# *Volcanism in our Solar System*

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## *Introduction* ***(By Author1 and Author2)***

Volcanology is an aspect of our solar system that transcends individual planets, it's found in different forms through out our solar system. From the beautiful Mt. Kilauea in Hawaii to the majestic Olympus Mons on Mars, to the nitrogen geysers on Triton, volcanism proves that the terrestrial planets and satellites in our solar system are currently or at one point in their histories have been, living, breathing, geologic bodies.

Our project consisted of researching the types of volcanic features in our solar system, and what led them to occur. We researched, volcanoes on Venus, Mars, Io and the cryovolcanic activity on satellites in the outer solar system. We also looked into tidal friction that causes the internal heating for many of the outer solar system's satellites.

## *Volcanism in the Solar System* ***(By Author1)***

In our solar system, the terrestrial planets all share various similarities due to the fact that they were formed from the same stellar debris. Given that these planets were inwards of the frost line, they developed from the heavier elements and will have various features that will correlate to those featured on other planets. Some form of volcanism is present on most of these planets including Mars, Venus and as we know, Earth. Given that humans have had thousands of years to observe and study volcanic activity on Earth, there is much knowledge and understanding of why Earth has this violent geographical trait. However, it has only been in recent years that observation and study of these other terrestrial planets has led to the discovery of volcanic activity on both terrestrial planets and various moons. With the further understanding and comparison of volcanic features on Earth, we can further understand the volcanism present on other celestial bodies and thus understand more about the planet itself. Mars and Venus all display concrete evidence of past volcanic activity and some even depict signs of present activity.

Earth has a couple types of volcanoes that we, as humans, are the most familiar with due to our long past in dealing with them. Various volcanic features really define the sort of volcanism present on Earth explaining how the size and internal activity have developed the surface of the planet. Shield volcanoes are prominent on Earth, as well as Mars and Venus, and due to their nature tend to be the largest volcanoes in the solar system. Their eruptions exude a much less explosive force that has very fluid lava. This fluid quality does not allow the gradient of the volcanoes' slopes be any steeper than seven degrees or the lava will just keep slowing downwards. Due to that inability to form steeper mountains, shield volcanoes become very large and eventually tall with the immense amount of lava slowly building the mountain, layer by layer. While the shield volcanoes of earth do become immense, they do not get near the size of the enormous volcanoes present on mars, due to the constantly moving plate tectonics of Earth. The lava slow is disrupted by the continuous movement of the plates and does not allow the earthen shield volcanoes to grow to truly immense sizes. Mauna Loa is the largest and tallest mountain on our planet, if measuring from its start on the sea floor, and has been able to grow to this size due to its location of being on a hot spot and not the boundary of sub ducting tectonic plates.

Another type of volcanoes present on Earth is strato volcanoes, and they are characterized by their extremely explosive nature and overall conical shape. These comprise the larger number of individual volcanoes and some notable ones are Mt. Saint

Helens and Mt. Fuji. Their explosive nature is caused by the highly viscous nature of their lava and the way that the viscosity pressurizes the volcano until it explodes in a violent eruption. Viscous lava allows the building of steeper, less structurally sound earthen masses comprised of both lava and pyroclastic material and gives rise to the other name that associated to this formation, composite volcanoes. Due to the highly volatile nature of these volcanoes, they tend to not reach high altitudes with their frequent reshaping of their own landscape.

Both shield volcanoes and strato volcanoes are present and prominent on the Martian surface, a place known for its outstanding evidence of past volcanic activity. Most research and observations accomplished in relation to the planetary status of Mars have determined the red planet to be dead with an inactive core and solidified mantle. The size of a terrestrial planet greatly determines how long the planet can stay hot, and in a sense 'alive', and with Mars being just half the diameter of earth, the ratio of volume to surface area displays how internal heat loss is rampant on smaller planets. Given this fact, we have a dead planet to observe in its current stasis and extinct volcanoes observable to scientists so that they might determine the geographical history of the planet. Ways of determining the characteristics and life of a planet, involve comparative geography between that of the planet and Earth. Volcanic activity is a useful tool in this comparative geography and when looking at Mars, one can immediately observe the presence of many volcanic features on the surface.

Mars does not have tectonic plates like that of Earth but it does exhibit the trait of having various hot spots around the planet. The hot spot most noted would be the immense Tharsis Bulge located in the northern hemisphere of the planet, and this highly volcanically active, in the past, displays the most recent large amount of activity, and we know this because of the cratering present everywhere else on the planets surface. This evidence shows how the volcanoes on the Tharsis bulge had been resurfacing the region and erasing the traces of past impacts in the area. Olympus Mons, the solar system's tallest mountain, is a shield volcano on the noted region and is one of the younger volcanic features on the red planet. With a 500 km wide base, the mountain is roughly the size of Arizona, and is only second in sheer size to the immense Alba Patera. While also residing on the Tharsis Bulge, this shield volcano covers an area the size of the state of Texas, but is not nearly as tall as Olympus Mons. With a one degree slope, one could walk up the slope of Alba Patera and only rise around ten meters for every mile walked towards the summit. These super massive volcanoes were able to grow to this immense size due to the Martian planets' lack of tectonic plates, so the Tharsis Bulge was able to form and provide a consistent pathway for lava to flow consistently to the surfaces many volcanoes. The presence of small strato volcanoes peppering this surface of the Tharsis region gives evidence that those small peaks were once much taller volcanoes but have since become "lavabergs" in an ocean of lava flows from the large shield volcanoes in the region. An overall effect that the bulge has on the planet is seen in the Valles Marineris, the cutting scar across the face of Mars formed by the Tharsis Bulge ripping the crust apart as it grew in the northern regions. All volcanic features considered, there are basic similarities between Mars and Earth, but where they seem to differ greatly is due to the presence of plate tectonics on Earth and the dynamics associated with that.

Venus displays similar properties to that of Mars in that the second planet in our solar system also does not have tectonic plates and displays volcanic features through various hot spots on the surface. Volcanoes pepper the surface and the traditional shield and strato volcanoes are present as well as a volcanic feature specific to Venus. These features are pancake dome volcanoes that look like their names, with a smooth flat top and steep outer slopes. Their extremely viscous lava cannot travel far before solidifying so that gives rise to their namesake shape of large volcanic pancakes.

The spectrographic analysis of the Venusian atmosphere points to the planet still being volcanically active. SO2 levels in the atmosphere point to the planet still being alive and sound with volcanoes still erupting. Given that the volume of Venus is closer to the size of Earth, it should be much longer before the mantle of Venus cools like that of Mars due to the great difference in the volume to surface area ratios of both Mars and Venus. While Venus is larger than Mars and closer to the size of Earth, it will however cool quicker than Earth just because of Earths 20% larger volume. As long as the planet of Venus still has a working mantle, it will continue to have active volcanic hot spots peppering its globe and continue to be a geographically evolving planet.

In viewing the terrestrial planets of our solar system and their current or past volcanic activity, to the exclusion of Mercury, one can see the basic similar qualities between the planets. Whether delving into the core of the planet and observing the mantle, core and lithosphere or viewing the planet from above, one can see similarities between the planets and be able to compare and contrast the features to one another. Each planet does not reinvent the wheel so to say with a completely different planetary dynamic, so with further study of any terrestrial planet, the information determined can allow further understanding of a place like Earth. The main determining factor between greater variations in volcanic features seems to point to Earth's having tectonic plates and

Mars and Venuses lack thereof. Other than that, as discussed the basic form of shield volcanoes and strato volcanoes are present on all three planets and this really displays some of the fundamental similarities between those three planets.

## ***Tidal Heating*** ***(by Author2)***

Tidal forces bring thermal energy to places in our solar system which otherwise should have cooled down millions of years ago. This phenomenon is visible throughout our dynamic solar system. It brings different affects to different places. Our tides on earth are produced by the tidal forces we exert on the moon and the affect that the moon in turn has on us. The tidal force of Saturn can be used to account for its large rings that were most probably at one time a moon that ventured too close to Saturn and got torn apart once they reached the Roche Limit.

Tidal heating is the thermal heating of a planet due to the friction caused by tidal forces (Encyclopedia of Volcanoes). Tidal heating can be related back to volcanism because it keeps bodies geologically alive by keeping their interiors warm when they would have already become geologically inactive. It gives us the opportunity to take a closer look at satellites, such as some of the Jovian moons, Enceladus orbiting around Saturn, and Trition orbiting around Neptune, and possibly keep these places warm enough where life could form.

Io is the best example in our solar system of the direct affects tidal heating can have on a body. Before Voyager I flew by the Jovian system in 1979, many scientists believed Io to be geologically dead. Io is tidally locked to Jupiter, which means that the same side of Io is always facing Jupiter. Io’s eccentricity is nearly zero, making its orbit almost a perfect circle. This gave scientists reason to believe that Jupiter put no stress on Io that would make it volcanically active (Frankel).

There were however, some scientists that believed that there must have been something odd going happening on Io because of the fact that its temperature was not consistent. For the majority of the time, Io's daytime temperature was -150ºC and the nighttime temperature was found to be -200ºC, which was consistent with what it should be for Io's location so far away from the Sun (Frankel). However, every once in a while, temporary hot spots would arise with temperatures of 300ºC+.

This was enough evidence to lead physicist Stanton Peale to research the possibility of volcanism on the satellite. Peale created an equation which would predict the dissipation of energy on Io due to tidal heating. His equation read as follows:

$$\frac{dE}{dt} = \frac{36}{19} \frac{\pi \rho^2 n^5 R_s^7 e^2}{\mu Q}$$

ρ = the density of Io
n = (2π)/P
P=orbital Period
R = radius of satellite

Q = specific dissipation function
e = eccentricity
μ = the rigidity of the satellite

We do not know Q for Io, so he uses the Q for our moon, which we know to be 100. When we plug in all our numbers we get that $1.49 \times 10^{19}$ ergs/s as the total dissipation of energy on Io due to tidal heating (Peale). This was enough for Peale to predict volcanoes on the small satellite. He made this prediction public 2 months before Voyager I reached Jupiter, and when it got there, it was able to show that Peale's prediction was indeed correct.

This immense amount of energy dissipation can be accounted for by Io's 2:1 resonance with Europa. For every two times that Io goes around Jupiter, Europa only goes around once. Each time Io overtakes Europa; they both feel a slight tug from the other. This slight disruption is enough to push Io slightly out of its nearly perfectly circular orbit around Jupiter. Enough of a change in the eccentricity of the orbit occurs so that Jupiter's immense gravitation can cause cataclysmic effects on Io's interior. As Io is stretched and pulled, the bulge that forms is believed to rise and fall by 100 meters each cycle (Frankel). This is a significant change for such a body.

Everyone knows today that Io is a world full of spectacular eruptions and beautiful caldera and patera formations, with lava flows covering the entire satellite. Everyday new photos are being posted on NASA websites, taken by the latest spacecraft to visit our outer neighbors. We are learning new things about Io constantly and scientists always have their plates full with new and exciting data. The molten satellite still holds many mysteries, but we are slowly beginning to put the puzzle together.

There are some things that we do know about the surface composition of Io. It has the hottest lava flowing in the solar system (Lopes). For a long time, scientists believed the lava to be mostly composed of sulfuric particles, but the lava is far too hot for this to be the case. This has led many scientists to propose an ultra-mafic magnesium rich composition on Io where melt temperatures could vary from 1700K to 1900K. This is a lot how we picture prehistoric Earth must have been billions of years ago (Lopes).

## *CRYOVOLCANISM (By Author2)*

Cryovolcanism is one of the latest subject areas in planetary science to be gaining a lot of exposure. Since the Galileo mission went to Jupiter and determined that Europa might have a subsurface ocean, scientists have been studying how these icy satellites in the outer solar system remain geologically active, despite their small sizes and large distances from the sun. Studying these new environments has completely opened the doors to new ways in which life can exist. Now the coldest region of our solar system seems like the most likely place for extraterrestrial life of some sort.

Cryovolcanism is defined to be the eruption of liquid or vapor phases of water, or other volatiles, that would be frozen solid at the normal temperature of an icy satellite's surface (Lopes). It has the same capabilities as molten volcanism; cryolava can flow, sculpt and resurface terrain, leaving its mark on the terrestrial body. Their viscosities can range from frothy to runny, dense or sluggish, all depending on the composition. The lavas are mainly water based and might contain some methane and ammonia, both of which have lower freezing temperatures then water (Lopes). This means that there could possible be liquid ammonia and methane traces on these bodies, where it would be too cold for liquid water to run. This is very appealing to scientists studying them.

How large a satellite is, its composition, and its location in the solar system are all factors which determine whether or not a body would be able to maintain cryovolcanism (Lopes). Of course, that all depends on whether or not a body can maintain internal heat. There are a few ways in which a satellite or body can be internally active. If a body is large enough, gravity can help keep it warm for some time, through differentiation, but most of the satellites in the outer solar system are much too small to still be active because of this, also the decay of radioisotopes could maintain heat inside of a body. This is also a possibility for the outer satellites, but the most likely mechanism for keeping them warm is tidal heating. As we learned before, through Peale's equation, tidal heating can cause tremendous amounts of energy flowing through a body. The three main cyrovolcanically interesting bodies in our solar system at the moment are Europa, Enceladus and Triton.

Europa is one of the most interesting and popular places in our solar system for planetary scientists to study right now, second only maybe to Mars. With the discovery of it's possible subsurface ocean, scientists have been studying the new and unique features which cover the body.

Europa is covered with ridges and chaotic zones, which can all be explained with some sort of cryovolcanic activity. Europa is thought to have water underneath its crust of ice that consists of volatiles such as CO, $CO_2$, and $SO_2$. These volatiles make Europa act like a big soda can when, as a piece of ice which is less dense then its surrounding liquid begins to raise up to the surface, it begins to accelerate as it depressurizes. This causes many types of features on the surface of Europa.(Lopes)

Enceladus is one of the most beautiful objects in our solar system. It's light blue surface has the highest albedo in our solar system. It has two regions of significance which consist of a smooth southern hemisphere with odd striations, which scientists have come to call "tiger stripes" and the northern hemisphere which has a impact craters, consistent with other bodies in our solar system. It's clear from these two regions that Enceladus must have had some sort of resurfacing process fairly recently in it's history, geologically speaking. There are fresh ice deposits through out the body, causing its high albedo. Scientists are not quite sure what is causing its internal heating, but they are speculating that it has something to do with a resonance with another of Saturn's moons, Mimas.

The last satellite is Neptune's Triton. This is the only satellite in our solar system that is known for certain to have active cryovolcanism. There are visible plumes of nitrogen gas that raise from its surface up to 8 km. This is active volcanism found between 40ºS and 67ºS near its subsolar point.

$N_2$ and $CH_4$ have been identified on the surface of Triton and Co,$CO_2$ and $H_20$ ices are expected to be abundant in the crust. Triton's atmosphere is thin and consists of nitrogen vapor, and clouds of $N_2$ ice crystals.

The nitrogen plumes are believed to be caused by sunlight penetrating through a thin layer of nitrogen ice and being absorbed by dark carbon-rich impurities beneath the surface. This would cause a mild heating which would be enough to create an explosive venting of the gas because an increase of only 10 K would be enough to raise the vapor pressure of $N_2$ up to a 100 times what it would be otherwise. (Lopes)

Each of these three satellites share the unique characteristic of cryovolcanism and scientists are studying them intently to learn as much about them as possible. Volcanism will continue to be an important topic in planetary science, it connects all the terrestrial planets in such a way that we can hopefully one day understand where our solar system came from and what is in store for it in the future.

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