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Review

Extending the Rock Cycle to a Cosmic Scale

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Abstract

The rock cycle, a cornerstone of geosciences, describes rock formation and transformation on Earth. However, this Earth-centric view overlooks the broader history of rock evolution across the cosmos, with two fundamental limitations: (i) Earth-centric paradigms that ignore extraterrestrial lithogenesis, excluding cosmically significant rocks and processes, and (ii) disciplinary fragmentation between geological and astrophysical sciences, from the micro- to the macroscale. This review proposes an extension of the rock cycle concept to a cosmic scale, exploring the origin of rocks and their evolution from interstellar space, through the aggregation of solid materials in protoplanetary disks, and their subsequent evolution on planetary bodies. Through systematic analysis of igneous, metamorphic, and sedimentary processes occurring beyond Earth, we identify four major domains in which distinct dynamics govern the rock cycle, each reworking rocks with domain-specific characteristics: (1) stellar and nebular dynamics, (2) protoplanetary disk dynamics, (3) asteroidal dynamics, and (4) planetary dynamics. Here we propose the cosmic rock cycle as a new epistemic tool that could transform interdisciplinary research and geoscience education. This perspective reveals Earth's rock cycle as a rare and invaluable subset of rock genesis in the cosmos.

Keywords: rock cycle; planetary geology; teaching geosciences; philosophy of geology

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1. Introduction

The rock cycle is a cornerstone of geological science; however, surprisingly, no formal definition has been established. Early ideas from Leonardo da Vinci (1452–1519) and Steno (1638–1686), later improved by Hutton (1726–1797) and Lyell (1797–1875), have described how the interactions between the atmosphere, hydrosphere, biosphere, and geological processes shape and transform rocks on Earth [1–3]. This concept experienced a perspective shift with the formulation of plate tectonics, evolving from a fixist view to a mobilist model [4–6]. To introduce the concept of the rock cycle at a cosmic scale, one must first extend the definition of rocks. The widely accepted definition of "rocks" as "*solid, naturally occurring aggregates of minerals*" is pragmatically useful but suffers from both scientific and conceptual limitations. For example, referring to rock as only an aggregate of minerals fails to account for rocks composed substantially of glass or mineraloids. Providing a formal definition of rock is beyond the scope of this paper. We consider it more philosophically productive to engage with the concept of rock, rather than to pursue a universal, possibly unattainable, definition.

The informal idea of "rocks" often excludes other crystalline aggregates, such as water ice or even CO_2 and CH_4 ices, nitrogen ices, and even mixtures of different ices or mixed ices with rocky materials, despite their clear lithological significance in the outer Solar System and beyond. Another clear and illustrative example of a persistent misconception about the definition of rocks is the conventional distinction between "stony" and "iron" meteorites—as if iron meteorites were somehow not considered "rocks". In reality, iron meteorites are composed of minerals such as taenite and kamacite and should therefore be regarded as true rocks. Of course, geoscientists recognize that ices and metals meet petrological criteria, yet a terrestrial-centric perspective often implicitly excludes these lithologies from the concept of "rock". Planetary geoscientists need to think more broadly about their concept of rocks to include naturally occurring metals and ices, as they represent lithologies no less significant than commonly intended rocks and are widespread throughout the Solar System and beyond.

The rock cycle, as traditionally defined, describes Earth's system of interacting endogenic and exogenic processes that continuously reshape rocks. **Endogenic processes** are driven by internal heat—primarily from radioactive decay—which leads to the melting of rocks into magma, later crystallizing into igneous rocks. Mantle convection and tectonics drive rocks through different temperature and pressure conditions, causing metamorphism, metasomatism, or re-melting. **Exogenic processes** modify rocks through complex interactions between the lithosphere and atmosphere, hydrosphere, cryosphere, and biosphere—mainly powered by solar radiation and gravity. Although they involve only the Earth's crust, which represents a smaller volume than planet Earth, these processes produce a wide variety of rocks and involve numerous interconnected processes depending on the climate, the duration of the action of the exogenous agents, and the chemical/petrological characteristics of the rock. These dynamics operate via two fundamental mechanisms: weathering and erosion.

Weathering is the in situ physical and chemical breakdown of rocks and minerals at or near Earth's surface, occurring without material transport. It includes physical weathering and chemical weathering. Physical weathering involves the fragmentation of rocks into smaller particles without altering their mineralogical composition. Common mechanisms include thermal expansion, where repeated heating and cooling induce stress fractures; frost wedging, in which water infiltrates rock fractures, freezes, and expands, exerting mechanical force; and root wedging, whereby plant roots penetrate and widen cracks. Chemical weathering alters the original minerals in rocks through water- and atmosphere-driven reactions influenced by factors such as pH and redox conditions. Water–rock interactions can promote processes like dissolution and hydrolysis, which break down minerals into ions and secondary products. Atmosphere–rock interactions can also cause changes in mineral oxidation states, as well as other reactions such as carbonation. Chemical weathering processes are most active in warm, humid climates.

Erosion refers to the suite of processes responsible for the removal of rock and mineral fragments from exposed outcrops, as well as their transport toward depositional environments. Any dynamic flow interacting with the Earth's surface (e.g., air, water, ice, or gravity) can act as an erosive agent. These agents mobilize and displace surface materials through mechanisms such as aeolian abrasion (wind-driven sandblasting), fluvial entrainment and cavitation (in turbulent water), glacial plucking and scouring (by moving ice), and mass wasting (e.g., landslides). The erosive capacity of these flows depends on their velocity and density, and the physical properties of the materials involved. Collectively, these processes generate a continuous flux of sediment, redistributing particles from source areas to sedimentary basins. The activity of the different life forms on Earth, such as plants, fungi, lichens, and microorganisms, can significantly enhance both erosion and weathering. Over time, the buried sediments may undergo diagenesis, a combination of physical, chemical, and biological processes including compaction, cementation, and recrystallization, that lithifies them into sedimentary rocks. However, these newly formed rocks may later be re-eroded, metamorphosed, or even melted. The Earth's rock cycle is too complex to fully describe because it involves several physicochemical processes, and the above-mentioned are only the most well-known. In this paper, we aim to extend this complex network of Earth's processes beyond planet Earth.

Today, after 80 years, the rock cycle is considered established knowledge and is not often revisited in light of current knowledge. A new perspective is needed to solve two key problems in the traditional rock cycle. (i) First, the Earth-centered perspective of the rock cycle is now outdated. In the last century, studies in cosmochemistry and planetary geology have shown that geological processes extend beyond Earth's boundaries with analogue processes or very exotic ones. The proliferation of data and materials from distant worlds is exponentially increasing. (ii) Second, astronomy and planetary and Earth-based sciences are still considered distinct scientific fields due to differences in methodologies, terminologies, research approach, and dissemination platforms [7]. This rift requires an integrated approach that reconciles microscopic analysis of rocks, the mesoscale processes of planetary geology, and the cosmic scale of astrophysical and astrochemical phenomena [8]. Scientists have underlined the importance of applying this vision together from perspectives such as the astrobiological [9] or geochemical [10]. This approach, based on a flexible view of disciplinary paradigms, makes the boundaries less rigidly dependent upon epistemological models, leading to continuous intersections between knowledge [11], as happens for example between geophysics and medicine [12].

The *rock cycle*, in its various simplified graphic representations [13], is composed of the three main rock types—sedimentary, igneous, and metamorphic—and the processes that drive their transformations. This picture can be viewed as a functional pedagogical tool. Over the last century, diagrams have been considerably implemented in scientific research to such an extent that they have increasingly taken on an epistemic function. It is no coincidence that today they are considered true **tools for thinking** because they are, for all intents and purposes, elements of research [14]. They serve to outline the phenomenon being examined; the relationships, constant and variable, that explain their genesis; and the mechanisms that determine them [15].

2. The Four Domains of the Rock Cycle

To explain the formation and transformation of rocky materials, we identify four main lithogenic domains characterized by different physical and chemical conditions, resulting in distinct rock-forming mechanisms. The following sections discuss the four key domains of the cosmic rock cycle: (1) stellar and nebular dynamics, (2) protoplanetary disk dynamics, (3) asteroidal dynamics, and (4) planetary dynamics.

2.1. Stellar and Nebular Dynamics

Stars do more than shine; they are the cosmic factories that create the building blocks for planets and rocks [16]. Obviously, the rock cycle requires the presence of "rock-forming elements" in specific abundances. When a star reaches the end of its life as a supernova, it scatters rock-forming elements into the surrounding space. This process enriches the interstellar medium, paving the way for the formation of possible new stars, planets, and other celestial bodies. In this way, the **star life cycle** determines the available elements for the creation of rocks. Looking back in time, one question arises: "What was the first mineral in the cosmos [17]?" In the early stages, stars were primarily made up of hydrogen and helium, so it is plausible that only after the formation of carbon and oxygen, graphite and ices—such as water, methane, and carbon monoxide—or their polymorphs may have been among the first minerals to form in space [18]. The element abundances and chemo-physical characteristics of a nebula are also shaped by external factors such as stellar winds, cosmic rays, and supernova explosions, which "sculpt" the chemistry of molecular clouds, clearing low-density gas and creating denser regions, influencing planetary system formation [19,20]. Those dynamic interactions resemble geological processes on Earth, such as selective erosion, transport, and accumulation. The mineralogical evidence that interstellar minerals expelled from ancient stellar systems become the starting material for new stellar systems lies in what we call **presolar grains**—small bits of solid interstellar matter that formed in the outflows or explosions of ancient stars [21,22]. These stardust particles made of silicon carbide (SiC), diamond, and graphite survived the voyage through space and time. Their age predates the Solar System by up to 7 billion years [23], proving that their origin does not derive from our much younger Solar System. In any cyclic system, the choice of a starting point is arbitrary. Within the framework of a cosmic-scale rock cycle, we choose interstellar grains as a pragmatic reference, as they represent the mineralogical evidence that can be confidently identified and characterized. More broadly, the onset of the cosmic rock cycle lies in the transition from stellar processes to the formation of minerals in the interstellar medium.

Thus, stellar and nebular dynamics constitute the indispensable first stage of the rock cycle, seeding the interstellar medium with rock-forming elements and minerals, and governing subsequent rock-forming processes.

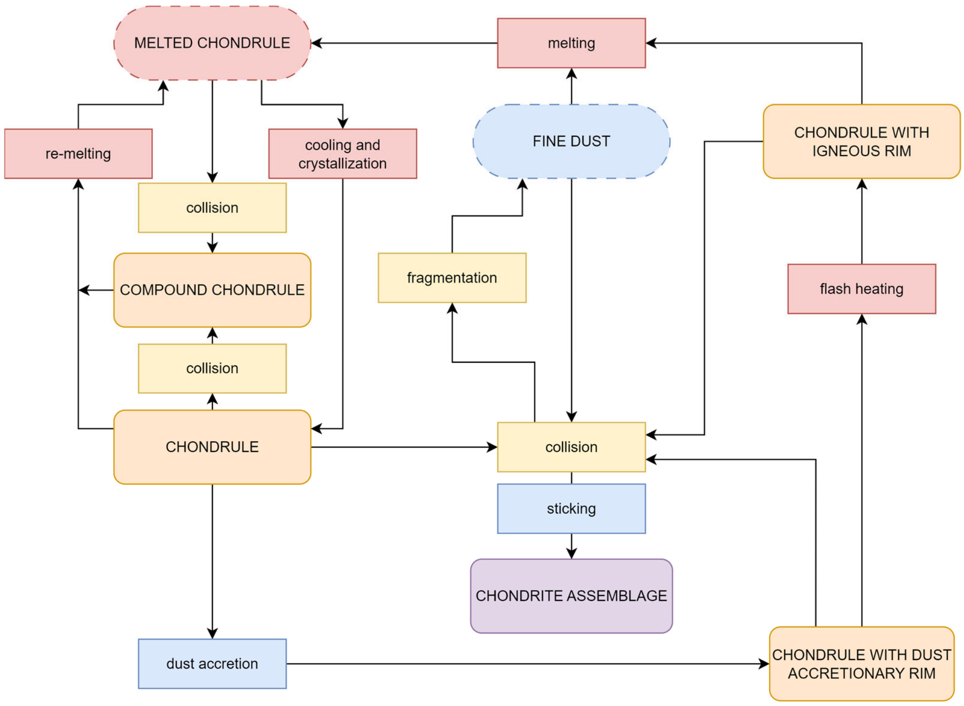
2.2. Protoplanetary Disk Dynamics

As gravity pulls nebular material inward, it forms a **protoplanetary disk** around a young star, where gas, dust, and ice will be mixed and processed to rocks. Protoplanetary disks host a wide range of physical and chemical processes, many of which remain only partially understood and continue to be the focus of active research. What we know about this environment has improved through the study of chondritic rocks and astrophysical modeling, and only recently directly imaged [24,25]. The chemistry of protoplanetary disks is not merely a continuation of interstellar chemistry but is processed by the radial and vertical gradients in temperature and density, accretion, and turbulent mixing [26–28]. The main first protoplanetary disk process, consisting of formation of a chemical dichotomy marked by the **snow line** [29,30], beyond which temperatures are low enough for volatile compounds like water, methane, and ammonia to freeze into ice while rocky materials still in the hot inner regions [31]. This process is recorded in rocks with distinct lithological characteristics: carbonaceous chondrites from the icy outer disk and non-carbonaceous chondrites from the dry inner disk [32,33].

Chondrite components preserve a micrometric record of early Solar System processes. Intense heating from viscous dissipation and irradiation from the protosun vaporize pre-existing dust. As cooling progresses, condensation of minerals occurs. **Refractory inclusions** (e.g., calcium-aluminum-rich inclusions) are high-temperature mineral assemblages condensed from a gas of solar composition and represent the oldest known rocks in the Solar System [34,35]. These tiny rocks consist mostly of refractory Ca, Al, Mg, and Ti minerals thermodynamically stable in a gas of solar composition above the condensation temperature of forsterite, at a total pressure of 10^{-4} bar [36,37]. Refractory inclusions also underwent multistage processes, driven by transient heating events, including partial or complete melting, evaporation, and reactions with nebular gas [38]. Those igneous-like processes happened in restricted regions near the protosun; then, refractory inclusions were transported radially outward to the chondrite-accretion regions [39]. Micrometric dust in the early solar nebula coalesced into larger clumps through electrostatic attraction and adhesion between solid dust grains. These aggregates were subsequently heated, partially or fully melted, and shaped into spherical droplets by surface tension, forming **chondrules**—millimeter-sized igneous rocks. Although there is no complete consensus regarding the process that led to the melting of the precursors of chondrules, several hypotheses have been proposed [40,41]. These hypotheses could all represent potential melting processes that occurred within our Solar System, or, possibly, in other stellar systems. Shock-wave heating, driven by eccentric planetesimals and protoplanets perturbed by Jovian and secular resonances, is a leading candidate for chondrule formation in the solar nebula [42]. **Compound chondrules** consist of two or more chondrules welded together formed through interactions between crystallized chondrules and melted chondrules [43]. **Fine-grained dust** rims are matrix-like materials surrounding chondrules [44]. These rims may have acted as a "velcro", facilitating the accretion of rimmed chondrules into centimeter-sized aggregates to asteroid formation [45]. Meanwhile, chondrules with dust accretionary rims floating free in space can undergo additional flash heating events that melt the surrounding dust. The petrographic evidence of this early Solar System process is directly observable in the chondrule textures, known as igneous rims [46]. Refractory inclusions, chondrules, and fine-grained dust follow a complex rock-cycle path, as exemplified in Scheme 1. Those components undergo a wide spectrum of collisional processes, including sticking, bouncing, mass transfer, cratering, erosion, abrasion, and fragmentation. Such processes have been characterized, modeled, and experimentally constrained, and in many cases quantitatively parameterized in terms of velocity- and energy-dependent thresholds [47,48], as well as through theoretical and numerical models [48,49]. Additionally, thermal processes, like melting or flash heating and chemical reaction in the protoplanetary disk environment, further modify these materials. Finally, refractory inclusions, chondrules, presolar grains, and matrix materials accreted and were processed in planetesimals to form chondrites, the oldest known sedimentary rocks in the Solar System [40]. The accretion of chondrite components into chondrites marks the fading of processes dominated by the protoplanetary disk and the onset of asteroidal processes.

Ultimately, we offer an example that highlights how the early formation of planets influenced processes within the protoplanetary disk. Observations of diverse exoplanetary systems and numerical models indicate that planetary formation perturbs the evolution of the protoplanetary disk through **planet–disk interactions** [50–54]. Such interactions can modulate turbulence, as well as radial and vertical mixing, thereby significantly contributing to the redistribution of solid material. In the early Solar System, for instance, it has been proposed that proto-Jupiter created a gravitational barrier that restricted the inward drift of carbonaceous chondrite material, limiting mixing between the two reservoirs [33,55]. However, this barrier was not entirely impermeable, as Jupiter's orbital migration scattered carbonaceous chondrite material into the inner disk [56,57], highlighting that early planetary formation, alongside the establishment of the snow line, is an important process in planetary evolution and must be considered in the rock cycle.

All the above-illustrated processes play a role in the formation of planetary materials. In the protoplanetary disk, rocks are cyclically reprocessed, representing a turbulent, chaotic, and highly energetic "factory" of rock formation in the early Solar System. As the rock cycle describes the environment in which rocks form, including the protoplanetary disk dynamics into the rock cycle is mandatory.



Scheme 1. This flowchart illustrates the complex chondrule rock cycle within the protoplanetary disk, showing how chondrules and fine-grained dust evolve through various thermal and collisional processes. Rounded rectangles represent products (e.g., chondrule, fine dust), and sharp-cornered rectangles represent processes (e.g., melting, fragmentation, dust accretion). Red = high-energy processes (melting, flash heating); Yellow = mid-energy processes (fragmentation, collisions); Blue = low-energy processes (sticking, accretion). Purple= the potential final stage of protoplanetary disk dynamics.

2.3. Asteroidal Dynamics

As chondritic pebbles accreted into asteroids, their increasing mass enabled the retention of internal heat. The main heat source in early asteroids was short-lived radioactive isotopes, particularly ^{26}Al. Chondritic material underwent progressive **thermal metamorphism**, causing chemical equilibration of chondrules and matrix, matrix crystallization, and ultimately chondrule destruction with complete recrystallization [58]. This thermal gradient, observed as a continuum in chondritic meteorites, supports the **onion-shell** model structure, where the most metamorphosed chondrites originate from the asteroid's deeper layers, closer to the heat source [59]. **Shock metamorphism**, resulting from hypervelocity collisions on their parent bodies, is a known exotic metamorphic process that can occur on a progressive scale of intensity [60]. Shock impact can also act as a melting process, producing melt veins [61,62].

Moreover, some asteroids underwent **aqueous alteration** [63,64], as evidenced by the presence of phyllosilicate minerals in carbonaceous chondrites. The process consists of a chemical reaction between anhydrous silicates and co-accreted water ice, melted by heat from radioactive decay or impacts [65]. Variations in the degree of aqueous alteration among chondrite specimens reflect differences in the relative abundances of initially co-accreted water ice, chondrules, and matrix [66]. In addition to short-lived radioisotopes, models (e.g., [67]) also suggest that water–rock interactions can lead to serpentinization, an exothermic process that can significantly contribute to the heat budget of asteroids.

Collisional grinding among planetesimals was extensive during early Solar System evolution. Those impacts can cause **brecciation** [68]. Some clasts may have been transported over significant distances before their incorporation, as evidenced by carbonaceous xenoliths found within ordinary chondrite hosts [69], indicating mixing between hydrous (e.g., phyllosilicate-rich) and anhydrous rocks that were subsequently incorporated into other forming planetesimals. Moreover, the asteroids Ryugu, Bennu, and Itokawa exhibit a **rubble-pile** structure, testifying to the continuous impact fragmentation and re-accumulation of these rocks. Obviously, the asteroids' rubble-pile structure is composed of different lithologies and thus consist of polygenetic materials [70] and also of different types occasionally. Thus, fragmentation and re-accretion into second-generation bodies can lead to further aqueous alteration [71] and metamorphism as illustrated in Figure 1. Petrographic evidence from the global meteorite collection indicates that aqueous alteration, metamorphism, brecciation, and re-accretion cyclically characterise asteroidal dynamics. Aqueous alteration followed by thermal metamorphism and also retrograde aqueous alteration has been reported (e.g., [71–73]). In line with previous work, Elephant Moraine 96029 is a representative CM chondrite that exhibits evidence of unusually mild aqueous alteration followed by a later phase of heating in its parent body [74]. The authors identify it as a regolith breccia because it is characterised by distinct lithologies mixed through impacts and re-accreted. Similarly, the exceptional finding of the Winchcombe meteorite shows eight distinct lithological units plus a cataclastic matrix [75]. The authors report significant heterogeneity in aqueous alteration across the specimen, ranging from intensely to moderately altered domains. The authors state that grain size and texture analyses indicate disruption of the original parent asteroid, with subsequent re-accretion forming a poorly lithified body. Sample-return missions on Ryugu (Hayabusa2) and Bennu (OSIRIS-REx) reinforced with petrologic evidence that the asteroids experienced thermal metamorphism, aqueous alteration, brecciation, and gravitational re-accretion, showing a complex geologic evolution (e.g., [76–80]). The growing body of evidence on petrogenetic processes in asteroidal environments—derived from both the meteoritic record and direct sampling through space exploration—demands the development of a robust framework linking rock textures and compositions to their formative asteroidal processes. Establishing such a framework is essential for recognizing that asteroidal evolutionary pathways of meteorites involve complex geological cycles and that decoding the mineralogical and petrographic record of these rocks is key to understanding how these processes operate within the broader rock cycle of the Solar System.

Asteroidal **differentiation** was widespread among planetesimals in the early Solar System. It occurred through a spectrum of metamorphic to igneous processes driven by the decay of short-lived ^{26}Al, impacts, formation time, accretion duration, chemical heat sources, and accretion models [81]. Asteroidal magmatism, well recorded in meteorite samples, ranges from limited partial melting to extensive magmatic activity, including the generation of basaltic and, in rare cases, more evolved lithologies. A well-documented example is provided by the HED meteorites, which are widely interpreted as products of magmatic differentiation on asteroid 4 Vesta [82]. Similarly, iron meteorites offer insights into the crystallisation of iron melts and point to an additional category of magmatism: ferromagmatism, that extends into planetary-scale evolution. Asteroid 16 Psyche is an excellent candidate for investigating geological processes involving iron melts, including the hypothesized phenomenon of ferrovolcanism recently proposed [83–86]. This emerging hypothesis shows how molten iron beneath an asteroid's crust rises and erupts onto the surface, like how silicate magma behaves on Earth. Ferrovolcanism may explain the anomalously low bulk density of asteroid 16 Psyche despite its metallic surface, by suggesting that iron lava flows cover an underlying rocky mantle. Intrusive ferromagmatism has been proposed as the formation mechanism for pallasites—meteorites comprising olivine crystals within an iron–nickel matrix. A new avenue of research has emerged to better understand ferrovolcanism, focusing on constraining the volatile gas content and temperature of the melts, as well as the stress state governing fracture mechanics in the asteroid's crust.

NASA's Psyche spacecraft, scheduled to arrive at asteroid 16 Psyche in 2029, promises to deliver groundbreaking insights into these enigmatic metallic worlds.

Weathering, in the classical rock cycle on Earth, is commonly illustrated as a main agent of erosion that produces sediments. Similarly, in non-Earth environments, **space weathering** is a process that alters the exposed surface of airless planetary bodies in open space, driven by cosmic ray exposure, solar wind irradiation, and micrometeoroid bombardment [87]. Space weathering can lead to significant surface modifications in different ways. Such effects include the formation of nanophase metallic iron, amorphization of silicate, and the darkening of asteroid surfaces, which masks the original rock composition and complicates spectral analysis [88,89].

Figure 1. The cosmic rock cycle. This diagram shows the cosmic rock cycle across four interconnected domains: nebular, protoplanetary disk, asteroidal, and planetary. At its center, Earth's processes are driven by the atmosphere, hydrosphere, lithosphere, biosphere, and magnetosphere, which shield against space weathering. However, Earth is an open system, influenced by meteoritic flux. This implies that the rock cycle extends beyond Earth, and the triangle of igneous, sedimentary, and metamorphic rocks can be applied on a cosmic scale, incorporating processes not considered in the conventional rock cycle. The cycle begins with interstellar grains spread by stellar processes. Then, chondritic components form in the protoplanetary disk and accrete into chondritic rocks. These rocks undergo metamorphism, aqueous alteration, impacts, and re-accretion in the asteroid parent body. Asteroids merge to form planetesimals, protoplanets, and eventually planets, which experience volcanism, tectonics, surface weathering, and material transport. Impact events eject material back into space, where it can be recycled onto other bodies. At the end of a star's life, mineral material is scattered into the cosmos, providing the raw ingredients for a new rock cycle.

Petrologic evidence from meteorites, supported by experiments and models, reveals that asteroids have experienced complex and recurrent cycles of fragmentation, accretion, alteration, metamorphism, and melting, highlighting the unique characteristics of the rock cycle in the asteroidal dynamics.

2.4. Planets Dominance

In classical conceptualizations of the rock cycle, Earth is often conceptualized as a closed system. However, the mass of our planet, which is commonly perceived as stable, is subject to a continuous small variation. A recent study has estimated that approximately 5.2×10^7 kg of interplanetary particles reach Earth's surface annually [90]. Although this amount represents only a minimal contribution to Earth's mass today, it was significantly more substantial during the earliest formative period of the planet's evolution—when the influx of extraterrestrial material had significant influence [91,92].

With this perspective, continuing the cosmic rock cycle, this section presents an overview of how rocks can be incorporated in planets, entering a new stage of the rock cycle: the planetary domain. The way planets form resembles a summary of the classical rock cycle, where pre-existing rocks—dust, meteoroids, and asteroids—gradually assemble together, undergoing melting, crystallization, metamorphism, and erosion over and over again until the planet becomes dynamically dominant in its orbital zone. Planet accretion is much studied and debated in the literature regarding the accretionary models of the Earth, for which we have more extensive information [93–96]. But the models can be applied broadly as universal models [97]. The two main proposed accretionary models are the homogeneous accretionary model and the heterogeneous accretionary model, involving different timescales and leading to diverse outcomes [98]. Indeed, the birth of a planet can be seen as partly analogous to the formation of a rock, which is why planetary accretion belongs in a cosmic rock cycle.

Once the planetary formation phase is over (since no universal threshold separates formation from evolution) a planet can be conceptualized as having obtained a mainly closed rock cycle that occurs through its own endogenic and exogenic processes, or at least that internal planetary processes govern the evolution of a planet's rock cycle more than external influences. While this may hold true for Venus, Earth, and Mars, it does not necessarily apply to other worlds in Solar System and beyond, where both surface and internal processes are currently influenced by dynamics beyond their planetary boundaries—such as tidal forces, cosmic radiation, and other phenomena that will be discussed in this subsection. Thinking about the rock cycle at a cosmic scale allows us to question the idea of complete isolation of Venus, Earth, and Mars from geological processes triggered from beyond their planetary boundaries (e.g., [99–103]) and to explore these processes in the context of their evolution over time (e.g., [104–106]).

In this review, we choose to not discuss those processes on other planetary bodies that are essentially analogous to those on Earth (e.g., volcanic eruption, magma crystallization, contact or regional metamorphism, wind erosion, etc.). Instead, we focus on more exotic processes that have never been considered in the classical cycle. In this way, we highlight how many processes are excluded from the canonical conceptualization of the Earth-centered rock cycle. Although Earth's rock cycle is well-known, it represents just one model among many lithogenetic processes operating throughout the Solar System. On Earth, the rock cycle is driven by both endogenic and exogenic forces, including interactions with the atmosphere, hydrosphere, and biosphere. However, not all planetary bodies in the cosmos share these features; some possess only a subset, while others lack them entirely. The vast majority of known planetary bodies, like Venus and Mercury, have long been considered to follow a one-way rock cycle, in which primordial magma oceans crystallize to form igneous rocks without significant rock recycling processes [107–109].

The efficiency of rock-processing mechanisms varies from planet to planet, depending on intrinsic factors such as gravity, composition, internal energy sources, and proximity to other celestial bodies. These mechanisms are also subject to change over time. For instance, Earth's rock cycle is highly dynamic due to its still-active plate tectonics, in stark contrast to Mars, where today tectonic activity is limited and the rock cycle correspondingly subdued [108,110]. During the Noachian and early Hesperian periods, however, the Martian rock cycle was more complex due to the widespread presence of liquid water and a more active hydrological system [111]. Magmatic activity generated igneous rocks which, under the influence of water, could undergo weathering, erosion, transport, and deposition, leading to the formation of sedimentary rocks. Additionally, localized thermal or shock metamorphism could modify both igneous and sedimentary precursors, with the possibility—unlike today—of reinitiating the sedimentary cycle through renewed surface processes. In contrast, the Amazonian period is characterized by colder, drier conditions and limited surface water activity, restricting the rock cycle to mainly unidirectional paths: either magma $\rightarrow$ igneous rocks $\rightarrow$ thermal or shock metamorphism, or direct alteration and cementation into sedimentary rocks without the possibility of recycling through aqueous processes. This results in a fragmented and incomplete rock cycle in the Amazonian terrains. Furthermore, Mars exhibits a partially decoupled geochemical cycle compared to Earth, with limited exchange between surface and subsurface reservoirs and sparse active recycling. Recent work highlights outstanding questions regarding element mobilization, preservation of redox gradients, and the long-term fate of volatiles and organics on Mars [112]. These unresolved issues are central to understanding both the geological evolution and the planet's past habitability. Reconstructing the Martian sedimentary cycle attracted attention (e.g., [113]), with orbital spectroscopy providing critical regional context for aqueous mineral distributions [114]. Recent in situ rover analyses document past rock cycle processes on Mars. For example, fracture-associated alteration halos in mudstones and sandstones—identified in Gale Crater—underwent multiple aqueous stages, including acidic leaching followed by mineral precipitation (e.g., [115]). Similarly, the Perseverance rover investigated Jezero crater's floor, revealing mafic igneous rocks modified by fluid-mediated reactions (e.g., [116]). Despite orbital and in situ data, reconstructing rock cycling and its temporal evolution remain challenging. A comparative planetary perspective is essential to correctly interpret planetary geological processes.

Contrary to the view that many planetary bodies across the Solar System are considered "geologically dead" [117] when compared to Earth, evidence of tectonic structures and other resurfacing processes reveals ongoing dynamism in their rock cycles. This subsection will explore some of the mechanisms that drive rock cycles in the planetary domain. Planetary surface age dating—by crater chronology, stratigraphy, and investigations of resurfacing processes—has long been an attractive area of research. The extensive literature produced in this field proves that the rock cycle is not exclusive to Earth's plate tectonics, but rather operates across the Solar System through a variety of mechanisms [118,119]. For example, lobate scarps and wrinkle ridges on Mercury and the Moon are surface expressions of endogenic forces, reflecting global shrinking due to interior cooling [120–123] or tidal despinning. On the airless planetary surface, as mentioned for the asteroid domain, space weathering occurs as an exogenic force. A striking example of its impact is the formation of hollows on Mercury, which illustrates how intense and transformative these processes can be [124].

Tidal heating is a significant energy source in some planetary systems, capable of inducing rock melting and sustained volcanic activity. Jupiter's moon Io serves as a prime example, where intense tidal forces from Jupiter and neighboring moons generate substantial internal heat, leading to widespread volcanism [125–127]. This tidal heating mechanism is not exclusive to Io; it affects various objects in the Solar System and may represent a widespread phenomenon across the cosmos [128,129].

Tidal forces and tidal heating can have significant consequences on icy worlds. The observed complex surface morphology of icy moons like Europa and Dione suggests that the surfaces of these worlds may have undergone tectonic cycles similar to Earth's Wilson cycles [130,131]. This Earth-like tectonic process is referred to as **cryotectonics** and has opened a new chapter in planetary geology. The way the icy crust, the possible underlying liquid ocean, and a possible rocky core interact with one another, and their respective thicknesses and characteristics raise a wide spectrum of geologic possibilities. Surface structures even strongly suggest subduction processes, indicating that the icy crust can be recycled into the interior. Additionally, **cryovolcanism**, observed on or suspected for numerous icy bodies across the Solar System—such as Europa, Enceladus, and Titan—plays a significant role in shaping the surfaces of icy worlds [132]. Cryovolcanism involves the eruption of ammonia-water or other volatile-rich fluids from a deep cryomagma reservoir onto the surface, mimicking terrestrial volcanism. Cryoeruptions contribute to the resurfacing of icy bodies by transporting fresh material from the interior to the surface, facilitating material recycling and crustal renewal. Erupted cryolava subsequently undergoes "weathering" through sublimation or radiation-driven breakdown, exemplifying a possible "icy rock cycle." On Titan, for example, the presence of cryovolcanoes such as Sotra Facula suggests active geological processes involving the eruption of slushy ice or other materials from the interior to the surface [133]. These cryovolcanic activities contribute to the geological evolution of these icy bodies. Similarly, Europa's surface and subsurface are chemically linked through dynamic processes including cryovolcanism, tectonics, and melting. Cryovolcanic activity can transport reduced compounds (e.g., H_2, CH_4) from the interior to the surface, while oxidized species—generated by sulfur implantation from Io and radiolytic processing of the ice shell—are transported downward via tectonic subduction, melting, and brine migration [134–136].

On small bodies, both volcanic and cryovolcanic plumes can escape due to low gravity and tenuous or absent atmospheres, dispersing material into space [137]. In some cases, this material may even be deposited onto neighboring planets or moons [138,139] mixing allogenic planetary material with local geology. Such interplanetary material exchanges represent geological processes operating on a truly cosmic scale.

The water cycle on Earth is a primary driver of the rock cycle, but other different types of **hydrospheres and atmospheres** exist in planetary environments across the cosmos. On Titan, Saturn's largest moon, a methane-based hydrosphere actively sculpts the landscape through rainfall, rivers, and lakes involved in complex photochemical–meteorological–hydrogeochemical processes [140]. Recent radar studies have revealed detailed information about the chemical composition and physical characteristics of Titan's hydrocarbon seas, indicating active tidal currents and ripples near estuaries [141]. The presence of rivers, lakes, and dunes formed by methane and ethane suggests a complex hydrological cycle analogous to Earth's, albeit with different substances [142].

Gas giant planets, both within our Solar System and among known exoplanets, present a different kind of challenge. Though lacking solid surfaces, their gravitational dominance influenced the formation of the protoplanetary disk and continues to regulate material flow between the inner and outer Solar System [143]. As previously mentioned, they also influence nearby moons through tidal forces. While traditionally seen as irrelevant to lithogenesis, gas giants exhibit extreme atmospheric conditions that can induce mineral formation, including the precipitation of diamonds [144]. Some exoplanets may undergo even more processes, such as the precipitation of molten metals [145]. As Earth's atmosphere actively shapes surface geology and drives the rock cycle, extreme planetary atmospheres should also be recognized as key agents in lithogenetic processes in the cosmos. Micrometeorites are a record of atmospheric entry melting, showing that ablation constitutes an additional igneous process capable of producing silicate melts on planets with substantial atmospheres [146].

Collisions are among the most widespread transformative processes in the cosmic rock cycle, capable of initiating a broad spectrum of geological effects. These include mechanical erosion, high-energy transport of materials, impact metamorphism, and the generation of melt through impact shock [147,148]. On solid planetary surfaces, collisions with asteroids or comets can breach the crust and excavate deep lithological layers, ejecting rock fragments into interplanetary space [149]. The blanketing effect of ejecta, which deposits vast amounts of impact-derived material over large areas, contributes substantially to the surface lithological evolution of rocky planets in their early ages by redistributing and mixing crustal compositions. The energy released during impacts can generate localized vaporization or melting, producing impact melt rocks, breccias, and high-pressure polymorphs such as coesite or stishovite. In some cases, impacts may form large basins or initiate long-lasting tectonic or volcanic activity by redistributing stress in the lithosphere [147,149]. The excavation of massive canyons or rift-like features can also result from the directional force of high-velocity impact streams [150]. On a larger scale, collisions have even shaped planetary systems themselves, as hypothesized for the Moon's formation through a giant impact [151]. Observations of other star systems, such as HD 23514 in the Pleiades cluster, reveal hot dust likely resulting from catastrophic collisions between rocky bodies, suggesting that such processes are common in planetary formation [152].

Therefore, collision-related processes are not only key to shaping individual planets, but also central to material redistribution and transformation on a system-wide or even interstellar level. These ejected materials may travel as meteoroids, eventually falling onto other planetary bodies, contributing to cross-planetary lithological exchange. This is exemplified by the records of lunar and Martian meteorite samples found on Earth. Conversely, it is also plausible that meteorites originating from Earth may be present on the surfaces of other planetary bodies [153,154]. Rocks formed on their parent planet may be ejected and travel through space for extended periods before arriving on a new planetary surface (potentially experiencing atmospheric ablation). Once deposited, the meteorite becomes part of the host planet's rock cycle, undergoing subsequent chemical alteration and physical modification. **Interstellar objects** are rocky bodies that have left their original stellar systems and travel through interstellar space [155–157]. In a theoretical scenario, they could potentially collide with planets in other stellar systems, re-entering a new rock cycle. Similarly, rogue planets ejected from their original systems may experience comparable fates.

The planetary dynamics outlined here demonstrate diverse efficiencies of rock processing, including mechanisms absent from Earth's rock cycle—such as interior shrinking, space weathering, tidal volcanism, cryotectonics and cryovolcanism, extensive collisional metamorphism, and intense impact-driven surface reshaping. The Solar System reveals an extraordinary variety of pathways through which rocks are transformed, inviting speculation on the yet-unknown processes that may operate on unexplored worlds across the universe.

3. Life and Death

The biosphere plays a fundamental role in the rock cycle, modulating global biogeochemical cycles and mediating atmosphere–hydrosphere interactions. Living organisms contribute to chemical alteration, transport, and sedimentation processes and, in some cases, are directly responsible for rock formation. For example, cyanobacteria contributions dramatically altered Earth's geochemistry during the Great Oxidation Event (~2.4 Ga), generating the deposition of banded iron formations (BIFs) and fundamentally reshaping planetary mineral evolution [158], and corals and foraminifera are extensive constituents of sedimentary rocks [159]. Furthermore, Homo sapiens has introduced "artificial rocks"—cements, ceramics, alloys, and polymers [160]. We do not aim to assess Homo sapiens' role in the rock cycle but simply note its ability as a life-form, moving away from an anthropocentric perspective. The DART mission demonstrated that human activity—as a biological process—can actively alter planetary surfaces through impact cratering and orbital deviation [161], and also transport rocks between previously isolated planetary environments [162]. Active research on asteroid mining suggests that microbial processes could facilitate extraterrestrial resource extraction, spreading, in this way, biosphere processes out from earth [163]. If similar biogeological processes occur elsewhere, the role of the biosphere in the rock cycle could be a universal phenomenon, influencing unexplored worlds. Moreover, the biosphere of one world might have the potential to spread to others.

As life dies, it returns into a biogeochemical cycle, including the rock cycle. As stars die, such as in a supernova, dust, rocks, and minerals are scattered across the universe, serving as raw material for new planetary systems [164]. Impact or gravity interaction may produce interstellar asteroids or launch into the cosmos rogue planets, transferring geological matter across stellar boundaries.

4. Conclusions

A comprehensive summary of all cosmic processes involving rocks is beyond the scope of this study. We focus on a particularly relevant subset to challenge the Earth-centric view of the rock cycle, emphasizing effects recorded in the petrologic record. Exotic igneous processes can arise from stellar and protoplanetary disk processes (e.g., chondrules and CAIs) to asteroidal and planetary processes (e.g., iron magmatism or tidal heating, impact and ablation melting). Sedimentary processes like alteration, erosion, transport, and sedimentation are not only linked to hydrosphere and atmosphere interactions but also include space weathering, a type of weathering not previously considered in the classic rock cycle. Metamorphic processes on Earth are attributed mainly to plate tectonics; however, in a cosmic context, shock metamorphism occurs due to hypervelocity impacts, a process that could be more frequent during the early epoch of planet formation.

The progress of geoscience depends on its integration with other sciences such as physics, chemistry, astronomy, and biology. The interdisciplinary approach allows us a multilayer view of the problem: it is a methodology already in use that is being resemantized using current knowledge. The goal is to create wider approaches of understanding reality that include increasingly broader classes of phenomena. Contrary to "hard sciences", geological explanations are never univocal, but composite: multiple causes, agents, and energies simultaneously contribute to generating phenomena. For this reason, the role of geoscientists is to develop a broad, integrative perspective on natural systems and to critically reassess and refine models in light of new knowledge, continuously reshaping it to reflect advancing understanding. Indeed, the rock cycle, from both a scientific and a science popularization and teaching perspective, can be considered as a case of Big Ideas: a tool of thinking that can function as general models to explain complex aspects of reality and, at the same time, can be used for the solution of other problems that gravitate around their theoretical core, offering very original solutions [165].

Extending the rock cycle to a cosmic scale may appear conceptually straightforward, no more extraordinary than adding newly discovered geological aspects. However, it poses a true challenge in planetary science. Only by reconstructing the complex pathways of rocks across time and through diverse environments, deciphering their continuous physical and chemical transformations, can we begin to address some of the field's most fundamental questions. An illustrative example of the power of this interdisciplinary framework is provided by Lugaro et al. ([16]), who reviewed the meteoritic short-lived radionuclide evidence, combined with their production in stars, applied to a galactic chemical evolution model. Their approach shows how the evolution of radionuclide abundances in the Milky Way Galaxy has important consequences for the thermo-mechanical and chemical evolution from a stellar nursery to thermal and chemical evolution of planetesimals, influencing early differentiation and potential habitability.

More open questions feed an active scientific debate and underscore the imperative for collaborative, interdisciplinary approaches that integrate diverse expertise. Indeed, despite increasing sophistication in analytical techniques, from remote sensing to petrography, mineralogy, elemental and isotopic geochemistry, experimental petrology, and modeling, results are often fragmented or contradictory. These inconsistencies highlight the absence of an integrative framework.

In addition to encouraging critical thinking, the cosmic rock cycle idea aims also to resolve the problem of fragmentation between micro- and macro-scale research. The increasing frequency of sample return missions provides microscopic insights into asteroidal and planetary processes, while remote sensing in the Solar System and observational studies of exo-solar systems contribute to a macroscopic understanding of planetary evolution and exoplanetary system formation. These processes are deeply interconnected, necessitating interdisciplinary collaboration and cross-domain knowledge transfer among scientists in planetary science, meteoritics, and astrophysics. Expanding the rock cycle to a cosmic scale is now essential for establishing a unified theoretical framework that integrates microscale processes with planetary and astrophysical phenomena and bridges isolated fields like geology, astrophysics, and planetary science.

The rock cycle has historically been developed through the study of the Earth, but these crystallized ideas are now limiting its scope, making it obsolete today and representing a missed opportunity for students and early career researchers to think about rocks in a broader context. This review reframes the rock cycle by moving beyond an Earth-centric perspective, situating Earth's geologic processes within a cosmic scale as ones among myriad environments where rocks are continuously shaped and transformed.

Therefore, we propose that this conceptual cosmic framework be formally recognized in the rock cycle. The rock cycle describes the petrogenetic processes that drive the continuous transformation of rocks—anywhere in the universe.

It conceptualizes the dynamic interaction between endogenic and exogenic forces, connects igneous, metamorphic, and sedimentary processes, encompasses microscopic and macroscopic scales, begins with the death of stars, participates in the formation and evolution of planetary systems, and coexists and evolves with possible biospheres.

Going beyond the meaning attributed so far, the significance of the rock cycle is now portrayed as a connecting ring, bridging the "stellar cycle" and the "life cycle"; it unifies fundamental processes across time, space, and disciplines, overcoming fragmented knowledge and affirming its epistemic dignity as a tool for interdisciplinary understanding.

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