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Quasicrystals from the edge: extreme environments, impact craters and the quest in other celestial bodies

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Quasicrystals, materials with long-range order but no periodicity, were first discovered in nature within the Khatyrka meteorite, a CV3 carbonaceous chondrite. Their occurrence demonstrated that hypervelocity impacts can generate quasiperiodic phases under transient conditions far from equilibrium, which survived for billions of years. Icosahedral and decagonal quasicrystals from Khatyrka formed at pressures exceeding 5 GPa and temperatures above 1200°C, as shown by their microstructures and association with shock-melted silicates and high-pressure polymorphs. Laboratory shock-recovery experiments reproduced these phases, confirming their synthesis during microsecond-scale shock pulses and their persistence after release. The presence of metallic aluminium, rarely stabilized in natural systems, indicates that extreme redox conditions are transiently established during impacts, enabling unusual alloy chemistries. Although rare in the meteoritic record, quasicrystals may be more widespread, their scarcity reflecting preservation biases and limited analytical focus on metallic phases. Advanced nanoscale diffraction and tomography methods, coupled with systematic surveys, are essential to uncover their distribution. Beyond meteorites, terrestrial craters, lunar breccias, Martian meteorites and asteroid samples are promising targets. Quasicrystals thus represent durable witnesses of impact processes, expanding the mineralogical tools for tracing high-energy events that shaped the early solar system.

Quasicrystals have always sat uneasily in the taxonomy of matter. Their long-range order without periodicity makes them both crystalline and non-crystalline, stable yet seemingly at the edge of instability. For decades after their laboratory synthesis, the question of their natural occurrence lingered unresolved, until the discovery of icosahedral quasicrystals in the Khatyrka meteorite provided incontrovertible evidence (Bindi *et al.*, 2009). That single discovery shifted the discussion: quasicrystals were no longer artefacts of controlled metallurgical experiments but witnesses of cosmic processes. And not just any processes – their genesis is tied to the most violent regimes available to planetary materials, those associated with hypervelocity impacts (Bindi, 2025).

The Khatyrka meteorite, classified as a CV3 carbonaceous chondrite (MacPherson *et al.*, 2013), encapsulates within its brecciated mass the record of a collisional history that extended back to the dawn of the solar system. Within its metallic assemblages are phases with icosahedral and decagonal symmetries – *i*-$Al_{63}Cu_{24}Fe_{13}$, icosahedrite (Bindi *et al.*, 2011), and *d*-$Al_{71}Ni_{24}Fe_5$, decagonite (Bindi *et al.*, 2015) – which crystallized not through slow cooling but within the furnace of shock metamorphism (Lin *et al.*, 2017; Meier *et al.*, 2018). Their context is unequivocal: they are embedded in alloys intimately intergrown with silicate phases that bear the

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characteristics of shock, including vitrified feldspar, high-pressure polymorphs and deformation lamellae (Hollister *et al.*, 2014; Lin *et al.*, 2017). The geochemical and textural evidence indicates formation during transient pressures exceeding 5 GPa and temperatures surpassing 1200°C. These conditions are diagnostic of hypervelocity impact, not of nebular condensation or magmatic crystallization (Tommasini *et al.*, 2021).

The microstructural details of these quasicrystals are instructive. Electron (Bindi *et al.*, 2009) and high-resolution synchrotron X-ray (Takakura *et al.*, 2025) diffraction reveal sharp fivefold, threefold and twofold axes, consistent with perfect quasiperiodic order. Their interfaces with surrounding crystalline phases are abrupt, with no transitional zones that would suggest slow interdiffusion (Hollister *et al.*, 2014). Instead, the quasicrystals appear as discrete domains, sometimes intergrown with crystalline approximants but maintaining their own forbidden symmetries. Nanoscale intergrowths of *i*- and *d*-type phases suggest rapid fluctuations in growth conditions, frozen in place by instantaneous quenching. These are not textures of equilibrium crystallization but of non-equilibrium pathways traced within microseconds of a shock event (Asimow *et al.*, 2016).

Laboratory shock-recovery experiments have corroborated this scenario. Projectile–target experiments, in which metallic targets are struck by high-velocity projectiles at 1–2 km s^{-1}, produce both icosahedral and decagonal quasicrystals in the recovered materials (Asimow *et al.*, 2016; Oppenheim *et al.*, 2017*a*; Oppenheim *et al.*, 2017*b*; Hu *et al.*, 2020; Hu *et al.*, 2024). The conditions correspond to transient pressures in the 5–20 GPa range, with shock durations of microseconds. These experiments demonstrate that quasicrystals nucleate reliably under shock and persist after release. The parallels with natural samples are direct: the quasicrystals in Khatyrka could have formed during precisely such a shock pulse, perhaps in an asteroidal collision billions of years ago.

Figure 1
AI-generated image showing a quasicrystal held by an astronaut in an extreme extraterrestrial environment. In the background, an active impact crater, a falling meteorite and distant celestial bodies evoke the high-pressure, high-temperature conditions under which quasicrystals can form and persist, linking planetary impacts to the search for these exotic phases beyond Earth.

What is remarkable is not only their formation but their survival. Once thought to be metastable curiosities, natural quasicrystals have endured for 4.5 billion years, surviving subsequent collisional processing, thermal metamorphism, and eventual delivery to Earth. Their endurance suggests that quasiperiodic structures occupy deep kinetic traps in the free-energy landscape of alloys. Under shock, the system may bypass crystalline approximants and fall into a quasiperiodic minimum, where it becomes kinetically frozen. The resilience of these configurations underlines the need to rethink models of stability. Quasicrystals are not fragile intermediates but robust end-points of certain non-equilibrium pathways.

The conditions of their formation are worth closer scrutiny. In the Al–Cu–Fe and Al–Ni–Fe systems, quasicrystals form at compositions close to known stability fields of laboratory-synthesized phases (Tsai *et al.*, 1987; Tsai *et al.*, 1989). But what is striking in natural samples is the presence of metallic Al, a phase rarely stabilized in natural environments. Its occurrence requires extreme reduction, an oxygen fugacity far below that of typical planetary settings. Shock events can transiently generate such conditions, as high-temperature melts drive redox reactions, liberating metallic Al that alloys with Cu and Fe. The presence of metallic Al in Khatyrka is therefore not an accident but a signature of shock-generated microenvironments with unusual chemical potentials. These fleeting conditions allowed quasicrystals to form, testifying to the complexity of impact chemistry (Fig. 1).

If hypervelocity impacts are natural factories for quasicrystals, then their potential distribution is vast. The early solar system was characterized by intense collisional activity. Asteroids and planetesimals collided at velocities sufficient to generate shock pressures in the tens of gigapascals. Every such collision represented an opportunity for quasicrystal synthesis, especially in bodies containing metal-rich assemblages. The rarity of their detection may reflect not their scarcity but our analytical limitations (Genge *et al.*, 2025). Standard meteorite characterization often overlooks metallic phases, focusing instead on silicates, oxides and sulfides. Quasicrystals, hidden within micrometre-scale metallic domains, could easily be missed without targeted diffraction studies. The challenge for the community is to undertake systematic, nanoscale surveys of metallic phases across diverse meteorite classes.

The search must not be confined to meteorites alone. The discovery of quasicrystals in the debris of the first atomic bomb test (Bindi *et al.*, 2021) and in artificial fulgurites (Bindi *et al.*, 2022), materials formed by lightning strikes, is an example. Terrestrial impact craters, for instance, are natural laboratories for shock synthesis, yet their record of quasicrystals remains elusive. This is partly a matter of preservation. On Earth, post-impact alteration rapidly transforms metallic phases. Hydrothermal circulation, weathering and tectonic activity act to erase delicate shock products. Unlike coesite or stishovite, which are robust high-pressure silica polymorphs, quasicrystals are vulnerable to oxidation. Still, fresh craters in arid environments may harbour them. The Barringer Crater in

Arizona, for instance, preserves shock-melted metal–silicate assemblages that could be fertile ground for quasicrystal searches. Young craters in Siberia or Antarctica may also retain metallic melts capable of containing quasicrystalline domains. The rarity of confirmed finds may reflect not impossibility but insufficient search intensity.

The recent discovery of proxitwelvefoldite, $Pd_3Ni_4Te_8$ (Bindi *et al.*, 2025), suggests the possible existence of a dodecagonal quasicrystal in the Pd–Ni–Te system. The structural features of proxitwelvefoldite, including its unique atomic arrangement and local twelvefold symmetry, indicate that it may represent a periodic approximant of a dodecagonal quasicrystalline phase. This finding provides new insights into the stability fields and formation mechanisms of complex metallic alloys within the Pd–Ni–Te compositional space, opening the possibility that genuine dodecagonal quasicrystalline order could emerge under specific thermodynamic conditions.

The Moon offers a more favourable archive. Its surface, unmodified by atmosphere or hydrosphere, preserves impact products for billions of years. Lunar regolith breccias contain clasts from multiple impact events, many of which experienced extreme pressures and temperatures. Within these breccias, metallic inclusions could host quasicrystals. The preservation potential is enhanced by the Moon inert environment. The South Pole–Aitken basin, the largest known impact structure in the solar system, represents an especially promising site. Sampling campaigns that return melt breccias from such basins should prioritize searches for quasicrystalline phases.

Mars, too, is a candidate. Its surface bears the scars of giant impacts, and Martian meteorites already display high-pressure phases such as maskelynite, majorite and ahrensite (Ma *et al.*, 2016). The presence of metallic inclusions in some Martian lithologies raises the possibility of quasicrystal formation under shock. Ejection events that launch Martian meteorites into space involve shock pressures comparable with those inferred from Khatyrka. If quasicrystals formed during these events, they could be preserved within Martian meteorites now available for study. Their detection would not only expand the known inventory of natural quasicrystals but also provide a new window into Martian impact history.

Asteroids remain the most promising context. Their compositions are diverse, their collisional environment is intense, and their lack of geological processing enhances preservation. The Khatyrka meteorite likely originated from such a body, where repeated collisions generated the conditions for quasicrystal formation. Sample-return missions now provide the opportunity to test this hypothesis directly. Hayabusa2, which returned samples from Ryugu, and OSIRIS-REx, which sampled Bennu, both targeted carbonaceous asteroids with metallic phases. Detailed nanoscale analyses of these samples may yet reveal quasicrystals. Even if none are found, the negative result would constrain the chemical and physical parameters of quasicrystal formation, sharpening our models.

Methodologically, detecting quasicrystals in extraterrestrial samples demands advanced tools. Conventional X-ray diffraction (XRD) or electron microprobe techniques are insufficient. Instead, selected-area electron diffraction, synchrotron microdiffraction and aberration-corrected transmission electron microscopy (TEM) are essential. Atom probe tomography adds the ability to reconstruct three-dimensional atomic distributions, invaluable for identifying nanoscale quasicrystalline domains within complex intergrowths. These techniques are labour-intensive but necessary, as quasicrystals often occur in small, localized regions. Machine learning applied to large datasets of diffraction patterns could accelerate discovery, enabling automated recognition of forbidden symmetries (*e.g.* Liu *et al.*, 2023).

Theoretical modelling complements experimental and observational work. Density functional theory and molecular dynamics simulations have begun to map the energy landscapes of quasicrystals under pressure (*e.g.* Munevar *et al.*, 2025). These models suggest that quasicrystals occupy local minima separated by substantial barriers from crystalline approximants. Under shock, rapid quenching can trap the system in these minima. The persistence of quasicrystals over cosmic timescales reflects the depth of these traps. Yet much remains unknown. How broad are the compositional fields that permit quasiperiodic order? How do pressure and temperature expand or contract these fields? Extending simulations to other alloy systems (such as Al–Ni–Fe, Al–Mg–Cu, Al–Ti–Fe) could identify new candidates for quasicrystal formation, guiding both experiments and meteoritic searches.

Quasicrystals also invite comparison with other shock products. Silica polymorphs such as coesite and stishovite are routine indicators of impact events, stable enough to persist in terrestrial rocks. Diamonds, too, form under shock from graphite or carbonaceous matter (Nestola *et al.*, 2020). Metallic glasses, produced by rapid quenching of melts, are common in impact environments. Quasicrystals occupy the same family of shock products but add a distinctive twist: they are ordered, yet aperiodic. Unlike glasses, they have sharp diffraction patterns; unlike crystals, they exhibit forbidden symmetries. Their formation requires not just rapid quenching but a trajectory through alloy composition space that intersects quasicrystal stability fields. In this sense, they are more selective markers of shock, encoding both physical and chemical conditions with unusual specificity.

The cosmochemical implications are profound. Quasicrystals are not merely mineralogical curiosities; they are records of high-energy events that shaped planetary bodies. Their presence constrains redox conditions, pressure–temperature paths and shock histories. Their survival over billions of years indicates resilience that must be accounted for in models of planetary evolution. They remind us that impacts, while destructive, are also creative, generating phases inaccessible to equilibrium processes. In the case of quasicrystals, impacts produced forms of order that had been deemed impossible until their laboratory synthesis.

The search for quasicrystals on other celestial bodies is not speculative but a logical extension of what we have already found. Their occurrence in one meteorite implies a broader distribution. Each new discovery would expand our understanding of how matter organizes under pressure. Missions returning samples from asteroids, the Moon or Mars should incorporate quasicrystal detection into their analytical strategies. Meteorite collections should be revisited with targeted searches. Shock experiments should broaden their scope to include more diverse alloys. Computational models should map the possible stability fields. Together, these efforts will build a more complete picture of quasicrystal occurrence across the solar system.

Quasicrystals are products of extremes, born in microseconds of shock and frozen for billions of years. They carry with them the imprint of collisions that shaped planetary surfaces and sculpted the solar system. They demonstrate that forbidden symmetries are not anomalies, but recurrent outcomes of matter driven beyond its limits. For the community that studies them, the challenge is clear: to extend the search systematically, to interpret their occurrence within the broader framework of planetary science, and to recognize in their structures the record of environments where chaos gave rise to new forms of order. Quasicrystals are messengers from the edge, witnesses of cosmic violence, and enduring testaments to the creativity of extreme environments.

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Conflict of interest

The author declares that there are no conflicts of interest.

Data availability

All the discussed data have been reported in published papers cited in the references list.

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