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Worlds Beyond Earth: Impact Craters

Scars of Cosmic Collisions

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Conclusion

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

An impact crater is a depression in the surface of a solid astronomical body formed by the hypervelocity impact of a smaller object. In contrast to volcanic craters, which result from explosion or internal collapse, impact craters typically have raised rims and floors that are lower in elevation than the surrounding terrain. Impact craters are typically circular, though they can be elliptical in shape or even irregular due to events such as landslides.

Impact craters range in size from microscopic craters seen on lunar rocks returned by the Apollo Program to simple bowl-shaped depressions and vast, complex, multi-ringed impact basins. Meteor Crater is a well-known example of a small impact crater on Earth. Impact craters are the dominant geographic features on many solid Solar System objects including the Moon, Mercury, Callisto, Ganymede, and most small moons and asteroids.

On other planets and moons that experience more active surface geological processes, such as Earth, Venus, Europa, Io, Titan, and Triton, visible impact craters are less common because they become eroded, buried, or transformed by tectonic and volcanic processes over time. Where such processes have destroyed most of the original crater topography, the terms impact structure or astrobleme are more commonly used.

In early literature, before the significance of impact cratering was widely recognised, the terms cryptoexplosion or cryptovolcanic structure were often used to describe what are now recognised as impact-related features on Earth. The cratering records of very old surfaces, such as Mercury, the Moon, and the southern highlands of Mars, record a period of intense early bombardment in the inner Solar System around 3.9 billion years ago. The rate of crater production on Earth has since been considerably lower, but it is appreciable nonetheless.

Earth experiences, on average, from one to three impacts large enough to produce a 20-kilometre-diameter (12 mi) crater every million years. This indicates that there should be far more relatively young craters on the planet than have been discovered so far. The cratering rate in the inner solar system fluctuates as a consequence of collisions in the asteroid belt that create a family of fragments that are often sent cascading into the inner solar system.

Formed in a collision 80 million years ago, the Baptistina family of asteroids is thought to have caused a large spike in the impact rate. The rate of impact cratering in the outer Solar System could be different from the inner Solar System. Although Earth's active surface processes quickly destroy the impact record, about 190 terrestrial impact craters have been identified.

The largest craters, the multi-ring basins of the Moon and Mercury, run to thousands of kilometers across, and the ages span the whole history of the solar system: a few craters on Earth are younger than the oldest human cities, while the great basins of the Moon were excavated before life on Earth had learned to breathe oxygen.

There are approximately twelve more impact craters/basins larger than 300 km on the Moon, five on Mercury, and four on Mars.

Jinlin Crater is a recent impact crater in Deqing County, Guangdong Province, southern China, about 90 metres (300 ft) deep and with a diameter varying between about 820-900 metres (2,690-2,950 ft) across. The crater is tilted, the impact having occurred on a hillside slope, so it is slightly elliptical; its upper rim is about 200 metres (660 ft) higher than its lower. The meteorite that created the Jinlin Crater is estimated to have been 30 metres (98 ft) in diameter.

The impact is tentatively dated to have occurred during the current Holocene geological epoch, or less than 11,700 years ago. If this dating is correct, the Jinlin Crater is by far the largest known Holocene impact crater. A 2025 study analyzed evidence of shock metamorphism in the crater to confirm that it was created by an impact event. The age estimate reported in the initial study was based solely on an analysis of the weathering of the crater rocks.

Such weathering analysis is subject to relatively large error, making this age estimate imprecise. Further analysis, such as radiometric argon-argon dating, could help date the impact more precisely. Jinlin Crater was discovered (recognized as an impact crater) in 2025. That it has been preserved for thousands of years is somewhat unexpected, as the region it's in has a climate featuring heavy rain and high humidity, which generally cause rapid erosion of such features. List of impact craters on Earth

The reader who has never thought about the subject should be handed its strangest fact up front, because it frames everything the chapters will do: Earth is the most cratered planet in the solar system that shows almost no craters. The Moon wears two hundred million years of history openly; the Earth has taken every blow the Moon has taken and more, and hides nearly all of it, in the oceans, under forests and cities, folded into mountains and erased by rain, and the science this book describes is, more than half the time, the art of finding what the planet itself has tried to bury.

Chapter 01: The Discovery of Impact Craters

The discovery of impact craters is the story of how science learned, slowly and against its own instincts, that rocks fall from the sky and leave scars. Every civilization had seen the Moon's pockmarked face, and for most of recorded history no one thought those marks, or the curious round depressions on Earth, had anything to do with each other or with anything arriving from space. The chapter that follows is the argument's history: the eyewitnessed falls that were dismissed, the desert crater that one stubborn mining engineer staked his fortune on, the geologists who proved him right after his death, and the space age that settled the question wholesale. The reader should carry one number as context: the modern catalogs count roughly two hundred confirmed terrestrial craters, and nearly all of them were accepted as impact structures only in the last seventy years.

They are also selectively found in the stable interior regions of continents. Few undersea craters have been discovered because of the difficulty of surveying the sea floor, the rapid rate of change of the ocean bottom, and the subduction of the ocean floor into Earth's interior by processes of plate tectonics.

Daniel M. Barringer, a mining engineer, was convinced already in 1903 that the crater he owned, Meteor Crater, was of cosmic origin. Most geologists at the time assumed it formed as the result of a volcanic steam eruption. In the 1920s, the American geologist Walter H. Bucher studied a number of sites now recognized as impact craters in the United States. He concluded they had been created by some great explosive event, but believed that this force was probably volcanic in origin.

However, in 1936, the geologists John D. Boon and Claude C. Albritton Jr. argued that the huge underground structures buried beneath the Texas coast were of cosmic origin. Grove Karl Gilbert, the era's most respected geologist, had studied the Moon's craters and concluded they were volcanicggested in 1893 that the Moon's craters were formed by large asteroid impacts. Ralph Baldwin in 1949 wrote that the Moon's craters were mostly of impact origin. Around 1960, Gene Shoemaker revived the idea. According to David H.

Levy, Shoemaker "saw the craters on the Moon as logical impact sites that were formed not gradually, in eons, but explosively, in seconds." For his PhD degree at Princeton University (1960), under the guidance of Harry Hammond Hess, Shoemaker studied the impact dynamics of Meteor Crater. Shoemaker noted that Meteor Crater had the same form and structure as two explosion craters created from atomic bomb tests at the Nevada Test Site, notably Jangle

U in 1951 and Teapot Ess in 1955. In 1960, Edward C.

T. Chao and Shoemaker identified coesite (a form of silicon dioxide) at Meteor

Crater, proving the crater was formed from an impact generating extremely high temperatures and pressures. They followed this discovery with the identification of coesite within suevite at Nordlinger Ries, proving its impact origin. Armed with the knowledge of shock-metamorphic features, Carlyle S.

Beals and colleagues at the Dominion Astrophysical Observatory in Victoria, British Columbia, Canada and Wolf von Engelhardt of the University of Tubingen in Germany began a methodical search for impact craters. By 1970, they had tentatively identified more than 50. Although their work was controversial, the American Apollo Moon landings, which were in progress at the time, provided supportive evidence by recognizing the rate of impact cratering on the Moon. Because the processes of erosion on the Moon are minimal, craters persist.

Since the Earth could be expected to have roughly the same cratering rate as the Moon, it became clear that the Earth had suffered far more impacts than could be seen by counting evident craters. Impact cratering involves high velocity collisions between solid objects, typically much greater than the speed of sound in those objects. Such hyper-velocity impacts produce physical effects such as melting and vaporization that do not occur in familiar sub-sonic collisions.

On Earth, ignoring the slowing effects of travel through the atmosphere, the lowest impact velocity with an object from space is equal to the gravitational escape velocity of about 11 km/s. The fastest impacts occur at about 72 km/s in the "worst case" scenario in which an object in a retrograde near-parabolic orbit hits Earth. The median impact velocity on Earth is about 20 km/s.

However, the slowing effects of travel through the atmosphere rapidly decelerate any potential impactor, especially in the lowest 12 kilometres where 90% of the Earth's atmospheric mass lies. Meteors of up to 7,000 kg lose all their cosmic velocity due to atmospheric drag at a certain altitude (retardation point), and start to accelerate again due to Earth's gravity until the body reaches its terminal velocity of 0.09 to 0.16 km/s. The larger the meteoroid (i.e.

While an object of 9,000 kg maintains about 6% of its original velocity, one of 900,000 kg already preserves about 70%. Extremely large bodies (about 100,000 tonnes) are not slowed by the atmosphere at all, and impact with their initial cosmic velocity if no prior disintegration occurs. Impacts at these high speeds produce shock waves in solid materials, and both impactor and

the material impacted are rapidly compressed to high density.

Following initial compression, the high-density, over-compressed region rapidly depressurizes, exploding violently, to set in train the sequence of events that produces the impact crater. Impact-crater formation is therefore more closely analogous to cratering by high explosives than by mechanical displacement. Indeed, the energy density of some material involved in the formation of impact craters is many times higher than that generated by high explosives. Since craters are caused by explosions, they are nearly always circular - only very low-angle impacts cause significantly elliptical craters.

This describes impacts on solid surfaces. Impacts on porous surfaces, such as that of Hyperion, may produce internal compression without ejecta, punching a hole in the surface without filling in nearby craters. This may explain the

'sponge-like' appearance of that moon. It is convenient to divide the impact process conceptually into three distinct stages: (1) initial contact and compression, (2) excavation, (3) modification and collapse.

In practice, there is overlap between the three processes with, for example, the excavation of the crater continuing in some regions while modification and collapse is already underway in others. In the absence of atmosphere, the impact process begins when the impactor first touches the target surface. This contact accelerates the target and decelerates the impactor. Because the impactor is moving so rapidly, the rear of the object moves a significant distance during the short-but-finite time taken for the deceleration to propagate across the impactor.

As a result, the impactor is compressed, its density rises, and the pressure within it increases dramatically. Peak pressures in large impacts exceed 1 terapascal to reach values more usually found deep in the interiors of planets, or generated artificially in nuclear explosions. In physical terms, a shock wave originates from the point of contact. As this shock wave expands, it decelerates and compresses the impactor, and it accelerates and compresses the target.

Stress levels within the shock wave far exceed the strength of solid materials; consequently, both the impactor and the target close to the impact site are irreversibly damaged. Many crystalline minerals can be transformed into higher-density phases by shock waves; for example, the common mineral quartz can be transformed into the higher-pressure forms coesite and stishovite.

Many other shock-related changes take place within both impactor and target as the shock wave passes through, and some of these changes can be used as

diagnostic tools to determine whether particular geological features were produced by impact cratering. As the shock wave decays, the shocked region decompresses towards more usual pressures and densities. The damage produced by the shock wave raises the temperature of the material.

In all but the smallest impacts this increase in temperature is sufficient to melt the impactor, and in larger impacts to vaporize most of it and to melt large volumes of the target. As well as being heated, the target near the impact is accelerated by the shock wave, and it continues moving away from the impact behind the decaying shock wave. Contact, compression, decompression, and the passage of the shock wave all occur within a few tenths of a second for a large impact.

The subsequent excavation of the crater occurs more slowly, and during this stage the flow of material is largely subsonic. During excavation, the crater grows as the accelerated target material moves away from the point of impact. The target's motion is initially downwards and outwards, but it becomes outwards and upwards.

The flow initially produces an approximately hemispherical cavity that continues to grow, eventually producing a paraboloid (bowl-shaped) crater in which the centre has been pushed down, a significant volume of material has been ejected, and a topographically elevated crater rim has been pushed up. When this cavity has reached its maximum size, it is called the transient cavity. The depth of the transient cavity is typically a quarter to a third of its diameter.

Ejecta thrown out of the crater do not include material excavated from the full depth of the transient cavity; typically the depth of maximum excavation is only about a third of the total depth. As a result, about one third of the volume of the transient crater is formed by the ejection of material, and the remaining two thirds is formed by the displacement of material downwards, outwards and upwards, to form the elevated rim.

For impacts into highly porous materials, a significant crater volume may also be formed by the permanent compaction of the pore space. Such compaction craters may be important on many asteroids, comets and small moons. In large impacts, as well as material displaced and ejected to form the crater, significant volumes of target material may be melted and vaporized together with the original impactor.

Some of this impact melt rock may be ejected, but most of it remains within the transient crater, initially forming a layer of impact melt coating the interior of the transient cavity. In contrast, the hot dense vaporized material expands

rapidly out of the growing cavity, carrying some solid and molten material within it as it does so. As this hot vapor cloud expands, it rises and cools much like the archetypal mushroom cloud generated by large nuclear explosions.

In large impacts, the expanding vapor cloud may rise to many times the scale height of the atmosphere, effectively expanding into free space. Most material ejected from the crater is deposited within a few crater radii, but a small fraction may travel large distances at high velocity, and in large impacts it may exceed escape velocity and leave the impacted planet or moon entirely.

As ejecta escapes from the growing crater, it forms an expanding curtain in the shape of an inverted cone. The trajectory of individual particles within the curtain is thought to be largely ballistic.

Small volumes of un-melted and relatively un-shocked material may be spalled at very high relative velocities from the surface of the target and from the rear of the impactor. Spalling provides a potential mechanism whereby material may be ejected into inter-planetary space largely undamaged, and whereby small volumes of the impactor may be preserved undamaged even in large impacts. Small volumes of high-speed material may also be generated early in the impact by jetting.

This occurs when two surfaces converge rapidly and obliquely at a small angle, and high-temperature highly shocked material is expelled from the convergence zone with velocities that may be several times larger than the impact velocity. In most circumstances, the transient cavity is not stable and collapses under gravity.

In small craters, less than about 4 km diameter on Earth, there is some limited collapse of the crater rim coupled with debris sliding down the crater walls and drainage of impact melts into the deeper cavity. The resultant structure is called a simple crater, and it remains bowl-shaped and superficially similar to the transient crater.

In simple craters, the original excavation cavity is overlain by a lens of collapse breccia, ejecta and melt rock, and a portion of the central crater floor may sometimes be flat. Above a certain threshold size, which varies with planetary gravity, the collapse and modification of the transient cavity is much more extensive, and the resulting structure is called a complex crater.

The collapse of the transient cavity is driven by gravity, and involves both the uplift of the central region and the inward collapse of the rim. The central uplift is not the result of elastic rebound, which is a process in which a material with elastic strength attempts to return to its original geometry; rather the collapse is a process in which a material with little or no strength attempts to return to

a state of gravitational equilibrium.

Complex craters have uplifted centers, and they have typically broad flat shallow crater floors, and terraced walls. At the largest sizes, one or more exterior or interior rings may appear, and the structure may be labeled an impact basin rather than an impact crater.

Meteor Crater, or Barringer Crater, is an impact crater about 37 mi (60 km) east of Flagstaff and 18 mi (29 km) west of Winslow in the desert of northern Arizona, United States. The site had several earlier names, and fragments of the meteorite are officially called the Canyon Diablo Meteorite, after the adjacent Canyon Diablo. Meteor Crater lies at an elevation of 5,640 ft (1,719 m) above sea level.

It is about 3,900 ft (1,200 m) in diameter, some 560 ft (170 m) deep, and is surrounded by a rim that rises 148 ft (45 m) above the surrounding plains. The center of the crater is filled with 690-790 ft (210-240 m) of rubble lying above crater bedrock. One of the features of the crater is its squared-off outline, believed to be caused by existing regional jointing (cracks) in the strata at the impact site.

Despite an attempt to make the crater a public landmark, the crater remains privately owned by the Barringer family to the present day through their Barringer Crater Company. The Lunar and Planetary Institute, the American Museum of Natural History, and other science institutes proclaim it to be the "best-preserved meteorite crater on Earth". It was designated a National Natural Landmark in November 1967.

The crater was created about 50,000 years ago during the Pleistocene epoch, when the local climate on the

Colorado Plateau was much cooler and damper. The area was an open grassland dotted with woodlands inhabited by mammoths and giant ground sloths. The object that excavated the crater was a nickel-iron meteorite about 160 ft (50 m) across. The speed of the impact has been a subject of some debate.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.