

Explosive lunar fission above a large low-velocity province

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Abstract The giant impact hypothesis for the Moon’s origin has had difficulty explaining the nearly identical isotopic compositions of Moon rocks and rocks from Earth’s silicate mantle and crust. These similarities are instead more compatible with the Darwin-Wise hypothesis that the Moon arose by fission of a rapidly spinning Earth. To overcome problems with the fission model concerning structural stability and angular momentum conservation, some authors suggested that lunar fission was feasible on a more slowly rotating Earth if assisted by a nuclear explosion near the core-mantle boundary. In this light we consider the possible roles of the large low-velocity provinces (LLVPs). These long-lived structures have been implicated in diverse geophysical processes ranging from deep mantle plumes to continental breakup and mass extinction events. While the LLVPs have been seen as possible remnants of the giant impactor, we propose that one of them was the site of lunar ejection. Internal heating of the liquid core is suggested to have given rise to an equatorial belt just under the core-mantle boundary analogous to the one recently detected by Ma and Tkalčić [Sci Adv 10(35):eadn5562, 2024]. Upwellings of heat and volatiles from this belt then generated two antipodal, equatorial bulges: the precursors of the Pacific and African LLVPs. Prior to the emergence of plate tectonics, core heat was mainly dissipated by networks of deep mantle plumes extending above the proto-LLVPs. These plume networks represent conduits of weakened mantle through which proto-lunar materials could later rise in a focused ejection. Continuing heat buildup in the core eventually triggered a

cataclysmic explosion in the Pacific proto-LLVP, possibly analogous to a planetary-scale kimberlite eruption. This explosion launched LLVP and overlying mantle material into a low Earth orbit, where it coalesced to form the Moon. Some possible sources of additional energy to power the explosion are considered, including nuclear fission, bolide impacts and a hypothetical gravitational decay process culminating in a ‘Λ event’.

Keywords Large low-velocity provinces · Deep mantle plumes · Lunar fission model · Kimberlite

1 Introduction

Despite being studied for well over a century, there is still great uncertainty concerning the origin of the Moon. A central problem to be solved in Moon origin models relates to the isotopic composition of Moon rocks. Numerous studies have shown that their isotopic compositions for many elements (O, Cr, Ti, K, Si, W) are very similar to those of the bulk silicate Earth (BSE, i.e., mantle + crust) (e.g., de Meijer et al. 2013; Melosh 2014). Recent measurements of O isotopes show that they are nearly identical (Fischer et al. 2024). These similarities are in stark contrast to the widely varying isotopic compositions seen in other bodies of the Solar System.

The most straightforward hypothesis to explain the isotopic similarities is that the Moon was formed mostly of BSE material. In his classic fission model, George Darwin (1879) proposed that the Moon separated from a rapidly spinning Earth. Centrifugal forces and the resonant effects of solar tides overpowered gravity at the equatorial regions, leading to the Moon’s separation. To boost the tidal and centrifugal forces, Darwin’s model was later refined by supposing

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that formation of the Earth's core triggered a faster rotation rate for the proto-Earth (Wise 1963, 1969). Together with a reduction in the Earth's moment of inertia, this would have allowed Earth's rotation period to reach the critical value of 2.65 h required for Moon separation in Darwin's model. Unfortunately for the fission hypothesis, the Earth-Moon system today has only ~27% of the angular momentum that a fast-spinning proto-Earth would have had and a convincing rationale for the fate of the missing three-quarters of angular momentum has never been found (de Meijer et al. 2013). The high spin rates supposed by Darwin and Wise would likely also have induced severe structural instabilities and a possible breakup of the proto-Earth.

Prior to the discovery of the isotopic similarities, there had been a coalescence of views towards an alternative model of Moon origins, the giant impact hypothesis. In this hypothesis, a Mars-sized body ('Theia') collided with the proto-Earth, creating a debris ring which then coalesced to form the Moon. The hypothesis initially arose to explain another feature of Moon rocks. Compared to Earth rocks, the Moon's are strongly depleted in volatile elements such as Na, K, Rb and especially water. It had earlier been suggested by Ringwood (1960) that such depletion could have occurred if the Moon formed out of Earth mantle material that had vaporized and then recondensed under conditions permitting volatiles to escape (Melosh 2014). This scenario could fit with vaporization of mantle material in a giant impact followed by condensation into an orbiting disk.

The isotopic similarities later found in Earth and Moon rocks were very difficult to explain with the giant impact models, however, eventually leading to a so-called 'isotopic crisis' (Melosh 2014). In collision modeling, Moon silicates contain a much higher mass fraction of Theia (up to 70 wt.%) than Earth rocks (~10 wt.%) (Melosh 2014; Fischer et al. 2024). If Theia was compositionally different from proto-Earth and had a different differentiation history, the Moon silicates would then almost certainly have had different isotopic ratios than the proto-Earth. The actual isotopic signatures of Moon rocks implied, however, that little if any of Theia's mass could have ended up in the Moon, in direct conflict with the collisional modeling. Mechanisms to explain the discrepancy, such as a similar distribution of Theia materials in the Moon and proto-Earth or vigorous post-impact mixing between the proto-Earth and the proto-lunar disk, were also problematic (Melosh 2014; Fischer et al. 2024).

Numerous attempts were later made to reduce the Theia signature in the Earth-Moon system. Proposals such as those of Čuk and Stewart (2012) and Canup (2012) however left the Earth-Moon system with too much angular momentum – the same problem encountered by the fission model. Recently, Fischer et al. (2024) suggested that a highly metallic Theia could have fused with the Earth's core after impact, with the proto-lunar material ejected from the side

of the Earth opposite the collision site. This would result in a Moon formed entirely of Earth mantle material and an Earth mantle largely devoid of Theia material. The pre- and post-collisional angular momentum of the Earth-Moon system was not considered in their model.

In a different vein, Yuan et al. (2023) linked the origins of the Moon to the formation of the two large low-velocity provinces (LLVPs) at the core-mantle boundary (CMB). These ancient structures, together with their attached networks of deep mantle plumes, are thought to have had prominent roles in continental breakup and in major mass extinction events (e.g., Cucchiari et al. 2025). In the model by Yuan et al., the LLVPs represent buried relics of Theia. Their simulations showed that a fraction of Theia's mantle – assumed to be intrinsically denser than the proto-Earth's – could form multi-kilometer wide blobs which sank and formed LLVP-like thermochemical piles atop the Earth's core. Like the model of Fischer et al. (2024), the isotopic problem would be solved – essentially by hiding Theia.

While not mentioning the LLVPs directly, de Meijer et al. (2013) proposed a variation of the fission model to explain the isotopic crisis. The fission of the Moon could have occurred on an Earth rotating more slowly than in the Darwin-Wise model if assisted by a nuclear explosion occurring at the CMB. Their model built upon several earlier proposals (Anisichkin 1997; Voronin 2007; Anisichkin et al. 2008) and was later updated by Reuver et al. (2016). In this model, the Moon-forming explosion was triggered by nuclear fission in a 'deep georeactor'. This would have required the release of ~ 10^{30} J of energy from a point just above the CMB, an estimate later reduced to 1×10^{29} J (Reuver et al. 2016). Hydrodynamic modelling showed that a shock wave created by rapidly expanding plasma could disrupt and expel overlying mantle rock. Immediately after separation from the Earth, the proto-lunar materials orbited the Earth at a distance $r_{EM} = 1 \times 10^8$ m, just beyond the Roche limit. The proto-Earth's rotation period would have been ~5.8 h, immediately increasing after the separation event to ~9.0 h. The proto-Earth thus did not have to rotate appreciably faster than in giant impact models, overcoming the main problem of Darwin's hypothesis.

Developing the above suggestions, we now suggest, like Yuan et al., that the origins of the Moon and the LLVPs are indeed interconnected. But rather than modelling the LLVPs as remnants of Theia, we propose that the precursors of the two LLVPs predated the Moon's existence. In Darwin's hypothesis, equatorial elongation induced by centrifugal and solar tidal forces precedes ejection of a Moon-sized mass. Mirroring this process, we suggest that rotational and solar tidal forces—together with ongoing core heating—generated antipodal upwellings of the liquid core along with partial mantle melting. The resulting bulges on the CMB are seen as precursors of the African and Pacific LLVPs. Building

on the analyses of de Meijer et al. (2013) and Reuver et al. (2016), we then consider scenarios in which energy channeled through a proto-LLVP could have assisted lunar ejection. Several candidates are suggested for the sources of additional energy needed to eject the Moon. In addition to nuclear fission, we also consider bolide impacts and a theoretical process involving conversion of gravitational energy to photon energy.

The explosive event which gave rise to the Moon would have occurred in a specific context. In the period just after core segregation on the proto-Earth, the efficient modern system of heat delivery to the surface via mantle convection and plate tectonics would not yet have been in place. Any additional heat generated in the core would consequently have been less efficiently carried to the Earth's surface, most likely by deep mantle plumes alone. In this case energy could have accumulated over millions of years in the proto-LLVPs until an explosion in one of them ejected the Moon.

In this LLVP-centric model, the Earth's geological history unfolds in three distinct phases. The first phase is the formation of the two proto-LLVPs. Here we build on recent evidence given by Ma and Tkalčić (2024) for a toroidal equatorial belt of superheated fluids existing just below the CMB. This belt has seismic velocities $\sim 2\%$ lower than in the core generally. This distribution was considered consistent with light elements like O and H being relatively more abundant in the torus than in the outer core generally and with the observed pattern of greater heat transfer in equatorial than in polar regions. In keeping with our broad proposal, it is suggested that this equatorial belt in the present Earth is generated by ongoing heat release in the core and that this belt originated on the proto-Earth via the same process. Superheated material from the newly formed belt, presumably also rich in light elements, was then focused in the two proto-LLVPs. Deep mantle plumes rising from the proto-LLVPs then weakened the overlying mantle and through their concerted action established a pathway for later lunar ejection.

In the second phase, energy accumulated either rapidly or steadily in the proto-LLVPs until one of them—presumably the Pacific—acquired the 10^{29} – 10^{30} J of energy necessary for Moon ejection. A cataclysmic explosion, which we liken to a planetary-scale kimberlite eruption, then launched material from this proto-LLVP and the overlying silicate mantle into a low Earth orbit. In broad terms the sequence of steps from explosion to Moon formation then essentially follows that of de Meijer et al. (2013) and Reuver et al. (2016).

In the final, ongoing phase, continuing heat release into the core is suggested to account for later events on the Precambrian and the present Earth that have resisted clear explanation thus far. After the Moon ejection, pressures would soon have started to build in the LLVPs again. A cycle of pressure buildup in the core followed by explosive

release in superplume explosions would then account for the periodic formation of large igneous provinces (LIPs) and their associated mass extinctions. Eventually, continuing heat release from the LLVPs gave rise to the efficient modern system of plate tectonics. With mantle plumes and plate tectonics in place, pressures in the core never again reached the levels attained prior to the Moon's ejection. The African LLVP thus never experienced a similar catastrophic event.

The organization of the paper is as follows. In Sect. 2 the energetics of lunar ejection assisted by rotation are reviewed. Some possible sources of the additional energy required for ejection are discussed in Sect. 3. In Sect. 4 the nature and origin of the LLVPs are discussed. In Sect. 5 the mechanism of lunar ejection is considered with an analogy to kimberlite eruptions. The evolutionary connections between lunar ejection and later geophysics and the mechanisms of moon formation on other planets are discussed respectively in Sect. 6 and 7.

2 Energetics of lunar ejection

In Darwin's original proposal, the early Earth is treated as a rapidly rotating, viscous/fluid spheroid. The Moon separated from an equatorial bulge produced by this fast rotation in conjunction with the solar tides. The required rotation period to allow fission was just 2–3 h, a figure later considered too close to the Earth's break-up speed to be plausible (e.g., Reuver et al. 2016). Moreover, as noted above, the angular momentum associated with this rotation period could not be located in any part of the present Earth-Moon system.

Assuming that the present angular momentum of the Earth-Moon system was similar to that of the proto-Earth prior to lunar ejection, de Meijer et al. (2013) considered how much additional energy would be required to lift a lunar mass of silicate materials from Earth's surface into a stable orbit beyond the Roche limit. Their estimates were later refined by Reuver et al. (2016) using boundary conditions derived for Moon formation models generally.

From Reuver et al. (2016), the total energy T_{tot} of the proto-Earth prior to lunar ejection is

$$T_{\text{tot}} = \frac{L^2}{2I}, \quad (1)$$

where L is the spin angular momentum and I the moment of inertia of the proto-Earth. In the final two-body system (Earth + Moon), the total energy T_{tot}^{EM} is given by

$$T_{\text{tot}}^{EM} = \frac{1}{2} \left(I_M \omega_M^2 + I_E \omega_E^2 - \frac{Gm_M m_E}{r_{EM}} \right). \quad (2)$$

Here I_M and I_E are the respective moments of inertia of the Moon and Earth; ω_M and ω_E the respective rotational

frequencies; m_M and m_E the respective masses; and r_{EM} the separation distance between the Moon and Earth. The energy difference between the one-body and two-body states is obtained from (1) and (2). The energy value of the two-body state has a maximum value, which corresponds to a maximum separation distance r_{\max} .

The ‘release energy’ required to place the Moon beyond the Roche limit is given by

$$T_{\text{release}} = T_{\text{tot}}^{EM} - T_{\text{tot}} + G \frac{m_M m_E}{a - r_{EM}}, \quad (3)$$

where a is the proto-Earth’s long axis. The last term accounts for the difference in gravitational potential of proto-lunar material initially positioned near the surface of the proto-Earth and in its stable orbit.

The release energy for a variety of situations was calculated by Reuver et al. (2016) and shown here in Table 1. Since angular momentum is conserved in their explosive fission model, the radius of the initial lunar orbit and the energy required for the transition are coupled. A greater amount of release energy is thus required to place the Moon in orbits having smaller rather than larger r_{\max} values. In scenarios with $L/L_0 > 1$, r_{\max} was found to be inside the Roche limit $\sim 1.8 \times 10^7$ or even within the radius of the Earth. To remain in a stable orbit, r_{\max} must exceed or at least lie within the Roche limit range, which they estimated as $1\text{--}1.8 \times 10^7$ m. For this reason, Reuver et al. excluded values for L/L_0 larger than 1.5. This criterion they noted also rules out some giant impact scenarios, such as Čuk and Stewart (2012), where $L/L_0 = 2\text{--}2.5$. Negative values in the table were considered nonphysical, since the rotating proto-Earth would have more energy than the final Earth-Moon system.

In their initial model, about 2.5×10^{30} J of energy was found to be required to expel the Moon from the Earth’s surface. This value was obtained assuming that the angular

momentum of the proto-Earth was similar to that of the present Earth-Moon system and that the oblateness of the proto-Earth was very high at $a/c = 2$, where a and c are the Earth’s long and short axes respectively. This energy estimate was later reduced to 10^{29} J when the model was found to be still physically relevant for a reduced oblateness of $a/c = 1.2$, as can be seen in Table 1 (Reuver et al. 2016). This value is still quite high, however. Oblateness values in the range $a/c = 1.05\text{--}1.15$ would be more realistic and in some cases perhaps require less energy. Despite this uncertainty concerning oblateness, the release energy of $10^{29}\text{--}10^{30}$ J serves as a useful benchmark and for simplicity we will assume that such amounts are required to eject the Moon.

The present hypothesis requires that the release energy was generated mainly in the Earth’s core. Using a rate of energy generation in the core of 100 TW and a median time interval between core segregation and Moon origin of 100 Ma, the total energy generated in the core would have been 3×10^{29} J, which falls in the middle of the $10^{29}\text{--}10^{30}$ J range. This rate of 100 TW far exceeds the present-day heat budget of the entire Earth, estimated at only ~ 46 TW. Some possible sources of this large internal heating which triggered the LLVP explosion are discussed in Sect. 3, while possible sinks for this energy are considered in Sect. 6.

3 Sources of ejection energy

In the present hypothesis, the main premises are that the core and LLVPs arose before the Moon was formed and that the mantle had cooled sufficiently after core formation to allow heat to be efficiently trapped in the proto-LLVPs. For these reasons, gravitational energy released during formation of the core is an unlikely source of energy for lunar ejection. Here we briefly consider three possible sources

Table 1 Release energy (in Joule) needed to form an Earth–Moon system from a differentiated proto-Earth, as a function of angular momentum ratio L/L_0 , maximum Earth–Moon distance r_{\max} and oblateness a/c

Angular momentum ratio L/L_0	EarthMoon distance r_{\max} (10^7 m)	Oblateness			
		$a/c = 1$	$a/c = 1.25$	$a/c = 1.5$	$a/c = 2$
0.9	0.9	-3.13×10^{29}	4.27×10^{29}	9.51×10^{29}	1.65×10^{30}
1.0	0.9	-6.91×10^{29}	2.83×10^{29}	9.73×10^{29}	1.90×10^{30}
1.1	0.7	-1.09×10^{30}	1.45×10^{29}	1.02×10^{30}	2.19×10^{30}
1.25	0.7	-1.70×10^{30}	-3.39×10^{28}	1.15×10^{30}	2.74×10^{30}
1.5	0.6	-2.84×10^{30}	-3.27×10^{29}	1.46×10^{30}	3.84×10^{30}
1.81	0.5	-4.35×10^{30}	-5.83×10^{29}	2.10×10^{30}	5.72×10^{30}
2.3	0.4	-7.24×10^{30}	-1.00×10^{30}	3.45×10^{30}	9.45×10^{30}
3.0	0.4	-1.22×10^{31}	-1.41×10^{30}	6.30×10^{30}	1.67×10^{31}

The negative values were considered unphysical and only the ones in bold to be plausible. (Reproduced from M Reuver et al. (2016), Boundary conditions for the formation of the Moon, Netherlands Journal of Geosciences 95, licensed under CC BY 4.0)

for the ejection energy needed to form the Moon: nuclear fission, bolide impacts and decay of gravitational energy.

3.1 Nuclear fission/fusion

Building on their earlier work (de Meijer and van Westrenen 2008), de Meijer et al. (2013) advanced the hypothesis that a natural nuclear explosion at or near the CMB could have provided the release energy required for lunar ejection. Unlike natural nuclear georeactors, such as those in Gabon, the deep georeactors in their model employ fast-moving neutrons and are thus more akin to fast breeder reactors. They arise in their model through the concentration of lithophilic, fissile elements like U and Th in the CMB region in a so-called ‘hidden reservoir’—a mantle reservoir possibly segregated from normal plate tectonics (e.g., Boyet and Carlson 2005). De Meijer et al. noted that at the time of Moon formation the isotopic abundance of ^{235}U was far higher than today (20%–30%), so that the bulk silicate Earth could in principle have contained on the order of 10^{16} kg of fissile uranium.

While this mass is of the same order as that required to yield the necessary energy, concentrating it into a single reservoir near the CMB, detonating all of it at once and converting the released energy efficiently into the mechanical work of ejecting a lunar-mass fragment is problematic. de Meijer et al. (2013) also noted several factors that would make confirming evidence that a deep georeactor ever existed hard to find. Helium and xenon isotope ratios in Moon rocks, for example, could be signatures of georeactor activity, but these depend on the amount of supercritical georeactor material that was ejected—an unknown quantity. They concluded that the correspondence in isotopic and elemental composition between the bulk silicate Earth and lunar rocks was in fact the strongest evidence for their model. On the other hand, Degueldre and Fiorina (2016) found that a deep georeactor could conceivably have reached criticality on a proto-Earth, triggered by ^{235}U and with Th as absorber. An unresolved issue they noted, however, is whether actinides could have sufficiently segregated in any particular Earth layer to have allowed this to happen.

The situation could conceivably change, however, if we consider a slower buildup of heat from nuclear fission prior to the time of lunar ejection. Of the present global heat flow of ~ 46 TW, about 20 TW is estimated to be from radiogenic heating in the crust and mantle (Lay et al. 2008). As noted by de Meijer et al. (2013), radiogenic power in the proto-Earth at 4.5 Ga was presumably much higher, a common estimate being ~ 225 TW. This amplification arises from the higher early abundances of ^{235}U , ^{238}U and other radionuclides. While these lithophilic species would be more concentrated in the crust and upper mantle, the premise of a hidden reservoir for such elements near the CMB could again be invoked.

For heat to accumulate in the proto-LLVPS, it would only be necessary that heat was added to them faster than it was removed. In the initial absence of effective mantle cooling mechanisms like plate tectonics, accumulation of this much energy at an LLVP root could thus have been the precursor to ejection—provided that the hidden reservoir exists. In this case the timescale to accumulate the $\sim 10^{29}$ – 10^{30} J required for lunar ejection might have been on the order of 10–140 Ma, which matches the time window for the Moon’s formation of 50–150 Ma after core segregation (e.g., Touboul et al. 2007). As discussed more fully in Sect. 4, a slow energy release of this magnitude could also have contributed to long-term thermal weakening, plume activity and the formation of LLVPs themselves.

In this general context we briefly mention the proposal by Terez and Terez (2011) that the explosion near the CMB which gave rise to the Moon was triggered by nuclear fusion rather than fission. Following Wang (1990), they noted that the excess heat emissions observed from the gas giant planets Jupiter, Saturn and Neptune cannot be explained by radioactivity. Larin’s model of the Earth’s formation was used to argue that the Earth’s core could contain vast quantities of hydrogen that could fuel fusion. Since temperatures and pressures in the Earth’s core are too low for conventional thermonuclear fusion, however, their model relies on an unsubstantiated cold fusion process involving pycnonuclear reactions.

3.2 Bolide impacts

As noted earlier, the giant impact model for lunar origin faces severe limitations concerning isotopic abundances, angular momentum and other factors. With the LLVP mechanism proposed herein, however, the possibility remains that one or more giant impacts could have delivered extra energy to the core which over time eventually triggered the explosion. In their analysis of the core heating of giant impacts and its evolutionary role in the Earth’s geodynamo, Zhou et al. (2024) simulated collisions for a wide range of impactor masses, velocities and angles of incidence. While core heating was negligible for smaller impactors with a low angle of incidence, large impactors such as the canonical Theia one were able to raise the core temperature by up to 3000 K. Significantly, this core heating was most prominently displayed in the outer core, the same region that gives rise to the Ma-Tkalčić belt, LLVPs and lunar ejection in the present scheme.

One or more pulses of heating in the outer core due to giant impacts – even if occurring well prior to the ejection event – might thus conceivably have supplied the extra release energy for lunar ejection. This scenario bears similarities to the recent giant impact model of Fischer et al. (2024), in which the impactor fuses directly with the Earth’s

core and proto-lunar mantle material is ejected from the opposite side. The latter hypothesis requires a direct hit of the impactor on the core region as well as an angle of impact in line with the Moon's orbital plane.

These restrictions could be relaxed if the impactor energy is added to energy already accumulated in the core and LLVPs through other heating processes. In this hybrid scenario, the LLVPs, perhaps already having plume assemblages, would represent points of weakness in the lower mantle through which the impactor energy could be funneled. In this way the protolunar materials ejected by the impact would more naturally reside in the Moon's subsequent orbital plane. Similar considerations apply if the core temperature was raised more gradually through a succession of smaller impacts until the threshold for explosive ejection was attained. In either case the proto-LLVP conduits for collisional energy would more easily promote the lunar ejection sequence.

3.3 Energy from gravitational decay and Λ

A more hypothetical source of explosive energy involves conversion of the internal gravitational energy of bodies to photons in a process linked to Einstein's cosmological constant Λ . A possible decay of the Earth's internal gravitational energy has been connected to Dirac's notion that the gravitational constant changes over time as $\dot{G}/G = -H_0$ (Dirac 1937). Pascual Jordan suggested that this gravitational decay gave rise to a very slow expansion of the Earth's radius (Jordan 1962, 1971; Kragh 2015; Edwards 2016, 2019). This expansion involved volcanism and associated phase changes of minerals within the Earth's mantle.

While there is little evidence that the gravitational constant G changes at all over time (Kragh 2015), the gravitational energy within a system could still be subject to a decay process involving the Hubble redshift. In geophysical and astrophysical contexts there is indeed much evidence to suggest that gravitational potential energy is converted to photon energy within masses or mass systems. The rate of this conversion is governed by a central equation

$$L_\Lambda = -UH_0 \quad (4)$$

where U is the internal gravitational energy (conventionally negative), H_0 is the Hubble constant and L_Λ is the so-called ' Λ luminosity' (Edwards 2006, 2008, 2012, 2014, 2022, 2024). The latter term replaces the term previously used, the Hubble luminosity, to emphasize the cosmological connection.

The model process is based on the idea that the gravitational potential energy in mass systems is simply electromagnetic energy in another form. For example, spacetime can be modelled as an optical medium comprised of

filaments of gravitons consisting of overlapping photon pairs (Annala 2022; Annala and Wikstrom 2022; Edwards 2012, 2022, 2024; Grahn et al. 2018; Steinbach 2024). If the total electromagnetic energy content of the universe—both ordinary photons and spacetime photons—is considered constant, then any losses of photon energy due to the Hubble redshift must elsewhere bring masses together in gravity. This would increase the magnitude of energy in their mutual graviton filaments, $|U|$. In a zero-sum game, photon blueshifts arising from the Λ luminosity must lead to masses being pushed apart, decreasing $|U|$.

Observational evidence for the Λ luminosity can be found in the excess heat radiated from planets (Edwards 2006, 2016, 2019); the bolometric luminosities of white dwarfs, neutron stars and supermassive black holes (Edwards 2008, 2012); and a secular increase in the orbital radius of moons about planets and of planets around the Sun (Zhang et al. 2010; Křížek et al. 2022; Vavryčuk 2023). The Λ luminosity also forms the basis for a model of quantum gravity (Edwards 2014, 2022, 2024) and a unified shell model for black holes and a black hole universe (2024). These shell structures can be described in general relativity using the Ni solutions for their relativistic field equations (Ni 2011; Neslušan 2015, 2017, 2019; DeLyra et al. 2023). On the cosmic scale, energy-depleted photons reenergized by the Λ luminosity are suggested to furnish the cosmological constant Λ in Einstein's original sense of a counterbalancing agent to gravity.

The excess thermal radiation of planets and their moons is also in line with Eq. (4) (Edwards 2006). For the smaller planets and moons of the Solar System, it is noteworthy that estimates of internal heating using the assumptions that it raises either radiogenically or through the gravitational Λ process yield surprisingly similar results. In making predictions of volcanic activity on exoplanets, Quick et al. (2020) used a baseline of heating values derived for planets

Table 2 Estimates of radiogenic versus Λ heating for selected planets and bodies of the Solar System

	$R (R_E)$	$M (M_E)$	H_Λ (TW)	H_{rad} (TW)
Earth	1	1	550	40
Venus	0.82	0.95	350	29
Mars	0.53	0.107	11	2.7
Mercury	0.38	0.055	3.9	2.3
Pluto	0.19	0.0022	0.013	0.053
The Moon	0.27	0.012	0.27	0.3
Ganymede	0.41	0.025	0.73	0.48
Callisto	0.38	0.018	0.42	0.32
Charon	0.095	.00027	0.00033	0.0044

Radius and mass are in Earth units. The third column is the internal heating due to the Λ luminosity and the last column is the radiogenic heating

and planetary moons of the Solar System. For simplicity they assumed that the Earth's own heat emission is entirely radiogenic in origin and that the radiogenic heating of the other bodies is proportional to Earth's on a per mass basis. A selection of their baseline values is shown in Table 2 for bodies in which tidal heating is negligible. These values are shown alongside estimates for Λ heating, here denoted as H_Λ . The H_Λ estimates use the same formula for internal gravitational potential energy commonly used for the Earth, $U = -0.6GM^2/R$.

For most of the planets and moons in Table 2, the difference between the two estimates is small. A trend is nonetheless apparent with larger bodies tending to have higher values for H_Λ , due to the dependence on M^2 , and smaller bodies having higher H_{rad} . More direct testing methods are thus required to verify the true magnitudes of H_Λ and H_{rad} in geological heating processes.

Of the Earth's gravitational potential energy at present, it is estimated that 36.8% is in the core and of that only 2.1% is in the inner core (Burša and Hovorková 1994). Thus, about one-third of the energy generated inside the Earth through the Λ luminosity would be deposited directly in the outer core, the remaining two-thirds in the mantle. Since the volume of the core is only about 1/8 that of the Earth, however, the rate of energy deposition is over three times faster in the core than in the mantle. The temperatures produced through L_Λ would thus increase more rapidly in the CMB than in the mantle and the energy flux across the CMB would be greater than through any layer above. This temperature difference could thus give rise to the LLVPs.

From Eq. 4, the total energy derived from the Earth's Λ luminosity at present is $-U_E H_0$, where $U_E = -0.6GM_E^2/R_E$. With $U_E = -2.5 \times 10^{32}$ J and for $H_0 = 2.2 \times 10^{-18}$ s⁻¹, the Earth's total would be 550 TW. From the above estimates, ~200 TW of this would be generated in the core and the remaining ~350 TW in the mantle. While these values far exceed conventional estimates for heat flows in the core and mantle, they can possibly be linked to phase changes induced in the mantle associated with mantle plumes and the emergence of plate tectonics (Edwards 2016, 2019). These points will be discussed further in Sect. 6.

4 Origin of the large low-velocity provinces

We next return to our basic hypothesis that the Moon was ejected above an LLVP. The key to the hypothesis concerns the origin and nature of the LLVPs. The African and Pacific LLVPs sit on the CMB and extend thousands of kilometers laterally and possibly more than 1000 km vertically above it (Wang and Wen 2004; Cotaar and Lekic 2016; McNamara 2019; Panton et al. 2025). They are characterized by

low seismic wave velocities compared to the lower mantle generally.

The origin of these structures has been in many ways as mysterious as the Moon's. It has been suggested, for example, that LLVPs represent subducted oceanic crust that has accumulated over billions of years (Christensen and Hofmann 1994). Recent simulations indicate, however, that such crust would have higher rather than lower seismic velocities relative to the surrounding mantle (Wang et al. 2020). Oceanic crust could also have been too thin and lacking in negative buoyancy to survive the descent to the CMB intact and form structures there (McNamara and Zhong 2005). Alternative approaches feature LLVPs originating from crystallized remnants of a basal magma ocean (Labrosse et al. 2007) or as anomalies linked to Fe³⁺ enrichment of the mantle mineral bridgmanite (Wang et al. 2021).

LLVP material could alternatively have been derived in part from the core. A core origin would be consistent with present-day LLVPs having elevated Fe compared to the lower mantle. As noted above, the presence of iron has been suggested to account for the low shear velocities of the LLVPs (Wang et al. 2021). At the same time, given that the low seismic velocities seen in the equatorial toroidal belt on the CMB were attributed by Ma and Tkalčić (2024) to possibly elevated concentrations of light elements like O and H, enrichment of LLVPs with light elements obtained from this belt could also explain the slow seismic velocities. These two possibilities are not incompatible, however, if LLVP materials are seen as being sourced from the Ma-Tkalčić belt.

The notion that the LLVPs are massive, compact and mostly continuous 'piles' of anomalous material extending upward from the CMB has itself been challenged by Davaille and Romanowicz (2020). Combining high-resolution seismic tomography (model SEMUCB-WM1 and other models) with fluid mechanics constraints, they suggested that each LLVP is better described as a bundle of thermochemical plumes. In their view, the long-wavelength appearance of the two antipodal LLVPs in filtered tomographic images reflects a degree-2 signature of underlying bundles of thermochemical plumes rather than the monolithic structures usually envisaged. Only when the tomography is filtered to long wavelengths do the plume bundles appear as two broad, smooth provinces.

Concerning the long-term evolution and roles of LLVPs, Dziewonski et al. (2010) had earlier suggested that the LLVPs could have anchored mantle convection in a degree-2 configuration, a pattern in global-scale convection or density anomalies characterized by two dominant, nearly antipodal anomalies. These patterns are favored in a rotating, convecting spherical shell subjected to strong basal heating. The LLVP-centered anomalies in this case correspond to two 'hot' or 'dense' upwelling regions

separated by roughly 180° , together with complementary downwellings. As noted by Davaille and Romanowicz (2020), this equatorial, antipodal configuration confers rotational stability to the Earth with respect to its moments of inertia. On a rapidly rotating proto-Earth, this could thus have minimized the system's rotational energy while maintaining symmetry about the equatorial plane.

On the proto-Earth, an equatorial belt of anomalously hot material near the CMB analogous to the Ma-Tkalčić belt would have represented a zone of enhanced heat flux from the core. The two proto-LLVPs can then be seen as logical extensions of this belt. Supposing once again like Ma and Tkalčić (2024) that the seismic velocities in the belt reflect a high concentration of light elements (eg H, O), then subsequent migration of these light elements to the LLVPs would enhance plume buoyancy. Over some tens of millions of years following core formation, heating from radiogenic or other sources discussed in Sect. 3 would have allowed thermal energy to steadily accumulate within the LLVPs.

Circulation of heated fluids in the toroidal belt can also be linked to the Earth's magnetic field. The mechanism and energy requirements for the geodynamo, either in the Earth at present or in the proto-Earth, are still not well understood (e.g., Gubbins et al. 2003). One estimate of the maintenance energy of the geodynamo is that it roughly equals the total heat flow estimate of 46 TW (Terez and Terez 2011), which is well above current estimates for heat release in the core at present. Prior to significant plume flows, this route for energy dissipation from the core could have been the primary one.

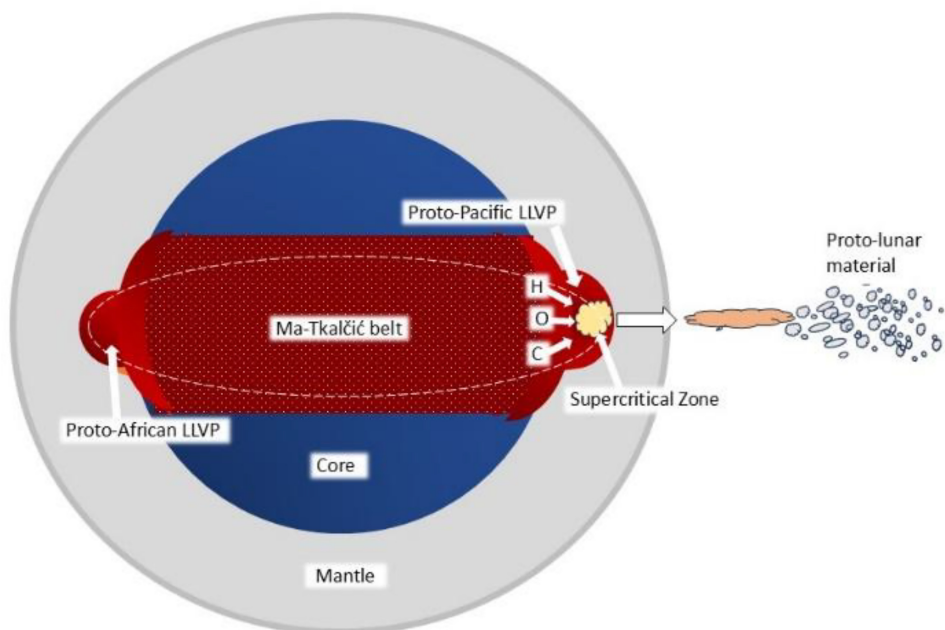
5 Lunar ejection above an LLVP

We next consider the Moon ejection event within the LLVP context. The basis sequence is shown in Fig. 1. Our model supposes that energy generated in the core first accumulated in the Ma-Tkalčić torus and was then focused in the attached proto-LLVPs, raising temperatures and pressures therein. The heat accumulating in proto-LLVPs is suggested to not only supply the ejection energy but also precondition the mantle for lunar ejection. The existence of two antipodal LLVPs prior to Moon formation would potentially have created partially molten conduits above the CMB. Because degree-2 planforms are stable over geologic timescales (Li and Zhong 2009), these antipodal structures could persist long enough to accumulate energy and volatiles from the core, eventually serving as possible loci for lunar fission.

The LLVP plume bundles in this case could have reduced the energy threshold for rotational fission. Plume-driven mantle heating would have produced long-term tensional stresses and zones of reduced strength, particularly around the plume-rich margins of the LLVPs. The latent heat required to melt a lunar mass of silicate rock is much less than the energy needed for ejection itself, at $\sim 10^{28}$ J. This much energy could have readily accumulated within the time window for lunar ejection. Since melt fractions of just a few percent reduce effective shear viscosity and strength dramatically, a proto-LLVP accumulating melt mass comparable to a lunar mass would produce a weak, mobile column that can deform and uplift far more rapidly than cold rock.

As noted earlier, the primordial Ma-Tkalčić belt and by extension the two attached proto-LLVPs were possibly enriched with light elements like C, O and H. Given

Fig. 1 Explosive lunar ejection model. Heating of the core generates the Ma-Tkalčić belt and proto-LLVPs enriched with light elements. Due to energy trapping, supercritical zones arise in the proto-LLVPs with elevated pressures and temperatures. An explosion in the Pacific proto-LLVP ejects the proto-lunar material



that the present-day CMB features pressures and temperatures exceeding the critical points of water, CO₂, CH₄ and other volatiles, conditions in the proto-LLVPs could have favored the formation of supercritical fluid zones capable of storing vast quantities of energy. The light elements present in LLVP plume columns would in addition have enhanced plume buoyancy. With rapid ascension and decompression of melt materials, exsolution of these volatiles would have produced local overpressures capable of further fracturing the weakened mantle.

Within the framework of the model of de Meijer et al. (2013), where the proto-Earth was rotating with a period of 4–6 h, the combined effects of this tensional pre-stressing and localized mantle weakening—together with rotational flattening—would have brought the planet close to mechanical instability. A comparatively modest additional energy input could then have triggered catastrophic rupture, ejecting mantle material that subsequently coalesced to form the Moon.

As was discussed in Sect. 3, heating of the core and/or CMB could have occurred through diverse processes, some fast and some slow. General continuity with the plume bundle model of LLVPs is more attainable with slower core heating, which as mentioned could include radiogenic heating, a succession of small bolide impacts or a decay of Earth's gravitational energy.

At the same time, the hypothesis requires that the removal of core heat by LLVP plume bundles could not have been *too* efficient. As noted above, a precondition for a LLVP-based ejection mechanism is that the heat released into the CMB and proto-LLVPs could accumulate over time rather than prematurely leaking out. Only in this way could the $\sim 10^{29}$ – 10^{30} J of energy be loaded in a LLVP magma chamber prior to explosive release. On this point, it is generally assumed that plate tectonics with its mantle cooling effects was rudimentary at this time or absent altogether. With initially slower rates of upward migration of melts in plumes, conditions would have been favorable for stabilization of supercritical phases in deep magma chambers.

The timing of the ejection event would have been dictated by the thermal maturation of the LLVP system over tens of millions of years after the core's formation. Based on Hf-W analyses of lunar rocks, the Moon's formation has been estimated to have occurred 50–150 Ma after core-mantle differentiation (e.g., Touboul et al. 2007). On the proto-Earth, either radiogenic, gravitational or bolide sources could have provided ~ 200 TW of core heating over millions of years. To acquire the $\sim 10^{29}$ – 10^{30} J of energy required for ejection at this rate would thus have taken $\sim 10^7$ – 10^8 Ma, which is in the time window for the Moon's formation after core segregation.

5.1 Kimberlite analogy

Concerning the actual explosive ejection event, a possible analogy is provided by Kimberlite eruptions. Kimberlites represent some of the most rapid and energetic volcanic events known, with eruption velocities approaching supersonic speeds. They are characterized by a deep mantle source, volatile-rich magma and a sudden catastrophic breaching of the overlying lithosphere, resulting in explosive venting through narrow conduits. While kimberlite eruptions are still not well understood, they afford a conceptual analogy whereby stress energy in the mantle breaches the lid and allows rapid pressure release. In the context of the early Earth, the LLVP root region could act as the long-term energy reservoir which triggered the kimberlite-like eruption beneath a mechanically weakening mantle lid.

At some point after the $\sim 10^{29}$ – 10^{30} J of required energy had accumulated in one proto-LLVP, the pressure within the supercritical zone exceeded the mechanical strength of the overlying mantle rocks. Once failure was initiated, volatile exsolution would have driven a runaway ascent process, focusing the energy into a vertical conduit-like flow. Otherwise, the eruption scenario is not dissimilar from the ejection model of de Meijer et al. (2013). Depressurization induced the supercritical fluids to rapidly expand and transition to gaseous or plasma states. The resulting shock wave and rapidly expanding plasma in the LLVP plume chamber would have produced an extremely energetic plume, analogous to a kimberlite eruption but on a scale many orders of magnitude greater. Typical kimberlite eruptions release on the order of 10^{14} – 10^{15} J of energy, compared to the $\sim 10^{29}$ – 10^{30} J of ejection energy required in the lunar ejection. The proposed event is thus not a simple scaling-up of a kimberlite eruption, but a fundamentally larger phenomenon drawing on planetary-scale energy reservoirs, including rotational energy and core heating processes such as those mentioned in Sect. 3.

The explosion ejected LLVP material and significant amounts of silicate-rich mantle material into a low Earth orbit, where it then coalesced to form the Moon. An equatorial position for the ejection of proto-lunar material maximizes the rotational energy available for the Moon's ejection and moreover is consistent with the angle of the Moon's present orbit.

The possibility also arises of a staged ejection of mass through multiple kimberlite-like eruptions rather than a single mass ejection. A staged process would however have created further complications in coalescence of the proto-lunar materials.

5.2 Pacific moon

The great size and circularity of the Pacific basin—together with the relatively later activity of the African superplume—suggest that the Moon was ejected above the structure that was precursor to the Pacific LLVP. In relation to Darwin's original hypothesis, it had earlier been supposed by Osmond Fisher that the Moon arose from the trench region of the Pacific (Terez and Terez 2011). The large and circular Pacific basin has been resurfaced many times by plate tectonics.

Following the Moon ejection event, heat release from the core may have been assisted by new conduits formed as a result of the explosion itself. Accordingly, temperatures and pressures within the core and the proto-LLVPs would have plummeted, never again reaching the levels attained prior to the Moon's ejection. A second major ejection event above the African proto-LLVP was thus suppressed.

In this context, Panton et al. (2025) attributed the greater height of the African LLVP relative to the Pacific one to increased subduction of dense oceanic lithosphere into the Pacific LLVP over the last 1.2 Gyr. This potentially made the Pacific LLVP denser and less buoyant than the African. The greater height of the African LLVP can also be explained in the present model. Without a similar ejection event, the African LLVP would have had relatively prolonged and undisturbed growth compared to the Pacific.

5.3 Lunar volatile depletion and hemispheric asymmetries

As emphasized by Wise (1963, 1969), the fission model predicts a fundamental difference in character between the lunar nearside and farside. The nearside has a thin crust ~20–30 km and features Fe-rich mare basalts, where the FeO content can reach 16–20 wt%. The farside has a much thicker crust ~50–60 km and is rich in anorthosite (Ca-rich plagioclase). It has a very low FeO content, typically 3–6 wt%. In the classic fission model, the farside represents material from the large tidal bulge—which would contain upper mantle and crust materials—while the nearside would feature deeper mantle material.

In the present modified hypothesis, however, the Moon would form from a mixture of mantle, crust and LLVP material. As noted earlier, a supposed high iron density in the LLVPs led to proposals that LLVPs have contributions from a metallic Theia (Yuan et al. 2023) or that they are enriched with Fe³⁺ from the mantle mineral bridgmanite (Wang et al. 2021).

Prior to Moon ejection in our model, proto-LLVPs could alternatively have been enriched with iron migrating from the underlying Ma-Tkalčić belt. Subsequent ejection of material from the proto-Pacific LLVP could thus possibly account for the higher FeO Moon fraction, as well as for

the small lunar core itself. Due to their density, iron-rich materials from the proto-LLVP would have attained relatively lower orbits during the explosive fission event and thus contribute more heavily to the near side of the forming Moon. In contrast, higher-altitude ejecta originating from the BSE would dominate the farside, resulting in the observed lower FeO content there. The Moon's nearside-farside iron asymmetries can thus be accounted for within this revised fission hypothesis.

In addition to addressing the isotopic crisis of giant impact models, lunar ejection through a kimberlite-style eruption can also explain the relative depletion of volatile elements and water in Moon rocks. As noted in the introduction, part of the original rationale for the giant impact hypothesis was to account for the relative scarcity of volatiles in the Moon. In our model, the Moon-forming explosion would have been triggered by supercritical phases of light elements in the proto-Pacific LLVP. The materials raised into orbit around the Earth would have been a mixture of this LLVP material and overlying material from the silicate mantle. Subsequent loss of volatiles from the proto-lunar disk in space would thus be expected in the same way as in the giant impact hypothesis.

In this context, Wise (1963) further observed that the fission hypothesis also accounts for the Moon's orbit aligning with the Earth's rotation and for the near circularity of this orbit. It also explains why the same face of the Moon is always pointed to the Earth. Whether originating as an elongation of the whole Earth (in Darwin's model) or mainly of the liquid core (in the present model), the Moon-forming materials would have had no angular momentum relative to the Earth. The same face of the Moon would thus always be pointed at Earth.

6 Subsequent geological evolution

Models of the Moon's formation should also be evaluated as to whether they can shed light on later and ongoing stages of planetary evolution. Giant impact models typically address the Moon-forming event only without much focus on later events. By contrast, the explosive ejection mechanisms discussed here can potentially be connected more closely to the main drivers of planetary evolution: deep mantle plumes and plate tectonics. In making these connections, however, a question arises. If so much heat was added to the core to enable lunar ejection, and this heat deposition was ongoing, where is the signature of such strong internal heating in the Earth today? Bolide impacts can be safely excluded as drivers of later evolution, since their incidence declined precipitously following the time of the Moon's formation.

One possible sink for large energy inputs involves a slow increase in the Earth's radius (Edwards 2006, 2016, 2019).

With a very slow Earth expansion, the rate of energy deposition would balance the energy required to increase the Earth's radius and thereby its gravitational potential energy, U_E . With the work done by plumes in raising the Earth's mantle and increasing the Earth's radius, the plume temperatures and pressures would drop, as in a conventional heat engine. Earth expansion would thus effectively serve as a heat sink.

As noted above, lunar ejection driven by continuous core heating in the 50–100 Ma interval between core segregation and the Moon's ejection would require a steady input of ~100–200 TW. As noted in Sect. 3, this energy input could fit with either radiogenic or gravitational decay heating. Such inputs would be balanced with a slow expansion of the Earth's radius of 0.1–0.2 mm yr⁻¹ (Edwards 2019).

While the possibility of a steady, slow Earth expansion is generally unrecognized in geophysics, there is much evidence for it at the present time (Edwards 2016, 2019). This evidence derives chiefly from the work of Wenbin Shen and coworkers. Using space geodetic methods, Shen et al. (2011, 2015a) found net rates of expansion of 0.24 mm•yr⁻¹ and 0.12 mm•yr⁻¹. Measurements of sea level using satellite telemetry Earth indicated expansion in oceanic areas of 0.4 ± 0.67 mm•yr⁻¹ (Shen et al 2015b). Shen et al. (2011) also used gravimetric data to test the expansion hypothesis. This data suggested that the Earth is currently expanding at a rate of 0.17–0.21 mm•yr⁻¹. In this context, it is critical to note the distinction between slow expansion and fast expansion models. The latter call for expansion rates of typically ~5 mm•yr⁻¹, which are not observed in the geospatial and other studies mentioned above (Edwards 2016).

A large energy deposition in the core can moreover be paired with ongoing slow Earth expansion to form a unified geophysical model (Edwards 2016, 2019). The key notion is that the energy driving this expansion is carried upwards by deep mantle plumes. This is based on the finding that deep mantle plumes extend all the way down to the CMB (French and Romanowicz 2015). The geographic positions of these plumes are seen to be closely aligned with those of the Pacific and African LLVPs. It is assumed here that these plumes first emerged from the proto-LLVPs, with the Pacific superplume also being associated with conduits formed in the Moon-forming event.

Deep mantle plumes afford a simple mechanism for slow Earth expansion. While these plumes presently appear to easily traverse the 670 km barrier into the upper mantle, much evidence suggests that subducting slabs encounter greater resistance crossing this barrier on the other way towards the CMB. Nolet et al. (2006) noted that if the mass flows do not balance there would be a net flow of mass from the deep lower mantle into the upper mantle. Such an imbalance would result in a net increase in mantle volume, since the high-density mineral assemblages of the lowermost

mantle would transform with decompression and phase transition into lower-density assemblages typical of the upper mantle. An increase in Earth's radius would then also be implied. An imbalance between upward and downward flows of mantle material is consistent with the already mentioned findings by Davaille and Romanowicz (2020) indicating that the LLVPs are rising plume bundles rather than compact piles formed by subducting slabs or remnants of Theia.

The magnitude of the total potential radial increase was estimated using data for the African superplume. Taking data for this superplume from Nolet et al. (2006) and using a simple volume conversion factor—for high-density lower mantle material to low-density upper mantle material—it was estimated that the rate of radial increase of the Earth due to this plume alone would be 0.13 mm•yr⁻¹ (Edwards 2019). To raise the Earth this much would require ~100 TW of power. Assuming a proportional increase for the remaining plumes, the total plume power could be as much as 200–300 TW.

Another possible large sink for internal heat is the Earth's geodynamo. If, for example, the Earth's geodynamo has a maintenance energy two or three times the estimate of Touboul et al. (2007), or ~100–150 TW, this could also balance core heating inputs.

6.1 Large igneous provinces

Similarly to the LLVPs, the origins of the large igneous provinces (LIPs) have been the subject of much debate. Flood basalts and LIPs have Sm/Nd ratios consistent with a derivation from the LLVPs (Jackson and Carlson 2011). Palaeo-geographic relationships between Phanerozoic LIPs and LLVPs further suggest that most LIPs that erupted in the past 320 Myr did so directly over an LLVP (Davies et al. 2015; Torsvik et al. 2008, 2010; Austermann et al. 2014; Cucchiaro et al. 2025). Inputs of energy in LLVPs through radiogenic or Λ heating would be consistent with this ongoing theme, as the initial drivers of mantle melting/upwelling and plume generation.

7 Moons of other planets

If the Moon did originate by ejection from Earth, one might expect to find evidence of similar ejection events in other planets. To make such comparisons it is necessary to examine the specific conditions in each planet which might favor or disfavor an ejection event. Only a brief coverage of this large topic is given here. A guiding conjecture is that material rich in lighter elements like O and C would be ejected further from the respective planets than denser material rich in iron and heavier elements.

For the Λ luminosity mechanism specifically, the large iron core of Earth with its high mass and density would have had an enhanced capacity to drive core heating and generate this gradient across the CMB compared to the other planets. From Table 2 it is apparent that only Earth and Venus of the inner planets would have had a sufficient Λ luminosity to drive an ejection event. Venus's rotation is very slow relative to Earth's, however, and so the release energy to eject a moon from Venus would be much greater than for the proto-Earth. At the same time, the temperature difference between the CMB and the surface is possibly one-fifth smaller on Venus than on Earth. Mantle convection on Venus may thus only be about half that of Earth's, which alone could explain the present lack of plate tectonics on Venus (Aitta 2012).

The gas giants do have a sufficient H_{Λ} to possibly have ejected their moons, however, and this could have happened on Jupiter. For the four largest moons of Jupiter, the densities scale inversely with distance from Jupiter – from the innermost planet, Io, with a density of 3.53 g cm^{-3} to the outermost one, Callisto, having a density of $\sim 1.83 \text{ g cm}^{-3}$. The same pattern in density is not seen in the moons of Saturn, Uranus and Neptune. The bulk density of Saturn is very small, less than that of water. Much of Saturn's mass is in a gaseous phase and the temperature difference between the small core of Saturn and the overlying mobile gaseous phase would not approach that of Earth's. Similar conditions hold for Neptune and Uranus. To summarize, these planets may have too light a core and too gaseous a mantle for the lunar ejection process to be effective.

8 Discussion and conclusions

In this paper, we propose that the large low-velocity provinces formed soon after core segregation on the proto-Earth as thermal, partly tidal-induced outgrowths of the CMB. These structures first appeared as thermal instabilities in the CMB above a precursor structure to the equatorial Ma-Tkalčić belt, suggested then as now to carry heat and volatiles from the core. The proto-LLVPs arose antipodally at weakened sites in the CMB and thereafter acted as preferential reservoirs of heat and volatiles (e.g., CO_2 , H_2O). In this capacity they are suggested to serve as nucleation sites for a catastrophic, possibly kimberlite-like eruption. In a planetary-scale eruption, energy and volatiles released into a narrow conduit produced an impulse sufficient to loft proto-lunar material past the Roche limit.

The model we propose can also be seen as an extension of the Darwin-Wise rotational fission model. Rotation would bring the proto-Earth to a near-critical state, while the LLVP-triggered eruption provides the final push needed for Moon formation.

Certain difficulties in the nuclear fission model of de Meijer et al. (2013) were pointed out concerning the concentration of radionuclides at one site near the CMB. In this paper, we have identified alternative possible sources of energy for the explosion including bolide impacts, decay of gravitational energy and a slower release of radiogenic energy. All of these require further substantiation, both observationally and theoretically.

Whatever the ultimate energy source, the assisted ejection model could explain several geochemical and geophysical observations. The isotopic similarity of Earth and the Moon is naturally reproduced if the Moon's bulk composition reflects that of the Earth's mantle and crust, with important inputs as well from the LLVPs. The origins of the LLVPs themselves can be linked to processes possibly evident today at the extant CMB—in particular, the proposed migration of heat and volatiles into these structures from the hot Ma-Tkalčić belt. Angular momentum conservation in the Earth-Moon system can also be reconciled with the proto-Earth having a 4–6 h day.

Our LLVP-impulse model finally suggests that Moon formation was not by pure rotational fission, giant impact or a single nuclear explosion acting alone. The alternative picture is that energy released from the core and focused in the proto-LLVPs pushed the rapidly rotating Earth beyond its stability threshold. This model offers a coherent explanation for the energetics, timing, and geochemistry of the Earth-Moon system and motivates further investigation into the thermochemical evolution of the LLVPs, their volatile content and their possible role in early Earth dynamics.

Testing the LLVP-triggered ejection hypothesis would require an integrated research program. High-resolution global seismic tomography could further constrain the density, composition and shape of LLVPs, allowing assessment of their capacity to store heat and volatiles. Geochemical studies focusing on isotopic anomalies in deep-sourced plume volcanism could reveal signatures of primitive reservoirs linked to the proto-lunar source region, while numerical modeling of rapid decompression events in a near-critical, rapidly rotating Earth could clarify whether a single impulsive eruption could eject sufficient mass into stable orbit beyond the Roche limit or if multiple eruptions would be required. Studies of the geodynamos of Earth and other planets are also needed to better constrain their contributions to internal heat budgets. Finally, improved tidal evolution models might better constrain the initial Earth-Moon angular momentum state and test whether the system could indeed have evolved from a slightly supercritical, rotation-dominated configuration of a proto-Earth.

Given the findings of a general, non-tidal secular increase in the orbits of moons and planets—not to mention the possibilities of a slowly expanding Earth or a release of gravitational energy related to Λ —critical attention should also

be given to such non-standard threads of planetary research which could impact so strongly on the Moon problem. This approach had earlier been recommended by Wise (1963)—over sixty years ago.

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