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P2_05 Volcanoes on Io

Nick Attree, Jamie Sinclair, Jon Stock, Chris Rivers

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

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Abstract

Jupiter's volcanic moon Io is highly active. This paper seeks to quantify this volcanism by comparing Io's measured thermal output to the theoretical energy production from tidal heating. Methods for transferring this energy to the surface are then discussed.

Introduction

Io is the innermost of Jupiter's four Galilean moons and, alongside Enceladus and Triton, is one of only three solar system bodies outside the Earth on which active volcanism has been observed [1]. Io's surface is dominated by volcanic products, such as lava flows, erupted sulphur frosts and volcanic plumes which have been observed rising hundreds of kilometres above it.

Io's total volcanic output can be estimated by integrating its infrared emissions over the whole surface. Several spacecraft have made such measurements and the current best estimate is $\sim 1 \times 10^{14} W$ which corresponds to a surface heat flux of $q = 2.5 W m^{-2}$[2]. The source of this enormous heat flux will be discussed below.

Tidal Heating

Io's orbit around Jupiter is elliptical, with the eccentricity being maintained over time by gravitational interactions with the other Galilean satellites (mean-motion or Laplacian resonance) [1]. This means that the tidal bulge raised on Io by Jupiter varies in magnitude as it progresses around its orbit. It will also oscillate backwards and forwards with respect to fixed features on the surface in a process called libration. Both of these movements cause friction within Io, dissipating energy and causing heating. The magnitude of this heating is given by

$$P = \frac{21}{2} \frac{k_2}{Q} \frac{(nR)^5}{G} e^2, \qquad [3]\ (1)$$

where k_2 is the tidal Love Number, Q is the dissipation factor, $n = 4.1106 \times 10^{-5}\, rad\, s^{-1}$ [4] is the orbital mean motion, $R = 1821 km$ [4] is the radius of the satellite, $G = 6.673 \times 10^{-11} m^3 kg^{-1} s^{-2}$ is the gravitational constant and $e = 0.0041$ [1] is the eccentricity of the satellite's orbit.

The tidal Love number and dissipation factor are dimensionless numbers which measure the satellite's internal structure (its rheology) which is in turn dependent on the thermal state; creating a complicated feedback loop between tidal heating and internal melting. For the purposes of this paper the above, simple formula for a homogenous body, ignoring complex terms, will be used to produce a rough estimate, as in [3]. Substituting best estimates of $k_2 = 1.3043$ and $Q \sim 100$ [4] into (1) gives

$$P = 8.11 \times 10^{13} W,$$

similar in magnitude to the total volcanic power output quoted above.

Heat Transport

Modelling suggests that most of this tidally generated heat is dissipated in the upper mantle, deep within Io, so how is it transferred to the surface?

If the heat is transported by conduction then the following equation for conduction through a thin shell [1] can be used

$$\Phi = k \frac{T_t - T_b}{d} \qquad (2)$$

where Φ is heat flux in Wm^{-2}, k is thermal conductivity, T_t and T_b are the temperature at the top and bottom of the shell respectively and d is the thickness of the shell. Taking Φ as the measured $2.5Wm^{-2}$ surface heat flux, $k \approx 3W(K \cdot m)^{-1}$ [5] and setting $T_t = T_s = 100K$, the surface temperature, and $T_b = T_m = 1600K$ [2], the melting temperature of Io's rocky material, (2) can be rearranged to

$$d = k\frac{T_s - T_m}{\Phi} = -1800m \qquad (3)$$

where d is now the depth from the surface at which the crust begins to melt i.e. $1.8km$.

A crustal thickness of less than 2km is unrealistically small compared to current models that put the thickness at a much larger 20 to 30km [6]. The internal heat is therefore clearly not transported by conduction through a solid crust and as the crust is not a molten ocean pure convection of material is also ruled out. The only remaining plausible mechanism is advective transport: the flow of magma through faults in the solid crust.

Discussion

The estimation for tidally generated heat shows a power similar in magnitude to the measured power of surface volcanism. If the tidal heating is considered an 'input' into the Io system and the volcanism it's 'output' then the two are roughly balanced, suggesting that Io is in thermodynamic equilibrium. This is important for further modelling and is not necessarily the case for all solar system bodies. Enceladus, for example, is not in equilibrium, with its volcanic output greatly exceeding its tidal heating input [7].

As discussed above constraints on the crustal thickness suggest that heat is transferred by advection. That is, the bulk movement of molten material, driven by pressure differences and buoyancy, towards the surface where the energy it carries can then be radiated away to space. This flow is confined to cracks and weak points in the crust, allowing the rest of the crust to remain cool and solid enough to support large mountains. This is the so called 'heat pipe' model for Io's volcanoes [6].

Conclusion

Calculations suggest that Jupiter's moon Io is most likely in thermodynamic equilibrium with the heat generated within it by tidal forces balanced by its volcanic output. Furthermore it is shown that conduction is unlikely to be the mechanism by which heat is transferred from the interior to the surface, lending support to volcanic advection through a system of heat pipes as the preferred model.

It should be noted that all calculations here are necessarily rough as information on the interior of other planets is difficult to ascertain from remote sensing alone. We cannot therefore rule out other methods of heat transfer or thermodynamic disequilibrium in Io but they do seem unlikely based on the evidence presented here.

References

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