×10^{9} W 0.0019 W/m^2

Table 3.3: Tidal Heating in Io-like, Europa-like and Enceladus-like Exomoons in Jupiter-like exoplanets

3.2.1 Proposed Candidate and Tidal Heating Calculations

From Table 2.3, an explanatory system is selected, which is not only closer to Earth for performing observations but also has same spectral type as that of the Sun. This candidate is given in Table 3.4. No planets have been detected for Eta Cassiopeia so far. Thus, a Jupiter like exoplanet and Io-like and Europa-like exomoons are simulated around the planet of Eta Cassiopeia and tidal heating for such exomoons is calculated. These calculations for exomoons of Eta Cassiopeia are given in Table 3.5.

Name	Spectral type	Distance (light years)	Solar Mass	Planets
Eta Cassiopeia A	G3 V	19.4	0.9-1.1	0

Table 3.4: Proposed candidate for exomoon observations

Star	Exoplanet	Exomoon	Tidal Heating (Case 1)
Eta Cassiopeia	Jupiter-like	Io-like	9.31×10^{13} W 2.22 W/m^2
		Europa-like	3.426×10^{11} W 0.011 W/m^2

Table 3.5: Tidal heating in exomoons of a Jupiter-like exoplanet of Eta Cassiopeia

CHAPTER 4

CONCLUSION

Based on the results of this study, more accurate values for tidal heating in Galilean moons and Saturnian moon Enceladus are calculated. The published value for tidal heating Io is very close to the calculated values. However, for Europa and Enceladus, the published and calculated values do not match. For Europa, the tidal heating was calculated using love number as 2.08 (Cassen, Peale and Reynolds, 1980). The correct love number for Europa is 0.073 (Chen, Nimmo and Glatzmaier, 2014). Thus, the calculations for Europa are more accurate in this study.

A planetary habitable zone based can be estimated based on the tidal heating. For Jupiter, the planetary habitable zone is estimated to be somewhere between 5.375×10^8 m and 8.981×10^8 m for Io and Europa sized moons. As seen from Table 3.3, tidal heating for exomoons can be easily calculated. Since these exoplanets are not within range of radio observations, another candidate is proposed for detection of exomoon. Eta Cassiopeia is so far the best candidate to detect an exomoon if it possesses a Jupiter-like exoplanet.

CHAPTER 5

FUTURE WORK

Based on these results, a paper is being written titled: "Detection of Exomoons in Planetary Habitable Zones" by Sanskruti Sharma, Marialis Rosari-Franco and Dr. Zdzislaw Musielak. The paper will be submitted to the Monthly Notices of the Royal Astronomical Society.

Using the tidal heating calculations, the power of radio emissions for Io could be determined in future. The power of radio emissions for Io-like exomoons can be calculated for exoplanets given in Table 3.3. Using the same tidal heating calculations, planetary habitability zone for each exoplanet can be determined. Similarly, planetary habitable zone for Saturn can also be determined.

The power of radio emissions for assumed exomoons of Eta Cassiopeia can be calculated and this system can be observed through radio telescopes. If radio emission from Eta Cassiopeia is detected and they match the calculated emissions, then not only a Jupiter-like exoplanet can be confirmed but also the first exomoon can be detected.

APPENDIX A

PLOTTING EXOPLANETS USING PYTHON

```
import matplotlib.pyplot as plt
import numpy as np

RA = [3.02, 17.02, 17.42, 2.33, 19.47, 23.26, 1.14, 23.38, 2.16,
11.22, 17.44, 1.36, 15.13, 8.55, 16.13, 00.49, 15.53, 17.44]
DEC = [49.43, 47.05, 72.09, -19.36, 34.25, 8.38, -5.03, 48.59,
43.46, -24.46, -51.50, 41.24, -25.18, 1.33, 13.14, -24.08, 12.54,
50.02]

name = ['BD 49 828b','HD 154245b','HD
162004b','HIP11915','HD187123 c','HD220773 b','HD7449
c','HD222155 b','HD13931 b','HD98800 b','mu Ara e','ups And
e','HD134987 c','GJ 328 b*','HD145934 b*','HD4732 c','NN SER
c#','mu Ara c#']

specanddist = ['KO, n/a','G8V, 58.90 ly','G0V, 72.28 ly','G5V,
186.89 ly','G5, 163.08 ly','F9, 159.82 ly','F8V, 127.20 ly','G2V,
160.14 ly','G0, 144.16 ly','K5, 150.00 ly','G3IV-V, 49.90
ly','F8V, 42.93 ly','G5V, 72.42 ly','K7, 64.58 ly','K0,
n/a','KOIV, 184.28 ly','WD+M, 1630 ly','G3IV-V, 49.90 ly']

plt.figure(figsize=(11,8.5))
ax = plt.subplot() #or use ax=plt.gca() which returns the current
active axes object instead of creating a new one.
plt.scatter(RA, DEC, color = 'blue', s= 50)

ax.annotate('BD 49 828b', (RA[0]+0.5,DEC[0]+3.0),weight='bold')
#Text(3.52,52.43,'BD 49 828b')

ax.annotate(specanddist[0], (RA[0]+0.5,DEC[0]-2),fontsize=10)
#Text(3.52,47.43,'KO, n/a')

ax.annotate('HD154245 b', (RA[1]-4.5,DEC[1]-4.0),weight='bold')
#Text(12.52,43.05,'HD154245 b')

ax.annotate(specanddist[1], (RA[1]-4.5,DEC[1]-9.),fontsize=10)
#Text(12.52,38.05,'G8V, 58.90 ly')

ax.annotate('HD162004 b', (RA[2]+0.5,DEC[2]+1.),weight='bold')
#Text(17.92,73.09,'HD162004 b')

ax.annotate(specanddist[2], (RA[2]+0.5,DEC[2]-4.),fontsize=10)
#Text(17.92,68.09,'G0V, 72.28 ly')

ax.annotate('HIP 11915', (RA[3]+0.5,DEC[3]),weight='bold')
#Text(2.83,-19.36,'HIP 11915')
```

```
ax.annotate(specanddist[3], (RA[3]+0.5,DEC[3]-5.),fontsize=10)
#Text(2.83,-24.36,'G5V, 186.89 ly')

ax.annotate('HD187123 c', (RA[4]+0.5,DEC[4]-4.0),weight='bold')
#Text(19.97,30.25,'HD187123 c')

ax.annotate(specanddist[4], (RA[4]+0.5,DEC[4]-9.0),fontsize=10)
#Text(19.97,25.25,'G5, 163.08 ly')

ax.annotate('HD220773 b', (RA[5]+0.5,DEC[5]),weight='bold')
#Text(23.76,8.38,'HD220773 b')

ax.annotate(specanddist[5], (RA[5]+0.5,DEC[5]-5.),fontsize=10)
#Text(23.76,3.38,'F9, 159.82 ly')

ax.annotate('HD7449 c', (RA[6]-1.6,DEC[6]+7.),weight='bold')
#Text(-0.46,1.97,'HD7449 c')

ax.annotate(specanddist[6], (RA[6]-1.6,DEC[6]+2.),fontsize=10)
#Text(-0.46,-3.03,'F8V, 127.20 ly')

ax.annotate('HD222155', (RA[7]+0.5,DEC[7]),weight='bold')
#Text(23.88,48.59,'HD222155')

ax.annotate(specanddist[7], (RA[7]+0.5,DEC[7]-5.),fontsize=10)
#Text(23.88,43.59,'G2V, 160.14 ly')

ax.annotate('HD13931 b', (RA[8]+0.8,DEC[8]-4.),weight='bold')
#Text(2.96,39.46,'HD13931 b')

ax.annotate(specanddist[8], (RA[8]+0.8,DEC[8]-9.),fontsize=10)
#Text(2.96,34.46,'G0, 144.16 ly')

ax.annotate('HD98800 b', (RA[9]-1.6,DEC[9]-8.),weight='bold')
#Text(9.62,-32.46,'HD98800 b')

ax.annotate(specanddist[9], (RA[9]-1.6,DEC[9]-13.0),fontsize=10)
#Text(9.62,-37.46,'K5, 150.00 ly')

ax.annotate('mu Ara e', (RA[10]+0.5,DEC[10]+5.),weight='bold')
#Text(17.94,-46.5,'mu Ara e')

ax.annotate(specanddist[10], (RA[10]+0.5,DEC[10]),fontsize=10)
#Text(17.94,-51.5,'G3IV-V, 49.90 ly')

ax.annotate('ups And e', (RA[11]-3.5,DEC[11]+7.),weight='bold')
```

```
#Text(-2.14,48.24,'ups And e')
ax.annotate(specanddist[11], (RA[11]-3.5,DEC[11]+2.),fontsize=10)
#Text(-2.14,43.24,'F8V, 42.93 ly')
ax.annotate('HD134987 c', (RA[12]+0.5,DEC[12]),weight='bold')
#Text(15.63,-25.18,'HD134987 c')

ax.annotate(specanddist[12], (RA[12]+0.5,DEC[12]-
5.0),fontsize=10)
#Text(15.63,-30.18,'G5V, 72.42 ly')

ax.annotate('GJ 328 b', (RA[13]+0.5,DEC[13]-3.),weight='bold')
#Text(9.05,-1.67,'GJ 328 b')

ax.annotate(specanddist[13], (RA[13]+0.5,DEC[13]-
8.0),fontsize=10)
#Text(9.05,-6.67,'K7, 64.58 ly')
ax.annotate('HD145934 b', (RA[14]+0.5,DEC[14]-3.),weight='bold')
#Text(16.63,10.14,'HD145934 b')

ax.annotate(specanddist[14], (RA[14]+0.5,DEC[14]-
8.0),fontsize=10)
#Text(16.63,5.14,'K0, n/a')

ax.annotate('HD4732 c', (RA[15]-3.,DEC[15]-8.),weight='bold')
#Text(-2.51,-32.08,'HD4732 c')

ax.annotate(specanddist[15], (RA[15]-3.,DEC[15]-13.),fontsize=10)
#Text(-2.51,-37.08,'KOIV, 184.28 ly')

ax.annotate('NN SER c', (RA[16]-4.,DEC[16]+0.5),weight='bold')
#Text(11.53,13.04,'NN SER c')

ax.annotate(specanddist[16], (RA[16]-4.5,DEC[16]-
4.5),fontsize=10)
#Text(11.03,8.04,'WD+M, 1630 ly')

ax.annotate('mu Ara c', (RA[17]-0.1,DEC[17]+7.0),weight='bold')
#Text(17.34,57.02,'mu Ara c')

ax.annotate(specanddist[17], (RA[17]-0.1,DEC[17]+2.),fontsize=10)
#Text(17.34,52.02,'G3IV-V, 49.90 ly')


plt.grid(True)
plt.axhline(y= -54, linewidth=2, color = 'grey', linestyle='--')
#<matplotlib.lines.Line2D object at 0x03F623F0>
```

```
ax.annotate('GMRT South DEC Limit',(5,-60),weight='bold')
#Text(5,-60,'GMRT South DEC Limit')
plt.ylim(-80,80)
#(-80, 80)
plt.xlim(-3,29)
#(-3, 29)
plt.title("Possible Targets", weight = "bold")
#Text(0.5,1,'Possible Targets')
plt.xlabel('Right Ascension (hours)',weight='bold')
#Text(0.5,0,'Right Ascension (hours)')
plt.ylabel('Declination (degrees)',weight='bold')
#Text(0,0.5,'Declination (degrees)')
plt.savefig('All planets 2- sans.png')
plt.show()
```

APPENDIX B

CALCULATING TIDAL HEATING USING PYTHON

```
def TidalHeating():
      G = 6.67408*(10**(-11))
      import math
      r = float(input("r, radius of satellite = "))
      M = float(input("M, mass of planet= "))
      m = float(input("m, mass of satellite= "))
      Q = float(input("Q, dissipation factor= "))
      e = float(input("e, eccentricity= "))
      a = float(input("a, semimajor axis= "))
      n = math.sqrt((G*M)/(a**3))

      k2_love = (input("k2, love number (if unknown type:
none)="))

      if k2_love == "none":
            mu = float(input("mu, rigidity = "))
            rho = float(input("rho, density = "))
            g = float(input("g, surgace gravity = "))
            k2_love = (3/2)/(1+((19*mu)/(2*rho*g*r)))
      elif k2_love != "none":
            k2_love = float(k2_love)

#Case 1: synchronous orbit, low e, zero obliquity, satellite is a
homogeneous sphere
      E_T =
(e**2)*(21/2)*(k2_love/Q)*((G*(M**2)*(r**5)*n)/(a**6))
      print ("Case 1 Tidal heating is %s" % str(E_T))

      beta = math.sqrt(1-(e**2))

      f0_e = 1+ (31/2)*(e**2) + (255/8)*(e**4) + (185/16)*(e**6)
+ (25/64)*(e**8)
      f1_e = 1+ (15/2)*(e**2) + (45/8)*(e**4) + (5/16)*(e**6)
      f2_e = 1+ (3)*(e**2) + (3/8)*(e**4)
      f3_e = 1- (11/6)*(e**2) + (2/3)*(e**4) + (1/6)*(e**6)

      zeta_e = (2/7)*(f0_e/(beta**15)) - (4/7)*(f1_e/(beta**12))
+ (2/7)*(f2_e/(beta**9))
#Case 2: moderate to high e, uniform density satellite, k2 =
3h2/5, sin delta = 1/Q (for small 1/Q)
```

```
      dEdt_2 =
(zeta_e)*(21/2)*(k2_love/Q)*((G*(M**2)*(r**5)*n)/(a**6))
      print ("Case 2 Tidal heating is %s" % str(dEdt_2))

      I = (input("I, obliquity (if not considering type: 000) =")
if I != "000":
              I = float(I)
              delta = float(input("longitude of node of equator
on orbit plane with respect to pericenter = "))
              zeta_e_I = ((2/7)*(f0_e/(beta**15))) -
((4/7)*(f1_e/(beta**12))*(math.cos(I))) +
((1/7)*(f2_e/(beta**9))*(1+((math.cos(I))**2))) +
((3/14)*(e**2)*(f3_e/(beta**13))*((math.sin(I))**2)*(math.cos(2*d
elta)))
#Case 3: for e and non zero obliquity
              dEdt_3 =
(zeta_e_I)*(21/2)*(k2_love/Q)*((G*(M**2)*(r**5)*n)/(a**6))
              print ("Case 3 Tidal heating is %s" % str(dEdt_3))

              N_e = (f1_e)/(beta**12)
              omega_e = (f2_e)/(beta**9)
              x = math.cos(I)
              Na_e = (f0_e)/(beta**15)
              zeta_L_e_x = (2/7)*(Na_e - ((((N_e)**2)*(2*(x**2)))
/ (omega_e*(1+(x**2)))))

#Case 4: asymptotic nonsynchronous rotation
              dEdt_4 =
(zeta_L_e_x)*(21/2)*(k2_love/Q)*((G*(M**2)*(r**5)*n)/(a**6))
              print ("Case 4 Tidal heating is %s" % str(dEdt_4))
      elif I == "000":
            print ("Case 3 and 4 cannot be calculated")
TidalHeating()
```

APPENDIX C

PLOTTING VARIATION OF TIDAL HEATING WITH VARYING SEMI MAJOR AXIS USING PYTHON

```
def THsemi():
        from matplotlib import pyplot as plt
        import numpy as np
        import scipy as sp
        import math

        G = 6.67408*(10**(-11))

        r = float(input("r, radius of satellite = "))
        M = float(input("M, mass of planet= "))
        m = float(input("m, mass of satellite= "))
        Q = float(input("Q, dissipation factor= "))
        e = float(input("e, eccentricity= "))
        a = 600987546.7 #initial semi major axis of moon

        k2_love = float(input("k2, love number (if unknown type:
none)="))

        while a < 1000987546.7:
            semimajoraxis = []
            Tidal1 = []
            a += 2000000
            semimajoraxis.append(a)
            n = math.sqrt((G*M)/(a**3))

     Tidal1.append((21/2)*(k2_love/Q)*((G*(M**2)*(r**5)*n*(e**2))
     /(a**6))/(41698064.74e6))
            #tidal heating divided by surface area of moon to get
tidal heating in W/m2

            print (Tidal1)
            print (semimajoraxis)
```

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Sanskruti Sharma is currently pursuing an Honors Bachelor of Science in Physics with a double major in Mathematics. After completing her undergraduate education, she plans to attend graduate school in theoretical astrophysics. Apart from academics and research, Sanskruti is also interested in philosophy of Hinduism and its relationship with scientific thought.