doi:10.20944/preprints202303.0327.v1

INFERENCE OF DYNAMIC GEOPHYSICAL CONDITIONS AND PROBABILITY OF ADVANCED LIFE IN POTENTIALLY HABITABLE ROCKY EXO PLANETS

Varnana.M.Kumar[1],T.E.Girish[2*],P.E.Eapen[3],Thara.N.Sathyan[4],Biju Longhinos[5],Sony.K.S[2], Binoy.J[4]

1. Department of Physics, Mar Ivanios College, Bethany Hills, Trivandrum 695015, INDIA , ORCID ID : 0000-0001-8248-6865
2. Department of Physics, University College, Trivandrum 695034, INDIA
3. Department or Physics, SG College, Kottarakkara 691531 , Kerala, INDIA
4. Department of Physics, Government College for Women, Trivandrum 695014 , INDIA
5. Department of Geology, University College, Trivandrum 695034, INDIA

* Correspondence: :E mail : tegirish5@yahoo.co.in

Abstract: Using a simple model for internal heat evolution and mass-internal heat relations found for rocky exo planetary objects in the inner solar system we have inferred the phases of volcanism at earth (EA) or host star ages (SA) in 52 potentially habitable rocky exo planets. We have also calculated the internal tidal heat contributions and magnetic moments of these exo planets. Based on these results we have inferred the probability of existence of life favouring geophysical conditions in the above exo planets at EA and SA. In M star associated exo planets, occurrences of super flares and long night periods may pose problems for the development of advanced life .

Keywords : habitable planets; exo planets; advanced life; M stars; geophysical conditions

---

INTRODUCTION

Our scientific quest for finding life outside our solar system has already passed through three distinct phases. The first phase began in late sixties with the launch of SETI project (Tarter, 2001) aiming to detect alien communication signals through radio astronomy. The second phase began with the discovery of the first extrasolar planet in 1995 (Mayor and Queloz, 1995) The third phase is related to our recent attempts to map the extrasolar planet atmospheres using space telescopes (Yip et al, 2022). However Earth remains still as the lone planet with confirmed advanced life in the Universe (Spiegel and Turner, 2011). More than 5200 exoplanets have been identified till date (NASA, 2023) and only 63 (1.2 %) of them are considered to be potentially habitable (University of Porto Rico, 2023) . Different criteria (Meadows and Barnes, 2018 ; Kopparapu et al, 2019) has been evolved for identifying potentially habitable extrasolar planets (PHESP). The important habitability criteria for exo planets are summarized in Table 1 in which we have also included the criteria mentioned in the PHESP website maintained by University of Porto Rico in Arecibo.

Ideas of cessation of major volcanism in rocky planetary bodies in the solar system discussed in published literature is shown in Table 2.Varnana et al (2018) using a simple thermal evolution model for the rocky planetary objects in the solar system found that a critical internal heat flux compared to that of current Earth is required to sustain very intense and widespread volcanism (major volcanism) in these objects. In this study it is shown that cessation of major volcanism happened in the geological past in Moon, Mars, Mercury and Venus when their surface heat flux decreased below the current average surface heat flux of Earth. Some regularities in the time evolution of volcanism in the inner solar system is also found in our previous studies (Varnana et al, 2020; 2021a;2021b;2023).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

Table 1. Summary of habitability criteria for exo planets.

Parameters	Habitability Criteria/Related Phenomena	Remarks
1 Exo planet Mass	Upper Limits: 5-10 Earth masses	
2 Exo planet Radius	Upper Limits: 1.5-2.5 Earth radii	
3 Exo planet density	3-8 gm/cm^3	
4 Exo planet Magnetic fields	Planetary mass and rotation	Thermal dynamo
5 Exo planet Atmosphere	O_2, O_3 and CO_2	
6 Internal Heat and Geology of Exo planet	Volcanism in Exo planet	Crust and atmosphere creation
7 Liquid water In Exo planet	Exo planet in habitable zone	Geodynamics
8 Host star Spectral class	G, K and M stars	Main sequence Life time
9 Active phenomena in host star	Super flares	Shielding by planetary magnetic fields and atmospheres

Table 2. Volcanic cessation models of rocky planets reported in literature.

Reference	Model Descriptiom	Results/Remarks
Solomon(1978)	Volcanic Cessation model for stagnant lid planets	Inferred volcanic cessation ages of Mercury, Moon and Mars
Reese et al. (2007)	Volcanic cessation model for Venus	No exact period of cessation of volcanism in Venus reported
Oorth et al. (2008)	Volcanic cessation model for Venus	No exact period of cessation of volcanism in Venus reported
Kite et al.(2009)	Volcanic cessation models for planets with plate tectonics/stagnant lid conditions and different masses	Inferred volcanic cessation age of Venus
Lenardic et al. (2004)	Model for cessation of ancient plate tectonics in Mars	Implications of the model on the geological evolution of earth is reported
Varnana et al (2018)	Model for cessation of volcanism for rocky planets in the solar system	Prediction for cessation of major volcaism in Earth in the near Geological future
Byrne (2019)	Evolution of volcanism in the inner solar system planetary bodies	Reported volcanic cessation ages ofMoon,Mars,Venus and Mercury
Cheng(2018)	Model for the geological time evolution of plate tectonics in Earth	Inferred that plate tectonics in Earth will end by 1.45 Gyrs from now.

Based on our results on previous studies on the time evolution of volcanism in the inner solar system , we have tried to infer dynamical geophysical conditions in 53 potentially habitable extrasolar planets listed in the University of Poerto Rico (2023) Catalogue. Using solar system rocky planet analogy we have inferred the phases of volcanism if any in these extrasolar planets at earth and host star ages. We have then calculated the magnitude of tidal heating and magnetic moment of these PHESP using procedure available in published literature (Hector Javier Durand-Manterola, 2009; Driscoll and Barnes, 2015) Based on these inferences and calculations we have inferred the probability of finding life

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

favouring geophysical conditions such as water, oxygen, ozone and magnetic field shielding at earth and host star ages for these PHESP.

2. OUR RESULTS ON THE TIME EVOLUTION VOLCANISM IN THE INNER SOLAR SYSTEM ROCKY PLANETARY OBJECTS

We will now describe the results obtained from our previous studies on the time evolution in the inner solar system planetary bodies (Earth, Moon, Mars, Venus and Mercury).

2.1 A simple model for the geological time evolution of internal heat flux in rocky planetary objects in the solar system

The surface heat flux of all rocky planetary objects in the inner solar system in our model (Varnana et al., 2018) is assumed to evolve with time as

$$S(t) = S_o \exp(-\lambda t) \qquad (1)$$

Here

S_o is the surface heat flux at time of formation of the planetary body S(t) is the surface heat flux at time t reckoned in Gyrs

λ is the decay constant (1.5×10^{-17} s^{-1}) for chondrite composition (Turcotte and Schubert, 1982, Grott and Breuer, 2008)

Assuming best available S values (Varnana et al, 2018)) for the current time (t =4.5 Gyrs) for solar system rocky planetary bodies we can find S_o and time evolution of internal heat flux in these bodies using (1).

We could find a linear regression relation between mass (Mp) and surface heat flux (Varnana et al, 2020) of rocky planetary bodies in the solar system. See also a Fig 1. The regression equation is

$$S= 0.084\ Mp + 0.014 \qquad (1\ )$$

Here Mp is expressed in Earth mass units.

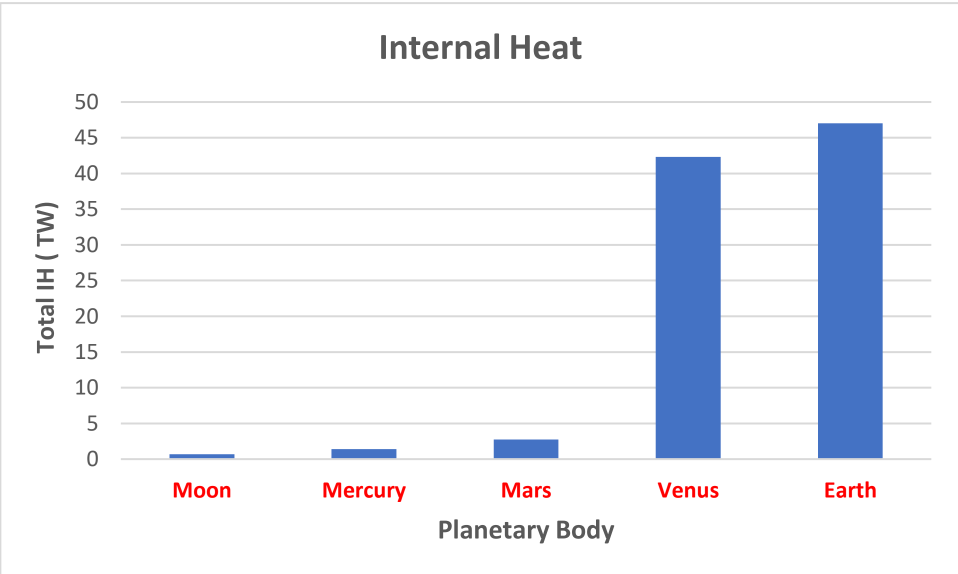

Figure 1. The current (age: 4.5 Giga Years since formation) total internal heat (IH) inferred for different rocky planetary objects in the inner solar system based on best available observations. It is interesting observe that the quantity of IH is ordered by the Planetary body mass.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

2.2. Phases in the volcanic activity evolution and critical internal heat values inferred for solar system rocky planetary objects in the solar system

1. Earth :

The peak age of volcanism is inferred (0.5-1 Gyr) to be coinciding with the remarkable geophysical events in our Earth: Snow Ball Earth Ice age and inner core formation (Gernon et al., 2016; Stephane Labrosee and Melina Macouin ,2013). The mean value of internal heat S inferred from our model during the peak age is 0.133 Wm^{-2}.

2. Moon :

The peak age of volcanism is inferred (3.6-3.9 Gyr) to be coinciding with intense Mare volcanism on the Moon and also associated with strong global lunar magnetic fields possibly existing at that time (Doris Breuer et al.,2010,Sonia et al.,2014; James Green et al.,2020). The mean S inferred during the peak age from our model is 0.1062 Wm^{-2}. The cessation age of major volcanism on the Moon (inferred in our model as 3.3 Gyrs) almost coincides with the period of disappearance or significant decline in the inensity of lunar magnetic fields (James Green et al, 2020). The mean S during the cessation age is inferred to be 0.085 Wm^{-2}.

3 Mars :

The peak age of volcanism in Mars (inferred in our model between 3.7-4.1 Gyrs) coincides with the period of possible existence large water bodies and strong global magnetic fields in the planet (Eric Chassefière et al., 2013). The mean S inferred using our model during the peak age is 0.12 $Wm^{-2.}$ The cessation age of major volcanism in Mars (inferred in our model as 3.5 Gyr) coincides with the disappearance of water bodies and strong magnetic fields on this planet. This is also accompanied by major atmospheric changes (Eric Chassefiere et al., 2013; Shi., 2016).

4. Venus :

The peak age of volcanism in Mars (inferred in our model between 0.5-1 Gyr) witnessed very intense and widespread magmatic phenomena in the geological history of this planet (Romeo and Turcotte ,2009). The inferred mean S from our model during peak age is 0,125 Wm^{-2} . During the cessation age of major volcanism in Venus (inferred by us as 0.0025 Gyrs) there is a significant decline in volcanic activity Only spatially restricted and low intensity volcanism observed during and after the cessation of major volcanism in this planet (Smrekar et al, 2010).The mean S during cessation age is inferred to be 0.091 Wm^{-2}.

5. Mercury:

The peak age of volcanism in Merury (inferred in our model between 3.55-4.1 Gyrs) coincides with the period of beginning of magnetic field generation in this planet(Catherine et al., 2015). The mean S value during the peak age is inferred to be 0.11 Wm^{-2} The period of cessation of major volcanism in this planet (3.5 Gyrs) is associated with global contraction (Chrane Kelsey and Christian Klimczak ,2017) in Mercury. The value of S during the cessation period is inferred to be 0.094 Wm^{-2}.

The average of mean S values (Peak phases) Sp = = 0.12 ± 0.0109 Wm^{-}

The average of mean S values (Cessation phases) Sc = 0.922 ± 0.0045 Wm^{-2}

It is interesting to find that RMS or scatter in Sp is found to be 9 % and for Sc it is found to be only 4.9 %. This suggests that Sp can be considered as the critical value of internal heat flux reached during the peak phase of volcanism in all solar system rocky planetary objects including Earth. Similarly Sc ca be considered as the critical internal heat flux reached during cessation phase of major volcanism in all solar system rocky planetary objects (excluding Earth) .

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

3. FINDING VOLCANIC PHASES OF THE EXO PLANETS USING SOLAR SYSTEM ANALOGY AT EARTH AND HOST STAR AGES.

Different steps in the inference of the phase of the volcanic activity if any in the given exo planet with inferred rocky composition using solar system analogy is described below

Step 1 : Calculation of surface heat flux of exo planet at earth age

Se = So Exp (-ƛt) *(1)*

Here Se is the surface heat flux at earth age of the exo planet
The equation (2) is assumed to be valid for all rocky exo planets so that
Se (Wm-2) = 0.084 Me + 0.014 (2)
Here Me is the mass of the exo planet in earth units.
From (2) we can calculate the value of Se

Step 2 : Calculation of the surface heat flux of exo planet at host star age

From (1) we can write an expression for finding the constant So
So = Se/[Exp (-ƛt)] (3)
Here t=4.5 X 10^9 years , ƛ=
After finding So we can use (1) to calculate the value of surface heat flux of exo planet at
star age (Sa)
Sa = So exp (-ƛt) (4)
Substituting the values of So from (3) and star age t in (4) we can find Sa.

Step 3: Finding the volcanic phase of the exo planet using solar system results

Here it is assumed that the critical values of S at peak and cessation phases of volcanism if any in the exo planet is same as found for the inner solar system given by equations . The rules for indentifying the volcanic phases of the rocky exo planet are :

(i) If Se or Sa is < Sp then the exo planet volcanism is in the **Ascending phase**.As a sub-classification if Se or Sa < Sp/2 then the volcanic phase is assigned as **Early Ascending** and if Se or Sa >Sp/2 then the volcanic phase is assigned as **Late Ascending**

(ii) If Se or Sa =Sp then the exo planet is in the **Peak phase**

(iii) If Se or Sa values is between Sp and Sc then the exoplanet is in the **Declining phase**

(iv) If Se or Sa =Sc then the exo planet is in the **Cessation phase**

(v) If Se or Sa > Sc then the exo planet is in the **Post-cessation phase**

Using the best available values for the masses of PHESP we have determined the phases of the volcanism if any in different rocky extrasolar planets at both earth and host star ages (if star age is known) using the above procedure. The results are given in Table 3. Here we have avoided calculations for rocky exo planets whose inferred mass exceeds eight earth masses.

Table 3. Inference of volcanic phases of selected exo planets at earth age and host star ages [SC-host: Spectral class of host star, EU: earth units, EA: earth age, SA: star age].

	Exoplanet	SC-host	Mp (EU)	Age (Gyr)	Peak age (Gyr)	Cessation age (Gyr)	Volcanic phase (EA)	Volcanic phase (SA)
1.	Teegarden Star-b	M	1.05	8	4.16	4.72	Declining	Post cessation
2.	TOI-700-d	M	2.25	1.5	5.61	6.17	Late Ascending	Early Ascending
3.	K2-72-e	M	2.21		5.58	6.13	Late Ascending	
4.	Trappist-1d	M	0.4131	7.6	2.59	3.15	Post Cessation	Post Cessation
5.	Kepler-1649-c	M	1.2	---	4.41	4.96	Descending	

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

6.	Prox Cent-b	M	1.27	4.85	4.51	5.07	Peak	Descending
7.	GJ 1061 d	M	1.6	---	4.95	5.51	Late Ascending	
8.	GJ 1061 c	M	1.7	---	5.07	5.62	Late Ascending	
9.	Ross128-b	M	1.4	9.48	4.70	5.25	Late Ascending	Post Cessation
10.	GJ273-b	M	2.89	---	6.11	6.66	Late Ascending	
11.	Trappist-1e	M	0.692	0.50	3.42	3.98	Post Cessation	Early Ascending
12.	GJ667C-c	M	3.8	2.00	6.6	7.22	Late Ascending	Early Ascending
13.	GJ667C-f	M	2.7	2.00	5.97	6.53	Late Ascending	Early Ascending
14.	Kepler 442-b	K	2.7	2.90	5.97	6.53	Late Ascending	Early Ascending
15.	Wolf 1061 -c	M	3.41	---	6.44	7.00	Late Ascending	
16.	Trappist 1f	M	1.039	7.6	4.14	4.68	Declining	Post Cessation
17.	LHS 1140 -b	M	6.38	5.00	7.72	8.27	Late Ascending	Late Ascending
18.	Kapteyn-b	M	4.8	8.00	7.13	7.69	Late Ascending	Post Cessation
19.	Kepler 186 -f	M	1.71	4.00	5.08	5.63	Late Ascending	Late Ascending
20.	Teegarden Star-c	M	1.11	8.00	4.26	4.82	Descending	Post Cessation
21.	Kepler 186f	M	1.71	4.00	5.08	5.63	Late Ascending	Late Ascending

Table 3. (contd).

	Exoplanet	SC-host	Mp (EU)	Age (Gyr)	Peak age (Gyr)	Cessation age (Gyr)	Volcanic phase (EA)	Volcanic phase (SA)
22.	GJ667C-e	M	2.7	2.00	5.97	6.53	Late Ascending	Early Ascending
23.	Tau cet-f	G	3.93		6.73	7.28	Late Ascending	
24.	Trappist-1g	M	1.34	7.60	4.61	5.17	Declining	Post Cessation
25.	GJ 682-b	M	4.4	6.4	6.96	7.51	Late Ascending	Late Ascending
26.	Kepler 452b	G	3.29	6.0	6.37	6.92	Late Ascending	Near Peak
27.	Kepler 62 e	K	36	7.00	1.13	1.19		
28.	Kepler-1652b	M	3.19		6.31	6.86	Late Ascending	
29.	Kepler 1544b	K	3.82		6.67	7.23	Late Ascending	
30.	Kepler-296e	M	2.96	4.20	6.16	6.71	Late Ascending	Late Ascending
31.	Kepler 283-c	K	3.97		6.75	7.30	Late Ascending	
32.	K2-296-b	M	3.22	-	6.32	6.88	Late Ascending	
33.	Kepler 1410b	K	3.82	4.07	6.67	7.23	Late Ascending	Late Ascending
34.	K2-3 d	M	2.80	1.0	6.04	6.60	Late	Early

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

							Ascending	Ascending
35.	Kepler-1638b	G	4.16	4.37	6.84	7.40	Late Ascending	Late Ascending
36.	Kepler-296f	M	3.89	---	6.71	7.26	Late Ascending	
37.	Kepler-440b	K	4.12	1.3	6.82	7.38	Late Ascending	Very early Ascending
38.	Kepler-705b	M	5.1	3.89	7.26	7.81	Late Ascending	Late Ascending
39.	Kepler-1653 b	K	5.35	7.7	7.36	7.91	Late Ascending	Declining
40.	GJ 832 -c	M	5.4	9.24	7.37	7.93	Late Ascending	Post Cessation
41.	Kepler-1606b	G	4.94	4.27	7.19	7.75	Late Ascending	Late Ascending
42.	Kepler-1090b	G	5.69	4.37	7.48	8.04	Late Ascending	Late Ascending
43.	Kepler-61b	K	5.27	1.0	7.32	7.88	Late Ascending	Very early Ascending

Table 3. (contd).

	Exoplanet	SC-host	Mp (EU)	Age (Gyr)	Peak age (Gyr)	Cessation age (Gyr)	Volcanic phase (EA)	Volcanic phase (SA)
44	K2 18- b	M	8.9 b2	--	8.41	8.97	--	--
45	Kepler 443-b	K	6.04	3.2	7.6	8.46	Late Ascending	Early Ascending
46	Kepler 1701-b	K	5.57	--	7.44	7.99	Late Ascending	--
47	Kepler 22-b	G	36	--	--		--	--
48	LHS 1140-b	M	6.38	5	7.72	8.27	Late Ascending	Late Ascending
49	Kepler 1552-b	K	3.64	3.31	6.57	7.83	Late Ascending	Early Ascending
50	K2-9b	M	5.69	1	7.48	8.04	Late Ascending	Early Ascending
51	Kepler 1540-b	K	6.76	2,51	6.57	7.03	Late Ascending	Early Ascending
52	GJ 180-c	M	6.4	5	7.72	8.28	Late Ascending	Late Ascending
53	Kepler 1632-b	F	6.6	3.09	7.79	8.34	Late Ascending	Early Ascending
54	Kepler 298-d	K	6.8	--	7.85	8.41	Late Ascending	--
55	GJ 163-c	M	6.8	3	7.85	8.41	Late Ascending	Early Ascending

4. INFERENCE OF MAGNETIC MOMENTS OF PHESP

The magnetic moment of extrasolar planets (Mg)can be calculated from mass and rotation periods of these planets. We can make use of the following expression (Hector Javier Durand-Manterola, 2009) or our calculations.

$$Mg = 1 \times 10^{-5} [(m_p \sigma)/P]^{1.1106} \quad (1)$$

Here M is in units of A/m^2

m_p is the mass of the exo planet in kg

σ is the internal electrical conductivity of the planet. For rocky planets we can assume

$$\sigma = 1.2 \times 10^5 \text{ S/m} \quad (2)$$

P is the rotation period of the planet in seconds.

For extrasolar planets near M stars the rotation period will be identical to orbital period due to tidal locking. For extrasolar planets near K or G stars we can assume that their rotation period is similar to that of Earth.

Using this procedure we have calculated the magnetic moment of potentially habitable extrasolar planets for which relevant data is available. The results are shown in Table 4.

Table 4. Magnetic moment calculations for exo planets (Me=8,22 x10^22 A/m²).

	Exoplanet	Rotation period (days)	Magnetic moment (A/m^2)	Ratio with that of Earth (Me) *
01.	Teegarden's Star b	4.91	6.6x10^21	0.0825
02.	TOI-700 d (N)	37	1.1x10^21	0.0137
03.	K2-72 e	24.15	2.58x10^21	0.0312
04.	TRAPPIST-1 d	4.04	2.66x10^21	0.0325
05.	Kepler-1649 c	19.53	1.66x10^21	0.0200
06.	Proxima Cen b	11.18	3.15x10^21	0.0400
07.	GJ 1061 d	12.43	3.87x10^21	0.0475
08.	GJ 1061 c	6.68	8.20x10^20	0.0523
09.	Ross 128 b	9.86	4.19x10^21	0.0523
10.	GJ 273 b	18.64	4.62x10^21	0.0577
11.	TRAPPIST-1 e	6.1	3.26x10^21	0.0407
12.	Kepler-442 b	1	9.39x10^22	1.1737
13.	Wolf 1061 c	17.87	5.82x10^21	0.0727
14.	GJ 667 C c	28.14	3.98x10^21	0.0497
15.	GJ 667 C f	39.02	1.89x10^21	0.0236
16.	Kepler-1229 b	86.82	3.02x10^21	0.0377
17.	TRAPPIST-1 f	9.2	3.26x10^21	0.0407
18.	Kepler-62 f	1	1.85x10^24	23.12
19.	Teegarden's Star c	11.4	2.76x10^21	0.0345
20.	Kepler-186 f	129	3.04x10^20	0.0038
21.	GJ 667 C e	62.24	1.13x10^21	0.0141
22.	tau Cet f	1	1.65x10^23	2.025
23.	TRAPPIST-1 g	12	3.16x10^21	0.038
24.	GJ 682 b	17.48	7.9x10^21	0.0987
25.	Kepler-452 b	1	1.36x10^23	1.7
26.	Kepler-62 e	1	1.91x10^24	23
27.	Kepler-1652 b	38	2.34x10^21	0.029
28.	Kepler-1544 b	1	1.6x10^23	2
29.	Kepler-296 e	34	2.44x10^21	0.0305
30.	Kepler-283 c	1	1.67x10^23	2.08
31.	K2-296 b	28	3.32x10^21	0.0415
32.	Kepler-1410 b	1	11.62x10^23	0.02025

Table 4. (contd).

	Exoplanet	Rotation period (days)	Magnetic moment (A/m^2)	Ratio with that of Earth
33.	K2-3 d	44	1.73x10^21	0.0216
34.	Kepler-1638 b	1	1.76x10^23	2.2
35.	Kepler-296 f	63	1.67x10^21	0.0208

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

36.	Kepler-440 b	1	1.74x10^23	2.17
37.	Kepler-705 b	56	2.57x10^21	0.032
38.	Kepler-1653 b	1	2.32x10^23	0.029
39.	GJ 832 c	35	4.6x10^21	0.057
40.	Kepler-1606 b	1	2.13x10^23	2.66
41.	Kepler-1090 b	1	2.62x10^23	3.27
42.	Kepler-61 b	1	--	--
43.	K2-18 b	32	8.84x10^21	0.1105
44.	Kepler-443 b	1	2.65x10^23	3.31
45.	Kepler-1701 b	1	2.43x10^23	3.03
46.	Kepler-22 b	1	1.91x10^24	2.38
47.	LHS 1140 b	24	8.39x10^21	0.1048
48.	Kepler-1552 b	1	1.52x10^23	1.9
49.	K2-9 b	10	1.95x10^22	0.2437
50.	Kepler-1540 b	1	3.01x10^23	3.76
51.	GJ 180 c	24	8.42x10^21	0.105
52.	Kepler-1632 b	1	2.93x10^23	3.66
53.	Kepler-298 d	1	3.03x10^23	3.78
54	Kapteyn-b	49	2.78x10^21	0.034
55	GJ 163 c	25	8.6x10^21	0.1075

5. TIDAL HEAT CONTRIBUTIONS IN EXTRASOLAR PLANETS

The tidal heating rate of the extrasolar planets due to the influence of its host star are calculated by using the relation obtained by Driscoll and Barnes (2015) .The relation is as follows

$$H=\frac{63(GM_S)^{\frac{3}{2}}M_S R_p{}^5}{4Q_{p\prime}}a^{-\frac{15}{2}}e^2$$

The tidal heating rate per unit area (Wm⁻²) is given by

$$T_H=\frac{63(GM_S)^{\frac{3}{2}}M_S R_p{}^3}{16\pi Q_{p\prime}}a^{-\frac{15}{2}}e^2$$

where

M_s is the Mass of the host star in solar mass units

M_P is the Mass of the extrasolar planet

R_P is the Radius of the planet which is obtained from the mass- radius relationship (Sotin et al., 2007)

a is the Semimajor axis of the extrasolar planet

e is the Eccentricity of the orbit

Q'_P is the tidal dissipation factor function

$$Qp'=\frac{3Qp}{2k} \qquad (4\text{-}4)$$

where Qp is the tidal dissipation parameter

k is the Love number

The value of Q_P' =500 for the Love number 0.3(Mardling and Lin, 2004; Dickey et al., 1994) which may varies with the composition and structure. The internal tidal heat contributions of different PHESP are given in Table 5 and is generally found to be very small.

Table 5. Tidal Heat calculations for PHESP.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

	Hoststar	Spec-tral Class	M_S (SU)	Age of the Host star (Gyr)	R_P (ER units)	a (AU)	e	Tidal Heat (Wm^{-2})
1.	Teegarden's Star -b	M	0.089	8	1.02	0.0252	0.1	$0.018x10^{-5}$
2.	TOI 700 -d	M	1.72	1.5	1.19	0.163	0.110	$2.53X10^{-11}$
3.	K2 72- e	M	0.27	--	1.29	0.106	0.11	$5.05x10^{-11}$
4.	TRAPPIST-1d	M	0.080	7.6	0.388	0.0222	0.0083	$1.56x10^{-10}$
5.	Kepler-1649-e	M	0.1977	---	1.06	0.0649	---	---
6.	Pro Cent- b	M	0.120	4.85	1.08	0.048	0.350	$3.38x10^{-8}$
7.	GJ 1061-d	M	0.230	---	5.51	0.054	0.53	$1.13x10^{-5}$
8.	GJ 1061 -c	M	0.120	---	1.18	0.035	0.290	$3.24x10^{-7}$
9.	Ross 128-b	M	0.168	9.48	1.11	0.049	0.116	$5.73x10^{-9}$
10.	GJ 273-b	M	0.290	---	1.51	0.091	0.100	$2.34x10^{-10}$
11.	Trappist -1e	M	0.080	0.50	0.92	0.028	0.007	$2.59x10^{-10}$
12.	GJ 667C-c	M	0.330	2.00	1.77	0.125	0.020	$1.69x10^{-12}$
13.	GJ667C-f	M	0.330	2.00	1.45	0.156	0.030	$3.97x10^{-13}$
14.	Kepler-442b	K	0.609	2.90	1.34	0.409	0.040	$1.01x10^{-15}$
15.	Wolf -1061c	M	0.250	---	1.66	0.089	0.110	$3.5x10^{-10}$
16.	Kepler -1229 b	M	0.43	3.72	1.40	0.3006	0.0	----
17.	Trappist -1f	M	0.080	0.50	1.405	0.037	0.011	$2.82x10^{-10}$
18.	Kepler-62f	K	0.690	7.00	1.41	0.718	---	---
19.	LHS 1140-b	M	0.146	5.00	1.635	0.087	0.290	$1.25x10^{-19}$
20.	Kapteyn-b	M	0.281	8.00	1.6	0.168	0.210	$8.23x10^{-10}$
21.	Kepler -186f	M	0.480	4.00	1.17	0.356	0.040	$1.18x10^{-11}$
22.	Tee-garden'Star-c	M	0.089	8.00	1.04	0.043	0.0	---

Table 5. (contd).

	Hoststar	Spec-tral Class	M_S (SU)	Age of the Host star (Gyr)	R_P (ER units)	a (AU)	e	Tidal Heat (Wm^{-2})
23.	Kepler 186-f	M	0.544	4.00	1.17	0.432	0.04	$3.78x10^{-16}$
24.	GJ667C-e	M	---	2.00	1.45	0.213	0.020	---
25.	Tau cet-f	G	0.783	5.8	1.81	1.334	0.16	$2.66x10^{-10}$
26.	Trappsit 1-g	M	0.080	7.60	1.129	0.045	0.003	$7.5x10^{-10}$
27.	GJ 682-b	M	0.273	6.4	1.93	0.08	0.08	$8.74x10^{-18}$
28.	Kepler 452-b	G	1.04	6.0	1.63	1.046	0.035	$2.72x10^{-18}$
29.	Kepler 62-e	K	0.690	7.00	1.61	0.427	---	---
30.	Kepler 1652-b	M	0.40	3.20	1.6	0.165	---	---
31.	Kepler 1544-b	K	0.81	2.34	1.78	---	---	---
32.	Kepler 296-e	M	0.800	4.20	1.53	0.174	0.330	$7.09x10^{-10}$
33.	Kepler-283c	K	0.596	---	1.82	0.341	0	---
34.	K2 296-b	M	---	---	1.61	0.079	0.33	$3.65x10^{-7}$
35.	Kepler 1410-b	K	0.63	4.07	1.74	---	----	---
36.	K2-3d	M	0.6	1.0	1.48	0.2086	0	---

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

37.	Kepler 1638-b	G	0.97	4.37	1.87	0.745	0	---
38.	Kepler 296-f	M	0.5	---	1.77	0.255	0.33	9.72×10^{-11}
39.	Kepler 440-b	K	0.57	1.3	1.86	0.34	0.242	3.59×10^{-13}
40.	Kepler 705-b	M	0.53	3.89	2.06	0.230	---	---
41.	Kepler 1653-b	K	0.72	7.7	2.13	0.4706	---	---
42.	GJ 832-c	M	0.45	9.24	--	0.163	0.18	---
43.	Kepler 1606-b	G	0.9	4.27	2.03	---	----	---

Table 5. (contd).

	Hoststar	Spec-tral Class	M_S (SU)	Age of the Host star (Gyr)	R_P (ER units)	a (AU)	e	Tidal Heat (Wm^{-2})
44.	Kepler-61 -b	K	0.64	1.0	2.11	0.27	0.25	3.75×10^{-12}
45.	K2-18b	M	0.36	---	2.306	0.142	0.2	7.8×10^{-9}
46.	Kepler 443-b	K	0.74	3.2	2.30	0.495	0.11	2.3×10^{-14}
47	Kepler 1701-b	K	---	---	2.22	---	---	---
48.	Kepler 22-b	G	0.97	7.08	2.33	0.849	0	---
49	LHS 1140-b	M	0.179	5	1.64	0.0957	0.096	
50	Kepler 1552-b	K	0.85	3.31	2.41	---	---	---
51	K2-9b	M	0.3	1.0	---	0.091	---	---
52	Kepler 1540-b	K	0.74	2.51	2.41	---	---	---
53.	GJ 180-c	M	0.43	5	---	0.129	0.09	---
54.	Kepler 1632-b		1.12	3.09	2.41	0.305	---	---
55	Kepler 298-d		0.65	---	2.45	0.305	---	---
56	GJ 163-c	M	0.40	3.0	2.43	0.124	0.03	1.39×10^{-11}

6. DYNAMIC GEOPHYSICAL CONDITIONS FAVORING LIFE IN POTENTIALLY HABITABLE EXO PLANETS

Major geophysical events in rocky planets can be linked to their thermal history in general and evolution of volcanism in particular. The geological history of inner solar system (especially for planets Earth and Mars) suggest that this can be linked to volcanic phases (Varnana et al, 2021a) The emergence of widespread water bodies can be expected in a rocky planet during peak phase of volcanism using Mars analogy. The possibility that these water bodies can disappear during the cessation and post cessation phases of volcanism cannot be ruled out. Major changes in atmospheric composition can be expected as an outcome of intense volcanic activity in these planets (Unterborn et al, 2022) reference) So most likely the emergence of oxygen can be expected during the peak phases of volcanism. Emergence of ozone requires more time and hence it is likely to emerge during the declining phases of volcanism in the rocky planets. Magnetic shielding of harmful particle radiation from the host stars is possible in extrasolar planets if its magnetic

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

moment is at least comparable to that of Earth. In planets like Mars and Moon global magnetic fields existed during the peak and declining phases of volcanism in their geological history (Breuer et al , 2010).

We will now try to infer the probability of existence of life favoring geophysical conditions in potentially habitable extrasolar planets from our knowledge of internal heat evolution and volcanic activity phases. This will be done for both earth age and host star ages. The probability of life favoring geophysical conditions depending on the phase of volcanism in extra solar planets is given in Table 6. Based on this Table and from volcanic phases (in Table 3) we have found the probability of life favoring geophysical conditions in PHESP for both earth and host star ages. The results are given in Table 7.

Table 6. Dynamic probability of finding some life favoring geophysical conditions in PHESP (L: low, M: moderate, H: high) during different volcanic phases in these planets.

Phase of Volcanism	Water	Oxygen	Ozone	Mag field shielding (Dynamic)
Early Ascending	L	L	L	L
Late Ascending	L	M	L	L
Peak	H	H	L	H
Declining	H	H	H	H
Cessation	M	M	M	L
Post Cessation	L	M	M	L

Table 7. Inference of probability of biogenic elements and shielding magnetic fields in selected exo planets based on our dynamic geophysical model. [1: earth age (EA), 2: star age (SA), Probability values: H (high), M (moderate) and L (low)] Habitability score is the sum of H values found for each planet.

	Exoplanet	water	O_2	O_3 or equivalent	Mag Shielding (static)	Mag Shielding (dynamic)	Habitability Score
1.	Teegarden Star-b	1 H 2 L	1 H 2 M	1 H 2 M	1 L 2 L	1 H 2 L	EA: 4 SA: 0
2.	TOI-700 -d	1 H 2 L	1 H 2 M	1 H 2 M	1 L 2 L	1 H 2 L	EA: 4 SA: 0
3.	K2-72-e	1 M	1 M	1 M	1 L	1 M	EA: 0
4.	Trappist -1d	1 L 2 L	1 M 2 M	1 M 2 M	1 L 2 L	1 L 2 L	EA: 0 SA: 0
5.	Kepler-1649-c	1 H	1 H	1 H	1 L	1 H	EA : 4
6.	Prox Cent-b	1 H 2 H	1 H 2 H	1 M 2 H	1 L 2 L	1 H 2 H	EA: 3 SA: 4
7.	GJ 1061 d	1L	1M	1L	1L	1L	EA:0
8.	GJ 1061 c	1L	1M	1L	1L	1L	EA:0
9.	Ross128-b	1L 2L	1M 2M	1L 2M	1L 2L	1L 2L	EA:0 SA:0
10.	GJ273-b	1L	1M	1L	1L	1L	EA:0
11.	Trappist-1e	1L 2L	1M 2L	1M 2L	1L 2L	1L 2L	EA:0 SA:0
12.	GJ667C-c	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
13.	GJ667C-f	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
14.	Kepler 442-b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
15.	Wolf 1061 -c	1L	1M	1L	1L	1L	EA:0
16.	Kepler 1229-b						

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

17.	Trappist 1f	1H 2L	1H 2M	1H 2M	1L 2L	1H 2L	EA:4 SA:0
18.	Kepler 62-f						
19.	LHS 1140 -b	1L 1L	1M 1M	1L 1L	1L 1L	1L 1L	EA:0 SA:0
20.	Kapteyn-b	1L 2L	1M 2M	1L 2M	1L 2L	1L 2L	EA:0 SA:0

Table 7. (contd).

	Exoplanet	water	O_2	O_3 or equivalent	Mag Shielding (static)	Mag Shielding (dynamic)	Habitability Score
21.	Kepler 186 -f	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0
22.	Teegarden Star-c	1H 2L	1H 2M	1H 2M	1L 2L	1H 2L	EA:4 SA:0
23.	Kepler 186f	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0
24.	GJ667C-e	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
25.	Tau cet-f	1L	1M	1L	1H	1L	EA:1
26.	Trappist-1g	1H 2L	1H 2M	1H 2M	1L 2L	1H 2L	EA:4 SA:0
27.	GJ 682-b	1L 1L	1M 1M	1L 1L	1L 1L	1L 1L	EA:0 EA:0
28.	Kepler 452b	1L 2H	1M 2H	1L 2L	1H 2H	1L 2H	EA:0 SA:4
	Kepler 62 e						
30.	Kepler-1652b	1L	1M	1L	1L	1L	EA:0
31.	Kepler 1544b	1L	1M	1L	1H	1L	EA:1
32.	Kepler-296e	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0
33.	Kepler 283-c	1L	1M	1L	1H	1L	EA:1
34.	K2-296-b	1L	1M	1L	1L	1L	EA:0
35.	Kepler 1410b	1L 2L	1M 2M	1L 2L	1H 2H	1L 2L	EA:1 SA:1
36.	K2-3 d	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
37.	Kepler-1638b	1L 2L	1M 2M	1L 2L	1H 2H	1L 2L	EA:0 SA:0
38.	. Kepler-296f	1L	1M	1L	1L	1L	EA:0
39.	Kepler-440b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
40.	Kepler-705b	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0
41.	Kepler-1653 b	1L 2H	1M 2H	1L 2H	1H 2H	1L 2H	EA:1 SA:5

Table 7. (contd).

	Exoplanet	water	O_2	O_3 or equivalent	Mag Shielding (static)	Mag Shielding (dynamic)	Habitability Score
42.	GJ 832 -c	1L 2L	1M 2M	1L 2M	1L 2L	1L 2L	EA:0 SA:0

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

43.	Kepler-1606b -	1L 2L	1M 2M	1L 2L	1H 2H	1L 2L	EA:1 SA:1
44.	Kepler-1090b	1L 2L	1M 2M	1L 2L	1H 2H	1L 2L	EA:1 SA:1
45.	Kepler-61b -	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
46.	. K2-18-b						
47.	Kepler-443 b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
48.	Kepler-1701-b	1L	1M	1L	1H	1L	EA:1
49.	Kepler 22b						
50.	Kepler 1552b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
51.	K2-9b	1L 2L	1M 2L	1L 2L	1L 2L	1L 2L	EA:0 SA:0
52.	Kepler-1540 b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
53.	GJ180c	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0
54.	Kepler 1632b	1L 2L	1M 2L	1L 2L	1H 2H	1L 2L	EA:1 SA:1
55.	Kepler 298d	1L	1M	1L	1H	1L	EA:1
56.	GJ 163 c	1L 2L	1M 2M	1L 2L	1L 2L	1L 2L	EA:0 SA:0

7. DISCUSSION

Geological time evolution of volcanism in the inner solar system planetary bodies is found to show some distinct patterns like the existence of peak and cessation phases. Further these phases are found to be associated with distinct geophysical changes or transitions in these bodies and they occur when their internal heat flux values is close to certain critical values as described earlier. The later result suggest that rocky planetary volcanism is some kind of a self-organised physical phenomena. Large volcanic craters in a rocky planet is a manifestation of very intense and widespread volcanism or part of major volcanic activity.

In Fig 2 and Fig 3 we have plotted the variations in the number of occurrences of largest volcanic craters in Mars and Moon respectively as a function of geological time (data for the above plots are from Table 15.1and Table 15.2 in Hiesinger and Tanaka, 2020) During peak phases of volcanism in these planetary objects we could find maximum number of such craters. During cessation phases of major volcanism, the number of such craters simply disappear. This provides an independent evidence to the existence peak and cessation phases of major volcanism in these planets. The dating of large volcanic craters on Venus showed that they occurred during the peak phase (resurfacing phase) of volcanism. The recent surface heat flux measurements suggest that the current average surface heat flux of Venus is about 90 % of the current average surface heat flux value for Earth [Smrekar et al, 2023] This supports our inference that cessation of major volcanism happened in this planet in the very recent geological past. All the shield volcanoes which occurred in the geological history of Mercury occurred during the inferred peak phase of major volcanism. The phenomenon of global contraction in this planet (Klimczak, 2017) can be associated with the cessation phase of major volcanism.Recent studies support the occurrence of coldest ice age on Earth (Crayogenian period, 630-720 Gyrs) and the emergence of inner core (0.5-0.7 Gyrs) in association with the peak phase of volcanism in our planet (Gernon et al,2016; Zhang et al, 2020). The inferred volcanic activity evolution in a Earth like rocky extrasolar planet is shown in Fig 4.

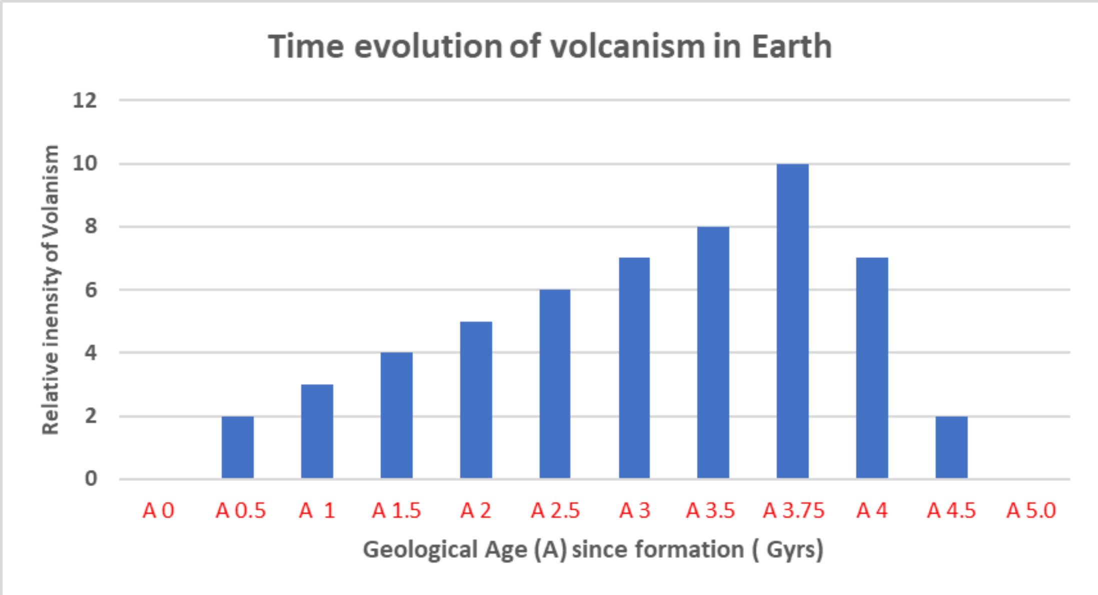

Figure 2. Inferred time evolution of volcanism in Earth based on best available observations. This is also true for an Earth like rocky exo planet.

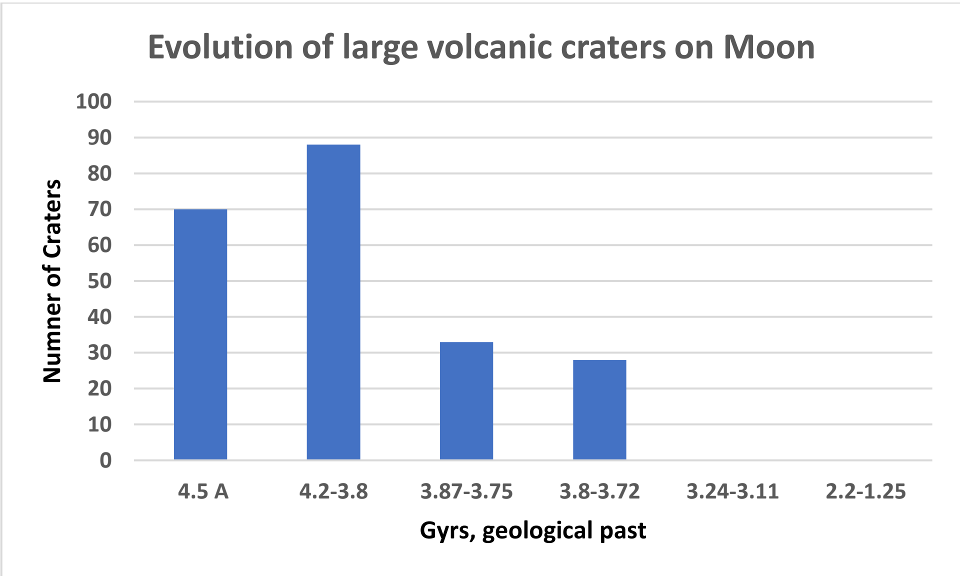

Figure 3. Geological time evolution of the observed number of large volcanic craters on the Moon.

 doi:10.20944/preprints202303.0327.v1

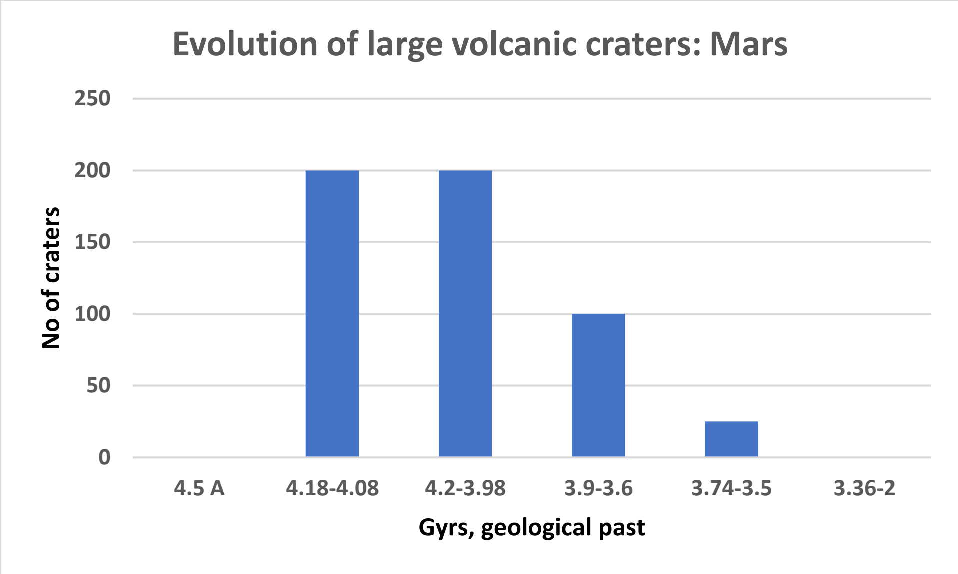

Figure 4. Geological time evolution of the observed number of large volcanic craters on Mars.

In our earlier studies we could find some patterns and self-organised behaviour in the geological time evolution of planetary volcanism in the inner solar system. The results of these studies are now extended to rocky extrasolar planets to infer the volcanic phases at earth and host star ages of these planets. The probability of finding water, oxygen , ozone and magnetic field shielding in 52 potentially habitable extrasolar planets is also determined. The mass and age of extrasolar planets will decide the dynamic habitable conditions in these planets. According to our calculations life favouring geophysical conditions can be found with high probability in extrasolar planets with an age greater than 3.75 Gyrs if their mass is comparable to Earth. The same is most probable in extrasolar planets at an age greater than 5 Gyrs if their mass is twice that of our Earth.

The distribution of the inferred volcanic phases of 52 potentially habitable exo planets at Earth and Star ages is shown in Fig 5 and Fig 6 respectively. From Table 6 we can understand that dynamic life favouring geophysical conditions is relatively more probable for Peak and Decmining phases . However number of PHESP in these volcanic phases is observed to be relatively small. At the current age or host star age number of PHESP with high habitability score (4 or more) is found to be only three out 52 exo planets . From Table.7 we identify these planets as Prox Cent b, Kepler 452 b and Kepler 1653 b. So out of 5200 exo planets confirmed so far only a very small percentage is likely to have geophysical conditions favourable for the development of advanced life.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 March 2023 doi:10.20944/preprints202303.0327.v1

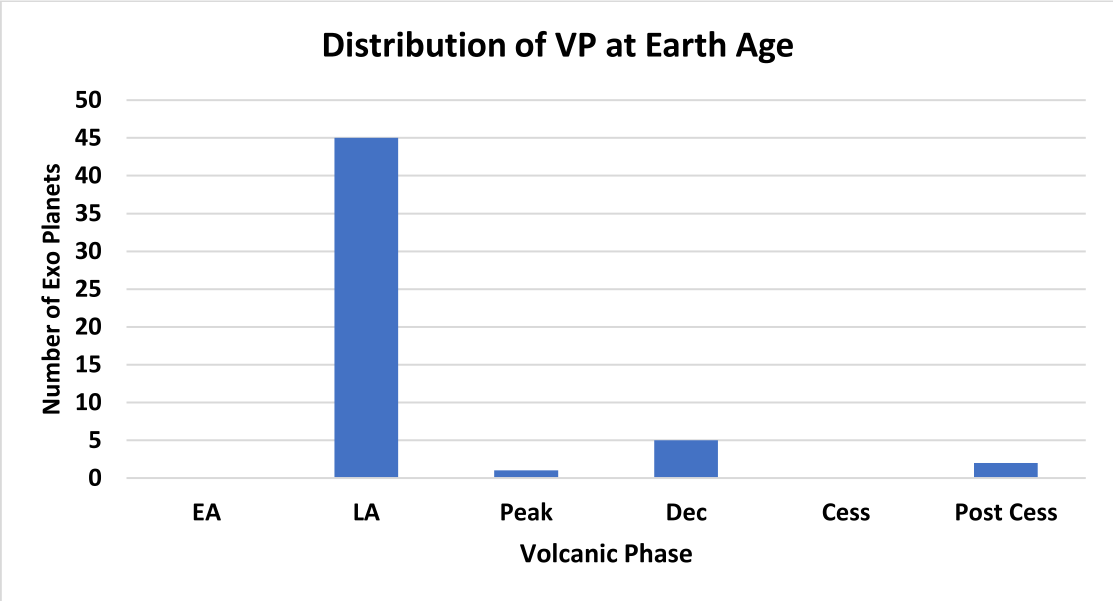

Figure 5. Frequency distribution of Volcanic Phases of PHESP at Earth age (EA: Earlt Ascending, LA: Late Asending, Dec: Declining, Cess: Cessation, Post Cess: Post Cessation).

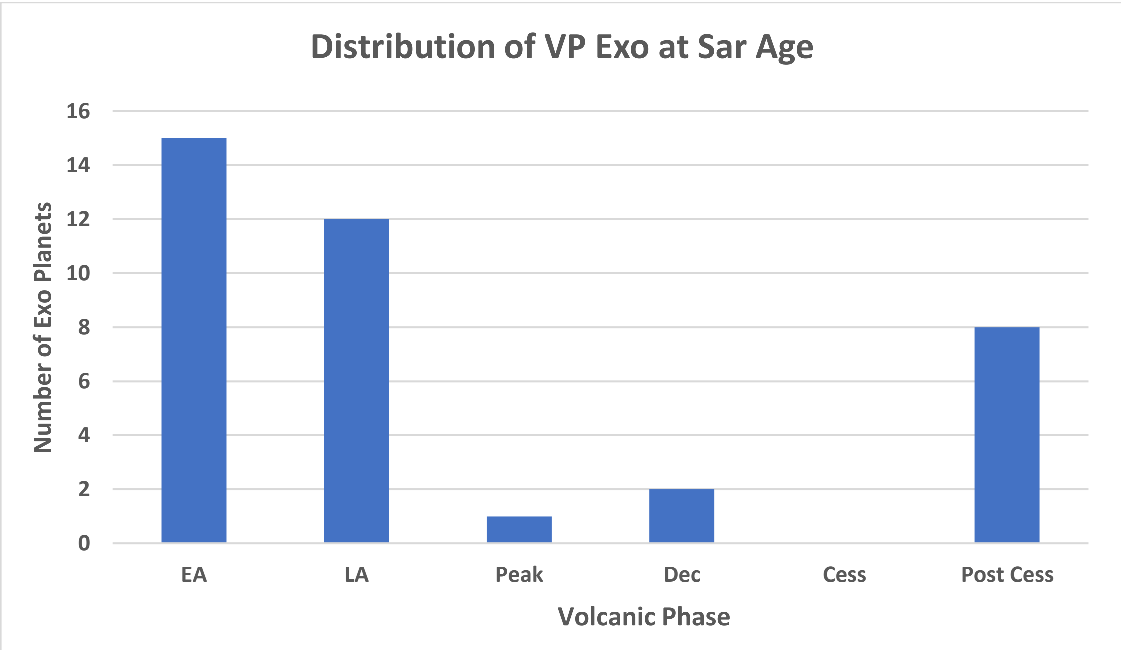

Figure 6. Frequency distribution of Volcanic Phases of PHESP at host star age (EA: Early Ascending, LA: Late Ascending, Dec: Declining, Cess: Cessation, Post Cess: Post Cessation).

We know that M stars and associated extra solar planets are more frequent in our galaxy. Hence we look forward to find habitable extra solar planets near M dwarfs like our nearest star Proxima Centauri. Incidentally we could infer high habitability score for Prox cent-b from our calculations in this paper. Two conditions possess challenges to the development of advanced life in extrasolar planets near M stars. They are (i) hazardous space weather conditions due to super flares near M stars. (Herbst et al , 2019; Lincom and Loeb, 2017; Airapetian et al, 2020) (ii) Long night periods of M star extrasolar planets due to their inferred slow rotation periods . The second condition will prohibit emergence of Earth like plant life in these planets (Leman and Chmanaeva, 1977) .Experimental detection of plant life in extra solar planets will become necessary in this context (Girish and

Sony, 2008, Covone ad Lenco, 2021). The possibility of development of alien plant life with slow circadian rhythms can not be also ruled out (Sony et al, under preparation).

RESULTS

1. Based on the results related to time evolution volcanism in rocky planetary bodies in the solar system we have found a methodology to infer dynamical geophysical conditions in 56 potentially habitable extra solar planets (PHESP) listed by University of Porto Rico
2. The geophysical conditions in a rocky planet is suggested to evolve with phases of volcanism in these planets. So we have inferred volcanic phases in PHESP at both earth (EA) and host star ages (SA) based on the mass and age data of these exo planets .
3. The probability of finding life favoring geophysical conditions (water, oxygen, ozone and intensity of magnetic fields) in rocky PHESP is then inferred at EA and SA based on solar system analogy.
4. Exo planets with high probability of having advanced life is inferred to be rare in our investigations due to the diverse and complex habitability criteria . In this context the low probability of emergence of plant life in exo planets around M stars is also pointed out due to its very long night periods.

REFERENCES

Airapetian, V.S et al (2020). Impact of space weather on climate and habitability of terrestrial-type exoplanets. International Journal of Astrobiology 19, 136–194. https://doi.org/10.1017/ S1473550419000132

Barnes, R., Jackson, B., Greenberg, R., and Raymond, S. N. (2009) Tidal limits to planetary habitability. The Astrophysical Journal Letters, 700(1), L30.

Byrne, P. K.(2019) A comparison of inner Solar System volcanism. Nat Astron,4(1), 321–327. DOI:10.1038/s41550-019-0944-3

Cheng,Q. (2018) Extrapolations of secular trends in magmatic intensity and mantle cooling: Implications for future evolution of plate tectonics. Gondwana Res.,63,268-273 ,DOI:10.1016/j.gr.2018.08.001

Covone ,G and Ienco , R.M, Luca Cacciapuoti and Laura Inno (2021) Efficiency of the oxygenic photosynthesis on Earth-like planets in the habitable zone, MNRAS 505, 3329–3335 (2021), https://doi.org/10.1093/mnras/stab1357

Dickey, J.O., Bender, P.L., Faller, J.E., Newhall, X.X., Ricklefs, R.L., Ries, J.G., Shelus, P.J., Veillet, C., Whipple, A.L., Wiant, J.R., Williams, J.G., and Yoder, C.F. (1994) Lunar Laser Ranging: a continuing legacy of the Apollo program. Science 265:482–490

Doris Breuer, Stephane Labrosse ·and Tilman Spohn (2010) , Thermal Evolution and Magnetic Field Generation in Terrestrial Planets and Satellites, Space Sci Rev 152: 449–500

Driscoll , P.E and Barnes,R (2015)Tidal Heating of Earth-like Exoplanets around M Stars: Thermal, Magnetic, and Orbital Evolutions, Astrobiology, 15(9), DOI:10.1089/ast.2015.1325

Eric Chassefière, Benoit Langlais, Yoann Quesnel, and François Leblanc (2013) The fate of early Mars' lost water: The role of serpentinization, JGR Planet, 118,1123–1134, doi:10.1002/jgre.20089

Gernon, T., Hincks, T., Tyrrell, T. et al. (2016) Snowball Earth ocean chemistry driven by extensive ridge volcanism during Rodinia breakup. Nature Geosci ,9, 242–248.

Girish T.E and Sony.K.S (2008) Vibrational Spectroscopy and Search for Extra-terrestrial Life, AIP Conference Proceedings , **1075**, 196 , https://doi.org/10.1063/1.3046211

Grott, M., and Breuer, D. (2008), Constraints on the radiogenic heat production rate in the Martian interior from viscous relaxation of crustal thickness variations, Geophys. Res. Lett., 35, L05201, doi:10.1029/2007GL033021.

Hector Javier Durand-Manterola (2009)Dipolar magnetic moment of the bodies of the solar system and the Hot Jupiters,Planetary and Space Science,57, 1405-1411, https://doi.org/10.1016/j.pss.2009.06.024.

Herbst.K , Papaioannou.A , Banjac.S , and Heber.B (2019) From solar to stellar flare characteristics On a new peak size distribution for G-, K-, and M-dwarf star flares .A&A, 621, A67 , https://doi.org/10.1051/0004-6361/201832789

Hiesinger.H and Tanaka.K (2020) The Planetary Time Scale, Editor(s): Felix M. Gradstein, James . Ogg, Mark D. Schmitz, Gabi M. Ogg,Geologic Time Scale 2020,Elsevier, 443-480,
https://doi.org/10.1016/B978-0-12-824360-2.00015-2.

James Green , David Draper, Scott Boardsen ,Chuanfei Dong (2020) When the Moon had a Magnetosphere, Sci. Adv. , 6 : eabc0865.

Johnson .C.L et al (2015) Low-altitude magnetic field measurements by Messenger reveal Mercury's ancient crustal field, Science , 348, 892-895

Kite , E.S., Manga,M. and GaidosE.(2009) Geodynamics and rate of volcanism on massive Earth-like planets. ApJ, 700(2),1732,10.1088/0004-637X/700/2/1732

Klimczak.C (2017) Timing and rate of global contraction on Mercury, GRL 44, 3082-3089, https://doi.org/10.1002/2017GL072711

Kopparapu, R,K, Wolf E.T, and Meadows.V.S (2019), Characterizing Exoplanet Habitability, arXiv:1911.04441[astro-ph.EP]

Leman.V.M and Chmanaeva.T.N (1977), Reactions of Plants to Long Absence of Light Phytotronic Newsletter, 16, 12-14.

Lenardic, A., Nimmo, F., & Moresi, L. (2004) Growth of the hemispheric dichotomy and the cessation of plate tectonics on Mars, J.Geophys.Res.Planets,109(E2), DOI:10.1029/2003JE002172

Lingam, M and Loeb. A . Risks for Life on Habitable Planets from Superflares of Their Host Stars.The Astrophysical Journal, 848:41 (2017) , **DOI** :10.3847/1538-4357/aa8e96

Mardling R.A and Lin.D.N.C (2004) On the Survival of Short-Period Terrestrial Planets, ApJ, 614 ,955, DOI 10.1086/423794

Mayor, M.; Queloz, D. (1995). A Jupiter-mass companion to a solar-type star. Nature. 378 (6555), 355–359.

Meadows, V.S. and Barnes, R.K. (2018). Factors Affecting Exoplanet Habitability. In: Deeg, H., Belmonte, J. (eds) Handbook of Exoplanets . Springer, Cham.https://doi.org/10.1007/978-3-319-30648-3_57-1

NASA (2023) , Exo planet archive, available at https://exoplanetarchive.ipac.caltech.edu/, accessed on January 23rd ,2023

Orth, C. P., Solomatov, V. S., Reese, C. C., & Head, J. W (2008) A Simple Cooling Model for the Cessation and Distribution of Volcanism on Venus. LPI, (1391), 1360.

Reese, C. C., Solomatov, V. S., & Orth, C. P. (2007) Mechanisms for cessation of magmatic resurfacing on Venus. J. Geophys. Res. Planets, 112(E4), 10.1029/2006JE002782

Romeo, I and D.L. Turcotte (2009) The frequency-area distribution of volcanic units on Venus: Implications for planetary resurfacing, Icarus, 203, 13-19.

SETI Institute (2020) How Many Habitable Planets are Out There? , available in https://www.seti.org/press-release/how-many-habitable-planets-are-out-there

Shi.X.H, (2016) Death by Magnetic Field: the story of Mars Atmosphere, available in : https://depts.washington.edu/astron/old_port/TJO/newsletter/spr-2016/xinyu.pd

Smrekar,S.E., Stofan, E. R., Mueller,N., Treiman, A., Elkins-Tanton ,L., Helbert, J &Drossart, P. (2010) Recent hotspot volcanism on Venus from VIRTIS emissivity data. Science, 328(5978), 605-608. 10.1126/science.1186785

Smrekar, S.E., Ostberg, C. & O'Rourke, J.G. (2023) Earth-like lithospheric thickness and heat flow on Venus consistent with active rifting. Nat. Geosci. **16**, 13–18 . https://doi.org/10.1038/s41561-022-01068-0

Solomon,S.C.(1978) On volcanism and thermal tectonics on one –plate planets. Geophys.Res.Lett., 5(6),461-464, 10.1029/GL005i006p00461

Sonia. M. Tikoo, Benjamin P. Weiss, William S. Cassata, David L. Shuster, Jérôme Gattacceca, Eduardo A. Lima, Clément Suavet, Francis Nimmo, Michael D. Fuller (2014), Decline of the Lunar Core Dynamo, Earth Planet.Sci.,Lettrs, 404, 89-97, https://doi.org/10.1016/j.epsl.2014

Sotin, O. Grasset, A. Mocquet,Mass–radius curve for extrasolar Earth-like planets and ocean planets,Icarus,Volume191,Issue1,2007,337-351, https://doi.org/10.1016/j.icarus.2007.04.006

Spiegel.D and Turner, E.L (2011) Bayesian analysis of the astrobiological implications of life's early emergence on Earth, Proceedings of the National Academy of Sciences, 109(2), 395-400, DOI: 10.1073/pnas.1111694108

Stéphane Labrosse and Mélina Macouin (2003) The Inner core and the Geodynamo, C. R. Geoscience, 335 ,37–50.

Tarter.J (2001) The Search for Extraterrestrial Intelligence (SETI), Annu. Rev. Astron. Astrophys. 39, 511–48

Turcotte, D.L. and Schubert, J. (1982) Geodynamics. John Wiley and Sons, New York, pp 450.

University of Puerto Rico (2023) The Habitable Exo planet Catalouge, available at https://phl.upr.edu/projects/habitable-exoplanets-catalog, accessed on January 10, 2023

Unterborn C.T et al (2022) Mantle Degassing Lifetimes through Galactic Time and the Maximum Age Stagnant-lid Rocky Exoplanets Can Support Temperate Climates,ApJL 930, L6, DOI :10.3847/2041-8213/ac6596

Varnana M.Kumar., Girish,T. E., Biju, L., Thara, N.S.and Anjana ,A.V.P. (2018) Cessation of Volcanism on Earth-Possibilities in near geological future,arXiv:1808.01333 [physics.geo.ph]

Varnana.M.Kumar., Girish, T. E., Thara, N.S., Biju, L., Anjana, A.V.P and Binoy J.(2020), On The Geological Time Evolution of Volcanism in the Inner Solar System, arXiv:2005.13200 [astro-ph.EP]

Varnana.M.Kumar., Girish, T. E., Thara, N.S., Biju, L., Anjana, A.V.P and Binoy J.(2021a) Evidence for Critical Internal heat values during Significant Geophysical Transitions in the Inner Solar System Planetary bodies in association with Volcanism,arXiv:2105.05676[physics.gen-ph]

Varnana.M.Kumar, Girish, T. E. , Sathyan, N. S. , Longhinos, B. . Binoy, J (2021b) Inferring Time Evolution of Volcanism in Extrasolar Planets and its Implications on Habitability, AASTCS8, Habitable Worlds 2021, id. 1117. Bulletin of the American Astronomical Society, 53,e-id 2021n3i1117

Varnana M. Kumar , Thara N. Sathyan, T.E. Girish, P.E. Eapen, Biju Longhinos and J. Binoy (2023) Inference of Magnetic Fields and Space Weather Hazards of Rocky Extrasolar Planets From a Dynamical Geophysical Model , In : D. Bisikalo, D. Wiebe & C. Boily, eds, The Predictive Power of Computational Astrophysics as a Discovery Tool , Proceedings IAU Symposium No. 362, ,175-176, doi:10.1017/S174392132200148X

Yip.K.H et al (2022) ESA-Ariel Data Challenge NeurIPS 2022: Inferring Physical Properties of Exoplanets From Next-Generation Telescopes, arXiv:2206.14642 [astro-ph.EP]

Zhang.Y et al (2020) Reconciliation of Experiments and Theory on Transport Properties of Iron and the Geodynamo,PRL, 125, 078501 , DOI: 10.1103/PhysRevLett.125.07850